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The potential for ground-sourced cooling of domestic buildings in desert

By

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A doctoral thesis submitted in partial fulfilment of requirements for the award of Doctor of Philosophy at Loughborough University Loughborough, Leicestershire

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Abstract
of a PhD Thesis on
The Potential for ground-sourced cooling of domestic buildings in desert
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In many dry desert climates such as in Kuwait, the summer season is long with a mean daily maximum temperature of 45°C. A round 80% of total electricity generation is consumed by air-conditioning systems in domestic buildings. A hybrid cooling technique to reduce the domestic cooling demand would have both environmental and economic benefits for Kuwait. A passive cooling technique, which assists the situation, is ground cooling. In this thesis a thermal model of an earth air heat exchanger (EAHE) has been developed to calculate the pre-cooling of ventilation air that can be achieved for a building through use of a buried pipe below ground surface. The predictions of the model were validated against other published models and data showed very good agreement (within the range of ±0.6°C). Parametrical analysis for the model was conducted to ascertain the best configuration as part of this modelling process, it was necessary to also predict subsoil temperature. Using an existing model (Labs 1989) hourly predictions are made of the soil sub-surface temperature as a function of depth below ground surface and time of the year. The treatment employs a value of soil thermal diffusivity based on the amplitude method and an accurate assessment of the physical properties of Kuwaiti soil. The subsoil temperatures were compared against measured Kuwaiti ground temperature values, and these showed good agreement within an accuracy of about ±1°C. Information about the underground sub-surface environment (i.e. subsoil temperatures and subsoil cooling potential in terms of cooling/ heating degree-days) with particular reference to Kuwait is
presented in this thesis. Both models (EAHE and subsoil environment models) were encoded within the TRNSYS environment. A Kuwaiti Typical Meteorological Year (TMY) was prepared and simulation was used to calculate the cooling load of an efficient prototype Kuwaiti dwelling with and without EAHE assistance. The simulation of the dwelling with EAHE assistance showed potential for reducing the cooling loads by up to 30%. The cost effectiveness of applying an EAHE system to a typical Kuwaiti building (example building) has been investigated using life cycle costing techniques for an assumed period of 25 years. Whilst the EAHE system at present appears to be a pessimistic investment for the Kuwaiti consumer based on the current electricity tariff, it is, however, cost-effective for the Kuwaiti government.

Results are presented of analyses based on changes to electricity tariffs and to government subsidy levels. These results provide useful guidance to inform future policy and decision-making by the government of Kuwait.
DEDICATION

To my mother Kordia and my step mother Shua’a,
For their prayers and good wishes

To my wife Jawharrah,
For her endless patience and support

For my daughters Assma, Norah and Maha and my son Ahmed,
For their smiles and tolerance during this long research work
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This work, or any of my previous degrees, would not have been completed if it was not for the unending support of my parents. I only wish my father alive to see it done.
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Chapter 1: General Introduction

1.1 Introduction

Economic and industrial development in countries which have a dry desert climate has led to an increasing demand for electricity, much of which is consumed in air conditioning systems which have a high peak summer demand due to the high external dry-bulb temperatures. Reduction of energy consumption in buildings is a major aim worldwide and is a particular challenge in desert climates. Such conditions exist in a number of areas throughout the world: one such area is the State of Kuwait, which is located in a dry desert region characterised by high temperature extremes with an average afternoon maximum value of 45°C for a period of about six months of the year. The harshness of the climate in Kuwait requires domestic air conditioning to be deployed between the beginning of April and the end of October. Hence, there is a significant use of energy by the domestic air conditioning sector in Kuwait, domestic air-conditioning accounts for about 70%-80% of electric power consumption in Kuwait and despite the fact that there is a reduction in the population of Kuwait in the summer season, the load for the months May-September is 33% higher than the year-round average (Al-Ajmi et al 2002a, Al-Ajmi et al 2002b). Hence methods for reducing this energy demand would have clear economic and environmental benefits.

Furthermore, as power generation is generally by means of a fossil fuel-fired plant, there is a clear link between electricity consumption and carbon dioxide and other combustion emissions. The increased ambient temperatures, which will result from climate change, have the potential to further exacerbate this situation, (Al-Ajmi et al 2002a).
There are a number of ways in which energy consumption of a building can be reduced. Several attempts were presented to solve the existing problem in Kuwait (some of these are presented in Chapter 2), yet domestic energy consumption is still increasing. In order to have an impact on any significant scale, any strategy should be capable of application to existing buildings. A passive cooling strategy which could favourably affect this situation is ground-sourced cooling, either by direct coupling of the building (the building’s envelope is in direct contact with earth) or by the use of an Earth-Air Heat Exchanger (EAHE), with specific reference to the state of Kuwait. This study is focused on the Earth-Air Heat Exchanger (EAHE), also known as a ground cooling pipe/tube, as a potential means of reducing domestic air conditioning loads in dry desert climates like that of Kuwait. The EAHE consists of a buried pipe through which outdoor ambient air is drawn and supplied to the building, usually by means of a fan. The cooling ability of the earth-air heat exchanger is affected by many conditions such as weather, soil properties and parameter variations (i.e. pipe length, pipe diameter, air flow rate inside the pipe, and burial depth of the pipe below ground surface.

1.2 The Importance of the Research to the State of Kuwait

Power stations in Kuwait are generally run by means of oil fuel and natural gas, which comprise the main national income in Kuwait, and have a clear link with electricity consumption. Energy prices have witnessed a sharp increase in the last three decades as a result of several major international energy crises in the area where Kuwait is located. These are, namely:

- The 1973/74 oil embargo.
- The 1979 crisis, arising from the political upheaval and subsequent revolution in Iran.
• The political upheaval and consequences of the Iraq/Iran war (first Gulf War) during 1980/89, which targeted the oil tankers.

• The political upheaval and subsequent invasion by Iraq of the state of Kuwait (Second Gulf War) during 1990/91. This resulted in the firing of most of the Kuwaiti oil wells, which paralysed much of the Kuwaiti government's income and as a result consumed most of the new generation savings which were used to repair all the damages resulting from this invasion.

• Current crises in the Middle East, arising from the political upheaval and the existing situation between Palestinian and Israel.

As a consequence of the above events, energy prices have escalated worldwide due to the uncertainties affecting the supply of oil. Power stations consume fossil fuels (oil and natural gas), that are a valuable market price, and thus more energy consumption would lead to consume more fossil fuels. Addition to the cost of fossil fuels consumed by power stations in Kuwait, cost of buildings, equipping, running maintaining the equipment, and distributing the power after it has been generated are also implies to the total cost of energy consumption (Nadeem et al 1996). The government of Kuwait subsidises about 93% of domestic energy consumption (Al-ragom et al 1998). This means that the Kuwaiti consumer pays a very low electricity tariff which contributes to the increase in power demand and to wastage and uneconomic usage of electric energy, despite the fact that a campaign to save energy was started by the government more than a decade ago. The annual per capita energy consumption in Kuwait has grown at an average rate of 7.7%, whilst that for industrialised countries is about 2-3% (Al-Temeemi, 1995). The government of Kuwait has been increasing the number of power stations, seeing this as the only solution to meet the electricity needs brought
about by the growth of population (31% within 6 years); this, however, will exacerbate the problem further (more details in Chapter 2). Hence, use of new energy sources to reduce (domestic) energy consumption becomes a very attractive issue in Kuwait. This is explored in this thesis by the potential use of the Earth-Air Heat Exchanger (EAHE).

1.3 The Aim and Objectives of the Research

The aim of this study is to investigate the potential of ground-based cooling as a means for reducing domestic energy consumption in Kuwait (or similar environments).

The objectives of this study are as follows:

- To draw attention to the energy consumption problem in Kuwait and how it is exacerbated as a result of its weather situation (Chapter 2).
- To investigate and predict Kuwait subsoil temperatures using an existing (Labs 1989) model and Kuwait soil properties. The suitability of Labs’ model for predicting subsoil temperature in conditions similar to those of Kuwait will be ascertained by comparison with measured Kuwaiti ground temperatures. The concept of subsoil degree-days will be introduced and investigated as a means for estimating the potential cooling/heating ability of the ground (Chapter 4).
- To develop a theoretical model of the Earth Air Heat Exchanger (EAHE) that works to predict the temperature of outlet air that in turn will be used to ventilate a typical Kuwaiti domestic building. The EAHE model will be validated by comparison with data from two published sets of measured data and one theoretical study. Parametrical studies will be conducted to optimise the EAHE system configuration (Chapter 5).
• Using parametrical analysis, and based on Kuwaiti construction material for a typical house, to determine the best configuration for a Kuwaiti residence for use as an energy-efficient prototype example and which will be equipped with the EAHE (Chapter 6).

• The energy saving of the example building equipped with the EAHE system will be assessed and compared with the same building without EAHE assistance (Chapter 7).

• Cost-effectiveness analysis will be conducted of the example building equipped with the EAHE system from the viewpoints of both the Kuwaiti consumer and the Kuwaiti government and advice will be offered to aid decision-making (Chapter 8).

1.4 Research Methodology

Several tasks were identified in this study to investigate the cooling potential of the subsoil environment via the EAHE as a means to ventilate a Kuwaiti prototype building. These tasks are described next.

1.4.1 Literature Review

A search of the literature on the subject under investigation has been undertaken during the initial phase in this study. Developments in the subject have also been regularly reviewed during the course of the study period. The major papers reviewed are listed in the reference section at the end of this thesis. Literature that has been reviewed include papers on the modelling of subsoil temperatures with the use of measured soil properties and earth air heat exchangers (or earth cooling pipe/tubes), as well as reports on experimental studies. Articles on the performance of the earth air heat exchanger under different climatic conditions (e.g. cold, tropical, Mediterranean,
and humid climate) were also examined. Additional articles included the calculation of cooling loads using different methods, such as degree day methods, and simulation programs e.g. TRNSYS-PREBID. Other articles related to analysis of the cost effectiveness of different types of building systems were also reviewed.

1.4.2 Mathematical Modelling

A theoretical model of the EAHE was developed for predicting the outlet air temperature and cooling potential of this system in a desert climate. The mathematical model is of a circular buried cooling pipe as a cross-flow heat exchanger with one fluid unmixed (the air), with negligible thermal resistance of the pipe walls. An external thermal resistance was provided by a concentric cylinder of earth of arbitrary thickness, which was exposed to an undisturbed ground temperature as a boundary condition.

Labs’ mathematical model of ground temperature (or subsoil temperature) was used to predict the subsoil temperature at depths below the ground surface and at times different of the year. The accuracy of Labs’ model at any particular site depends mostly on measured soil properties taken from site location. Thus measured input parameters are taken from two Kuwaiti sites in this study. Soil thermal diffusivity is an important parameter which was found using two methods, namely straightforward definition of thermal diffusivity and the ratio of the annual amplitude at two layers, otherwise known as the Direct Amplitude Method (DAM).

1.4.3 Model Validation

In order to test the proposed EAHE model it is important first of all to validate the Kuwaiti subsoil temperature predictions against the subsoil temperatures measured at
site location (Kuwait ground temperature). The EAHE system was validated by comparison with three published works:

- There are two experimental studies with parameters that would be similar to the proposed application of the EAHE system; one in India by Shingari (1995) and the other is in the USA by Dhaliwal et al (1984). In these two studies, ambient air temperatures entering the EAHE system (pipe inlet) were used with respect to other parameters (see Chapter 5). The outlet air temperature of the EAHE model developed in this work showed good agreement with these two experimental studies outlet air temperature.

- A theoretical developed study by Mihalakakou et al (1995) used a simplified method based on the overall performance of the earth-air heat exchanger. The authors provided easy-to-use tables with step by step procedures. Their model was adapted into a TRNSYS-TYPE using a Kuwait Typical Meteorological Year (TMY) and simulated against the EAHE model developed in this work; results were compared (see Chapter 5).

1.4.4 Simulation Program

In this research, the subsoil environment and EAHE performance were investigated in a desert climate like that in Kuwait using the TRNSYS/IISIBAT simulation programme. The IISiBat (one of TRNSYS packages, see Chapter 3) simulation program was used to conduct: (i) Subsoil temperature predictions and cooling/heating potential assessments using degree-days techniques. (ii) EAHE system performance. (iii) Assessments of example building performance with and without the EAHE system using TRNSYS-TYPE 56 and TRNSYS-PREBID facility (multi-zone building simulation model) (see Chapter 3, Chapter 4, Chapter 5 and Appendices B and C). EAHE was also encoded into MATLAB program, which is capable of being
used for parametrical study of the performance of the EAHE system. Further explanations follow.

i) Subsoil temperature was predicted using a programme called “Type 262”. Type 262 was modelled using a Fortran subroutine, which was then developed and encapsulated into the TRNSYS/IISiBat environment. Monthly cooling/heating degree-days were predicted using TRNSYS-EQUA and Equations in Appendix (B), (see Figure 1.1).

ii) The Earth Air Heat Exchanger (EAHE) modelled used a programme called Type 264. Type 264 was modelled using a Fortran subroutine, which was then developed and encapsulated into the TRNSYS/IISiBat environment system. The EAHE performance was determined, and parametrical studies were carried out using MATLAB programme.

iii) The performance of the example building with and without the EAHE system was simulated using the TRNSYS-TYPE 56 and TRNSYS-PREBID facilities (multi-zone building simulation model) as shown in Figure 1.2. (Also see Chapter 3, Chapter 4, Chapter 5 and Appendices B and C).
Outputs: Type262

Ground Temp.

Parameters:
- $z$ Par(1)
- $T_m$ Par(2)
- $\alpha$ Par(3)
- $t_o$ Par(4)
- $A_s$ Par(5)

TRNSYS-EQUA

SSDD

Base-Temp.

---

**Figure 1.1** Component configuration of TRNSYS–Subroutines with model Type262

---

Kuwait Weather File (TMY) Type9

EAHE Model Type 264

Building Model Using TRNSYS-Type56

Solar Radiation Processor TRNSYS-Type16

Sky-Temperature TRNSYS-Type69

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**Figure 1.2** TRNSYS system configuration for the simulation of EAHE system thermal performance using cooling degree-days and TRNSYS-TYPE56
1.5 Outline of Thesis

This thesis is organised into 9 chapters. They are as follows:

Chapter 1: General introduction

An introduction to the need for studying ground passive cooling by means of the EAHE system in a desert climate like that in Kuwait. The importance of the research, the objectives, and the methodology of this research are presented.

Chapter 2: Kuwait Profile

The chapter establishes the relevance of the research to Kuwait, this included literature reviews of: Kuwait weather conditions, building types, materials and construction techniques in Kuwait, domestic energy consumption profile, prior studies of energy consumption improvements and innovations, and the need for this EAHE system.

Chapter 3: Software for simulation program

The chapter reviews the TRNSYS simulation programme and its components, it also highlights the TRNSYS-subroutines used in this research.

Chapter 4: Sub-soil environment profile in Kuwait

In this chapter, the analysis of the underground subsoil environment in a desert climate with particular reference to Kuwait is presented. Using an existing model by Labs' (1989), hourly predictions are made of the soil subsurface temperature as a function of depth below ground level and time of the year. The treatment employs values of thermal diffusivity based on the amplitude method and an accurate assessment of the physical properties of Kuwaiti soil. The subsurface temperatures predicted using the model were compared against measured Kuwaiti ground temperature values, which showed that the best agreement with the model predictions
occurred for a soil thermal diffusivity value of $0.0038 \text{ m}^2/\text{hr}$. The degree-days technique (for quantifying the severity of the climate and relating it to energy used for the space heating/cooling of buildings) is used to show the potential of the subsurface environment for moderating building energy usage.

Chapter 5: EAHE Model

In this chapter, the background to the EAHE system or earth cooling pipe/tube is reviewed. A theoretical model of the EAHE is developed for predicting the outlet air temperature and its cooling potential in desert climates like that in Kuwait. The model was validated against other published models and shows good agreement. For the optimum design of the EAHE system an extensive sensitivity analysis (5 cases) was performed.

Chapter 6: Example Building

In this chapter, building materials are selected for the example building that will be equipped with the EAHE system. A comparison between two Kuwaiti common walls, known as ‘Classical’ and ‘AAC’ is presented. Parametric studies were conducted on an example building to represent the design guidelines pertaining mostly to energy conservation measures of the building envelope, namely window types, size and direction, infiltration and ventilation.

Chapter 7: Example building with assistance of the EAHE system

In this chapter, the EAHE system was remodelled to include fan energy consumption and thus, complete system of EAHE. Energy consumption of the example building with and without assistance of the EAHE system is presented. The period for operating the EAHE system during the year is established.

Chapter 8: Cost effectiveness of the EAHE with the example building
In this chapter the cost effectiveness of applying the EAHE system to a typical Kuwait domestic building (example building) is presented using life cycle costing techniques. One of the life cycle techniques is payback period analysis using Net Present Value (NPV). Cost-effectiveness analysis for both the Kuwaiti consumer and the Kuwaiti government is presented over a period of 25 years.

Chapter 9: Conclusions and further studies

In this chapter, the conclusions and further studies are presented.
Chapter two: Kuwait profiles

2.1 Introduction

Over the last forty years, the state of Kuwait has increased tremendously in population. In 1965, the total number of Kuwaitis and Non-Kuwaitis was 467,339 while in 1995 this figure became 1,575,982 with the expectation of a population of 2,274,980 in 2001. This represents an increase of about 31% within a 6 year period (Ministry of Planning 1999). Today, nearly 70% to 80% of the peak electricity loads are due to air-conditioning plant, and as the population grows the demand of comfort increases (MEW 2000). As seen from Figure 2.2, as the energy produced increases, the demand for energy keeps pace. This difference between energy produced and consumed is about 14% over the years from 1988 to 1999 (MEW, 2000).

In the past, power stations in Kuwait consumed natural gas, which was available and was regarded as a waste product of the oil industry, and if not used locally, was flared off at oil-gathering centres. The cost of providing electricity to the consumer, however, consists not only of the price of the fuel needed to supply the generators, but also the cost of building, equipping, running and maintaining the generating infrastructure, and of distributing the power after it has been generated (MEW 2000). These costs have risen by a factor of four in the past few years (MEW 2000, MEW 1999). Moreover, natural gas is no longer available as it is turned into petrochemical products through local industries, or is exported as a valuable product. All the power stations1 (run on natural gas, crude oil or fuel oil that has a world market price). However, sales of oil and natural gas comprise the main national income for Kuwait.

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1 In Kuwait, electricity and water are produced by desalinating seawater by employing thermal steam turbines and multistage flash desalination units, (Nadeem et al 1996).
These have been given top priority in development projects adopted by the Kuwaiti government, depending on the balance between production level (oil) and national consumption (for development) (Ministry of Planning 1999). Therefore, and because the price of oil has risen four-fold within the last two decades, there has been a substantial rise in revenue, which, in turn, expands economic growth. This growth leads to rapidly expanding towns, cities and industries in Kuwait. Development year after year, together with the growth in power consumption that occasionally reaches the maximum peak load of the power produced over the summer period (MEW 2000), leads to widespread electrical “load shedding” and power cuts in some areas in Kuwait. In addition, Kuwait needs even more power stations to support its rapid growth of consumer for electrical demand. The electrical demand of all Kuwaiti sectors in year 1988 is shown in Figure 2.3, where it can be seen that the domestic sector is the highest figure of 48% of total electrical consumption (Essam 1993). The domestic sector of the economy consumed 48% of the total national electricity energy general compared with other sectors, reading it the largest consumer. The percentage consumptions for other sectors are shown in Figure 2.3, (Essam 1993). The continuous increase in energy consumption has been due to the increased use of energy in buildings as a requirement for the improvement of the standard of living in Kuwait. In range of 70% (Maheshwari et al 2001) to 80% (MEW 2000) of this energy is consumed by domestic air conditioning (which is generally deployed between the beginning of April to the end of October). Despite the fact there is a reduction in population in summer, the load for the months May to September is 33% higher than the year-round average (Al-Ajmi, 2002a). Domestic air conditioning energy consumption for Kuwait and other countries consumption compares as follows (see Figure 2.1):
Untied Kingdom 22%; USA 21%; Australia 21%; Saudi Arabia 65% (in Eastern Area), (Al-hammad et al 1992).

Eastern and Middle Area of Saudi Arabia has a similar desert climate to that in Kuwait.

Figure 2.1 Domestic air-conditioning energy consumption for Kuwait, UK, USA, Australia and Saudi Arabia.

Furthermore, due to the increase of electricity demand in the domestic sector, government of Kuwait is planning to build further 8 power station plants with a power supplement of 240 MW to keep up with the rapid growth of economic development plans (Alr’ai Alam 2001). The true cost to the Kuwaiti government of generated electricity in Kuwait is several times (about sixteen times) the price at which it is sold (Al-awadhi et al 1989, Eltony 1996). Therefore, electricity used by residential
buildings in Kuwait is growing at a disproportionate and increased rate. The relatively low electric tariff to consumer is about 2 files per Kilowatt hour (0.002 files per kWh, equivalent to £ 0.004 per kWh) (Al-Ragom et al 1998, Eltony 1996) which contributes to increased power demands due to the wastage and uneconomic usage of electric energy. The annual per capita energy consumption has grown at an average of 7.7%, while that for industrialized countries is about 2-3% (Al-Temeemi 1995), which reflects the waste and extravagance prompted and encouraged by the very low price of electricity.

The Kuwaiti government has become aware of the importance of energy conservation practice during the last decade and even more so after the Gulf War of 1991, in which a substantial amount of financial and energy resources were destroyed by the Iraqi soldiers when they withdrew from Kuwait. For these reasons, the Kuwaiti government is trying to find solutions to the problem and wants to solve the problem somehow.

At present, erecting more power stations would appear to be the most obvious solution, though this has implication for sustainability ‘global warming’ risk. In the view of this, the Kuwaiti government is now spending more money and time thinking of hybrid new sources of energy, or suitable renewable energy sources which may help to cut down electricity demand rather than increasing power station plants which will further burden the Kuwaiti national budget.
Figure 2.2 Annual electrical energy generation and consumption in Kuwait (Million kWh)

Figure 2.3 Percentage of electrical consumption by sector for 1989 in Kuwait (Essam 1993).
2.2 Geological consideration

Kuwait is a small country located in the northwestern corner of the Arabian Gulf. The Arabian Gulf is bound in the east and in the southwest by the Kingdom of Saudi Arabia, and in the north and west by the Republic of Iraq. The total land area of Kuwait is 17818 km². The land surface is that of flat sandy desert with very small rocky hills. There are shallow valleys called “Wadi” in the desert such as Wadi Albateen, and Wadi Al-shigaia. There are low limestone fine silts and mud between high and low tide along the coastline in the eastern region -see Figure 2.4. The land in Kuwait gradually slopes from the western region of Kuwait to the Arabian Gulf at the east region “coastline” at an average slope of 1 in 500. (Allison 1974b, Ministry of planning 1999).

Figure 2. 4 Kuwait Geographical Map.
2.3 Characteristics of Kuwait Climate

Kuwait State is located between 29° 13' latitude North and longitude 47° 58' East at a mean sea level (m.s.l) of 45m. The weather in Kuwait is characterized as a typical hot dry desert climate in summer with high temperature extremes and intense solar radiation with clear skies. The summer season in Kuwait starts at the beginning of April and continues until the end of October, with the highest temperatures being recorded in July and August with an afternoon average maximum of 45°C (see Figure 2.5 and Figure 2.6), these are the very critical cooling months through the day and night. During the summer season the mean ambient air temperature is 37°C (Kuwait International Airport, 1995,1983). During the short winter, the weather is dry and comfortably cool, and generally mild, the minimum temperature recorded being below 5°C, occasionally reading zero. The winter monthly mean temperature does not normally fall below 10°C (Al-Ajmi et al 2002b). Precipitation is low and dust storms are common. In addition, the air is generally dry. Average relative humidity in Kuwait during the summer is in the range of 14% to 42% while during the winter is in the range of 42% to 80% (Al-Ajmi et al 2002b). In the months of July-August, the diurnal variation in temperature exceeds 19°C-see Figure 2.5. The prevailing wind in Kuwait (about 60% of all winds) is from the north to northwest and reaches the country after having passed over the western Asian land mass. When the winds come from the southeast across the Arabian Gulf, this results in warm to hot weather and a lightly humid condition lasting for a very short time during the summer, and cool with little damp conditions in winter.

Kuwait is subjected to intense solar radiation that has a strong influence on Kuwait’s climate in the summer see-Figure 2.7, and Figure 2.9 as well for diffuse radiation. The
total radiation falling on vertical and horizontal surfaces in all directions N, NE, E, SE, S, SW, W, NW, H are shown in Figure 2.8. It can be observed from the chart in Figure 2.8 that the solar intensities on horizontal surfaces are the greatest at mid-July, reaching 940 W/m² (Allison 1979a). This may cause roof surfaces to be under high intensity solar radiation which leads to the consideration that the roof is a critical point in a building and needs to be considered very carefully in order to minimise the heat gain into the building. The orientation of the building and its windows in a desert climate a very crucial subject, which may need further consideration by researchers for Kuwait.

Figure 2.5 Ambient dry bulb temperature (DBT) and wet bulb temperature (WBT) from the beginning of July till mid-August (recorded by Kuwait International Airport, year of 1995).
Figure 2.6 Ambient temperature as recorded by Kuwait International Airport (year of 1995).

Figure 2.7 Global radiation of Kuwait for whole year recorded by Kuwait International Airport (year of 1995)
Figure 2.8 Direct solar radiation on vertical and horizontal surfaces during Mid-July in Kuwait (Allison 1979a).

Figure 2.9 Diffuse Radiation (Kuwait TMY) from the beginning of May till end of September (recorded by KISR 1995).
2.4 Building Type in Kuwait

The Government of Kuwait supports people of limited income so as to have equality of socio-economic circumstances with other prosperous Kuwaiti people. Hence, a public housing programme was adopted in the early 1950's (Al-shatti, 1989). This programme is basically as a ‘rent to own’ strategy programme. The typical dwelling units found in Kuwait can be divided into two categories. The first type is the government dwelling type NHA (National Housing Authorities), which is the majority of housing types in Kuwait which is similar in design and construction materials with a high standard of quality (Figure 2.10). The second type is the private dwelling that is financed by the government and is built by the owner of the house (Figure 2.12).

Private houses are built similarly like NHA houses in terms of thermal performance of the exterior walls and roof building materials due to the requirement of the building code in the municipality of Kuwait. However, the private house owner has the right to design his house freely with consultant engineering firms, based on the requirement of the municipality; the latter body grants approval for all civil and architecture work, as does the Ministry of Electricity and Water (MEW) for electricity and energy work.

In this thesis, the example building to be equipped with an EAHE has construction materials that are similar to NHA housing (for more details see Chapter 6).
2.5 Materials and Techniques of Construction in Kuwait

In past times, Kuwaiti builders utilized the available local materials to fulfil their construction needs. Buildings in the past basically were built from mud mixed with straw or with stones or bricks made of mud, bamboo, palm tree mattes and wood beams.

Ceilings were built from wood beams called mangrove poles, with a diameter of 10 cm. These were supported by the wall at a spacing along the wall of 30-40 cm. Then, layers of bamboo were placed on top at 45 degrees to the wood beams, and above that, palm tree mattes were placed on top of the bamboo, followed by mud until it covered the tree mattes, then a layer of ash, then another layer of mud (Allison 1973,1975, Al-awadhi et al 1990).

Walls were built from mud, mud brick or mud with stone from the sea, using a large thickness of wall (the thickness of the wall was between 40-60cm) to support the
ceiling wooden beams (e.g. Figure 2.11). However, the ceiling and the massive mud wall helps to slow the absorption of heat from direct solar radiation, to diffuse it and to delay its impact on interior spaces (Al-awadhi et al 1990).

In present times, building materials in Kuwait have changed, as have building technologies since the time when oil was discovered (in the late 1930's and the beginning at the of the 1940's). New imported building materials arrived such as cement, steel, masonry blocks, aluminium glass, finishing materials, sand–lime brickwork, and all kinds of paints, tiles, stones...etc, for use in flooring, roofing, and walls.

Figure 2.11 Old house showing a large thickness of mud wall, or mud brick wall.

Most Kuwaiti domestic buildings are nowadays built from reinforced concrete with masonry blocks and various types of exterior finish. They have large windows and doors.
In fact, the design of most private houses in Kuwait in the late sixties, seventies and eighties had concentrated on better facades with large areas of glass and large opening doors, paying no attention to the heat gain or loss. In addition, luxury interior designs made no effort to be energy conscious, while air-conditioning is used extensively to overcome the indoor thermal discomfort in the summer period.

Unfortunately, such buildings with all their advantages and disadvantages, were erected in the Kuwaiti environment with complete disregard to climatic conditions (e.g. Figure 2.12), since comfort could be ensured through unchecked use of air-conditioning. However, the government has started to realise the impact of energy cost on the national budget. The Government has encouraged Kuwaiti institutes to participate in solving the problem. One of these is Kuwait Institute for Scientific Research (KISR), which was established by the government to be associated with new technologies, which may help finding solutions to the problem.

2.5.1 Code of Practice

The Ministry of Electricity & Water (MEW) publication on rules and regulations for design of air-conditioning systems in Kuwait conditions, Third Edition 1983 stated that the recommended “U” values for external walls and roofs shall not exceed the following: (MEW 1999, 1983)

- External walls = 0.568 W/m² °C
- Roof = 0.4 W/m² °C
However, the code of the Ministry of Electricity & Water (MEW) has not been modified since the year 1983 (Maheshwari 2001), since when more effective energy-efficient products and techniques have developed. Some work is now going on to update the building code in Kuwait. However, to date, the example building that will be used in this thesis to examine the EAHE system (in Chapter 6) is chosen to be one of the most common building materials used in Kuwait with a “U” value that meets the MEW standard.

Figure 2.12 Private building in Kuwait with a large area of glass showing little consideration of energy issues.
2.6 Thermal performance and Energy Consumption of Kuwaiti dwellings

Cooling, heating, ventilation and air-conditioning of buildings are the most important factors that contribute to energy waste in Kuwait (Maheshwari et al 2001). However, energy conservation in Kuwaiti buildings has been studied through several technical innovations and improvements by Kuwait Institute for Scientific Research (KISR) and some other Kuwaiti researchers. In the following sections, literature is reviewed relating to energy conservation and thermal performance of Kuwaiti buildings (all information provided are based on the custody of each author): Topics addressed cover:

- The environment and human comfort in Kuwaiti buildings.
- Reduced cooling load through the application of insulation.
- Reduced cooling load through using white or whitewash colour of an exterior building surface.
- Reduction of cooling load by controlling heat gains through the openings.
- Experimental studies illustrating heat gain effects in Kuwaiti buildings.
- Solar energy and indirect evaporative cooling in Kuwait.

2.6.1 The environment and human comfort in Kuwaiti buildings

The human body has to maintain a core temperature very close to 37°C and since heat is being generated all the time, the body has to continually dissipate this in order to maintain the thermal balance of the body.
There is no absolute standard of comfort; it varies from the tolerance of one individual to another and their feelings regarding ideal environmental conditions. In Europe, the preferred indoor temperature varies from 18-21°C, while in Kuwait the preferred indoor temperature is in the range between 23-27°C (Allison 1980, Jarrar 1979). This is due to the greater heat contrast in summer between Kuwait and Europe.

Experimental studies have been made by several authors in the Kuwait Institute for Scientific Research (KISR) to establish indoor thermal comfort guidelines in Kuwait. The studies discovered the following:

Allison (1979) made a series of thermograph readings taken over a seven-day period in July 1978 within different types of enclosure in Kuwait. All of these enclosures (buildings) were inhabited and all the windows were boarded up—refer to Table 2.1. In Table 2.1, it is clear that the indoor air temperature swings less with the enclosure that is built with a massive wall of mud, having 50cm thickness and 30cm thick roof. In general, one may observe that the more massive the building fabric the lower the indoor swings of temperature (Allison, 1979).

There are many variables not taken into account in the above experiment which will have a substantial effect on the internal temperatures shown above. Some of these are the size of the building, shape, window size, colour, contact with ground, ventilation and infiltration, surroundings environment and internal heat gains.
Table 2.1 Indoor air Temperature for Different Types of Enclosure in Kuwait, artificial heating and cooling absent.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Open shade</td>
<td>43.3</td>
<td>28.4</td>
<td>35.9</td>
</tr>
<tr>
<td>Canvas tent</td>
<td>50.1</td>
<td>28.2</td>
<td>39.2</td>
</tr>
<tr>
<td>Wooden hut</td>
<td>45.8</td>
<td>31.6</td>
<td>38.7</td>
</tr>
<tr>
<td>11cm Block hut with 10cm concrete roof</td>
<td>43.9</td>
<td>32.7</td>
<td>38.3</td>
</tr>
<tr>
<td>20cm Block hut with 10cm concrete roof</td>
<td>41.1</td>
<td>33.1</td>
<td>37.1</td>
</tr>
<tr>
<td>30cm Brick and block hut with 10cm concrete roof</td>
<td>39.5</td>
<td>34.3</td>
<td>36.9</td>
</tr>
<tr>
<td>50cm thick mud walled house with 30cm mud roof</td>
<td>36.8</td>
<td>35.8</td>
<td>36.3</td>
</tr>
</tbody>
</table>

In a similar manner, a study conducted by Allison (1979) measured indoor temperatures for several types of enclosure in Kuwait. The experimental values of indoor temperature for mean and daily temperature swings are shown in Table 2.2. From Table 2.2 one can clearly see how hot it is likely to be inside a building in Kuwait and how this will fluctuate on a daily basis with change of construction materials.
Table 2.2 Prediction Values for Indoor Mean Temperature and Daily Temperature Swings for Different Type of Enclosure:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Light sheeted construction</td>
<td>Mean ambient temp.+5 °C</td>
<td>± 7 °C</td>
</tr>
<tr>
<td>(aluminium, galvanised sheet)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prefab construction</td>
<td>Mean ambient temp.+3.5 °C</td>
<td>± 5 °C</td>
</tr>
<tr>
<td>(polystyrene/plywood)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete slab construction</td>
<td>Mean ambient temp.+3 °C</td>
<td>± 4 °C</td>
</tr>
<tr>
<td>Concrete block construction</td>
<td>Mean ambient temp.+2.5 °C</td>
<td>± 2.5 °C</td>
</tr>
<tr>
<td>Block faced with brick or stone</td>
<td>Mean ambient temp.+2 °C</td>
<td>± 1.5 °C</td>
</tr>
</tbody>
</table>

2.6.2 Reduce cooling Load through Insulation

The Kuwait Institute for Scientific Research (KISR) has carried out several research projects in energy consumption, trying to reduce the energy demand caused by the uncomfortably high temperatures that last for about six months from April to October. However, in this section, concentration will focus solely on energy conservation and its relationship to environmental problems. One of the methods that will be very effective in decreasing energy consumption in buildings is the use of a proper thickness of wall and roof insulation.

Experiments were carried out by Parks et al (1980) at KISR on huts during October when outside temperatures reaches 44°C for an insulated and non-insulated hut. In the first few days of the experiment, the daily cooling load for the non-insulated hut was about 50 kWh, while the insulated hut cooling load was 24 kWh. This constitutes a
reduction of almost 50% of cooling demand. Other work showed an economical analysis concentrating on the benefit of using the different insulation thickness (1,2,3,4,5in) over twenty years for a typical villa. This benefits the Kuwaiti government as well as the user as the saving is estimated to be around 16,000 KD (£36,000) (Ghanem et al 1980, Al-Ragom et al 1998).

Using a simulation program, Fereig et al (1983) proposed insulation to the wall and the roof of Kuwaiti buildings with thermal resistances of 1.8 m²C/W and 1.54 m²C/W respectively, which reduced the cooling load of the building by 32%, with a saving on the peak cooling load is 21%. The most effective wall to be insulated was found to be the east wall.

Experimental results found by Al-awadi et al (1990), and by Essam (1993) highlights further important results and recommendations regarding heat gain in buildings. One of the greatest heat gains is through the roof. An insulated roof can be a useful and profitable means for reducing the air conditioning load in Kuwaiti buildings. In the case of villa in Kuwait, when foam concrete was used on the top of the roof the peak load was reduced by 100,000Btu/hr, a saving of about 8 tons (29.28kW) of air conditioning plant, with value of about 2000 KD (£4000). The cost of laying the foam concrete at the price (at the time) was equal to 200 KD (£400). However, at the present time, more thermally-efficient building materials are being used in Kuwaiti buildings which can minimise and help control the heat gains through the roof.
2.6.3 Reduce cooling Load through using white or whitewash colour on the exterior building surfaces

White wash or a white material applied to the exterior walls and roof would also help to control the energy consumption. Painting or applying a material with a whitewash colour also helps (Allison, 1979a, 1793). The rays of the sun consist of not only visible light, but also ultraviolet and infra-red rays. Not all of these rays are reflected in equal amounts. Thus, white paint reflects nearly all the visible light (that is why it looks white), but absorbs a greater proportion of the longer infra-red rays with a net amount of solar energy reflected of about 80% (Markus et al 1980, Allison 1979a). The whitewash paint reflects the same amount of visible light and thus looks equally white, but it also reflects a greater proportion of infra-red rays so that the net amount solar energy which is reflected is over 90% (Essam 1993). However, the reduction in air conditioning load is not less than 3 tons, which may equate to 750 KD (£1500) for a three-storey building (Essam 1993).

2.6.4 Reduction of cooling load by controlling heat gains through the openings

Windows play an important role in reducing heat gains. Essam (1993) and Allison (1979a) found that the use of internal blinds or curtains may be effective in reducing only about 25% of heat gains, while external shutters or canvas awnings are 70% to 80% effective. Furthermore windows with double glass will reduce the air conditioning load by 2 tons (7kW), (Essam, 1993).
2.6.5 Reduction of heat gains in Kuwaiti buildings (case study)

An example of two houses was investigated by Allison (1980, 1979a) for heat gains in the harsh summer climate like that in Kuwait. This example gives the magnitude of heat gains and how they are affected by orientation, shading of windows, colour surfaces and use of insulation.

Two houses, each 20 metres long, 12 metres wide and 4 metres high, have 15% window area in each wall. One window pair faces north-south, the other faces east-west. The roof of each house consists of a plain 15-cm thick concrete slab and the walls are of standard sand-cement block with sand-lime bricks and renderings internally sand-cement rendering. All surfaces are light coloured (absorption coefficient =0.5). The time of the year is Mid-July. Heat gains found are shown in Table 2.3 and are in Watts.

It is noticeable from Table 2.3 that orientation has little effect on mean heat gains, while the great effect is found when the insulated roof is increased in thickness.

Table 2.3 Heat gains from roof, wall, windows, infiltration, and occupancy for two houses with different orientations.

<table>
<thead>
<tr>
<th>Descriptions</th>
<th>House1 Average(W)</th>
<th>House1 Peak(W)</th>
<th>House2 Average(W)</th>
<th>House2 Peak(W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar through the roof</td>
<td>2640</td>
<td>9600</td>
<td>2640</td>
<td>9600</td>
</tr>
<tr>
<td>Solar through the walls</td>
<td>2160</td>
<td>3420</td>
<td>2210</td>
<td>3490</td>
</tr>
<tr>
<td>Solar through the windows</td>
<td>4750</td>
<td>10890</td>
<td>5690</td>
<td>11580</td>
</tr>
</tbody>
</table>
### 2.6.6 Solar Energy

In the past solar energy in Kuwait was used in the summer for water heating, where water tanks are situated on the top of buildings. The use of solar energy system has improved worldwide since the last decade. In Kuwait some attempts using PV-system was found through the following literature.

Using Photovoltaic-powered solar domestic hot water systems (SDHW) in Kuwait was investigated by Ghoneim et al. (2000). The system includes Photovoltaic arrays instead of solar collectors used in a common solar water heating systems. A five-parameter PV model (i.e. Photocurrent, which is proportional to the irradiance on PV, the diode reverse saturation current which is the current that will flow backward through the diode if subjected to large reverse bias voltage, the series resistance, curve fitting parameter and shunt resistance) was used to accurately predict the I-V (current-Voltage relation) characteristic of amorphous silicon. This model subroutine was encapsulated into TRNSYS-simulation program to investigate the performance as well as economical feasibility of PV-SDHW systems in Kuwait climate. The system is supposed to provide the hot water load for a Kuwaiti house of six persons and the hot water load was assumed to be 30kg/day per person. Economical analysis based on
Life cycle saving (LCS) was carried out which shows that PV-SDHW system are not feasible in Kuwait for the price of the PV modules equal to US$5/W_p. However the system may become effective when price of PV modules reduced to 50% (i.e. US$2.5/W_p). Thus, the system still waiting for further advancement technology to reduce the PV-modules price. On the other hand, Abdullah et al (2002) examined the performance as well as economic feasibility of grid-connected Photovoltaic system in the Kuwaiti climate. The proposed system consists of crystalline solar modules mounted on the building roof and an inverter to convert PV dc output to ac voltage. The building receives electricity from both the PV array and the utility grid. In this system, the load is the total electricity energy consumption in building. A program was written and encapsulated into TRNSYS environment, using the five-parameter PV model, which is applicable to both crystalline and amorphous PV module, was used to determine the performance of the solar modules. The program together with other TRNSYS- subroutines, conform the simulation (i.e. weather generated data (Type 54) for hourly solar radiation and ambient air temperature, etc). In this study, it was found that the energy production changes significantly with both the array orientation and the azimuth angle and the maximum energy generation from the PV arrays corresponding to array slope equal to 20° (i.e. latitude- 10°) and for arrays facing south (azimuth angle=0°). With these configurations, the annual performance from 20kW_p PV array satisfies a reasonable a ratio of about 70%, which gives an indication, that grid-connected PV system installed in Kuwait may become economically feasible. In addition, sometime the PV generation actually exceeds the load, allowing the building owner to sell power back to the utility. This scheme is known as net metering, but it is not currently applied in Kuwait. A theoretical analysis for the cost of electricity generated from photovoltaic station located in Kuwait was
compared with the conventional units that used to generate electricity in Kuwait (Gas turbines and Steam turbines). Cost analysis was carried out showing all details i.e. capital cost, operating and maintenance cost and fuel cost. The results of these comparisons show that Photovoltaic station can not be used cost-effectively in Kuwait at present, due to the high capital cost of photovoltaic station, (Hassan et al, 1996, Al- hasan, 1997).

At the same time further applications in photovoltaic cells has been improved in very limited areas such as communication, and may soon for traffic lights, (Al-ababidi, 1999).

Kuwait, as one of the Arabian countries, has a great solar radiation potential as a number of sunshine per day especially at summer time, as can be seen from Figure 2.7 and Figure 2.8. Solar energy for heating/ cooling the buildings have great potential in Kuwait, but their application is limited as yet due to their high cost and the fact that their development is waiting for further advancement in this particular technology (Hassan et al, 1996, Al-ababidi, 1999).

2.6.7 Internal Heat Gains

Heat gains inside buildings increase the cooling load due to the heat generated by lights, people, equipment...etc. Values of internal heat gains for Kuwait were investigated by Allison (1979a) who found, that the average heat output of an individual is 67watts* and the average electric light generates 100W. For the average

* (i.e. found in ASHRAE handbook of fundamentals 115W for seated adult male, while that in Santamouris et (1996) is 65 times number of people)
domestic situation in Kuwait, the lighting load is estimated at 10 W/m² of the floor area, between 18.00 and 23.00 hours, and 5 W/m² between 06.00 and 18.00 hours. The average domestic loading from people is 1000 Watts (total) from 18.00 to 06.00 hours and 500 Watts (total) from 06.00 to 18.00 hours (Allison 1979a).

2.6.8 Application of indirect evaporative cooler

The Kuwait climate is a desert climate characterised as hot and dry. One technique that was found to be effective for cooling is the use of indirect evaporative coolers (Maheshwari et al 2001). An indirect evaporative cooler comprises of vertical passages through which outdoor air can flow, arranged so that the alternative passages provide humidification and sensible cooling of the air. For humidification, the inner surfaces of the passages are maintained under wet conditions using a continuous water spray over a coating of highly water-absorbent materials as seen in Figure 2.13. Part of the outdoor air, moving upward through this passage, humidified, bring down the surface temperature which cools the passing air without any moisture to be used for cooling applications (at outlet air temperature, point 2).
Results of the performance and benefits offered by indirect evaporative cooling in Kuwait climate shows a 30% reduction in the cooling load compared with the conventional A/C system (Maheshwari et al (2001)).

In Kuwait, electricity and water are equal in their importance and both are met by desalinating seawater. These cogeneration units, termed ‘dual purpose plants’ are employed using thermal steam turbines and multistage flash desalination units (Nadeem et al 1996). Hence, due to the shortage of water in Kuwait, the application of evaporative cooling (direct and indirect), may be found to be unattractive for the Kuwaiti government or consumer as well to implement evaporative cooling in Kuwait.
2.7 Summary and Discussion

In Kuwait domestic air conditioning is generally deployed between the beginning of April to the end of October. The highest air temperature occurs in July and August, with an average afternoon maximum value of 45°C. Domestic air-conditioning accounts for the major consumption of electric power, around 70%-80%. Despite the fact that there is a reduction in population in summer, the load for the months May – September is 33% higher than the year-round average. As the population in Kuwait grows, demand for electric energy goes up year after year. All power stations in Kuwait run on fuel oil (oil, crude oil or Natural gas) that has a world market price, which comprises the main national income for Kuwait. The cost of electric energy that government of Kuwait supplies is not just the cost of supplying generators, but the cost of equipping, running and maintaining the equipment and distributing the power after it is generated. This is several times the price at which it is sold. Kuwait’s energy problem has attracted serious attention from researchers in attempts to control the problem. Improved selection of building materials was proposed by several authors to minimise the heat gain to buildings from use of insulated products. Using insulation material with various thicknesses of insulation can reduce the daily cooling load by 50% of A/C cooling capacity. Building orientation, window type and opening size of curtains, and colour of the exterior walls of the building will contribute to reduce energy cooling demand in the building would also help in reducing cooling load by 25%. Further reduction may be achieved by the use of indirect evaporative cooling in the Kuwait climate, which could save around 30% in cooling loads, but the shortage of water in Kuwait hindered its practical applicability for the Kuwaiti government or consumer.
The exportation of solar energy in Kuwait is currently not cost-effective (due to its high capital cost), which may have caused the Kuwaiti government to wait for further advancement in this technology.

Decreasing or controlling energy consumption in Kuwait is given a high priority amongst the problems facing the government. The problem is serious, and whilst PV system and evaporator cooling techniques offer potential, they remain expensive solutions in terms of resources use. For this reason, a low-technology method such as ground passive cooling may offer advantages, and should be capable of application to existing buildings. Therefore, this study focused on the potential of Earth Air Heat Exchanger (EAHE), also known as the ground cooling pipe, as a potential means of reducing air conditioning loads in the desert climate like that in Kuwait.

A typical Kuwaiti dwelling (NHA housing) will be used to evaluate the effectiveness of the earth air heat exchanger (EAHE) in reducing cooling loads. An economical assessment of using of EAHE system will also be analysed and guidance drawn up to aid decision-making in Kuwait.
Chapter three: Software for simulation program

3.1 Introduction

The EAHE mathematical model and the Kuwaiti sub-surface temperature mathematical model will be encoded within the TRNSYS program environment. TRNSYS-II SBAT is one of the TRNSYS packages used in simulations. The TRNSYS program is a transient system simulation program with a modular structure. The modular nature of this program gives the Program much flexibility, it facilitates the addition to the program of mathematical not included in the standard TRNSYS library. TRNSYS is well suited to simulate the performance of systems the behaviour of which vary with time.

In the following sections a brief introduction and description of the TRNSYS simulation Program is given (i.e. some of the TRNSYS packages and TRNSYS subroutines). In addition, Appendix C includes TRNSYS components and configurations, the Fortran source code of the subsoil temperature model and the EAHE model.

3.2 TRNSYS and a description of its components

The TRNSYS Program is one of the most powerful tools used to simulate the performance of systems, whose behaviour is a function of the passage of time. This is the case where outside conditions influence the system’s behaviour, such as weather conditions, or if the system’s components themselves go through conditions that vary
with time, such as the subsoil temperature (Type 262, see Figure 3.7(g) Chapter 4) or the Earth-Air heat exchanger (EAHE, Type 264 see Figure 3.7(h) and Chapter 5).

Modular simulation of a system requires the identification of components whose collective performance describes the performance of the system. Each component has to be formulated by mathematical equations that describe their physical performance. The mathematical model for each component has to be formulated in the FORTRAN-code, so that they can be used within the TRNSYS Program. Formulation of the components has to be in accordance with the required TRNSYS format.

The TRNSYS format is a basic principle such as PARAMETERS, INPUTS, and OUTPUTS for each component. PARAMETERS are constant values used to specify a certain component. This can be, for example, as used in the EAHE model, a length of tube, diameter of tube, depth of tube, conductivity of soil, or specific heat of air. INPUTS are time-dependent variables that can come from a user’s supplied data source or from OUTPUTS of other components, (i.e. weather data reader). OUTPUTS are the performance of the system (Klein et al 1996). TRNSYS formatting for the EAHE model and subsoil environmental model are shown in Appendix C: Table (C.1), Table (C.2), Table (C.3), Table (C.4).

3.3 The TRNSYS-Package

The TRNSYS Program is a modular system simulation Program, which includes seven utility Programs: DEBUG, PREP, BID, PREBID, IISiBat, TRNSED, and TRNSHEEL. The TRNSYS Program gives the user many ready-made useful component models within the TRNSYS-library. The user can easily add his/her own component models. The TRNSYS library can be used by the user-formulated
components. In the next sections, some of the TRNSYS-packages are briefly introduced, but for more detailed assessment of each package the reader should consult the TRNSYS main manual, (Klein et al, 1996) or staff development at internet web site http://www.trnsys.com/ or http://sel.me.wisc.edu/trnsys/Default.htm.)

3.3.1 BID Or BIDWIN

The TRNSYS/BIDWIN or BID Program (Building Input Description), version 3 (an interface for creating building descriptions for Type 56) was developed from TRNSSOLAR ‘Energietechnik’ GmbH Nobelstr.15, 70569 Stuttgart Germany. The BID Program is a utility Program used for building simulation in the TRNSYS Program. PREBID (a multi-zone building model) creates a file that has all the building’s description and information, this file is called the *.BUI file. Then, within PREBID, a Program called BID or BIDWIN uses the information in the *.BUI file to generate three new files: a file containing the geometric information about the building (*.BLD), another file that contains the ASHRAE transfer function for walls and a file that describes the required inputs and available outputs of Type 56. The BIDWIN can be generated from within the PREBID.

3.3.2 PREBID

The TRNSYS/PREBID and BIDWIN Program, version 3 (an interface for creating building descriptions for Type 56) was developed from TRNSSOLAR ‘Energietechnik’ GmbH Nobelstr.15, 70569 Stuttgart, Germany in a Window operating system which provides the user with all the benefits of the window interface (see Figure 3.1).
PREBID is a menu-driven pre-processor to the building-input-description (BID) Program containing libraries of wall and layer types together with utilities to completely describe a multi-zone building. The PREBID contains data on materials of walls, layers and windows and are made available in libraries according to the standards of United States (ASHRAE) and Germany (DIN 4108). Describing new walls, layers and windows is possible through PREBID.

![Figure 3.1 The zone description within PREBID](image)

The PREBID Program creates a BID input file which must then be run in BID so that information can be available to the Type 56 component model (TRNSYS/PREBID 3.0 manual, (Klein et al, 1996).
outside air temperature or other ventilation. With ‘other ventilation’ (as assigned for
the EAHE system), BIDWIN generates a file that describes the required inputs and
available outputs of TRNSYS-Type 56, where the input of the EAHE system is listed
amongst the other inputs for the example building. Then, using a graphical
connection, the OUTPUT of EAHE (i.e. outlet air temperature) is connected with
INPUTS of TRNSYS-Type56, see Appendix C, Section C3 for more details.

3.3.3 IISiBat

The TRNSYS/IISiBat, version 1.2 (the Intelligent Interface for the simulation
Program) has been developed by the Centre for the Scientific Research in Buildings,
Sophia Antipolis, France. This Program is a general simulation environment
Program, which has been adapted to house the TRNSYS simulation software as
shown in Figure 3.2. A complete simulation package, from the simulation engine and
graphical connection Programs to the plotting and spreadsheet software, can be
incorporated into one environment Program, which makes TRNSYS much easier to
learn and use. IISiBat works using the Microsoft Windows operating system (Klein
et al 1996). Figure 3.2 shows the main IISiBat window, which first appears after the
IISiBat Program is completely loaded into the memory. ‘Window’ contains icons of
most TRNSYS-packages which, when selected with the mouse, launches the
application Programs contained in the IISiBat Program. Figure 3.3 shows the primary
window that is used to create and work with the TRNSYS system within the IISiBat
environment. This is called the ‘Assembly window’ and shows the complete project
of the example building equipped with the EAHE model, as seen in Figure 3.3. The
IISiBat window shown in Figure 3.3 contains several icons with lines connecting
them. Each icon represents a different component in the system (i.e. Type 9 (weather
data file), Type 16 (solar radiation), ...etc). The connections between the icons represent the pipes and wires or links that connect the physical components (OUTPUT to INPUT). There are a series of tools in the vertical column on the left side of the assembly window. This allows the user to place icons onto the working area, connect the icons as necessary, run the simulation, access the editor, access the spreadsheet and perform many other functions (Blair et al, 1996).

Figure 3.2: IISiBat Window contains most of TRNSYS package in Icons.
Figure 3.3: The complete project of the example building equipped with EAHE model on the IISiBat assembly window.

3.3.4 TRNSHEEL

The TRNSYS/TRNSHELL version 2 was developed by the Solar Energy Laboratory at the University of Wisconsin-Madison for Window 95, 98 or Windows NT. It is a mean-driven environment Program for TRNSYS. It is a Windows Program, which encapsulates many of the common operations and functions used in the simulation process, see Figure 3.4. The TRNSHELL environment Program is similar in operation to the IISiBat environment Program, but does not have utilities for the graphical connection of TRNSYS components. The TRNSHELL Program is most useful in debugging and manoeuvring existing TRNSYS input files (see the main manual for more details, (TRNSYS/TRNSHELL 2.0 manual), (Klein et al, 1996).
3.3.5 TRNSED

TRNSED is a Windows Professional front-end for TRNSYS, which allows many of the TRNSYS details to be hidden from the user, displaying only that information which is of importance to the user. The TRNSED is a utility Program included within the TRNSHELL and IISiBat environments. TRNSED provides a user-friendly interface for TRNSYS input files. TRNSYS input files may be modified using TRNSED to display only user-selected information, hiding some of the less important details from the user. TRNSED can only display the PARAMETERS and INPUTS where the user can easily edit values without any complications, see Figure 3.5 (Klein et al, 1996).
Figure 3.5: TRNSYS/TRNSED environment menu showing all PARAMETERS and INPUTS data created by the TRNSYS input File

### 3.3.6 ONLINE PLOTTER

The TRNSYS-ONLINE PLOTTER (Type 65) is an output device component routine, which allows the user to plot on screen the TRNSYS simulation results (plots online screen results without hard copies). The Online Plotter component, called Type 65, within the TRNSYS-library and the assigned sample is shown in Figure 3.7(d) (Klein et al, 1996; Schuler et al, 1997).
3.3.7 TRNSPRED

The TRNSYS-SPREADSHEET (Type 25) is a printer using the Windows spreadsheet and plotting Program that is similar to the Excel spreadsheet with all Excel toolbars. The spreadsheet Program works within the TRNSYS/IISiBat and TRNSHELL environment, allowing results to be presented in row and column cells. Results may be plotted in two or three dimensions, as seen in Figure 3.6. The TRNSHELL component, called Type 25, is within TRNSYS-library and the assigned sample is shown in Figure 3.7(f) (Klein et al, 1996); (Schuler et al, 1997).

Figure 3.6: The printer Type 25 (TRNSPRED), showing the output results and the chart in three-dimension
3.3.8 PREP

A DOS utility Program to generate ASHRAE wall transfer functions for use by the (Type19) single zone component model (Klein et al., 1996).

3.3.9 DEBUG

A DOS utility Program that is used to test user-written component routines for results or errors (Klein et al., 1996).

3.4 Standard TRNSYS component modules

Many component models come as standard with the TRNSYS-library and include many of the components commonly found in thermal energy systems. In addition, there are several utility subroutines in the TRNSYS-library that could be shared with other’s project as TRNSYS components. In the next sections, the focus will be on the TRNSYS-library that is involved in this thesis.

3.4.1 Type 9 (Data Reader or Weather Data Reader)

This component serves the purpose of reading data at regular time intervals from a logical unit number in hourly intervals that are arranged in lines. For example, assume the lines are as follows: days; month; year; hour; dry bulb temperature; wet bulb temperature; wind speed; global radiation; relative humidity; diffusivity radiation…etc. The Data Reader, called Type 9, within the TRNSYS-library and the assigned sample is shown in Figure 3.7(a). Most of the Data Reader (Type 9) applications use hourly weather files, which run for 8760 hours. The weather file could be modified as text or as an Excel file to be loaded as an external file to support and work as OUTPUTS to other models’ INPUT (Klein et al., 1996).
3.4.2 Type 16 (Solar Radiation Processor)

Another useful utility component within the TRNSYS-library is the solar radiation component which serves the purpose of supplying insolation data which is generally taken from the data reader (Type 9) at regular time intervals (i.e. hourly interval). The solar radiation Program, called Type 16, within the TRNSYS-library and the assigned sample is shown in Figure 3.7(c). This component interpolates radiation data, calculates several quantities related to the position of the sun, and estimates insolation on up to four surfaces of either fixed or variable orientation. Solar radiation, as all other TRNSYS components, has PARAMETERS, INPUTS specification and OUTPUTS data that are linked to other components' INPUTS (i.e. building simulations Type 56) (Klein et al, 1996).

3.4.3 Sky Temperature (Type 69)

The Sky-Temperature model was added to TRNSYS/IISiBat by Thomas Auer from TRNSSOLAR Energietechnik GmbH Nobelstr.15, 70569 Stuttgart, Germany. Sky-Temperature is calculated using the TRNSYS-subroutine model called Type 69 within the TRNSYS-library. The assigned sample for Type 69 is shown in Figure 3.7(e). This component model determines a fictitious sky temperature, which can be linked as an OUTPUT to TRNSYS-Type 56.

3.4.4 Type56 (Multi-Zone Building Simulation)

This component model is a TRNSYS component, which simulates thermal behaviour of a building having up to 25 thermal zones. The TRNSYS assigned sample for Type 56 is shown in Figure 3.7(b). In order to use this component, a separate pre-processing Program must first be executed. The Building Input Description needs to
be first established by a Program called (PREBID). BIDWIN within the PREBID Program will read and process a file containing the building’s description and will then generate three files, which will be used by the Type 56 component during the TRNSYS simulation, as explained in PREBID section 3.3.2 (Klein et al, 1996); (Schuler et al, 1997).

The TRNSYS-Type 56 model has two basic modes of operation, termed "energy rate control" and "temperature level control". In the energy rate control mode, the model calculates energy loads based only upon the net gains or losses from the space. The loads are considered to be independent of the heating or cooling equipment operation. The user specifies the set temperature for heating or cooling. The Program determines the energy necessary to keep the room at these set points. If the user desires a more detailed model of the heating and cooling equipment, a "temperature level control" approach is required, this is, where the room state reflects both the ambient condition and the heating or cooling equipment input (Klein et al, 1996; Blair et al, 1997; Bradley, 2001/2).

In this thesis, the TRNSYS-Type 56 model will be operated using the energy rate control method. (Klein et al, 1996; Blair et al, 1997).
Figure 3.7 Some of the IISiBat library icons: a) Type 9 (data reader), b) Type 56 (building simulation), c) Type 16 (solar radiation), d) online plotter, e) Type 69 (sky temperature), f) TRNSPRED Type 25, g) subsoil temperature model Type 262, and the Earth-Air Heat Exchanger (EAHE) Type 264.

3.5 Conclusion

TRNSYS is very well known and is one of the oldest simulation Programs. The TRNSYS Program is a transient system simulation Program with a modular structure, which gives the Program great flexibility, and facilitates the addition to the Program of mathematical models not included in the standard TRNSYS-library. The TRNSYS simulation Program is well suited to simulate the performance of a system whose
behaviour is dependent on the passage of time. The IISiBat Program, one of the TRNSYS packages that is a fully integrated simulation, works using windows, which allows the user to perform all necessary functions for using TRNSYS as well as graphically creating TRNSYS input files. This environment allows the user to assemble a TRNSYS simulation within a window and click another tool to run the simulation.

Despite there being available many software simulation Programs, TRNSYS is an exclusive simulation Program with features that are unique and unlikely to be found in many other simulation Programs. These are:

- The TRNSYS library has many component models (ready-made) that can be used with other models.
- The TRNSYS Program has the ability to add new mathematical models into the TRNSYS library. This would give the user the opportunity to use some TRNSYS-subroutines within the TRNSYS-library (i.e. Type 9 (weather data reader), Type 16 (solar radiation), building simulation Type 56, ...etc.) with his project.
- TRNSYS has all the features needed for a Program to be used in this method of study (i.e. Modular structure, TRNSYS Library includes other components needed in this work, etc).
- The PREBID Program (an interface for creating buildings with the Multi-zone description) is a Windows operating system (window interface); it contains libraries of wall, roofs’ materials layers and window and doors thermal properties. PREBID gives the user the facility to add new walls, roofs’ windows, doors, or construction material layers into the PREBID library.
Building simulation Programs using Type 56 work based on two modes of operation termed "energy rate control" and "temperature level control". Furthermore, this component model simulates thermal behaviour of a building having up to 25 thermal zones.

The TRNSYS-ISSiBat works using an object-oriented system, which integrates the component model and has the ability to be active and connected graphically with other component models' input (i.e. TRNSYS-library).

Various output devices such as Online plotter Type 65, TRNSPRED Type 25...etc. are available.

Large number of worldwide contributor's and users of expertise, i.e. USA, France, Germany, Sweden, Greece ...etc. Thus, TRNSYS operates in several languages such as English, France, ...etc.

In view of the above, TRNSYS was selected to be used for all simulation work in this thesis.
Chapter four: The Sub-surface environment in Kuwait

4.1 Introduction

Use of the ground, as a heating or cooling source, is not a new idea. The concept has been known and used for centuries to create a better living environment. Givoni (1981, 1993) reported that the ground mass beneath buildings can serve as a natural cooling or heating source for buildings either in a passive or an active way. In summer, the soil temperature at a depth of a few meters is always less than the average ambient temperature, thus having the potential to serve as a heat sink for heat transfer from buildings (Givoni, 1981, 1993). In winter the converse is true. Therefore, the ground can be considered as an almost infinite heat sink, offering the potential to increase passive cooling in the summer and passive heating in the winter. This is applicable at an appropriate depth, where the ground environment is stable and constant. Analysis of such systems requires accurate knowledge of the ground input variables (Labs, 1989). The heating or cooling potential in the ground is a consequence of annual weather changes from the hot summer to the cold winter season. According to Abrams (1985), there is a time lag between the annual cycles in temperature for the ground and for the air temperature. As ambient air temperature drops in the autumn season, ground temperature continues to rise. Similarly, in the summer as air temperature increases, ground temperature lags behind. This time lag varies according to depth; the greater the depth, the greater is the time lag between air temperature and ground temperature at that particular depth (Al-Ajmi et al, 2002b). One of the reasons that deep earth or ground is cooler than the summer ambient temperature is that the ground is isolated from the warmer conditions at the surfaces by the upper layers of soil (Abrams 1985). The underground environment in Kuwait,
which is characterised as having a desert climate, has to date not been fully explored as a potential source of cooling for buildings either in earth direct contact (which involves buildings totally or partially in direct contact with soil, such as underground sheltering) or indirect contact (which involves circulating the outdoor or indoor air through a buried pipe to pre-cool the air entering the building). The earth air heat exchanger system (or earth cooling pipe) is an example of the latter.

Khatry et al. (1978) presented a model that assumes a periodic variation of ground temperature, taking into account the periodicity of solar radiation and atmospheric temperature. This assumption does not conform with available measured ground temperatures and the experimental data for Kuwait (Moustafa et al. 1981). Furthermore, the model predictions are nearly identical to the sol-air temperature and have been carried out for one day of the year for a limited depth. Moustafa et al. (1981) and Al-Temeemi and Harris (2001) presented a ground temperature model using Labs equation, but the soil properties for Kuwait found in the literature are different from those incorporated in the model. Therefore, the following study aims to investigate underground temperatures in Kuwait and to establish an accurate assessment of the properties of Kuwaiti soil. Measurements of soil thermal performance are compared with predictions for an existing model (Labs 1989) in order to establish an appropriate predictive model of sub-soil temperature for use in Kuwaiti, or similar, desert climates. Furthermore, an objective of this study is to develop a sub-soil environment model for prediction of sub-soil temperature as a function of soil depth and time of the year for Kuwait based on Lab's model. This model will be used to supply an earth air heat exchanger model (see chapter 5) with values of the sub-soil temperature in an hourly basis for whole year. A degree-days approach for quantifying the condition of the underground "climate" and relating it to
energy use for space heating/cooling of buildings is presented in this chapter. An analysis of meteorological weather data for the years 1962-1982 was used to find the annual mean temperature, temperature amplitude and soil thermal diffusivity. A soil thermal diffusivity value for Kuwait was found based on two methods: i) the straightforward thermal diffusivity method, and ii) the ratio annual amplitude method (or Direct Amplitude Method (DAM)). The model has been encoded within the TRNSYS-IISiBat (see chapter 3 and Appendix C) environment, though not in the standard TRNSYS-IISBAT library.

4.2 Ground cooling and domestic dwellings

Kusuda and Achenbach (1965) presented a periodic heat conduction theory that can be used to predict the annual ground temperature variation. Labs and Keith (1982), Labs (1989) and other authors contributed by developing the model to be in a form in which time is represented in days and hours. Ground temperature models are used widely by most researchers in this field to calculate ground temperature (Khatry et al. 1978; William 1981; James and Ray 1981; Moustafa et al 1981; Givoni 1981,1993; Mac Donald et al 1985; Abrams 1985; Santamouris and Mihalakakou 1996; Al-Temeemi and Harris 2001). Other studies have focused on dwellings using the ground as a source of cooling in the summer and of heating in the winter. Some of these studies are describe next (Al-Ajmi et al 2002b).

In the northern Sahara, people used underground dwellings many centuries ago in which a central pit atrium was dug at a depth of usually between seven to twelve meters (but could be up to fifteen meters), together with several rooms that opened onto the atrium. After completing the digging of the central pit, an entry tunnel from
the side was dug, and finally, the rooms were excavated. The size of the rooms is 3 to 4 meters wide and 6 to 8 meters deep. The ceiling of the rooms is vaulted, with walls which diverge outward for increased structural stability. The depth of the rooms’ ceiling below ground level is between 4 to 10 meters. The temperature below ground level decreases gradually with depth until it reaches a thermally comfortable range, the wall temperature of the rooms being 27°C and remaining constant whilst the outside air temperature reached 49°C, (see Figure 4.2). However, the temperature inside the room was dependent on how frequently the door to the central atrium was opened and closed (see Figure 4.1(a)), (Cole 1981; Golany 1988). Ground dwellings were constructed in the same region and in neighbouring countries, using the same architectural approach, but with modern building materials (Figure 4.1(b)), (Golany 1992; Al-Mumin 2001).

Another example of a historical ground dwelling is in China. In the Huanghe River Valley in the north of China, about forty million people have lived in caves which are located deep in the ground at depths between three to six meters, thereby escaping from the summer heat and the winter cold, and enjoying a stable, thermal environment in the cave (Jiao, et al 1990). Similar practices are found in Northern Ghana, the area of Cappadocia in Turkey, the Mediterranean coast of Europe and the Near East, (Al-Ajmi et al 2002b).
A final example of the use of hybrid cooling in a historical dwelling is that of the ancient Persian wind tower used to catch the dry summer wind and circulate it down through the tower into the building basement. The air was then cooled by earth passive cooling to provide sensible cooling and was then passed over a water pond.
(fountain) to provide evaporative cooling of the air. The cooled air then flowed into the rooms in the basement and to the rooms above ground level to modify the indoor environment, as seen in Figure 4.3, (Al-Ajmi et al 2002b).

Figure 4.3 Ancient Persian Architecture Cooling System for Buildings

4.3 Ground Temperature

The ground temperature model devised by Labs (1981, 1989) can be used to calculate the temperature of undisturbed ground soil. Ground temperature exhibits a sinusoidal pattern of variation as a result of temperature fluctuations in the ground over a given time period. This sinusoidal fluctuation gives rise to the definition of 'amplitude' of the ground temperature. The amplitude of ground temperature variations is greatest at the ground surface; deeper below ground, the amplitude gradually decreases until it dies out completely. The temperature of undisturbed soil at any time and depth can be calculated based on Labs equation (Labs 1981a; 1981b, 1989; Givoni 1981, 1993). Likewise, models by Kusuda et al (1965), Kusuda et al (1983), Moreland et al (1980) and Labs (1989) have predicted the annual ground temperature variation similarly
without any considerations of surface cover (shading, vegetation, etc) or the moisture content of the soil (Givoni, 1993). The accuracy of the equation in predicting ground temperature at any particular site depends on the input variables. However, according to Labs (1981a, 1981b, 1989), when the variables of the equation are determined from field observations, the model frequently yields no more than ±1.1°C error. Predicting ground temperature at any depth and time of the year can be estimated from the following equation (Labs' model):

\[
T(z,t) = T_m - A_s e^{-z(\pi/8760,\alpha)^{-1}} \cos \left[ 2\pi \frac{8760}{8760 + 2 \times (8760 / \pi \alpha)^{0.5}} (t - t_o - \frac{z}{2 \times (8760 / \pi \alpha)^{0.5}}) \right]
\]

(4.1)

where:

- \( T(z,t) \) = Ground temperature at depth \( z \) (m) and at time \( t \) (hours) (°C)
- \( T_m \) = Mean annual ground surface temperature (°C)
- \( A_s \) = Annual surface temperature amplitude (°C)
- \( t \) = Time of the year measured in hours from the start (hours)
- \( t_o \) = Phase constant, i.e. the time of the year in hours from start when the minimum surface temperature occurs (hours)
- \( \alpha \) = Thermal diffusivity of soil (m²/hours)

In order to test the applicability of (Equation 4.1) to the Kuwaiti region and its desert conditions, it is necessary to use soil data from site location. Thus, in this research, measured input parameters were taken from two Kuwaiti sites (desert and coastal) having soil properties as shown in Table 4.1 and Kuwait climatological data summaries from year 1962 to 1982. These are used to predict Kuwaiti ground temperatures (desert climate) at depths of 1.2m, 2m, 3m, 4m and 5m. The results are shown in Figure (4.8).
Table 4.1 Soil properties, for Kuwaiti soil in Rawdatain (Desert Region) and Oqaila (Coastal Region), (Al-Ajmi et al 2002b).

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>Depth (Meter)</th>
<th>Density (kg/m³)</th>
<th>Water content (%)</th>
<th>Dry density (kg/m³)</th>
<th>Ground Temperature (°C)</th>
<th>Thermal resistivity (m°C/W)</th>
<th>Thermal conductivity (W/m°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rawdatain 1</td>
<td>1</td>
<td>2017</td>
<td>1.9</td>
<td>1980</td>
<td>23.8</td>
<td>2.2</td>
<td>0.45</td>
</tr>
<tr>
<td>Rawdatain 2</td>
<td>2</td>
<td>1802</td>
<td>3.1</td>
<td>1747</td>
<td>30.7</td>
<td>1</td>
<td>1.01</td>
</tr>
<tr>
<td>Rawdatain 3</td>
<td>3</td>
<td>1795</td>
<td>3.9</td>
<td>1728</td>
<td>29.3</td>
<td>1.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Oqaila 1</td>
<td>1</td>
<td>2040</td>
<td>3.7</td>
<td>1968</td>
<td>22.9</td>
<td>0.9</td>
<td>1.2</td>
</tr>
<tr>
<td>Oqaila 2</td>
<td>2</td>
<td>1798</td>
<td>3.2</td>
<td>1743</td>
<td>24.4</td>
<td>0.8</td>
<td>1.2</td>
</tr>
<tr>
<td>Oqaila 3</td>
<td>3</td>
<td>1709</td>
<td>2.2</td>
<td>1673</td>
<td>25.9</td>
<td>2</td>
<td>0.5</td>
</tr>
</tbody>
</table>

4.4 Applicable Values for Kuwait

The accuracy of Equation (4.1) in predicting ground temperature at any particular site depends mostly on how accurately the input variables can be estimated. Therefore, the ground temperature model variables considered to be in the equation are discussed next.

4.4.1 Mean Annual Ground Temperature ($T_m$)

The mean annual ground temperature ($T_m$) can be approximated by using the mean annual air temperature, which may be obtained from data from local weather stations such as the airport of Kuwait or the Kuwait Institute for Scientific Research (KISR) (Figure 4.4). The mean air temperature based on Kuwait climatological data summaries from years 1962 to 1982 is equal to 25.6°C (Kuwait International Airport 1983). For the United States, Labs (1979, 1981b, 1982, 1989), suggests adding 1.1°C
or 1.67°C to the mean annual air temperature. In Kuwait, the value of mean annual ground temperature $T_m$ used in this study was found by analysing the difference between the airport station climatological data which is located in a desert region (Kuwait International Airport 1995) and data taken at the Kuwait Institute for Scientific Research (KISR) station which is located in coastal region (Kuwait Institute for Scientific Research 1995). This difference is equal to 1.4 °C and leads to an approximated value of annual ground temperature $T_m$ equal to 27°C.

![Temperature Data Graph](image)

Figure 4.4 Meteorological Weather Data for Years 1962-1982, showing the analysis of the ambient temperature (daily avg. $T_{max}$, daily avg. $T_{min}$, monthly $T_{avg}$, and annual mean $T_{mean}$), annual mean air temperature, and annual temperature amplitude $A_s$.

### 4.4.2 Annual Surface Temperature Amplitude ($A_s$)

The annual surface temperature amplitude ($A_s$) for any region depends on such factors as its latitude, soil type, soil moisture content and the nature of the soil surface.
The annual surface temperature amplitude \( (A_t) \) can be approximated as the maximum of the average daily ambient air temperature minus the mean ambient air temperature averaged over the same period. This maximum of the average daily ambient temperature is equal to a value of 37.2°C and the corresponding mean annual air temperature over 20 years for Kuwait is equal to 25.6°C (Kuwait International Airport 1983). Therefore the amplitude equals 11.6°C (see Figure 4.4). On the other hand, Watson and Labs (1983) suggest that the annual surface temperature amplitude \( A_t \) can be estimated by taking one half of the difference between the monthly average air temperatures of July and January (which is found to be equal to 12.2°C). Yet Labs (1981a, 1981b, 1989) suggested adding 1.1°C to the annual surface temperature due to the change of soil properties. Accounting for the slight difference between coastal and desert weather in Kuwait, the value of \( A_t \) for Kuwait is estimated to be 13.3 °C (Al-Ajmi et al 2002b).

4.4.3 The Phase Constant \( (t_0) \)

The phase constant \( (t_0) \) is defined as the time of occurrence of the lowest ambient air temperature measured in days or hours since the beginning of the year. Most likely, the phase constant will fall in the range of 20 days (480 hr) to 40 days (960 hr) (Labs 1981a,b and 1989). According to the climatological summaries for Kuwait from 1962 to 1982, the lowest ambient temperature was recorded on 23\(^{rd}\) January (at \( t_0 = 23 \) days = 552 hrs).
4.4.4 Thermal Diffusivity ($\alpha$)

Soil thermal diffusivity ($\alpha$) plays an important role in predicting the ground temperature at any depth and for any time of the year. The determination of soil diffusivity has not been extensively studied for Kuwait or for desert climates. Thus, in this study, two methods were used for obtaining values for soil thermal diffusivity to facilitate finding the best approximate value for use in Equation (4.1) (the latter being used to predict the ground temperature). These methods are:

i) The use of the straightforward definition of thermal diffusivity as that of thermal conductivity of soil ($k$) divided by the multiple of density of soil ($\rho$) and the specific heat capacity of soil ($C$) as in the following equation:

$$\alpha = \frac{k}{\rho C}$$

ii) The use of the ratio of the annual amplitude at two layers $A_1$ and $A_2$ otherwise known as the Direct Amplitude Method (DAM). Current knowledge of soil thermal diffusivity and its behaviour is presented in the following studies.

Kusuda and Achenbach (1965) performed many analyses to determine average values of thermal diffusivity ($\alpha$) from three groupings intended to represent soil of low, medium, and high thermal diffusivity of the USA. The results obtained were 0.03, 0.049, and 0.070 m$^2$/day. In Table (4.4) an appraisal of several authors’ experimental results for thermal diffusivity and conductivity are presented, together with significant differences between results (Mac Donald et al 1985). According to Labs and Harrington (1982), the thermal diffusivity of soil should be lower in arid regions and higher in regions where moisture content is greater. Soil diffusivity values for certain regions change according to the annual patterns of precipitation, which in turn affects directly the level of the ground water table. In wet regions with a ground water table close to the surface, the soil will be saturated (the closer to the ground water
table, the higher the water content of the soil), which will increase the soil thermal conductivity. (Abrams 1985, Labs 1989, Givoni 1993). In regions where the ground water table is deep (20 meters or more below the ground surface), the soil will be low in water content. Consequently, the soil conductivity will be low which will decrease the soil diffusivity. In regions where the ground water table is deep, and during the rainy season, the upper layer of soil may have a higher water content than the lower layers. During the dry season, the lower soil layers have a higher water content than the upper layers, although it is also affected by other factors such as slope and permeability of the soil. In view of these factors, the determination of soil thermal diffusivity is quite difficult and its value can be highly changeable as an input variable in Equation (4.1) (Labs model). In general, a variation of 10% in the estimated value of soil thermal diffusivity might be considered to be an acceptable result (Fuhrer 2000).

4.4.5 Effective Sub-Soil Thermal Diffusivity value For Kuwaiti Soil

Evaluation of the sub-soil thermal diffusivity by using the straightforward definition of thermal diffusivity (Equation 4.2) may be used when the properties of soil are constant and known (Givoni 1993). However, using Equation (4.2) with the Kuwaiti soil properties as shown in Table (4.1) (average soil thermal conductivity (k), average soil density (ρ) and soil specific heat capacity (C) of 0.860W/m°K, 1874.5kg/m³, and 900J/kgK, respectively (Al-Juwayhel and El-refaee 1998) results in a soil thermal diffusivity value equal to 0.00184 m²/h.

For any given type of soil, from a knowledge of annual soil temperature patterns for two layers below ground (such as maximum and minimum temperature or the monthly temperature), it is possible to calculate the annual amplitude temperature for
each layer (Fuhrer 2000, Givoni 1993). This is the Direct Amplitude Method (DAM), as follows.

When the annual patterns of soil temperature variation for two layers are known, the effective soil diffusivity ($\alpha$) can be estimated using the DAM—see Equation (4.3) (Fuhrer 2000, Givoni 1981, 1993).

$$\alpha = \left(\frac{\pi}{365}\right) \left(\frac{z_2 - z_1}{\ln(A_{s1}) - \ln(A_{s2})}\right)^2$$

(4.3)

where:

$A_{s1}$ = Annual ground temperature amplitude of the first layer ($^\circ$C)

$A_{s2}$ = Annual ground temperature amplitude at the second layer ($^\circ$C)

$z_1$ = Depth of first layer below ground (m)

$z_2$ = Depth of second layer below ground (m)

Based on Kuwaiti ground temperature data for depths of 0.2m, 0.6m, 1.2m and 3m (Kuwait International Airport 1983) the annual ground temperature amplitude ($A_s$) at two layers is calculated and shown in Table (4.2), using the difference between the monthly average maximum ground temperature at a given depth minus the ground mean annual temperature at the same depth. This gives an annual ground temperature amplitude ($A_s$) of 6.93°C at a depth ($z$) of 0.2m. In a similar way, at depths of 0.6 m, 1.2m and 3m, values for ($A_s$) are equal to 3.72°C, 3.06°C and 2.16°C, respectively (Al-Ajmi et al. 2002b). Thus, using Equation (4.3), the predicted Kuwaiti effective soil diffusivity at the layer bounded by depths of 0.2m and 0.6m is estimated to be $\alpha = 0.00355 \text{m}^2/\text{day}$ (0.000148 m$^2$/hr). In a similar way, the best approximated soil diffusivity value ($\alpha$) at layers bounded by depths of 0.6 and 1.2m, and 1.2 and 3m are equal to 0.082 m$^2$/day (0.003417 m$^2$/hr), and 0.22915 m$^2$/day (0.00954 m$^2$/hr),
respectively. The results are summarized in Table (4.3). The soil thermal diffusivity value of 0.003417m²/hr for the layer bounded by depths 0.6 and 1.2m (middle layer) is found to give a prediction of the sub-soil temperature that agrees with the measured ground temperature obtained by Kuwait International Airport (1983). This value of soil thermal diffusivity for Kuwait at depths of 0.6 and 1.2m is found to be in the range of most of the experimental results shown in Table (4.4).

Table 4.2 Ground Temperature Amplitude ($A_s$) at a depth of 0.2m and Annual Mean Ground Temperature $T_m=27.4\, ^\circ C$

<table>
<thead>
<tr>
<th>Month</th>
<th>Max Temp. °C</th>
<th>Min Temp. °C</th>
<th>Monthly °C</th>
<th>Annual Amplitude °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>JAN</td>
<td>19.3</td>
<td>7</td>
<td>13.4</td>
<td>-8.11</td>
</tr>
<tr>
<td>FEB</td>
<td>22.3</td>
<td>9.2</td>
<td>16.5</td>
<td>-5.11</td>
</tr>
<tr>
<td>MAR</td>
<td>28.5</td>
<td>10.9</td>
<td>20.7</td>
<td>1.09</td>
</tr>
<tr>
<td>APR</td>
<td>32.5</td>
<td>18.6</td>
<td>26.6</td>
<td>5.09</td>
</tr>
<tr>
<td>MAY</td>
<td>40</td>
<td>25</td>
<td>32.9</td>
<td>12.59</td>
</tr>
<tr>
<td>JUN</td>
<td>43</td>
<td>31.7</td>
<td>37.6</td>
<td>15.59</td>
</tr>
<tr>
<td>JUL</td>
<td>43.5</td>
<td>33.3</td>
<td>38.6</td>
<td>16.09</td>
</tr>
<tr>
<td>AUG</td>
<td>44.9</td>
<td>33.6</td>
<td>38.6</td>
<td>17.49</td>
</tr>
<tr>
<td>SEP</td>
<td>40.5</td>
<td>30</td>
<td>35.9</td>
<td>13.09</td>
</tr>
<tr>
<td>OCT</td>
<td>36</td>
<td>17</td>
<td>29.8</td>
<td>8.59</td>
</tr>
<tr>
<td>NOV</td>
<td>38.1</td>
<td>12.8</td>
<td>22</td>
<td>10.69</td>
</tr>
<tr>
<td>DEC</td>
<td>23.5</td>
<td>7</td>
<td>16.3</td>
<td>-3.91</td>
</tr>
<tr>
<td>Average Temp. °C</td>
<td>34.34</td>
<td>19.68</td>
<td>27.41</td>
<td>$A_s = 6.932$</td>
</tr>
</tbody>
</table>

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Table 4.3 Thermal Diffusivity Values at Different Depths Using the Amplitude Method

<table>
<thead>
<tr>
<th>Depth Location (m)</th>
<th>Annual ground temperature amplitude Range °C</th>
<th>Thermal diffusivity (m²/day) ×10⁻²</th>
<th>Thermal diffusivity (m²/hr) ×10⁻⁴</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2m-0.60m</td>
<td>6.932-3.718</td>
<td>0.355</td>
<td>1.48</td>
</tr>
<tr>
<td>0.6m-1.2m</td>
<td>3.718-3.061</td>
<td>8.2</td>
<td>34.2</td>
</tr>
<tr>
<td>1.2m-3.0m</td>
<td>3.061-2.16</td>
<td>22.9</td>
<td>95.4</td>
</tr>
</tbody>
</table>

4.5 Field Investigation

Sub-surface soil was investigated on a site in Kuwait. Thermal conductivity was measured at depths of 1 m, 2m, and 3m at two different regions: Oqailah (a coastal region) and Rawdatain (a desert region) using a thermal conductivity probe and hardware system which is designed and built by Fugro Geotechnical Engineers B.V. of Leidschendam, Holland. The accuracy of the measurement is in the range of 5 to 10% (Annual book of ASTM Standards; 1993). The fieldwork was carried out in March and April 2001 when the ambient temperature in Kuwait seldom exceeds 35°C (though occasionally it reaches 38°C). The results of the Rawdatain area (desert region) show lower thermal conductivity values at a depth of 1m compared with that at 2m, but different results are shown for the Oqaila area (see Table (4.1)), (Al-Ajmi et al 2002B). Thus, the thermal conductivity of Kuwaiti soil in both regions averages to 0.8613 W/m°C which is very close to the result of 0.833 W/m°C as found by local utilities in Kuwait for the calculation of electric circuit ratings (cable rating) (Kellow et al 1983; Ismeal and Al-sanad 1992). These values are valid for soil not deeper than the ground water level, which for Kuwait is found to be in the range 9.1m-18.3m (Moustafa et al 1981). Ground water temperature in Kuwait has been accepted as being equivalent to the stable “steady state” ground temperature which in turn has
been found to be approximately equivalent to the mean annual average air temperature (Moustafa et al. 1981; Dhaliwal and Goswami 1984; Labs and Harrington 1982).

**4.6 Accuracy of the Input Variables**

Thermal conductivity, density and moisture content were investigated on site in two Kuwaiti regions, desert and coastal, at depths of 1m, 2m, and 3m. The value of thermal conductivity was found to be within the ranges 0.45W/mK to 1.22W/mK with an average of 0.86W/mK (Al-Ajrmi et al. 2002b). The density of Kuwaiti soil was found to be in the range 1709 kg/m³ to 2040 kg/m³, with an average of 1874.5kg/m³ and specific heat capacity equal to 900J/kgK (Al-Juwayhel and El-refaee 1998). Use of the straightforward definition of thermal diffusivity (Equation (4.2)) (value equal to 0.00184 m²/h) in Equation (4.1) is found to give poor agreement with measured ground temperature data obtained from Kuwait International Airport (1983), see Figure (4.6). However, using the ratio of the annual amplitude method (Equation (4.3)), (value of effective soil thermal diffusivity equal to 0.00341m²/h), gives good agreement between the predicted ground temperature and measured ground temperature as found by curve-fitting. However, a thermal diffusivity value of 0.0038m²/h was found to give the best agreement between predicted ground temperature and measured ground temperature. Referring to Figure (4.5), use of an effective soil thermal diffusivity value equal to 0.0038 m²/h for Kuwait as an input variable in the sub-soil temperature model (Labs model) gives a very good agreement with the measured ground temperature. This may be compared with the use of other values, as illustrated in Figure 4.6 and Figure 4.7. Moustafa et al. (1981) and Al-Temeemi and Harris (2001) found soil thermal diffusivity values using Equation
(4.2) for Kuwait equal to 0.0450m²/day (0.001875m²/h) and 0.053m²/day (0.002208m²/h), respectively. However, the results are inconsistent with respect to the measured ground temperature data (as shown in Figure (4.7)). Thus, a soil thermal diffusivity value of 0.0038m²/h is considered to be a reasonable approximation for Kuwait or maybe similar desert climates.

![Graph showing predicted and measured ground temperatures](image)

Figure 4.5 Predicted ground temperature at depth 4m using Labs' model and a thermal diffusivity value equal to 0.0038 m²/h vs. measured ground temperature (Kuwait International Airport 1983)
Figure 4.6 Predicted ground temperature at depth 4m using Labs' model and a thermal diffusivity value equal to 0.00184 m²/h vs. measured ground temperature (Kuwait International Airport 1983).

Figure 4.7 Predicted ground temperature at depth 4m using Labs' model and a thermal diffusivity value equal to 0.001875 m²/h (Moustafa et al. 1981) and 0.002208 m²/h (Al-Temeemi and Harris 2001) vs. measured ground temperature (Kuwait International Airport 1983).
4.7 TRNSYS program

In this thesis, ground temperatures and cooling/ heating degree hours were predicted using a program called Type 262 developed inside the TRNSYS environment. For more details, see Appendix C, section C.1, C.1.1 and C.2, Figure C.1, Table C.1 and Table C.2. Figure 4.8 illustrates the results obtained on a monthly basis over a whole year.

Figure 4.8 Predicted Kuwaiti Ground Temperature using (Equation 4.5) on a monthly basis for a whole year, TRNSYS-output type 25 at depth 1.2, 2, 3, 4 and 5m.
Sub-surface environment profile in Kuwait

Figure 4.9 Subsoil temperatures below ground level to a total depth of 5m in 1 meter increments, and a comparison between the total subsurface annual cooling degree-days and total atmospheric annual cooling degree-days.

Table 4.4 Soil thermal properties (Mac Donald et al 1985)

<table>
<thead>
<tr>
<th>Reference</th>
<th>Year</th>
<th>Thermal Diffusivity $m^2/h \times 10^{-2}$</th>
<th>Thermal conductivity $W/m \cdot ^{\circ}C$</th>
<th>Specific Heat KJ/m$^2$C</th>
<th>Density Kg/m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abrams D.W</td>
<td>1980</td>
<td>0.093-0.465</td>
<td>0.35-2.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Asrar &amp; Kanemasu</td>
<td>1983</td>
<td>-</td>
<td>0.20-1.6</td>
<td>1.48-1.96</td>
<td>1250-1400</td>
</tr>
<tr>
<td>Geotach W.D</td>
<td>1981</td>
<td>0.093-0.186</td>
<td>0.25-2.2</td>
<td>0.80-1.55</td>
<td>1600-2000</td>
</tr>
<tr>
<td>Cropsey M.</td>
<td>1966</td>
<td>0.3</td>
<td>3.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Carson J.E</td>
<td>1963</td>
<td>0.3</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Eckhoff &amp; Okos</td>
<td>1980</td>
<td>0.13</td>
<td>1.40</td>
<td>2.28</td>
<td>1760</td>
</tr>
<tr>
<td>Kusuda &amp; Achenbach</td>
<td>1965</td>
<td>0.08-0.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Scott N. R.</td>
<td>1982</td>
<td>0.21</td>
<td>1.78</td>
<td>1.6</td>
<td>1920</td>
</tr>
<tr>
<td>Spaskhah &amp; Boersma</td>
<td>1979</td>
<td>-</td>
<td>2.2-3.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Smith &amp; Yamauchi</td>
<td>1950</td>
<td>-</td>
<td>0.35-2.8</td>
<td>-</td>
<td>1440</td>
</tr>
<tr>
<td>Spangler &amp; Stombaugh</td>
<td>1983</td>
<td>0.0018-0.0032</td>
<td>1.3-2.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Penrod &amp; Stewart</td>
<td>1967</td>
<td>0.0027</td>
<td>1.68</td>
<td>1.38</td>
<td>1600</td>
</tr>
<tr>
<td>Lunardini</td>
<td>1981</td>
<td>0.001-0.004</td>
<td>0.12-1.0</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
4.8 Ground cooling potential:

The degree-days approach is a standard technique for quantifying the severity of the climate and relating this to energy use in the space heating/cooling of buildings. Applying this technique to Kuwait, the number of atmospheric annual cooling degree-days is found to be 1804 °C-days, with monthly values being shown in Figure (4.10) (see Appendix B-1). Hypothetically, the same approach could be used to quantify the “severity” of the underground “climate”. Here, the predicted values for subsurface (ground) temperature at a certain depth are used in place of the ambient air temperature in the traditional degree-day method whilst retaining the same base temperature as in the conventional case, (see Appendix B-2). According to ISO Standard 7730 (1984) in the case of the Kuwait region, the base temperature is equal to 20°C in the winter season (which starts from the middle of October and runs to the middle of April (181 days), while in the summer season the base temperature is equal to 24.5°C (starting from the middle of April and running to the middle of October (178 days)). Using the approach described above, the total number of cooling degree-days for the subsurface environment at a depth of 4m is calculated to be 754.5 °C-days. Monthly values for subsurface cooling degree-days are shown in Figure (4.10) and Figure (4.11) in comparison with conventional atmospheric values. The same technique was applied to find monthly subsurface heating and cooling degree-day values for the Kuwaiti subsurface environment at various depths below the ground surface (see Table (4.5)).

It should be emphasised that the concept of subsurface heating/cooling degree-days is not intended to relate directly to the energy consumed by a building but instead merely serves to illustrate the differing condition of the ‘climate’ above and below the ground surface. The aim of this is to give some indication of the cooling potential of
the ground for buildings in Kuwait if served by earth air heat exchangers as a means for pre-cooling air for the building.

Figure 4. 10 Monthly cooling degree-days values based on the Kuwaiti Subsurface environment and the atmospheric environment. The Figures show the number of degrees that the daily average temperature is above the base temperature for cooling (base taken as 24.5°C) (Appendix B-2).

Figure 4. 11 Monthly heating degree-days values based on the Kuwaiti subsurface environment and the atmospheric environment. The Figures show the number of degrees that the daily average temperature is below the base temperature for heating (base taken as 20°C) (Appendix B-2).
Table 4.5 Monthly subsurface heating and cooling degree-days values for Kuwaiti subsurface environment at various depths (see Appendix B-2).

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Subsurface heating degree-days C-Days</th>
<th>Subsurface cooling degree-days C-Days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nov</td>
<td>Dec</td>
</tr>
<tr>
<td>1</td>
<td>169</td>
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</tr>
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</tbody>
</table>

4.9 Results and Conclusion

In this chapter the Kuwait subsurface environment has been investigated in terms of its soil properties and ground temperature. The concept of subsurface cooling degree-days has been introduced as an indicator of the potential of the ground as a source for cooling in Kuwait or similar desert climate either directly by contact with ground soil (where the structure or skin of buildings is in contact with soil) or indirectly via an earth air heat exchanger. The results and conclusions are summarized as follows:

- Kuwaiti soil properties for the subsurface environment were found to be best approximated as 0.860 W/m°C, 13.3°C, and 27°C for thermal conductivity, annual surface temperature amplitude and mean annual ground temperature, respectively.

- Kuwaiti soil thermal diffusivity was found to be best approximated as 0.0038 m²/h, which falls within the expected experimental result for Abrams values for soil thermal diffusivity. Abrams’ soil diffusivity value is in the range of 0.00093 to 0.00465 m²/h-see Table (4.4) (MacDonald et al 1985).
• An existing model (Labs’ model) has been shown to be valid for predicting subsoil temperatures in Kuwait. Subsoil temperatures predicted using Labs’ model (Equation (4.1)) for a Kuwaiti (desert region) sub-surface were compared against measured Kuwaiti ground temperature values. It is shown that the best agreement with predictions from Labs model occurred for a soil thermal diffusivity value of 0.0038 m^2/h. This value is considered to be representative for soil not deeper than the ground water level. In Kuwait, the ground water level is found to be at depths in the range 9.1m-18.3m (Moustafa et al 1981).

• Substituting the value of mean annual ground temperature, annual surface temperature amplitude, and soil thermal diffusivity into Labs’ model (Equation (4.1)) yields the following equation for predicting ground temperatures in the Kuwait region to an accuracy of about ±1°C:

\[ T(z,t) = 27 - 13.3e^{-0.31z} \cos\left[\frac{2\pi}{8760}(t - 552 - 428.31z)\right] \]  

(4.5)

This expression will be used in subsequent simulation work within this thesis.

The concept of cooling degree-days for a sub-surface environment has been introduced. The total number of cooling degree-days for the Kuwaiti subsurface environment at a depth of 4m is equal to 754.5°C-days, while the number of conventional (atmospheric) annual cooling degree-days for Kuwait is found to be 1804 °C-days. Monthly subsurface degree-days of heating /cooling are shown in Table (4.5). This illustrates the potential of the ground as a source of cooling/heating for buildings that employ an earth air heat exchanger system in Kuwait.
Chapter five: The Earth - Air Heat Exchanger (EAHE)

5.1 Introduction

The achievement of indoor thermal comfort whilst minimising energy consumption in buildings is a key aim in most countries and is a particular challenge in desert climates like that of Kuwait. In general, most people feel comfortable indoors when the temperature is between 22 and 27°C and relative humidity is within the range of 40% to 60%, (Sawhney et al 1999). Such conditions are usually achieved through the use of air-conditioning in desert climates with consequent significant use of energy. Other methods therefore received attention, one of these being the pre-cooling of ventilation air through use of the subterranean environment. Cooling the air through buried pipes by means of an Earth-Air Heat Exchanger (EAHE) has been known for many years as a means for increasing a building’s comfort whilst decreasing its energy demand.

5.2 The Earth-Air heat Exchanger concept

The concept of the earth –air heat exchanger (EAHE) or earth cooling tube is that of a pipe or several pipes buried in the ground. One end of the pipe system (the inlet) permits the entrance of ambient air, whilst the other end of the pipe system (the outlet) releases that air to the interior of a building space. The outdoor ambient air that is drawn into the pipe inlet travels through the pipe and exchanges heat with the pipe walls which are in contact with the surrounding underground environment-see Figure 5.1. Thus heat is transferred to or from the surrounding soil by conduction through the pipe wall and convection with the tunnel air, tempering the air as it flows through the
The aim of EAHE system is to increase indoor thermal comfort whilst saving energy in domestic or other buildings.

![Schematic buried pipe system (EARE) and soil Environment.](image)

Figure 5.1 Schematic buried pipe system (EAHE) and soil Environment.

The applications of earth/ground cooling and the type of earth cooling pipes are discussed in the following section.

### 5.3 Applications of earth cooling

In chapter 4 the potential of the ground as a source of cooling/heating for buildings was introduced. In this chapter, an earth cooling system is introduced in which a buried pipe that is in direct contact with earth is used to cool the air supplied to a building that is located above the ground surface. There are two types of earth cooling pipe system, namely the open loop system or the closed loop system. The difference between the two systems is in the manner in which cooling air is circulated. The open loop system draws fresh outdoor air into the pipes, cools it, and delivers it to the
building interior, where the pipe inlet is open to the outside atmosphere and the pipe outlet is inside the building as seen in Figure 5.2. The closed loop system, however, recirculates air from the building rather than taking in outdoor air as seen in Figure 5.3. Here, air flows from the building interior through the earth cooling pipes and back to the building interior. The closed loop system may perform well as regards reducing the amount of cooling required in buildings, but no fresh ventilation air is introduced into the building, which in turn may create a health problem in the long term. Furthermore such a system, if used, would recirculate the air inside the building inclusive of the moisture content generated by breathing, cooking and washing. This would increase the relative humidity of the air that may be delivered through the pipe, which in turn could cause water vapour to be condensed inside the tube, and this may eventually cause mildew and fungi growth in the pipe (Abrams et al.1980, Givoni, 1993). In either system, the pipe field may be arranged below the ground surface in either parallel or series flow configurations or in series as a single straight pipe line configuration, thereby avoiding any bends (Figure 5.4).

In view of the potential health risk with the closed loop system, the open loop system is investigated in this work as an attempt to reduce building cooling demand in desert climates like that in Kuwait (see Figure 5.2).

There are some experimental and analytical studies of EAHE systems already in the literature. However, EAHE systems for buildings have not been investigated in desert climates like that found in Kuwait for example.

In the following section, relevant literature to date is reviewed.
Figure 5. 2 Earth cooling pipe in the open system approach.

Figure 5. 3 Earth cooling pipe in the closed system approach.
Figure 5.4 Earth cooling pipes: series and parallel air flow configurations in open and closed loop systems; a) and c) series, b) parallel.

5.4 Literature Review

Several studies on direct/indirect earth cooling techniques have been presented in published papers and conferences. The numbers of studies on the direct earth cooling system (such as underground structures) is large compared with indirect earth cooling techniques such as the earth cooling pipe or earth air heat exchangers. The use of earth as a heat source and a sink with underground tunnels as direct earth heating/cooling systems has existed in Islamic and Persian architectural design for a number of centuries (Bahadori, 1978), see Figure 5.5.
The earth cooling pipe system based on this concept has been repeated nowadays with an increase of reliability and performance.

One of the first scientific attempts for constructing an actual earth-air heat exchanger system (or Earth-air tunnel system) was made at Forman Christian College, Lahore, Pakistan, where outdoor air was drawn into the windows of a cellar and then down an air well to an underground tunnel. This tunnel made a rectangular circuit having a running length of 35m along its central line (the line was about 4m below the ground surface). The air was then drawn up through a central duct by means of a single fan and was distributed by other ducts to adjustable grilles. The fan was of low power and the system was not expected to be used for more than two rooms at a time. The cool air was shut off from unoccupied rooms by damper valves, one located suitably behind each grille. No data were provided regarding the performance of the system.
except that the author indicates the earth-cooled air stream provided reasonable comfort in summer weather (Sodha et al 1985).

Another series of attempts, however, modified the concept and instead of digging a large tunnel inside the ground, the pipes (made of materials like PVC) were laid down into the ground. In this section, a review of literature is made, presenting pervious studies of earth-air heat exchanger systems both empirically and theoretically. The following aspects are addressed: performance, effect of climate, system optimisation, EAHE systems with use of other cooling techniques and cost effectiveness.

5.4.1 Performance of earth-air heat exchangers

An extensive investigation by Francis (1981) reported on the field performance of an earth cooling pipe system that consisted of two buried pipes in the Midwest of the USA. This part of the USA has very cold winters, and hot, wet summers. This experimental study was carried out for two different cases. The first case consisted of two pipes 20cm in diameter and 120m long, buried to a depth of 3m, and used for cooling a swine house. The outdoor air (inlet ambient air) is blown by a 1 hp blower. The outdoor weather conditions for this experiment were dry bulb temperature of 35°C, wet bulb temperature of 31.7°C (humidity ratio is 0.026 and relative humidity is 80%). The air emerging from the pipes had dry bulb and wet bulb temperatures of 18.3°C and 13.9°C, respectively. The airflow rate per tube was 408 m³/hr and the air speed in the tubes was 3.4 m/s. No data were given in the paper regarding the soil temperature. The Coefficient of Performance (COP) for cooling was 18.5. However, the earth cooling pipe system described achieved almost all of its cooling ability (87% of the total) after a length of 60m. In the second case, Francis (1981) used a pipe of
15 cm diameter and length 17 m buried to a depth of 3 m below the ground surface. The airflow rate was 119 m$^3$/hr with ambient air at dry bulb and wet bulb temperatures equal to 26.4°C and 24.4°C, respectively. The outlet air temperatures from the pipe were 20.6°C dry bulb and 18.9°C wet bulb respectively, with a COP for cooling of 12.5. The author comments that a higher COP could be obtained by using a larger number of shorter pipes and during rainy periods the long-term cooling performance was better than during dry periods. However, from interpretation of two cases it appears that on EAHE system with longer pipes may produce a lower outlet air temperature and that may be limited to a pipe length of 60 m.

Similar to Francis (1981), but with the aim of investigating the field performance of different pipe materials, Scott et al (1982) investigated the use of a steel pipe of 45 cm diameter and 132 m in length, buried to a depth of 2.40 m in Ithaca, N.Y., USA. The experiments were carried out for a week of continuous operation. The outdoor diurnal temperature fluctuated between 25°C and 36°C with the soil temperature of 13.3°C. The air temperature emerging from the pipe was shown to exhibit a steady sinusoidal pattern in a range of about 15°C - 17°C. The authors present in this paper a result for continuous operation of the blower fan for a week which shows excellent results in reducing the outlet temperature to less than half that of the inlet temperature. However, the time length is not sufficiently long so as to examine the durability of the steel pipe in use as an underground pipe over a long period, so the high cost of steel piping needs to be considered in any cost-effectiveness evaluation.
5.4.2 Effect of climate on Earth-air heat exchanger performance

The performance of an earth cooling pipe system in a humid climate may suffer from condensation problems due to the fact that the surface temperature of the tube may be below the dew point temperature of the outdoor air, which in turn causes water vapour to be condensed inside the tube. In addition, water vapour being condensed inside the pipe may eventually cause mildew and fungi growth. Akridge (1981) compared the passive cooling performance of the ground in a humid region with passive heating; he confirmed that underground passive cooling techniques in hot humid regions are not practical despite the fact that the earth can provide sufficient sensible cooling. Thus, Akridge (1982) believes that, in a humid climate, the earth air heat exchanger may work better as an auxiliary air-conditioner rather than as a complete replacement for conventional air conditioning.

Dhaliwal et al (1984) examined experimentally the performance of an earth cooling pipe at North Carolina A&T State University, USA, using a corrugated plastic pipe 30cm in diameter and 25m in length buried to a depth of 2.4 m. The temperatures of air, pipe surface and soil at different locations were measured using iron–constantan thermocouples which were arranged along and around the pipe; the experimental measurements were made over a short time (24 hrs). From charts provided by the authors, it is shown that on a hot summer day, the temperature of the air is reduced from about 32°C to below 23°C for an airflow rate of about 391m³/hr. The authors stated that relative humidity of the outlet increased as expected, but did not reach 100%. Results provided in a table showed that relative humidity reached 94%. In general, the authors found that good potential for cooling could be implemented in the summer with high outdoor relative humidity. However, as seen from literature
reviewed above, whilst the performance of earth-air heat exchanger systems in humid climates increases (this may be due to the increase in thermal conductivity and thermal capacity of subsoil), water vapour being condensed inside the system can make the implementation of the system disadvantageous in humid regions.

Attempts were reported by several authors' papers to reduce the condensation of water vapour coming through the pipe, but with no adequate solution being found. Some attempts were reported by Nordham (1979), Francis (1981) and Tombazis et al. (1990) to avoid accumulation of the condensed water on the pipes by using a very small tilt of the buried pipes towards a small drain placed on the lowest part of the buried pipes. Given the climate of Kuwait, and similar hot, dry desert regions, problem with condensation are unlikely to occur.

In the following sections, literature about optimisation of earth-air heat exchanger system performance is reviewed within a number of categories that relate to variations that are possible in the design of such systems.

5.4.3 Effect of using multi-pipes

The effect of using multiple pipes in the earth-air heat exchanger is addressed in the work of Zoellick (1981). The work relates to the use of an earth-air heat exchanger system consisting of four separate PVC ducts each of diameter 15cm running to a house from a fan box located in the yard of the house in Oklahoma City, USA. The results of experiments showed that the system could cool the ambient air with a temperature in the mid-80's (27-32 °C), the air temperature drop between the air entering the pipe system and that leaving the system being approximately 5.6°C. During warmer days when temperatures were in the mid-90’s (32-37°C), the
temperature drop provided by the EAHE was more in the range of 8°C. From the table provided in the paper, the overall average performance of the system was a temperature drop of 2.5°C. Zoellick (1981) presented an equation for the steady-state heat loss rate through the walls of the PVC cylindrical duct, the equation originally being given in the 1977 ASHRAE Handbook of Fundamental (ASHRAE 1977) to calculate the rate of heat transfer from the circulated air and the exit air temperature from the system. An agreement between measured and predicted exit air temperatures of 1°C was found. Akridge et al. (1981) measured the performance of earth cooling pipes installed in a house in Georgia, USA, using two pipes each of 50cm diameter and 30 m in length and buried to a depth of 2 m below the ground surface with a soil temperature of about 21°C. The air flowing through the pipe in this study was at a temperature of 30°C at the inlet and 23°C at the outlet. Earth-air heat exchanger systems using a number of parallel pipes (30 pipes) of 30m in length, 20cm in diameter and buried to a depth of 1.5m below the ground surface were investigated by Tombazis et al (1990). Air velocities in the pipes were in the range 5-8m/s. The system was used for cooling a hotel complex in Greece during the summer period. The air temperature drop inside the pipes varies from 2°C for the early morning hours to 4-5°C at noon. The annual cooling load of the building was reduced to about 29% as a result of using this system. From the above literature, operating the EAHE system using multiple pipes may generally improve the performance of the EAHE system, but the cost associated with the increased size of excavation, installation and materials could become prohibitive (Labs 1989, Hendrick 1980).
5.4.4 Effect of system configuration with various parametric changes

Effects of various parametric changes on the performance of earth cooling pipe system such as the pipe length, diameter of the pipe, airflow rate inside the pipe, burial depth of the pipe, and ground surface condition were investigated in different regions and climates as found in the following literature. Chen et al. (1983) reported a study in Nebraska, USA, where increasing pipe depth below ground surface, pipe diameter and airflow rate would increase the cooling effect. Sodha et al. (1990) studied the required earth cooling tunnel length for four different surface conditions and its relation to cooling potential. Tables and charts show the relation between cooling potential and tunnel length for different surface conditions. For the normal surface condition (dry sunlit) of the earth, the required length of a tunnel (with normal tunnel parameters, namely depth equal to 4m, height and width equal to 1m, and air velocity equal to 3m/s) for supplying all the required cooling load is about 150m. With a shaded earth surface condition, this length of tunnel is reduced to 105m, and for a wet surface condition this length is reduced to about 78m. For a wet shaded surface condition, the required tunnel length is only 70m. Ishihara et al. (1992) used a full scale test house at Kumamoto University in Japan supplied by two pipes with a length of 16m and a diameter of 20cm to examine the effect of parametric changes (i.e. depth, airflow rate and type of soil surrounding the pipes) on the performance of earth cooling pipes. Results show that the room temperature with an earth cooling pipe is lower by more than one degree than that without earth cooling pipes. The performance of the system improved with increase of depth, decrease of airflow, and use of loam as an earth material for surrounding the pipes. Ishihara et al (1992) suggests that, most effective earth heat exchanger is the one with smallest pipe diameter. Similarly, Mihalakakou et al (1994) studied the influence of soil surface
conditions on earth-air heat exchanger performance. The performance of his system was compared for the cases of burial under a bare soil surface and burial beneath a short-grass surface in Greece. The results showed that exit air temperatures from the pipe when buried beneath short grass shows a decrease in temperature of about 2°C compared with burial beneath bare soil. Grassing of surfaces thus provides a considerable increase in the system’s potential cooling capacity. Furthermore, the performance of the earth cooling pipe improved with increase of pipe length, decrease of mass flow rate and pipe radius and increase of burial depth of pipe. In addition, the performance of the EAHE system depends strongly on soil properties, wet and shaded surfaces increasing the soil thermal conductivity which in turn improves the system’s performance. Mihalakakou et al (1994) concluded with results that were found to be similar to Ishihara et al. (1992), while results of Chen et al (1984) were different. This difference may be due to the location of each study (Nebraska USA, Greece, and Japan) or the time duration of operating the system, or pipe materials. Both Mihalakakou et al. (1994) and Ishihara et al. (1992) used PVC pipes, but no details are provided regarding the pipe material used by Chen et al. (1984).

In a similar approach as in Sodha et al (1990), an EAHE system performance was investigated by Sawhney et al. (1994) using soil surface treatments. The annual heating and cooling potential of an earth cooling pipe system of 50m length and 10cm radius and buried to a depth of 6m was investigated. The system was evaluated for three different climates as experienced at the locations of, Delhi, Jodhpur and Leh in India. In Delhi and Jodhpur, the main requirement is cooling, while in Leh the main requirement is heating. The effect of several soil surface treatments are considered: dry-sunlit, wet-sunlit, and wet-shaded sunlit. It is shown that the cooling potential increases and the heating potential decreases as the surface treatment is changed from
dry-sunlit to wet-shaded. The increase in cooling potential with change in surface conditions from dry-sunlit to wet-shaded surfaces can be as large as 250-400%, while the decrease in heating potential with change in surface conditions from dry-sunlit to wet–shaded can be as large as 50%-90%.

An extensive study of the performance of short and long earth cooling pipes in long term operation was reported by Perl et al (1996). In the year 1985, PVC (polyvinyl chloride) plastic pipes of 30 cm diameter and of two lengths, 30.5 m and 61m were buried 3m below the ground surface in an open farm field. One third horsepower (250W) electric motors were used to blow air from the inlet and to circulate it through the pipes. The pipes were arranged in two squares, each corner made of two 45° PVC elbows. The arrangement of the pipes was intended to facilitate combining the pipes to create a 91.4m linked pipe.

![Diagram of earth cooling pipe configuration](image)

**Figure 5.6 Earth cooling pipe configuration a) Plan view of 30.5m and 61m, b) Plan view of 91.4m.**

In 1991, the 30.5m and 61m-long pipes were jointed using the same diameter of pipe to make one long pipe of length 91.4m. Thermocouples were located along the pipe at 10m intervals and also thermocouples were positioned above the pipes at depths of
0.6m, 1.8m, 2.4m, 2.7m below ground. Further, thermocouples were sited below the pipes at 3.4m, 3.7m, and 4.3m below ground, and beside the pipes at 0.30m, 0.6m, and 1.2m as shown in Figure 5.6. The letters G, F, E, D, C, B, A in Figure 5.6 are the thermocouple locations along the pipe. The authors conclude that performance of the pipes through the years varies from year to year, the exit air temperature from the pipes is ‘relatively constant due to the comparative thermal stability of the soil mass’. The greatest cooling occurs over the longest length of the pipe. The pipes cool better in early summer when the soil temperatures are lower, and in the morning of each day before the surrounding soil is warmed by the heat transferred from ambient air.

From the preceding literature, the system configuration that potentially offers the best performance for an EAHE system, is one that has the soil covered with a wet shaded surface, perhaps by vegetation such as a grass surface, which as a result would maximise the EAHE performance and minimise its length. Furthermore, the EAHE performance may be improved with increase of pipe length, decrease of mass flow rate and pipe diameter and increase of burial depth of pipe.

5.4.5 Effect of using a large earth cooling tunnel as a sole air conditioning mechanism

A large earth cooling system can be used as the sole air cooling mechanism for a building space. Sodha et al (1985) built a cooling system consisting of a large earth-air tunnel system to provide thermal comfort inside a building complex at a hospital in Mathura, India, see Figure 5.7. The earth cooling system used consisted of a main tunnel and several subsidiary tunnels, the total length of the system being 1 km and its cross sectional area varying from 3.66x4.57m to 0.91x0.91m. Natural light inside the
tunnel was provided by skylights. The subsidiary tunnels cover the entire hospital building complex. Exhaust fans are provided at the outlet to draw tunnel air into the spaces. The main hospital building is three floors high and each floor receives tunnel air for heating /cooling of the rooms. Air temperatures were measured at several points along the tunnel using platinum resistance thermometers (PT-500). The performance of the tunnel during the summer period was monitored, and showed that dry-bulb ambient temperature at the inlet of the tunnel was in the range 24 to 43°C with the wet-bulb temperature varying between 16.5 and 27.5°C and relative humidity between 40 and 53%. The outlet air temperature from the tunnel showed variation in dry bulb temperature between 23 and 28°C and wet-bulb temperature between 28.8 and 26.5°C. During the winter period where the ambient air temperature varied between 4 and 21°C, it was observed that the outlet air temperature varied between 12 and 20°C. The authors of this paper believe that the earth–air tunnel system is an effective way to precondition ambient air during the summer. From the tables provided in this paper, the 80m long portion of tunnel has a daily average cooling capacity of about 512 kWh and a heating capacity of about 269 kWh. The authors concluded that passive cooling by means of an earth-air tunnel system is sufficient to provide adequate comfort conditions for the building in the summer, but that passive heating may not be sufficient to provide comfort conditions in the winter.
In another part of India, Sawhney et al. (1999) used earth cooling pipes as the sole air tempering mechanism for a building. The arrangement consisted of two concrete earth-air heat exchangers to pre-condition eight rooms of a guest house in the Energy Research Institute in India. The earth cooling pipes system consisted of two concrete heat exchanger pipes 85 m long and 0.5 m in diameter buried parallel to each other at a spacing of 1 m and at a depth of 2.5 m. Air is circulated through the two main pipes to the building space using a 3 horsepower (2.25kW) electric motor blower at the end of each pipe. The tempered air is supplied to rooms by ducts at a height of 2.2m above the floor, distributing air to all rooms in the building. The system was monitored continuously (day and night) for 31 days during the month of May 1997, maintaining an average value of air flow velocity of 6.3 m/s. The results show that during the summer period the outdoor ambient temperature varies between 22.5 and 44.2 °C, with relative humidity varying between 9.4 and 78.8 %. The delivered tempered air varies in dry bulb temperature between 25.3 and 28.4°C and in relative humidity...
between 4.8 and 70.3%. Also from tables provided it may be observed that during the
month of May the cooling potential of the system is 341 kWh with a monthly average
value of about 180 kWh. The COP of the system is about 3.35. Despite the fact that
the system described by Sawhney et al. (1999) and Sodha et al. (1985) provide good
performance, it is noticeable from the data provided that both systems achieved outlet
air temperatures slightly above the comfort range. The reason may be due to high dry
bulb temperatures in both regions of India. However, no cost-effectiveness was given
in either study in terms of comparison with conventional air conditioning. Such
information would help to clarify feasibility and aid architects, designers and
engineers in deciding where and how to implement such a system.

5.4.6 Earth-air heat exchanger with use of other cooling techniques

Use of earth-air heat exchangers with other cooling techniques was investigated by
Tiwari et al. (1993) who used various cooling techniques (namely evaporative cooling
and a wind tower) with an earth air heat exchanger in a cinema hall in India. The
authors monitored the temperature variation of the room using these cooling
techniques with respect to outdoor conditions. Results in terms of indoor temperature
variation were provided in a chart for the following cooling approaches: no cooling
technique; evaporative cooling technique; evaporative cooling and wind tower
technique; earth-air heat exchanger technique. Earth air heat exchanger was provided
by an earth tunnel of a rectangular cross sectional area of 0.25m$^2$; tunnel air velocity
was 2m/s with the soil temperature at a depth of 4 metres equal to 17°C under a wet
shaded surface. Results were shown in a chart with the earth air heat exchanger found
to be the most effective cooling technique, reducing the indoor air temperature of the
hall by about 33% more than the other approaches.
To summarise the results of literature reviews mentioned above, Table 5.1 is presented that includes the name of each author, region of the work, techniques used and a brief summary of the results.

From literature reviewed above it may be concluded that an earth air heat exchanger can improve indoor air temperature and as a result reduce energy consumption in buildings.

5.4.7 Cost effectiveness

There are several researchers who have analysed cost effectiveness of EAHE systems. Weisbecker et al (1981) used a multiple system of earth-air heat exchangers (10 pipes) which were divided into five pipes of 13cm diameter and five others of 15cm diameter (all were 61m long). No further data were given regarding the pipes' depth below ground. The system was used for heating a building apace. The authors reported a system cost of about $1/ft (£ 0.605/ft) to purchase and install the system, with a total cost of the complete system of around $2000 (£ 1208). A simple cost analysis showed that the system could be paid off after a 7.4-year period. In a similar way, Lemay et al (1995) in Québec, Canada, described a system consisting of 12 plastic pipes divided into three heat exchangers. All pipes were 30cm in diameter, 61m long and were buried at 3 metres. The economic analysis of the system revealed that the price of the electrical tariff would have to be 11 times higher than the current price to ensure profitability of the system. This implies poor cost-effective. Yet payback 7.5 years was found elsewhere (Weisbecker et al (1981).

Francis (1984) gives an estimation of costs for Earth Air Heat Exchanger systems as a function of $per unit length to be installed in the USA, which is a function of the
system size, depth and materials. For a plastic pipe with a diameter of 30 cm at a depth of 2m the cost is equal to $19/m (£ 11.5/m). For the same system buried to a depth of 2.5m costs are equal to $ 25.5/m (£ 15.4/m).

From these studies, it can be concluded that EAHE system costs may increase with the increase of depth below ground and system configuration (i.e. pipes’ length, pipes’ diameter, and pipe materials, etc).

Table 5. 1 Brief summary of the results in reviewed literature

<table>
<thead>
<tr>
<th>Author</th>
<th>Region</th>
<th>Techniques used</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zoellick (1981)</td>
<td>USA</td>
<td>Four pipes system</td>
<td>Temp. reduction of 2.5°C</td>
</tr>
<tr>
<td>Francis (1981)</td>
<td>USA</td>
<td>Two pipes system + single pipe</td>
<td>COP =18.5 and COP=12.5</td>
</tr>
<tr>
<td>(two cases)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Akridge et al (1981)</td>
<td>USA</td>
<td>Two pipe system</td>
<td>Temp. reduction of 7°C (water vapour problem)</td>
</tr>
<tr>
<td>Scott et al (1982)</td>
<td>USA</td>
<td>Long steel pipe</td>
<td>Reduces the outlet temperature to less than half that of the inlet temperature</td>
</tr>
<tr>
<td>Chen et al. (1984)</td>
<td>USA</td>
<td>Pipe configuration</td>
<td>increasing pipe depth, pipe diameter and airflow rate would increase the cooling effect</td>
</tr>
<tr>
<td>Sodha et al (1985)</td>
<td>India</td>
<td>Large earth air tunnel</td>
<td>Temp. reduction of 15°C</td>
</tr>
<tr>
<td>Tombazis et al (1990)</td>
<td>Greece</td>
<td>Large (and Multiple pipes) earth- air heat exchanger</td>
<td>Reduction of 29% of cooling Load</td>
</tr>
<tr>
<td>Study</td>
<td>Country</td>
<td>Surface Condition</td>
<td>Result</td>
</tr>
<tr>
<td>-------------------------------</td>
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<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>Sodha et al (1990)</td>
<td>India</td>
<td>Dry sunlit, shaded, wet and wet shaded</td>
<td>Length minimised by wet shaded surface.</td>
</tr>
<tr>
<td>Ishihara et al (1992)</td>
<td>Japan</td>
<td>Two pipe, Optimisation using sensitivity analysis.</td>
<td>Reduced indoor temp by 1°C</td>
</tr>
<tr>
<td>Tiwari et al (1993)</td>
<td>India</td>
<td>EAHE with other cooling techniques</td>
<td>EAHE reduces indoor temp. by 33% more than other techniques.</td>
</tr>
<tr>
<td>Sawhney et al (1994)</td>
<td>India</td>
<td>Surface condition</td>
<td>Cooling potential of wet shaded surface 250%-400% greater than dry surface.</td>
</tr>
<tr>
<td>Perl et al (1996)</td>
<td>USA</td>
<td>Long terms operation using short length and long length</td>
<td>Better cooling with long length, and in early summer</td>
</tr>
<tr>
<td>Sawhney et al (1999)</td>
<td>India</td>
<td>Two large earth air tunnels</td>
<td>Temp reduction of 15.8°C</td>
</tr>
</tbody>
</table>

5.4.8 Theoretical studies

Several authors have presented theoretical studies based on numerical techniques to investigate the performance of EAHE systems, examples being Jacovides and Mihalakakou (1995), Mihalakakou et al. (1994), Tiwari et al (1993), Dhaliwal et al (1984), and Elmer et al (1981). Each presented a theoretical model that involved dividing the length of the pipe into small segments, each of which has an energy balance calculated between air flowing through the pipe and the soil environment. In each segment exit air temperature is determined. All these models assumed soil
surrounding the pipes to be undisturbed and homogeneous with constant temperature, the value of which depends on the depth of the pipe below the ground surface and the type of soil (e.g. sand, mud, dry, wet, etc). This soil temperature is obtained as a measured value at desired depths. Sawheny and Mahajan (1994), Sodha et al (1994), Sodha et al. (1985) and Krarati and Kreider (1996) proposed a steady state analytical model to determine the annual heating and cooling potential of an underground air pipe system, while soil temperature was assumed as the mean annual temperature (or mean sol-air temperature). The later models neglect the hourly variations of input time dependent parameters (i.e. ambient temperature). Furthermore, theoretical models aforementioned experienced a problem with development of water content within the pipe system, where the pipe surface often is wet due to vapour condensation. Under these circumstances, a numerical calculation (based on one-, two—or three dimensional) of an earth cooling pipe was described taking into account the effect of moisture content transport in the ground and in the circulated air inside the pipe. Recent model by De Paepe and Janssens (2002) presents an analytical analysis of an earth air heat exchanger based on the definition of the heat exchanger effectiveness. In this model subsoil was assumed to be constant. Jacovides and Mihalakakou (1995) model was later extended by Mihalakakou et al. (1995), who developed a chart model that may be used as a simplified tool that could be presented for use by engineers in everyday practice (see APPENDIX A.1). Mihalakakou et al. (1995) has shown to give poor outlet air prediction at shallow depths see Figure 5.13. Further details for Mihalakakou et al. (1995) models will be found in section 5.5.2. A recent mathematical model presented by Energietechnik (2000) considers the pipe to be symmetrically surrounded in the radial direction by several layers of soil, each layer with different properties. In the axial direction the geometry is divided into short
segments. Each segment is represented by a branch of an electrical circuit. In Energietechnik 2000 model, the thermal properties of each layer are described by a resistance and capacitance (Hanby 2001). Energietechnik 2000 model has not been published yet (at time of writing this thesis, information about the model was obtained through personal contact with IEA-Annex 28 (Hanby, 2001)). All the above-mentioned models have been validated and have showed good agreement with measurements with the exception of Elmer et al (1981), Tiwari et al (1993), and Energietechnik (2000) and De Paepe and Janssens (2002). The model of Krarati, Kreider (1996) model was validated against the experimental data of Dhaliwal et al (1984).

All of these mentioned models in the literature are based on experiments or one-, two- or three-dimensional calculation. Although these applications can provide some indication on the design and operation condition of the EAHE system, they cannot, however be generalised for every region or climate and are highly complex. Recent experience (De paepe and Janssens, 2002) shows that these methods do not find their way from an academic level to every day practice, except that modelled by Mihalakakou et al. (1995). They are mainly used to show that the EAHE system is a promising and effective technology. Therefore the application for design is limited to people who are able to use the calculation codes. EAHE system is just one component in whole buildings system. Designers need a simplified way to predict the general performance of the EAHE. The designers main concern is to be able to select the right size of the EAHE (i.e. length, diameter, etc).

Thus, a simplified model to describe EAHE system is developed. The features outlined below are unlikely to be found in the aforementioned models:
Earth-Air Heat Exchanger (BARE) Chapter five

1. Hourly subsoil temperature prediction as a function of depth and time, which assists simultaneously the simulation of earth air heat exchanger with underground environment.

2. Inclusive of Fan energy consumption and temperature rise of circulated air inside the pipe.

3. Subsoil model that is capable of predicting the subsoil temperature and of estimating cooling \ heating degree days, and in that can be used as an object within the TRNSYS simulation programme simultaneously with earth air heat exchanger or other application; this requires special formatting in order to be used simultaneously with TRNSYS-type 56.

In this thesis, an Earth Air Heat Exchanger theoretical model has been developed to calculate the pre-cooling of ventilation air; the model works simultaneously with an hourly subsoil temperature prediction model. Both models were confirmed to produce a complete TRNSYS package, i.e. EAHE system, subsoil temperature, and building simulation program.

5.5 Earth-Air Heat Exchanger (EAHE) model

The earth air heat exchanger system presented in this thesis is modelled as two coupled heat transfer processes, namely:

- convection between air in the pipe and the pipe inner surface as the air flows through the pipe which is buried underground and,

- conduction between the pipe outer surface and the soil environment.

In order to analyse the performance of the EAHE system, the following assumptions are applied in the development of a suitable mathematical model:
1. Soil surrounding the pipe is isotropic, with homogenous soil thermal conductivity in all ground strata.

2. Thermal resistance due to the pipe material is negligible, (thickness of the pipe is very small).

3. The pipe is of uniform circular cross section.

4. The thermal effect of soil surrounding the pipe is negligible after a distance \( r \) from the pipe outer surface, where \( r \) is the pipe radius.

5. The surface temperature of the ground can be approximated to the ambient air temperature, which equals the inlet air temperature.

6. A Steady state one-dimensional model may characterise the behaviour of the EAHE and thermal storage of the subsoil around the pipe is neglected.

Regarding assumption 6., A steady state approach has been adopted by many previous studies and the error introduced by neglecting thermal effect has not been quantifying by anyone (Tzaferis et al 1992, De paepe and Janssens, 2002). This approach will be followed in this thesis.

### 5.5.1 EAHE Model Development

A circular ground cooling pipe was modelled as a cross-flow heat exchanger with one fluid unmixed (i.e. air). An external thermal resistance was provided by a surrounding concentric cylinder of earth of arbitrary thickness, which was exposed to an undisturbed subsoil temperature as a boundary condition. Several researchers have considered the appropriate thickness of the soil cylinder. Recommended thicknesses given by Zoellick (1981), Elmer et al.1981, Chen et al (1984) and Krarati and Kreider (1996) are: 30cm; a range between 2.5cm -167cm; 2.5cm or less; and 10cm,respectively. In this work, the thickness of the cylinder was taken as being equal
to the radius of the pipe ($r_1 = 2r$) (Al-Ajmi et al 2002a, Hanby et al 2002), (Figure 5.8), this radius being within the range of values recommended by the authors cited above.

A steady-state analysis gives the thermal resistance ($R_s$) of the "soil cylinder" as

$$R_s = \frac{\ln( r_1 / r )}{2\pi Lk}$$  \hspace{1cm} (5-1)

The thermal resistance ($R_c$) due to convection heat transfer between air in the pipe and the pipe inner surface may be expressed as:

$$R_c = \frac{1}{2\pi rLh}$$  \hspace{1cm} (5-2)

Figure 5.8 Earth air heat exchanger (EAHE) system with the layers shown in cross section.

where

$$h = \frac{Nuk_{air}}{d}$$  \hspace{1cm} (5-3)

Here, thermal conductivity of the air, $k_{air}$ in Equation (5-3) is calculated (Hanby 1994) using Equation (5.4):
\[ k_{air} = 0.02442 + (0.6992 \times T_a \times 1.0E - 4) \quad (5-4) \]

The convective heat transfer coefficient \( h \) in Equation (5-3) above is a function of Reynolds Number \( Re \), and Nusselt Number, \( Nu \), where

\[ Re = \frac{V d}{\nu} \quad (5-5) \]

Here, the kinematic viscosity of air, \( \nu \), in Equation (5-5) is calculated (Hanby (1994)) from Equation (5-6):

\[ \nu = 1.0E - 4 \times (0.1335 + (0.925 \times T_a \times 1.0E - 3)) \quad (5-6) \]

For fully developed laminar flow in a circular pipe, it is appropriate to use a constant value for Nusselt numbers equal to 4.36, (Yunus (1997)). For fully developed turbulent flow (\( Re > 10,000 \) and \( 0.7 \leq Pr \leq 160 \)) in a smooth pipe, the Dittus-Boulter correlation can be used as given by Yunus (1997) as:

\[ Nu = 0.023 Re^{0.8} Pr^{33} \quad (5-7) \]

However, a correlation that obtains agreement with data for smaller Reynolds numbers in fully developed laminar flow and turbulent flow, which is valid for the ranges \( 0.5 \leq Pr \leq 2000 \) and \( 2300 < Re < 5 \times 10^4 \) is proposed by Gnielinski, (CIBSE Guide (2001) and Incropera et al (1996)) as:

\[ Nu = \frac{(f/8)(Re - 1000)Pr}{1 + 12.7(f/8)^{1/2}(Pr^{2/3} - 1)} \quad (5-8) \]

Here, \( f \) is the friction coefficient for smooth pipes and is determined using Petukhov's relationship as illustrated in CIBSE Guide (2001), which is expressed as
\[ f = (0.79 \ln \text{Re} - 1.64)^{-2} \]  

(5-9)

The total thermal resistance \( R_{\text{tot}} \) between pipe air and surrounding soil of the Earth-Air Heat Exchanger (EAHE) system may then be determined from:

\[ R_{\text{tot}} = R_s + R_c \]  

(5-10)

The overall coefficient of heat transfer is defined by:

\[ U = \frac{1}{R_{\text{tot}}} \]  

(5-11)

Referring to Yunus (1997), Incropera et al (1996) and Alvarez et al (1995), the exit air temperature delivered at the pipe outlet may be expressed as:

\[ T_2 = T_a - (T_a - T_{(z,t)}) \varepsilon \]  

(5-12)

where the heat exchanger effectiveness \((\varepsilon)\) is given by:

\[ \varepsilon = 1 - e^{-\frac{U \Delta A}{\dot{m} \rho C_p}} \]  

(5-13)

in which \( \dot{m} = q \rho = A V \rho \)

The total energy loss/gain along the pipe may be expressed as:

\[ Q_p = \dot{m} C_p (T_a - T_2) \]  

(5-14)

The expression given as Equation 5-12 (i.e. exit air temperature delivered at the outlet of the pipe) comprises a steady state thermal model of an EAHE system. Equation 5-12 will be modified to include the rise of air temperature due to the fan power in chapter seven, which then used in this study to ventilate the interior space of the example building by linking it to TRNSYS-Type56 (building simulation model).
Use of Equation (5-14) permits calculation of heat loss/gain along the EAHE system length. INPUTS, PARAMETERS and OUTPUTS for the EAHE system model are shown in Figure 5.9. Fortran source code is shown in Appendix C, section C.2.1

![Information flow diagram for Earth-Air Heat Exchanger (EAHE) with its modelling components of INPUTS - PARAMETERS - OUTPUTS.](image)

The EAHE model above was validated by comparing predictions of outlet air temperature against measured results from two experimental studies. The two experimental works were carried out by Shingari (1995) and Dhaliwal et al (1984). In addition, an inter-model comparison was carried out. Here, predictions of outlet air temperature were compared against predictions from a model by Mihalakakou et al (1995). The latter model was itself validated against a set of experimental measurements taken by that author. In the next section these validations are described, beginning with inter-model comparison.
5.5.2 Comparison with Mihalakakou et al (1995)

The numerical model of Mihalakakou et al. (1994) was described based on coupled transfer of heat and mass into the surrounding soil and circular pipe, where the energy balance equation was described using a differential equation. The model is described in polar co-ordinates where the heat transfer process takes into account the overall thermal conductance of the earth air heat exchanger system including air, pipe and the soil environment surrounding the pipe to calculate energy loss/gain and the outlet air temperature of the system.

The Mihalakakou et al. (1995) developed their model as a simplified tool that could be presented as a chart for use by engineers in everyday practice (see APPENDIX A.1).

Mihalakakou et al. (1995) model was developed based on calculating the overall performance of the earth air heat exchanger using the following dimensionless parameter $U^*$ as follows:

$$U^* = \frac{(T_{in} - T_s)}{(T_{out} - T_s)}$$  (5-15)

where $T_{in}$, $T_{out}$, and $T_s$ are the air temperature at the pipe’s inlet, the air temperature at the pipe’s outlet and the subsoil temperature for undisturbed soil, respectively. $T_{in}$ and $T_s$ are a system parameters with known values, where the calculation of parameter $U$ depends on the direct knowledge of exit temperature at the outlet of the pipe $T_{out}$. In order to predict the value of $U^*$ a systematic analysis process was followed. Equation (5-15) presented above was used to calculate the values of $U^*$ for various sets of input parameters. Then a parametrical approach was followed such that each parameter affecting the variation of a factor is considered to be independent.
while the others remained unchanged. The parameters upon which $U^*$ depends are pipe lengths ($L$) volume airflow rate through the pipe ($SV$) and the depth ($D$) of the pipe below the ground surface. The $U^*$-coefficient values that correspond to $L=30m$, $SV=0.393m^3$, and $D=2m$ were selected as the $U^*$-reference profile.

The statistical analysis, based on a regression technique, was extended to create a database of $U^*$-coefficient data corresponding to the previously mentioned extensive set of input parameter values.

The whole process based on the authors' explanation was as follows:

The $U^*$ values corresponding to the reference values for parameters $SV$ and $D$ were fitted to a third degree polynomial function of the parameter $L$. Thus the equation expressing the $U^*$ reference profile is:

$$U^*_{ref}(L) = 0.9952 - 0.0168L + 0.00019L^2 - 9.57 \times 10^3$$ (5-16)

Furthermore, $U^*$-values were normalised for each parameter separately. The normalisation of $U^*$-values here is a statistical process where a parameter is considered to be the dependent variable for which a regression function has to be determined, while the other variables are considered as independent. The values were sorted into two groups of system parameters. In the first group the dependent parameter is $D$ and the independent parameters are $SV$ and $L$. In the second group the dependent parameter is $SV$ and $D$ and $L$ are the independent ones. The $U^*$-coefficient data in each group was normalised with respect to the reference value of the dependent variable for each value of the two independent variables. Thus, if the first group of $U^*_{SV, L}(D_i)$is a numerical by predicted value of $U^*$-coefficient.
corresponding to the $i, j, t$ values of the parameters SV, $L$, and respectively and that $U^*_{SV_i, L_j}$ is the $U^*$ at reference value for the dependent variable $(D_r)$ and for the given values of the two independent variables (SV) and ($L$), the relevant normalised $U^*$-coefficient value may be

$$U^*_{\text{norm}_{SV_i, L_j}}(D_r) = \frac{U_{SV_i, L_j}(D_r)}{U_{SV_i, L_j}(D_{\text{ref}})} \quad (5-17)$$

Similarly, for the second group the normalised $U^*$-Coefficient is:

$$U^*_{\text{norm}_{Di, L_j}}(SV_r) = \frac{U_{Di, L_j}(SV_r)}{U_{Di, L_j}(SV_{\text{ref}})} \quad (5-18)$$

Where $i, j$ and $t$ are values of $D, L$ and $SV$ respectively. These normalised $U^*$-values are then expressed as third-degree polynomials, applying a regression analysis. The fitting equations are:

$$U^*_{\text{norm}_{SV_i, L_j}}(D_r) = a_0 + a_1 D + a_2 D^2 + a_3 D^3 \quad (5-19)$$

$$U^*_{\text{norm}_{Di, L_j}}(D_r) = b_0 + b_1 SV + b_2 SV^2 + b_3 SV^3 \quad (5-20)$$

The coefficient of the polynomials in Equations (5-19) and (5-20) are given in Appendix A at the end of the thesis (Tables A.2-A.3).

A step by step calculation of earth air heat exchanger outlet air temperature is produced, which was then compared with corresponding values produced from the EAHE model presented in this thesis (see Appendix A.1). The model of Mihalakakou et al. (1995) was validated against an extensive set of experimental data, showing good agreement with his own experimental data.
The comparisons between the two models (i.e. Mihalakakou et al. (1995) model and EAHE model) have been performed using the TRNSYS-SIMULATION program (Klein et al 1996) and employed Kuwait hourly weather data. Mihalakakou et al. (1995) used an undisturbed constant soil temperature. However, the model described the subsoil temperature for Kuwait (described in chapter 4) is used to supply both models with subsoil temperature values. Figure 5.12 shows the TRNSYS configuration of the two simulation models.

![Figure 5.10](image)

Figure 5.10 The EAHE model comparison with Mihalakakou et al (1995) model at depth 2m using a month of July of Kuwait (TMY) data (Kuwait Institute for Scientific Research, 1995).
Figure 5.11 The EAHE model comparison with Mihalakakou et al (1995) model at depth 4 meters using Kuwait (TMY) data (Kuwait Institute for Scientific Research, 1995) for the period May-Sept,

Figure 5.10 and Figure 5.11 show a comparison of outlet air temperature predicted by the EAHE model and that of Mihalakakou et al. (1995) for July and for the period of the summer season (May-Sept) at depths of 2m and 4m. The comparison between the two models (as seen in the two graphs) shows good agreement. The difference between outlet temperatures as predicted by the two models remains within the range of ±0.1°C to ±0.6°C.

However, shallow depth below ground surface may not be applicable to Mihalakakou et al. (1995) model showing inconsistency in the outlet air temperature pattern which should follow a sinusoidal pattern, whilst outlet air temperature of EAHE model can predict outlet air temperature at all depths below ground, see Figure 5.13.
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Figure 5.12 TRNSYS System configuration for simulation models, EAHE and Mihalakakou et al. (1995) model comparison

Figure 5.13 At shallow depth below ground surface Mihalakakou et al (1995) model may not be applicable which shows inconsistency in prediction of outlet air temperature pattern which should follow a sinusoidal pattern, similar to that shown in the EAHE model prediction.
5.5.3 Comparison with experimental work of Shingari (1995)

An experimental study where input parameters were the same as those required by the EAHE model (see modelling components of INPUTS, PARAMETRS and OUTPUTS in Figure 5.9) was carried out in India by Shingari (1995). The study was conducted at a house in Punjab Agricultural University. A PVC pipe of 20cm diameter was laid in soil to a depth of 1.7 m with an undisturbed soil temperature of 20°C. The length of the pipe is 13 m, and it drew ambient air at the inlet, discharging it from the outlet. The experiment was carried out to examine the relation between the velocity of the air inside the pipe and the air temperature discharging from the pipe. The values of air velocity inside the buried pipe are as follows: 0.5m/s, 1.3m/s, 4.5m/s, and 10.5m/s.

The strategy in validating the EAHE model using Shingari's experimental study is based on data provided in the study and outlined in Table 5.3. These data were used in the EAHE model to predict outlet air temperature, which was then compared with Shingari's experimental values. Comparison of results is shown in Table 5.2 where good agreement can be seen, except for the velocity value of 0.5m/s. Here, a slight difference of outlet air temperature values between the EAHE predictions and Shingari's experimental results occurs. This difference may be due to the time required for the system to thermally stabilise. It is possible that if the experimental data were taken sequentially, then the first reading (for 0.5m/s) may not have been in steady state condition, see Table 5.2.
Table 5.2 EAHE model Vs Shingari (1995) experimental studies

<table>
<thead>
<tr>
<th>Velocity</th>
<th>Ambient air temp.</th>
<th>Shingari(experimental)</th>
<th>EAHE Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 m/s</td>
<td>33.6°C</td>
<td>30.3°C ±0.74</td>
<td>27.5°C</td>
</tr>
<tr>
<td>1.3 m/s</td>
<td>38.6°C</td>
<td>31.1°C ±0.47</td>
<td>30.18°C</td>
</tr>
<tr>
<td>4.5 m/s</td>
<td>37.5°C</td>
<td>33.5°C ±0.59</td>
<td>33.29°C</td>
</tr>
<tr>
<td>10.5 m/s</td>
<td>39.6°C</td>
<td>35.4°C ±0.33</td>
<td>35.87°C</td>
</tr>
</tbody>
</table>

5.5.4 Comparison with experimental work of Dhaliwal et al (1984)

The second set of available data (see Table 5.3) with input parameters that correspond to those required by the EAHE model come from experimental work carried out in the USA by Dhaliwal et al (1984). The difference between the Shingari (1995) experimental work and that of Dhaliwal et al (1984) is that Shingari examined the effect of air velocity inside the pipe, while Dhaliwal et al (1984) examined the effect of ambient air temperature entering the system. Dhaliwal et al (1984) conducted work in the outdoor environment of North Carolina A&T University using a pipe of 30 cm diameter and 24.7 m in length buried in the soil to a depth of 1.7 m. The soil properties and the system input parameter details are outlined in Table 5.3. The air temperature inside the pipe is taken at various lengths along the pipe using several thermocouples located inside and around the pipe. The ambient temperature and relative humidity were taken at ½ hour intervals over 24 hours. The experimental results shown by Dhaliwal et al (1984) consist of outlet air temperature and relative humidity values for selected hours. In the comparison between the Dhaliwal et al (1984) data and EAHE prediction, the experimental results for the first hour and after 17.5 hours were selected. The resulting outlet temperature predicted by the EAHE model is in good agreement with the experimental results, (see Table 5.4). The slight difference in outlet temperature values between the Dhaliwal et al. (1984) experiments and the
EAHE model prediction at the first hour may be due to the developing thermal stability of the soil mass surrounding the EAHE system at the beginning of the experiment.

From the above, it can be concluded that the EAHE model has been shown to predict an outlet air temperature that is in good agreement with data from Mihalakakou et al (1995), Shingari (1995), and Dhaliwal et al.(1995). Thus, the model can be used to describe the thermal performance of EAHE system (by linking it to TRNSYS-Type56). In order to maximise the performance of the EAHE system for cooling in a desert climate like that in Kuwait, a sensitivity analysis or parametrical study will be investigated next, based on the validation model.

Table 5. 3 Input parameters for three systems: Mihalakakou et al (1995), Shingari (1995), and Dhaliwal et al.(1995)

<table>
<thead>
<tr>
<th>System parameter</th>
<th>Mihalakakou</th>
<th>Shingari</th>
<th>Dhaliwal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe diameter(cm)</td>
<td>Table selection</td>
<td>20cm</td>
<td>30cm</td>
</tr>
<tr>
<td>Pipe length(m)</td>
<td>Table selection</td>
<td>13</td>
<td>24.7</td>
</tr>
<tr>
<td>Air velocity(m/s)</td>
<td>Table selection</td>
<td>At 0.5-1.3-4.5-10.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Soil temperature(°C)</td>
<td>As inputs Parameter</td>
<td>20</td>
<td>18.89</td>
</tr>
<tr>
<td>Pipe Depth (m)</td>
<td>Table selection 0.5m-6m</td>
<td>1.7</td>
<td>2.13</td>
</tr>
<tr>
<td>Soil Thermal conductivity</td>
<td>-</td>
<td>-</td>
<td>1.167W/m.°C</td>
</tr>
<tr>
<td>Soil Thermal diffusivity</td>
<td>-</td>
<td>-</td>
<td>0.00232m²/hr</td>
</tr>
<tr>
<td>Ambient Temperature (°C)</td>
<td>Any weather (Kuwait)</td>
<td>Provided</td>
<td>Provided</td>
</tr>
</tbody>
</table>
Table 5.4: EAHE model vs. Dhaliwal et al. (1984) experimental studies.

<table>
<thead>
<tr>
<th>Time</th>
<th>Air temperature</th>
<th>Distance from the inlet of buried pipe (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>3.35m</td>
</tr>
<tr>
<td>At first hour</td>
<td></td>
<td>25.56°C</td>
</tr>
<tr>
<td>(Dhaliwal et al. 1984)</td>
<td>1984</td>
<td></td>
</tr>
<tr>
<td>EAHE outlet air Temperature</td>
<td>24.94°C</td>
<td>24.43°C</td>
</tr>
<tr>
<td>After 17.5 hours</td>
<td></td>
<td>20.55°C</td>
</tr>
<tr>
<td>(Dhaliwal et al. 1984)</td>
<td>1984</td>
<td></td>
</tr>
<tr>
<td>EAHE outlet air Temperature</td>
<td>20.40°C</td>
<td>20.27°C</td>
</tr>
</tbody>
</table>

5.6 Sensitivity analysis of Earth Air Heat exchanger (EAHE)

The cooling ability of the earth air heat exchanger (EAHE) is affected by many conditions such as weather conditions, soil properties and parameter variation of the EAHE system (e.g. pipe length, pipe diameter, air flow rate inside the pipe, and depth of pipe below ground). An experimental approach for determining the thermal performance of an EAHE system is costly and it is difficult to investigate the impact of parameter variations. A simulation program, on the other hand, can overcome these disadvantages of field experiments with reliable and convenient results.

An earth air heat exchanger (EAHE) system was modelled using the TRNSYS-IISIBAT simulation program. The later EAHE model has been validated as described in the previous sections. EAHE model was also encoded into MATLAB program, which is capable of being used for parametrical study of the thermal performance of the EAHE system with Kuwait soil conditions. Input values such as soil properties...
and parameter variation of the EAHE system (i.e. pipe length, pipe diameter, air flow rate inside the pipe, and depth of pipe below ground) were used to calculate the cooling ability of the EAHE system. MATLAB program has more features in relating each parameter (length, diameter, airflow, depth, and soil thermal conductivity) to the outlet air temperature of the EAHE system. An extensive sensitivity analysis consisting of 5 cases as shown in Table 5.5 was performed. As seen in Table 5.5, the variables investigated that influence the thermal performance of the EAHE system are, namely: pipe length, airflow rate in the pipe, depth of the buried pipe below the ground surface and the soil thermal conductivity. For each variable, a sensitivity analysis was carried out using MATLAB program taking series of values for each case, where other variables in the same case remain constant.

The cooling ability of the EAHE system is measured in terms of the reduction in air temperature achieved after passage through the full length of pipe. In this section, the effect of the parameters stated in Table 5.5 is investigated. The aim is to produce guidance that may be used by designers, builders and homeowners to help maximise cooling potential in a desert climate. The results are discussed next.
Table 5.5 The factors effecting the simulation of the EAHE model.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Case</th>
<th>Length (m)</th>
<th>Flow rate m³/s</th>
<th>Depth (m)</th>
<th>Diameter (m)</th>
<th>Soil conductivity W/m °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influence of length</td>
<td>1</td>
<td>0-100</td>
<td>0.023</td>
<td>4</td>
<td>0.25</td>
<td>0.86</td>
</tr>
<tr>
<td>Influence of airflow</td>
<td>2</td>
<td>60</td>
<td>0-0.9</td>
<td>4</td>
<td>0.25</td>
<td>0.86</td>
</tr>
<tr>
<td>Influence of depth</td>
<td>3</td>
<td>60</td>
<td>0.023</td>
<td>0-7</td>
<td>0.25</td>
<td>0.86</td>
</tr>
<tr>
<td>Influence of diameter</td>
<td>4</td>
<td>60</td>
<td>0.023</td>
<td>4</td>
<td>0.1-1.8</td>
<td>0.86</td>
</tr>
<tr>
<td>Influence of soil</td>
<td>5</td>
<td>60</td>
<td>0.023</td>
<td>4</td>
<td>0.25</td>
<td>0-1.2</td>
</tr>
</tbody>
</table>

5.7 Cooling ability of the Earth Air Heat Exchanger (EAHE) system: Results of sensitivity analysis

5.7.1 Influence of pipe Length (Case 1)

To investigate the influence of pipe length, simulations have been carried out for a continuous pipe length, namely from 0-100m (Case 1) while the other parameter values remained unchanged. Figure 5.14 shows the effect of the pipe length increase the EAHE system performance. This reduction of the outlet air temperature of the pipe represents an increase of heat removal from the pipe with a corresponding increase of the system potential cooling capacity, as shown from Figure 5.14. Figure 5.14 shows that reduction of outlet air temperature with increase of pipe length would not be significant after a length of 60m.
Figure 5.14 Relation between pipe length (m) and outlet air temperature (°C).

5.7.2 Influence of Airflow (Case 2)

Figure 5.15 presents the results of simulations for a continuous airflow rates, namely from 0-0.9 m³/s (case2) while the other parameter values remained unchanged. It can be seen that an increase of airflow in the pipe within range of 0-0.9 m³/s may have a slight increase of the outlet air temperature. However, Figure 5.15 shows a sharp increase in outlet temperature when the airflow rate exceeds 0.09 m³/s (388.8 kg/hr).

Thus, a value of airflow rate limited to a range of 0.023 m³/s (100 kg/h) to 0.09 m³/s (388.8 kg/h) may be applicable to the EAHE system. De Paepe and Janssens (2002) suggest that, most effective earth heat exchanger is the one with smallest flow rate. Resulting to a similar finding of Ishihara et al. (1992). The EAHE system operated
with an airflow rate value of 100kg/h (0.023m$^3$/s) is shown to give a reasonable outlet air temperature in the desert climate like that in Kuwait.

Figure 5. 15 Relation between flow rate inside the pipe and outlet temperature.

5.7.3 Influence of pipe burial depth (Case 3)

The pipe burial depth is a vital factor that will affect the outlet temperature of the pipe. As explained in chapter 4, the Kuwaiti sub-surface temperature decreases with depth and varies with time of the year. Simulations have been carried out for continuous pipe burial depths, namely from 0-7m (case3) while other parameters remaining unchanged. From Figure 5.16, it can be seen that as the pipe depth increases from ground surface to 1m the outlet air temperature decreased by 1.7°C until it reaches 0.1°C at depth of 7m. However the cost of laying pipe at depth far below ground surface must also be considered.

An EAHE system buried to a depth of 4m may give a reasonable outlet air temperature in the desert climate like that in Kuwait, and thus, limit the cost of excavation.
Figure 5.16 Relation between pipe depth below ground surface and pipe outlet air temperature.

5.7.4 Influence of pipe diameter (Case 4)

Simulations were carried out for continuous values of pipe diameter, namely 0.10m-1.8m (case 4) whilst maintaining the same values of the other parameters. Figure 5.17 presents a slight increase of 0.3°C when the pipe diameter becomes 0.5m. Furthermore, from Figure 5.17, it can be seen that the outlet air temperature from the pipe increases as the pipe diameter increases. This may be explained by the fact that the convection heat transfer in Equation 5.3 has an inverse relation with diameter of the pipe. Thus an increase of pipe diameter leads to a reduction in the convection heat transfer which increases the thermal resistance between air flowing inside the pipe (see Equation 5.2) and the pipe surface. Thus the overall coefficient of heat transfer (U-value) of the pipe will be decreased, which creates a pipe surface with an effecting
higher 'insulation' that would result in an increase in EAHE system outlet air temperature. De Paepe and Janssens (2002) suggests that, most effective earth heat exchanger is the one with smallest pipe diameter. The EAHE system with diameter values in the range of 0.2-0.5m appears to give predict a reasonable outlet air temperature in the desert climate like that in Kuwait (see Figure 5.17). A diameter of 0.25m was thus, selected for the analysis in this thesis.

![Figure 5.17 Relation between pipe diameter of the pipe and outlet air temperature.](image)

### 5.7.5 Influence of soil thermal conductivity (Case 5)

The thermal conductivity of soil is one of the key factors that influence the cooling ability of the EAHE system. The thermal characteristics of the Kuwaiti sub-surface vary from area to area. As explained in chapter 4, there are two regions in Kuwait,
namely the coastal and the desert region. Each region has a different value of thermal conductivity based on the type of soil and its water content. However, a common value for the thermal conductivity and thermal diffusivity of Kuwaiti subsoil were used. As illustrated in chapter 4, (0.86W/m °C value as soil thermal conductivity of Kuwaiti subsoil and 0.0038m²/h value as soil thermal diffusivity). In this section the EAHE system with continuous values of soil thermal conductivity are examined for cooling ability.

Simulations were carried out for the buried pipe surrounded by soil with continuous values of thermal conductivity, namely, 0-1.2W/m°C (Case 5), while the other input parameter values remained unchanged. It can be seen from Figure 5.18 that outlet air temperature of the buried pipe decreases with the increase of soil thermal conductivity values. The reason for decreasing the outlet air temperature of the system is that, based on the soil thermal diffusivity equation ($\alpha = \frac{k}{\rho c_p}$ (refer to chapter 4)) the soil thermal diffusivity is directly proportional to thermal conductivity. Therefore when soil thermal diffusivity increases that will lead to a decrease in the subsoil temperature. As seen from Equation 5.12, this will lead to decrease the outlet air temperature of EAHE system. Hence Kuwaiti soil thermal conductivity was measured in the field, which found to be equal to 0.86W/m °C (refer to chapter 4).
Figure 5.18 Relation between soil thermal conductivity (W/m°C) and pipe outlet air temperature (°C).

5.8 Summary

Cooling the ambient air by means of an Earth Air Heat Exchanger (EAHE) involves two kinds of heat transfer between the soil, pipe, and the air circulating in the pipe whilst it is buried below the ground surface. Pre-cooling of the outdoor ventilation air then serves to reduce the cooling loads of buildings. An EAHE thermal model is presented to calculate the outlet air temperature from a buried pipe (EAHE) and the total energy loss/gain along the pipe. The EAHE model was validated against results from three other studies: one theoretical study by Mihalakakou et al (1995), and two sets of measured data by Dhaliwal et al (1984), and Shingari (1995). The validation
process shows that the proposed EAHE model agrees with all of the three published studies with respect to the input of common parameters and is therefore considered to be appropriate to simulate the thermal behaviour of an earth air heat exchanger. The EAHE model was combined with a model that predicts Kuwait sub-surface temperature (presented in chapter 4) using TRNSYS-IISIBAT simulation environment. These two models are capable of being used for examining the thermal performance of the EAHE system buried in a desert climate such as Kuwait. An extensive sensitivity analysis of 5 Cases as shown in Table 5.5 was performed. The variables influencing the thermal performance of the EAHE system (pipe length, airflow rate in the pipe, depth of the buried pipe below ground surface and subsoil thermal conductivity) were investigated. For each variable, sensitivity analysis was carried out taking continuous values for each case and keeping other variables as constant. The sensitivity analysis results showed the following:

- Outlet air temperature from the buried pipe reduces as pipe length increases. However, beyond about 60 m length, there is little further improvement. Thus a length of no more than 60m should be considered for an EAHE system with a single pipe configuration.

- Outlet air temperature from the buried pipe increases as airflow rate increases. However, airflow rates beyond about 0.09 m$^3$/s (388.8 kg/hr) should not be considered for EAHE system with single pipe configuration.

- Outlet air temperature from the buried pipe decreases as burial depth of the pipe increases. An EAHE system buried to a depth of 4m may give a reasonable outlet air temperature in the desert climate like that in Kuwait, and thus, limit the cost of excavation.
• Outlet air temperature from the buried pipe increases as the pipe diameter increases. However, the EAHE system with a diameter value beyond 0.5m may not provide a reasonable outlet air temperature in the desert climate like that in Kuwait. Thus, 0.25m diameter should be considered as reasonable design value.

• Outlet air temperature from the buried pipe decreases with increase of soil thermal conductivity values. However, soil thermal conductivity beyond about 1.2W/m°C shows to improve the pipe outlet temperature, which in fact unlikely found in desert region, due to the low moisture content found. Thus, a soil thermal conductivity value of no more than 0.86W/m°C should be considered for desert climate such as Kuwait.

Hence, the EAHE system parameter values that will be used in the next chapters (7 and 8) are: pipe length, airflow rate in the pipe, depth of the buried pipe below the ground surface and the soil thermal conductivity are equal to 60m, 100kg/hr (0.023 m³/s), 4m and 0.86W/m°C respectively. Furthermore, the parameters analysis conducted in this chapter serves to refine the design of single pipe EAHE system for desert climate like that of Kuwait, and provides useful guidance for constructions.
Chapter six: Example Building

6.1 Introduction

Domestic buildings in Kuwait are estimated to consume 70% to 80% of the electrical power generated (Annual Statistics 1999 and Statistical Yearbook 2000). The buildings are subject not only to high ambient air temperatures, but also to strong solar radiation, which strikes each part of the building in turn as the sun moves around a clear sky. Moreover, there is very low water vapour content in the air, which would otherwise help in dissipating or absorbing part of the spectral energy from the sun. However, the high ambient temperatures (see Figure 2.6), together with intense solar radiation (Figure 2.7) and other factors, affect the energy requirements of buildings. Factors include the following:

- Building location (altitude, latitude, longitude and orientation).
- Local weather conditions.
- Heat transfer and storage characteristics of the building’s elements, which depend on the various thermophysical properties of the building’s components, (See Table 6.4 and Chapter 2 for more details).
- Windows, doors and other openings.
- Shading of the exterior surface.
- Building dimensions.
- Indoor temperature, number of occupants, lighting and building usage.
- Primary and secondary air-conditioning systems.
- Ventilation and infiltration.
Each of these factors could influence the cooling load of the building. The degree of influence of each factor will vary from one building to another depending on the variation in architectural design, function of the building and materials used in the construction. In Kuwait, the Ministry of Electricity and Water (MEW) issued an energy conservation code in 1983. This code represents a set of regulations that guides the construction of new buildings. All houses that had received authorisation to be built prior to the code do not include any energy conservation measures. The National Housing Authority (NHA) undertakes to use new building materials that were not considered in the MEW code but are reliant on the information received from the Kuwait Institute for Science and Research (KISR). However, Kuwaiti building codes as embodied in MEW or NHA specifications still lack some technical guidance regarding wall materials, orientation of the building, window shading factors used and the ventilation and infiltration in Kuwaiti buildings.

Therefore, the aim of this chapter is twofold. Firstly to provide further guidance to enhance Kuwait’s building code, and secondly to arrive at a building design that is both energy-efficient and typical of local design for use with the EAHE system.

Such an “efficient” building (which gives the least energy consumption among the building cases in Table 6.6) is the example building that will be linked to the Earth-Air Heat Exchanger system (EAHE) for estimation of energy-saving potential.

An example building in each case is presented and modelled using the TRNSYS-PREBID (multi-zone building simulation) programme for hourly analysis of energy consumption and for the peak load in buildings (See Chapter 3 for the details of TRNSYS-PREBID).
6.2 Building Case study

The building case study that was chosen was fairly similar to a government dwelling type NHA (National Housing Authority), which is the major type of housing in Kuwait. These houses are unified in design and construction materials and one of a high standard in quality (see chapter 2). The dimensions of the building (single storey building) are 10m x 8.2m (as shown in Figure 6.1), giving a space living area of 82m$^2$ with height of 2.5 m. The building components for all cases are shown in Table 6.4, Table 6.5 and Table 6.6. There are several building component construction materials used in a Kuwaiti building. Building case components were chosen to be fairly similar to the building type used in the NHA housing programme (National Housing Authority) or the private housing programme (Al-Mudhaf et al 1997, Al-ragom et al 1998). Referring to Tables 6.4 and 6.5, NHA buildings are limited to two types of wall construction: ‘AAC’ wall (Autoclaved Aerated Concrete) and ‘classical’ wall.

An example building with input data as in Table 6.5, building materials as in Table 6.4 and case situations as in Table 6.6 was simulated using TRNSYS-PREBID. The following important factors are addressed in the investigation:

- Construction components of the example building.
- Building parametrical study for energy consumption analysis.
- Optimal energy consumption for the building cases.
- Design guidance for building in a desert climate.
Figure 6.1 Detailed plan layout of the building case.

Figure 6.2 North Elevation of building case.
South Elevation

Figure 6.3 South Elevation of building case.

East and West

Figure 6.4 East and West Elevation of the building case.
6.3 Construction components of the example building

The example building components consist of the exterior walls and the roof, the openings to the outdoors being represented by two windows each with an area of 1m² and a wooden door of area of 2 m². However, in the following sections, and using a desert climate as in Kuwait, building cases were investigated for two types of wall (AAC and classical) as used in Kuwait (see Table 6.4, Figure 6.6 and Figure 6.7) for the assumed cases in Table 6.6. In addition, the effects of glazing area and orientation were investigated. This will lead to the identification of an energy-efficient building design to be simulated with the Earth-Air Heat Exchanger in a hot desert climate similar to the Kuwait climate, so as to estimate a value for a typical 'good' level of energy saving potential.
6.3.1 Classical wall

The classical wall was introduced into the construction field in the early 1940s after the discovery of oil in Kuwait. Its initial form consisted of a concrete block and cement mortar. The elements of this wall developed gradually until the late 1970s, when thermal insulation was added. The overall thermal transmittance (U-value) for the classical wall is equal to 0.515 W/m² °C (see Table 6.1 and Figure 6.6), which meets the standards of MEW (i.e. U-value (exterior wall)= 0.568 W/m² °C, see chapter 2). There are several factors that make the classical wall more preferable and acceptable to Kuwaiti people, these are (Allison, 1979, 1985, Aasem, 1993):

- The classical wall is cheap in terms of its labour and materials.
- It is available and is produced locally in Kuwait by many construction factories.
- It is a strong wall and can tolerate holes to hang pictures or any other aesthetic items.
- Appropriate-skilled manpower is available in Kuwait for its construction.

The U-value of the classical wall may be found using the following equations:

\[
R = \frac{1}{U} \tag{6-1}
\]

\[
\frac{1}{U} = \frac{1}{\frac{1}{h_o} + \frac{x_{sl}}{k_{sl}} + \frac{x_{ins}}{k_{ins}} + \frac{x_{cb}}{k_{cb}} + \frac{x_{cp}}{k_{cp}} + \frac{1}{h_i}} \tag{6-2}
\]

Where \((h_o)\) and \((h_i)\) are the convective heat transfer coefficients at exterior and interior wall surfaces, respectively. In the case of Kuwait, \(h_o = 20.4\) W/m² °C.
\( h_i = 8.2 \, \text{W/m}^2 \, \text{°C} \) (Al-Mudaf et al., 1997). \( x \) is thickness (m) and \( k \) is thermal conductivity \( (\text{Wm}^{-1}\text{C}^{-1}) \), where subscript ‘sl’ denotes sand lime brick, subscript ‘ins’ denotes insulation, subscript ‘cb’ denotes cement block and subscript ‘cp’ denotes cement plaster.

The classical wall U-value can be calculated using Equation 6-2, to arrive at a value equal to 0.515 W/m\(^2\) °C (see details in Table 6.1).

**Table 6.1 U-value calculation for the classical wall**

<table>
<thead>
<tr>
<th>Building Component</th>
<th>Building Material</th>
<th>( x ) m</th>
<th>( k , \text{Wm}^{-1}\text{C}^{-1} )</th>
<th>( R , \text{m}^2\text{CW}^{-1} )</th>
<th>U-Value ( \text{Wm}^{-2}\text{C}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior walls</td>
<td>Sand- lime block</td>
<td>0.09</td>
<td>1.310</td>
<td>0.0687</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Insulation</td>
<td>0.05</td>
<td>0.032</td>
<td>1.56</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cement block</td>
<td>0.20</td>
<td>1.64</td>
<td>0.122</td>
<td></td>
</tr>
<tr>
<td>Height 2.5m</td>
<td>Cement plaster</td>
<td>0.02</td>
<td>1.0</td>
<td>0.02</td>
<td>0.515</td>
</tr>
<tr>
<td></td>
<td>( h_o )</td>
<td></td>
<td>20.4</td>
<td>0.049</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( h_i )</td>
<td></td>
<td>8.2</td>
<td>0.122</td>
<td></td>
</tr>
</tbody>
</table>
6.3.2 AAC Block Or Azel Block Wall

‘AAC’ (Autoclaved Aerated Concrete) is a cementitious matrix made by introducing air or gaps into the prepared slurry. The air is usually entrapped in a closed cell form (ACICO Manual, 1996). Since the early 1980s, the AAC Block has become popular in Kuwait's construction market. The technology of the AAC was brought from Germany through a local company called National Industries Company (NIC). However, NIC recently installed a plant that produces aerated concrete blocks (called the ‘Azel’ block) or the AAC block in Kuwait itself. The AAC blocks are made usually with bulk densities in the ranges 400-800 kg m$^{-3}$. Due to the good thermal insulation properties of this material, it was proposed as a replacement for the classical wall (see Table 6.4 (type1 and type2)). Thermophysical properties of the
AAC blocks were investigated by Kuwait’s Institute for Scientific Research. The results found were that the AAC block comes in three different density ranges: 50-240 kg m$^{-3}$, 245-480 kg m$^{-3}$ and 485-730 kg m$^{-3}$, corresponding to ‘lightweight’, ‘mediumweight’, and ‘heavyweight’, respectively. The thermal conductivity (k) values for the AAC blocks designated lightweight, mediumweight and heavyweight are 0.12, 0.13 and 0.16 $Wm^{-1}C^{-1}$ (Kellow et al 1985; ACICO Manual 1996), respectively. However, the most common AAC block used in Kuwait is one with a thermal conductivity equal to 0.145 $Wm^{-1}C^{-1}$ (Al-Mudhaf et al 1997). While the AAC block has been used in the Kuwaiti construction industry since the early 1980s to replace the classical wall (or to be an alternative), there are several advantages and disadvantages regarding the AAC wall.

- The AAC block works as two construction components in one element, namely block and thermal insulation.

- The AAC block is light, therefore it requires thickness in order for it to be used in exterior walls. It should be at least 20-25 cm thick in order to have a strong wall.

- The cost of the AAC block is close to the cost of the classical wall if thermal insulation is added. However, costs could be a lot higher if a layer of wire mesh (chicken mesh) was to be installed over the AAC block to strengthen and bond the cement plastering with AAC block.

- There are only two construction factories that produce the AAC block locally in Kuwait.

- It is not strong enough to tolerate holes in the wall to hang pictures or any other aesthetic items.
Despite the advantages and disadvantages of the two walls, the AAC block has been used by the National Housing Authority (NHA), the private sector and also in government buildings, irrespective of energy consumption issues. When applying Equation 6.3, and the values in Table 6.2, the U-value for the ACC wall is found to be equal to 0.556 $Wm^{-2}C^{-1}$ (see Table 6.2 and Figure 6.7), which meets the standards of MEW (i.e. U-value (exterior wall)= 0.568 $Wm^{-2}C^{-1}$, see chapter 2).

$$\frac{1}{U} = \frac{1}{h_a} + \frac{x_{sl}}{k_{sl}} + \frac{x_{cb}}{k_{cp}} + \frac{x_{aac}}{k_{aac}} + \frac{x_{cp}}{k_{cp}} + \frac{1}{h_i}$$

(6.3)

The subscript ‘aac’ denotes the AAC block cement, and other terms are as defined for Equation 6.2.

Table 6.2 Overall-heat transfer coefficient (U-value) for AAC wall

<table>
<thead>
<tr>
<th>Building Component</th>
<th>Building Material</th>
<th>$x_m$</th>
<th>$k_{Wm^{-1}C^{-1}}$</th>
<th>$R_{m^2CW^{-1}}$</th>
<th>U -Value $Wm^{-2}C^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior walls</td>
<td>Sand- lime block</td>
<td>0.09</td>
<td>1.310</td>
<td>0.0687</td>
<td>0.556</td>
</tr>
<tr>
<td></td>
<td>Cement plaster</td>
<td>0.02</td>
<td>1.0</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td>AAC block</td>
<td>0.22</td>
<td>0.145</td>
<td>1.52</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cement plaster</td>
<td>0.02</td>
<td>1.0</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Height 2.5m</td>
<td>$h_a$</td>
<td>20.4</td>
<td></td>
<td>0.049</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$h_i$</td>
<td>8.2</td>
<td></td>
<td>0.122</td>
<td></td>
</tr>
</tbody>
</table>
6.3.3 Roof

The traditional flat roof is almost universal in Kuwait. The roofs of dwellings were extensively used for sleeping areas before mechanical cooling was known and were also used as storage. However, the main reason why flat roofs continue to be largely used is due to the fact that Kuwaiti family members are increasing in number and size and they prefer to live together rather than move to another place. Therefore, more building space is required and can be obtained by extending either horizontally or vertically. Therefore, the flat roof is a more flexible and cheaper way for this type of building construction to be extended than any other roof. In view of this, the flat roof is very popular and is used by most Kuwaiti people. It is also specified by the
Kuwaiti Government through the NHA housing program. The roof has an overall U-value equal to 0.332 $Wm^{-2}C^{-1}$, which meets the MEW standard U value for roofs (i.e. $U$ (roof) = 0.4 $Wm^{-2}C^{-1}$). Therefore, the example building in this thesis will have a flat type of roof. The building materials of the flat roof used in the example building are chosen to be the same as for domestic building roof materials as used by the Government sector through the NHA programme and also by most of the private buildings in Kuwait. The thermophysical properties of the roof are shown in Table 6.4 and a detailed cross-section is shown in Figure 6.8 (Al-Mudhaf et al., 1997; Ministry of Electricity and Water, 1999).

Figure 6.8 Detailed construction section of Kuwaiti flat roof
The U-value for the common Kuwaiti roof with material thickness as \(x\) and thermal conductivity as \(k\) as shown in Table 6.3 is calculated using Equation 6.4 and is equal to 0.332 W/m\(^2\).K.

\[
\frac{1}{U} = \frac{1}{h_o} + \frac{x_{mt}}{k_{mt}} + \frac{x_{cm}}{k_{cm}} + \frac{x_{ss}}{k_{ss}} + \frac{x_{ins}}{k_{ins}} + \frac{x_{wp}}{k_{wp}} + \frac{x_{ss}}{k_{ss}} + \frac{x_{fc}}{k_{fc}} + \frac{x_{cs}}{k_{cs}} + \frac{1}{h_i}
\]  
(6.4)

Here subscript ‘mt’ denotes the mosaic tiles, subscript ‘cm’ denotes cement mortar, subscript ‘wp’ denotes water proofing, subscript ‘ss’ denotes sand screed, subscript ‘fc’ denotes foam concrete and subscript ‘cs’ denotes concrete slab.

Table 6.3 Overall-heat transfer coefficient (U-value) for Kuwaiti common roof.

<table>
<thead>
<tr>
<th>Building Component</th>
<th>Building Material</th>
<th>(x) in m</th>
<th>(k) in W/m(^\circ)K(^{-1})</th>
<th>(R) in m(^2)K/W(^{-1})</th>
<th>U-Value in W/m(^2)K(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof (flat) 8.2m x 10m</td>
<td>Mozaic tiles</td>
<td>0.02</td>
<td>1.104</td>
<td>0.01812</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cement mortar</td>
<td>0.02</td>
<td>1.0</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sand screed</td>
<td>0.02</td>
<td>1.0</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Insulation</td>
<td>0.05</td>
<td>0.029</td>
<td>2.43</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water proofing</td>
<td>0.003</td>
<td>0.140</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sand screed</td>
<td>0.02</td>
<td>1.0</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Foam concrete</td>
<td>0.05</td>
<td>0.21</td>
<td>0.238</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Concrete slab</td>
<td>0.15</td>
<td>1.77</td>
<td>0.0847</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(h_o)</td>
<td>20.4</td>
<td>0.049</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(h_i)</td>
<td>8.2</td>
<td>0.122</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Windows and doors in Kuwait vary in their thermal performance and material properties. In the following section, the windows and door are investigated, in order to promote a guideline strategy that may fulfil the lack in the Kuwaiti building codes of guidance regarding the best areas and thermal transmittances of these components.
6.3.4 Windows

Most windows in Kuwaiti buildings nowadays consist of a double pane of 6mm or 8mm-thick glass. Window frames and glazing are manufactured locally in Kuwait with U-values for single-pane-glass windows equal to 5.8W/m²K and 2.7W/m²K for double-pane-glass. There are some imported glazings with high thermal insulation that are used in commercial buildings. This latter type of ‘insulated’ glazing has a high thermal insulation achieved by using an air film with an insulated sheet between glazing (of the double pane). This type of glazed window is not produced in Kuwait and, therefore, high costs are involved in importing such materials.

When the sun’s energy impacts on a building’s envelope, heat will enter either directly through the transparent areas or it will be absorbed and the heat will enter the building by conduction through opaque elements. Inappropriate sizes of window openings could result in a large area of glass, which in the case of Kuwait’s buildings could be a major source of heat gain. Inappropriate choice of glass may transmit up to 85% of the heat gain from incident sunlight (Al-Temeemi, 1995). The total heat gains for a common Kuwaiti window in four directions were evaluated over a 24-hour period and are shown in Figure 6.9 (Al-Temeemi 1995 and Allison 1979).

Referring to Figure 6.9, for the case of the total heat gain through a common Kuwaiti window type plotted over 24 hrs for a day in mid-July, the highest total heat gain occurs at 15.00 hrs with a value of 467W/m² from a window facing west, whereas a total of 416 Wm² at 09.00 hrs occur when facing east. For north and south, the highest total heat gains were equal to 306 Wm² and 318 Wm², respectively, at 12.00 hrs.
Researchers have suggested that a glass area of $\frac{1}{16}$ of the floor area of a room should be satisfactory for lighting purposes in a hot dry climate (B.S. Saini, 1980). The issues are accounted for in the selection of cases for simulation, see case 3, case 6 and case 7 (Table 6.6). This investigation will lead to the identification of an efficient building design case for further simulation.

Figure 6.9 Total summer heat gains through windows facing four orientations in Kuwait during mid-July for 24hrs (Al-Temeemi 1995 and Allison 1979)

6.3.5 Door
The door used in the example building is 1 metre wide and 2 metres high. It consists of plywood on two sides with a 35 mm air gap in between. This is a typical construction material for a door in Kuwait. The direction of the door faces north and it has a U-value of $1.65\, Wm^{-2}\, C^{-1}$
Table 6.4 Thermophysical building materials of the example building components.

<table>
<thead>
<tr>
<th>Building components</th>
<th>Material (layers)</th>
<th>Thickness cm</th>
<th>Thermal conductivity KJ/hmK</th>
<th>Density kg/m³</th>
<th>Thermal capacity KJ/kgK</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sand-lime block</td>
<td>9</td>
<td>4.716</td>
<td>1918</td>
<td>0.795</td>
</tr>
<tr>
<td></td>
<td>Insulation</td>
<td>5</td>
<td>0.115</td>
<td>30</td>
<td>1.12</td>
</tr>
<tr>
<td></td>
<td>Cement block</td>
<td>20</td>
<td>5.904</td>
<td>2011</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>Cement plaster</td>
<td>2</td>
<td>3.4</td>
<td>2085</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>Sand-lime block</td>
<td>9</td>
<td>4.716</td>
<td>1918</td>
<td>0.795</td>
</tr>
<tr>
<td></td>
<td>Cement plaster</td>
<td>2</td>
<td>3.5</td>
<td>2085</td>
<td>0.840</td>
</tr>
<tr>
<td></td>
<td>AAC(Block)</td>
<td>22</td>
<td>0.522</td>
<td>489.0</td>
<td>0.879</td>
</tr>
<tr>
<td></td>
<td>Cement plaster</td>
<td>2</td>
<td>3.5</td>
<td>2085</td>
<td>0.840</td>
</tr>
<tr>
<td></td>
<td>Concrete slab</td>
<td>15</td>
<td>4.372</td>
<td>2297</td>
<td>0.921</td>
</tr>
<tr>
<td></td>
<td>Sand</td>
<td>4</td>
<td>1.213</td>
<td>1800</td>
<td>0.920</td>
</tr>
<tr>
<td></td>
<td>Cement cement</td>
<td>2</td>
<td>3.4</td>
<td>2080</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>Mozaic tiles</td>
<td>2</td>
<td>3.974</td>
<td>2284</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>Mozaic tiles</td>
<td>2</td>
<td>3.974</td>
<td>2284</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>Cement Mortar</td>
<td>2</td>
<td>3.4</td>
<td>2085</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>Sand screed</td>
<td>2</td>
<td>3.4</td>
<td>2080</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>Insulation</td>
<td>5</td>
<td>0.115</td>
<td>30</td>
<td>1.12</td>
</tr>
<tr>
<td></td>
<td>Water Proofing</td>
<td>0.3</td>
<td>0.504</td>
<td>934</td>
<td>1.507</td>
</tr>
<tr>
<td></td>
<td>Sand screed</td>
<td>2</td>
<td>3.4</td>
<td>2080</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>Foam concrete</td>
<td>5</td>
<td>0.756</td>
<td>351</td>
<td>0.879</td>
</tr>
<tr>
<td></td>
<td>Concrete slab</td>
<td>15</td>
<td>4.372</td>
<td>2297</td>
<td>0.921</td>
</tr>
</tbody>
</table>
Table 6. 5 Input data for the example building required by PREBID.

<table>
<thead>
<tr>
<th>Floor plan shape(m)</th>
<th>Rectangular 10m x 8.2m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall area(m²)</td>
<td>91</td>
</tr>
<tr>
<td>Roof area(m²)</td>
<td>82</td>
</tr>
<tr>
<td>Windows area(m²)</td>
<td>2 (2.45%)</td>
</tr>
<tr>
<td>Building volume(m³)</td>
<td>205</td>
</tr>
<tr>
<td>Windows type</td>
<td>Sliding windows with double-glazing</td>
</tr>
<tr>
<td>U-value of the window</td>
<td>2.7 W/m² K</td>
</tr>
<tr>
<td>Internal shading factor</td>
<td>0.82</td>
</tr>
<tr>
<td>Infiltration airchange</td>
<td>0.4AC/hr</td>
</tr>
<tr>
<td>Building coefficient of absorption</td>
<td>0.57</td>
</tr>
<tr>
<td>Ground reflectance</td>
<td>0.2</td>
</tr>
<tr>
<td>Inside design temperature(°C)</td>
<td>26</td>
</tr>
</tbody>
</table>

6.4 Building parametrical study for energy consumption analysis

Simulations were conducted on the example building, where material properties were used as shown in Table 6.4 and Table 6.5. A number of cases were considered in order to arrive at an energy-efficient example building for use with the EAHE system. In this way the influence of wall type, window area and orientation, together with infiltration rate, can be estimated. This provides further design guidance for Kuwait. The cases simulated are summarised in Table 6.6.

The energy consumption of the example building with and without the use of EAHE will be explained in the next chapter where the most efficient of the building cases will be chosen from amongst the cases in Table 6.6.
It should be emphasised that the data in the building cases shown in Table 6.6 does not cover all the building code’s necessary data. This is simply an attempt to fulfil the need for updated information on energy implications of building materials and design for Kuwait. This will contribute to the establishment of an enhanced building code of practice for Kuwait, though a comprehensive treatment of this issue is beyond the scope of this research.

Table 6.6 Building model cases for thermal analysis

<table>
<thead>
<tr>
<th>Case No</th>
<th>Building cases description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case (1)</td>
<td>Building model using AAC walls type and placing windows in East-West direction + Shading factor equal to 0.82 and infiltration equal to 0.4AC/h</td>
</tr>
<tr>
<td>Case (2)</td>
<td>Building model using Classical walls type and placing windows in East-West direction. + Shading factor equal to 0.82 and infiltration equal to 0.4AC/h</td>
</tr>
<tr>
<td>Case (3)</td>
<td>Case 2, but placing windows in North-South direction.</td>
</tr>
<tr>
<td>Case (4)</td>
<td>Case 3, but infiltration value equal to 0.60 AC/h</td>
</tr>
<tr>
<td>Case (5)</td>
<td>Case 3, but infiltration value equal to 1.0 AC/h</td>
</tr>
<tr>
<td>Case (6)</td>
<td>Case 3 with window area of 1/16 of floor area (6.25%)</td>
</tr>
<tr>
<td>Case (7)</td>
<td>Case 3 with window area of (9.7%)</td>
</tr>
</tbody>
</table>
6.5 Energy consumption for the building cases.

The seven building cases, shown in Table 6.6, were simulated using TRNSYS-PREBID (building simulation). The results are shown in Table 6.7, and comprise the hourly peak energy consumption, the monthly total energy consumption and the annual total energy consumption, all for space cooling. Figure 6.12 and Figure 6.13 show this information in histogram form for the cases. The monthly and annual total energy consumption for building Case 3 is seen to be the most energy efficient of the cases considered with monthly and annual total energy consumption figures of 1.52 MWh and 6.005 MWh, respectively. The monthly and annual total energy consumptions for Case 5 are the highest in terms of energy consumption (1.90 MWh and 7.48 MWh, respectively). This energy consumption is due mainly to the relatively high infiltration component (i.e. equal to 1AC/h). The results show that infiltration, which is the rate of uncontrolled air exchanged through unintentional openings such as windows, gaps, door cracks and wall cracks, accounts for an increase in 19.7% in the energy consumption with respect to building Case 3. Infiltration could be reduced in many ways; for the case of Kuwait, this could be done by mainly using weather strippers for windows and doors. The effect of increasing window areas (in Cases 6 and 7) shows an increase of 9.3% and 16% in annual energy consumption, respectively, with respect to Case 3 (See Figure 6.11). Figure 6.10 shows the comparison of cases 3 and 5, expressed graphically as energy consumption versus time. Similar plots were produced for the other case comparisons, giving rise to the overall figures given in Table 6.7. As seen in Table 6.8, the results of hourly peak and annual energy consumption per unit floor area
(W/m², kWh/m²) which is the hourly peak and annual energy consumption divided by the floor area of the example building case, showed that case 3 has the lowest peak and annual domestic energy consumption per building floor area of 41.8 W/m² and 73 kWh/m² respectively.

Figure 6.10 Example building energy consumption for case 3 vs case 5 (First week of Mid-July).
Figure 6.11 Bar chart showing the effect of different glazing areas on building case 3, case 6 and case 7.

Figure 6.12 Bar chart showing the peak energy consumption for all building cases.
Figure 6.13 Bar chart showing the annual energy consumption for all building cases.
Table 6.7 Energy consumption analysis for the seven cases

<table>
<thead>
<tr>
<th>Case no.</th>
<th>Peak energy consumption W</th>
<th>Monthly total energy consumption MWh</th>
<th>Annual total energy consumption MWh</th>
<th>Annual energy consumption (%) with respect to case(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case(1)</td>
<td>3490</td>
<td>1.57</td>
<td>6.22</td>
<td>3.4%</td>
</tr>
<tr>
<td>Case(2)</td>
<td>3440</td>
<td>1.54</td>
<td>6.08</td>
<td>12.3%</td>
</tr>
<tr>
<td>Case(3)</td>
<td>3430</td>
<td>1.52</td>
<td>6.005</td>
<td>0%</td>
</tr>
<tr>
<td>Case(4)</td>
<td>3760</td>
<td>1.65</td>
<td>6.52</td>
<td>7.8%</td>
</tr>
<tr>
<td>Case(5)</td>
<td>4430</td>
<td>1.90</td>
<td>7.48</td>
<td>19.7%</td>
</tr>
<tr>
<td>Case(6)</td>
<td>3740</td>
<td>1.65</td>
<td>6.62</td>
<td>9.3%</td>
</tr>
<tr>
<td>Case(7)</td>
<td>4020</td>
<td>1.76</td>
<td>7.16</td>
<td>16%</td>
</tr>
</tbody>
</table>
Table 6.8 The peak and annual total energy consumption per square meter (area of floor plan).

<table>
<thead>
<tr>
<th>Case no.</th>
<th>Peak energy consumption W</th>
<th>Peak energy consumption W/m²</th>
<th>Annual total Energy Consumption MWh</th>
<th>Annual total Energy Consumption kWh/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case(1)</td>
<td>3490</td>
<td>42.5</td>
<td>6.22</td>
<td>75.8</td>
</tr>
<tr>
<td>Case(2)</td>
<td>3440</td>
<td>41.9</td>
<td>6.08</td>
<td>74</td>
</tr>
<tr>
<td>Case(3)</td>
<td>3430</td>
<td>41.8</td>
<td>6.005</td>
<td>73</td>
</tr>
<tr>
<td>Case(4)</td>
<td>3760</td>
<td>45.8</td>
<td>6.52</td>
<td>79.5</td>
</tr>
<tr>
<td>Case(5)</td>
<td>4430</td>
<td>54</td>
<td>7.48</td>
<td>91</td>
</tr>
<tr>
<td>Case(6)</td>
<td>3740</td>
<td>45.6</td>
<td>6.62</td>
<td>80.7</td>
</tr>
<tr>
<td>Case(7)</td>
<td>4020</td>
<td>49</td>
<td>7.16</td>
<td>87.3</td>
</tr>
</tbody>
</table>

6.6 Design guidance for Buildings in Kuwait

The results of the energy consumption analysis using TRNSYS-PREBID with the seven study cases of the example building shows the following trends:

1. Use of the classical wall (case1) gives a reduction in annual energy consumption equal to 3.4% compared to the use of the AAC wall (case 2). This is because the classical wall has a U-value lower than that of the AAC wall (see Figure 6.10 and Table 6.7).
2. It was found that the infiltration component of the example building was the major contributor to the building's energy consumption (cases 3, 4 and 5). Thus, any effort to reduce energy consumption should be aimed towards decreasing the amount of uncontrolled air leakage. In building case 5, it was found that the infiltration value of 1AC/h is a main contributor to energy consumption in Kuwaiti buildings. The annual energy consumption of building case 4 (with an infiltration value of 0.6 AC/h), and building Case 5 (with an infiltration value of 1AC/h) show an increase of 7.8% and 19.7%, respectively, in comparison with building case 3.

3. The window area plays an important role in building energy consumption in the Kuwaiti environment. When the area of the window glazing was increased as in building case 6 and case 7, energy consumption increased to 9.3% and 16 %, respectively, with respect to case 3. Therefore, using large areas of glass in buildings in Kuwait is a major source of solar heat gains. There are certain treatments to the glazing that may reduce heat gains. For example, using double glazed windows can reduce heat gains by at least 10% (Al-Temeemi 1995), and also the placement of windows will have a considerable effect. Windows in the direction of north-south receive the least amount of radiation (see Figure 6.9). Therefore, windows in the Kuwaiti environment should face toward the north-south direction.

4. Case 3 presented in Table 6.6, Table 6.7 and Table 6.8 emerges as the best case from those simulated, as its annual energy consumption was found to be the minimum with a value of 6.005 MWh. Case 3 corresponds to the use of the
classical wall construction, orientating windows in a North-South direction, and having a relatively low infiltration.

6.7 Summary

Parametric studies were conducted on example buildings, where the materials were chosen as shown in Table 6.4. Seven cases were considered, which represented the designs typical of Kuwaiti domestic buildings. The effect of building envelope, window types, size and direction, infiltration and ventilation were investigated. The classical wall is shown to be more energy-efficient than the AAC wall, both walls being commonly used in Kuwait. The building cases were applied using details of building layout and cross-sectional area as shown in Figure 6.1, Figure 6.2, Figure 6.3, Figure 6.4 and Figure 6.5. Whilst not exhaustive, the simulations have shown the desirable trends that should be adopted in the design of domestic buildings in Kuwait. This can aid the development of future building codes. One case has been identified as being the most energy-efficient from amongst those investigated; this case will be used in the next chapter to assess the benefit of the EAHE / building system. Finally, it is important to note that the trends in energy consumption (observed as parameters were changed) have been as expected, giving confidence in, and confirming the validation of, the building simulations process.
Chapter seven: Example Building with Assistance of Earth-Air Heat Exchanger

7.1 Introduction

Domestic air-conditioning accounts for about 70-80% of electrical power consumption in Kuwait. Most dwellings in Kuwait could potentially benefit from the retrofitting of an Earth-Air Heat Exchanger (EAHE) system to improve energy efficiency and indoor comfort. The code of practice for energy conservation in Kuwaiti buildings was established in 1983 without the benefit of today’s energy conservation measures such as new building materials, or advice on orientation of buildings, efficiency of windows, infiltration and ventilation. In the previous chapter, seven Kuwaiti building cases were investigated to arrive at a candidate case that exhibits the least energy consumption. This also resulted in guidance to improve building standards and to increase the capabilities of building use and energy saving.

There are a number of ways in which the energy consumption of a building can be reduced. This chapter focuses on the evaluation of an EAHE as a potential means of reducing energy consumption in a prototype domestic building in a desert climate such as in Kuwait. To recap, an EAHE consists of a buried pipe through which air is drawn and supplied to the building by means of a fan, the latter being the only energy expenditure of the EAHE system. Simulation of an Earth-Air Heat Exchanger operated with an example building is presented in this chapter. The simulation compares the energy consumption of the example building when cooled by conventional air-conditioning (A/C) with and without the assistance of the Earth-Air
Heat Exchanger (EAHE). The lowest energy case building from the previous chapter is selected as the basis for comparison.

7.2 Example Building Without EAHE Assistance

In Chapter 6, a typical Kuwaiti domestic building that exhibits the least energy use from the cases studied was established. This was found to be the one with classical walls (thermophysical properties presented in Chapter 6, Table 6.4). The simulation input parameters for the example building were shown in Table 6.5 with orientation of windows towards the North-South direction and with a minimum area of glazing. Thus, the example building with the situation of Case 3 will be used in this chapter. The construction materials of the example building (Case 3) are shown again (for convenience) in Table 7.1, for more details about the material selection of walls, see Chapter 6. The example building dimensions and height are shown in Figure 6.1 and Figure 6.5 (10m length x 8.2m width x 2.5m height). The ‘classical’ wall type is shown to offer better energy conservation (detail is shown in Figure 6.6). The example building materials of the roof construction, with its detailed construction drawing, is shown in Figure 6.8 (Chapter 6). These components and the input data in Table 6.5 are used here in the building simulation TRNSYS-PREBID. The simulation of the example building cooled by air-conditioning (A/C) from the hour 2880 (beginning of May) to 6552 (end of September) is shown in Figure 7.1. The peak energy consumption for cooling occurs during the months of July and August, where the hourly average energy consumption in each of these months is equal to 1760 and 2040 W, respectively (see Figure 7.2), while the average hourly energy consumption over the entire period of the example building is about 686 W. This shows an increase in energy consumption during months of July and August of about 60-65% compared with the average hourly energy consumption. It can be seen from Figure 7.1 and
Figure 7.2 that energy consumption for cooling starts to decrease gradually after the middle of September. However, some cooling demand will still be needed occasionally until the middle of October (see Figure 7.2). Referring to Figure 7.2, the average hourly energy consumption of the months April and October are 108Wh and 462Wh respectively; in these months, the energy use for air-conditioning occurs mainly in the last two weeks of April and the first two weeks of October.

![Energy Consumption Graph]

Figure 7.1: Peak energy consumption during summer period in Kuwait [beginning of May to end of September] for domestic air conditioning without EAHE assistance.
Figure 7.2: The average monthly energy consumption for months during the summer season [April-Oct].

In the above results, the energy consumption of the example building for air conditioning only has been found. In Section 7.4, the example building will be equipped with the EAHE to assist with the interior space cooling. This system will be used as a mitigating feature in the example building to reduce the air conditioning cooling load. However, the EAHE system will have to draw and supply air to the building by a fan, which is the only energy expenditure that will be added to the example building’s energy consumption. In Section 7.3 therefore, the EAHE model (explained in Chapter 5) is remodelled to include fan energy consumption due to the pressure drop in the pipe.
Table 7.1: Details of building space components and their thermophysical properties

<table>
<thead>
<tr>
<th>Building components</th>
<th>Material</th>
<th>Thickness mm</th>
<th>Thermal conductivity W/mK</th>
<th>Density kg/m³</th>
<th>Thermal capacity kJ/kgK</th>
</tr>
</thead>
<tbody>
<tr>
<td>1- Exterior walls</td>
<td>Sand-lime block</td>
<td>90</td>
<td>1.31</td>
<td>1918</td>
<td>0.795</td>
</tr>
<tr>
<td></td>
<td>Insulation</td>
<td>50</td>
<td>0.032</td>
<td>30</td>
<td>1.12</td>
</tr>
<tr>
<td></td>
<td>Cement block</td>
<td>200</td>
<td>1.64</td>
<td>2011</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>Cement plaster</td>
<td>20</td>
<td>1.0</td>
<td>2085</td>
<td>0.84</td>
</tr>
<tr>
<td>2- Floor</td>
<td>Concrete slab</td>
<td>150</td>
<td>1.77</td>
<td>2297</td>
<td>0.921</td>
</tr>
<tr>
<td></td>
<td>Sand</td>
<td>60</td>
<td>0.337</td>
<td>1800</td>
<td>0.920</td>
</tr>
<tr>
<td></td>
<td>Sand cement</td>
<td>20</td>
<td>1.0</td>
<td>2080</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>Mosaic tiles</td>
<td>20</td>
<td>1.104</td>
<td>2284</td>
<td>0.8</td>
</tr>
<tr>
<td>3- Roof</td>
<td>Mosaic tiles</td>
<td>20</td>
<td>1.104</td>
<td>2284</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>Cement Mortar</td>
<td>20</td>
<td>1.0</td>
<td>2085</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>Sand screed</td>
<td>20</td>
<td>1.0</td>
<td>2080</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>Insulation</td>
<td>50</td>
<td>0.032</td>
<td>30</td>
<td>1.12</td>
</tr>
<tr>
<td></td>
<td>Water Proofing</td>
<td>3</td>
<td>0.14</td>
<td>934</td>
<td>1.507</td>
</tr>
<tr>
<td></td>
<td>Sand screed</td>
<td>20</td>
<td>1.0</td>
<td>2080</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>Foam concrete</td>
<td>50</td>
<td>0.21</td>
<td>351</td>
<td>0.879</td>
</tr>
<tr>
<td></td>
<td>Concrete slab</td>
<td>150</td>
<td>1.77</td>
<td>2297</td>
<td>0.921</td>
</tr>
</tbody>
</table>

7.3 Total Energy Consumption of the Earth Air Heat Exchanger (EAHE) Fan

To circulate air from the inlet of the EAHE system to the outlet of the EAHE system, a fan is needed. The fan’s energy consumption needed to move air through a pipe of a certain diameter and length is estimated as follows.

For air flowing through a pipe, the velocity pressure is expressed as

\[ P_v = 0.5 \times \rho \times V^2 \]  

(7.1)
where $V$ is the velocity of the flowing air. The difference in total pressure between the fan outlet and inlet is expressed as:

$$\Delta P_f = (P_r \times f \times L / d) + \sum K_f P_r$$

(7.2)

where the first term in Equation (7.2) represents pipe friction and $\sum K_f P_r$ is the additional pressure loss due to bends, fittings, flow split or flow merge sections. There are additional pressure losses due to the use of filters, (Jones, 1994). The term ‘$f$’ is the friction factor that was expressed earlier in Chapter 5 as Equation (5-9).

Fan air power ($P_f$) or power imparted by the fan to the air is given by:

$$P_f = q\Delta P_f$$

(7.3)

where $q$ is the volumetric flow rate. Hence, the fan energy consumption, due to blowing air through a pipe, is additional energy expenditure in the EAHE system. The fan power (shaft input power) is found from:

$$P_f = \frac{\Delta P_r \times q}{\eta_{fan}}$$

(7.4)

The total fan efficiency ($\eta_{fan}$) may be expressed as the ratio of total air power to the shaft power input, which typically is equal to 60% (Chadderton, 1993).

The power supplied by the fan is regarded as being converted to heat and causing an increase in temperature of the air as it flows through the pipe, (Jones 1994, Kreider et al 1994), hence:

$$\Delta T_f = \frac{\Delta P_r}{\eta_{fan} \times \rho \times C_p}$$

(7.5)
Here, the exit air temperature delivered through the pipe outlet may be raised by an amount \((\Delta T_f)\) due to the additional fan power, (Hanby et al 2002c). Therefore, the EAHHE outlet temperature \((T_2)\) in Equation (5-12) may be given as:

\[
T_{\text{outlet}} = T_2 + \Delta T_f
\]  

(7.6)

Thus the total heat transferred by the EAHHE system and fan to the air may be given as Equation (5-14) with \((T_2)\) substituted by \((T_{\text{outlet}})\), (Hanby et al 2002c):

\[
Q_{\text{net}} = \dot{m} C_p \times (T_a - T_{\text{outlet}})
\]  

(7.7)

The fan presence will lead to an increase in the outlet air temperature from the EAHHE; this, in turn, will increase the building energy consumption due to warming of the air, which the A/C must then cool. Referring to Figure 5.15 (Chapter 5), it can be seen that increases of air flow rate in the EAHHE system would lead to an increase in the outlet air temperature of the EAHHE system.

Airflow of 0.023 m\(^3\)/s as analysed by Ishihara et al (1992) has proved to be a satisfactory value to adopt, as this should provide sufficient cool air to the internal space of the building. In Chapter 5 this value of 0.023 m\(^3\)/s was found to give the lowest air outlet temperature from the EAHHE system with less heat being converted to raise the temperature of the air as it flows through the EAHHE system.

Several fan types have been used by various authors in this field, as a means for moving air in buried pipe systems. Francis (1981) used an air blower of 1 hp (750W) to pull ambient air through a pipe of diameter 20cm and 120m long. Zoellick (1981) used a fan of 1/6 hp (125W) to circulate the air through four pipes with a diameter of 20cm and lengths of 37m, 23m, 20m and 15m. Perl (1996) used an air blower of 1/3
Example building with assistance of Earth-Air Heat Exchanger

hp to drive ambient air through a pipe of diameter 30cm and 91.4 long. The fan in Perl’s (1996) experimental work was operated and monitored for several years (from 1985 to 1991). Continuous and intermittent operations of the fan were used during the experiment. However, a 1/3 hp (250 W) fan will be used for the simulation of this EAHE system, for the following reasons:

- fan power effect is typical of what is used in similar previous studies of this type.
- the chosen fan horsepower of 1/3(250W), which may be slightly above that required, will give a conservative estimate for the cost effective analysis to be conducted in the next chapter.

7.4 Example Building with EAHE Assistance

The example building of Case 3 (Chapter 6) is used again in this simulation. The EAHE was presented in Chapter 5 as a buried pipe below the ground surface at a certain depth where one end of the pipe system is used for the entrance of ambient air whilst the other end of the pipe system releases air to the interior of a building (open loop system). A sensitivity analysis of EAHE system parameters (five cases) as shown in Table 5.5 (Chapter 5) has been carried out. This showed that the EAHE system with the following parameters was the most effective: pipe diameter 0.25m, length 60m, depth 4m, and air mass flow rate equal to 100kg/h, based on Kuwaiti soil of thermal conductivity value equal to 0.86 W/m °C. This was the EAHE configuration employed here. Simulation was carried out using TRNSYS-PREBID (Klein et al, 1996). The TRNSYS components configuration diagram is shown in Appendix C, Section C3 and Figure C.2. The simulation was carried out for the period April to October, the hottest and most arid time of the year in Kuwait occurring from May to the end of September, with an average afternoon maximum air temperature
value of 45°C. The simulation was conducted for the example building cooled by air-conditioning in conjunction with the application of the EAHE, the EAHE delivering air directly to the occupied space. This latter case was compared against that of the building being cooled by air-conditioning alone (Section 7.2).

The total monthly heat removal rate from the example building with air-conditioning alone was found to occur in August and was calculated to be 1520 kWh. The figure for air-conditioning with EAHE assistance is 1110 kWh. The total annual heat removal rate from the building being cooled by air-conditioning alone is 6005 kWh, while that with air-conditioning and EAHE assistance is 4314 kWh, giving a total energy saving of 1690 kWh (see Table 7.2). Furthermore, the total annual energy consumption per unit floor area for the building being cooled by air-conditioning alone (Case 3) is 73 kWh/m² while that with air-conditioning and EAHE assistance is 52.4 kWh/m², a reduction of 21.4 kWh/m² (see Table 7.4). Thus, the Kuwaiti government may benefit by proposing an EAHE system in domestic buildings (housing programme) as in the Case 3 type as described in Chapter 6.

7.4.1 Time-controlled use of EAHE in domestic buildings

Time controlled use of an earth air heat exchanger is very important since operation of the EAHE at non-beneficial times may cause additional energy consumption in domestic buildings.

Values for the total monthly cooling capacity of the example building for the conditions stated from the beginning of April to the end of October are given in Table 7.2. It can be seen that the use of the EAHE can reduce energy consumption in most
cases. However, it is interesting to note that, in the month of October, the cooling energy requirement with the assistance of the EAHE is higher than that without the assistance of the EAHE. This is due to the fact that the sub-soil environment in October starts to shift its thermal cycle from the cooling to heating cycle (see Chapter 4). There is a lag in the thermal response of the soil mass. This shows the importance of controlling the period of operation of the EAHE system.

Furthermore, monthly average energy consumption of the example building with and without use of the EAHE from April to October are shown in Figure 7.4. This shows that for the months of April (which has very minimum energy consumption) and October values are higher with use of the EAHE system. The reason for this is that the sub-soil temperature value at a depth of 4m in April and October is lower than (or very close to) the ambient air temperature. The average sub-soil temperature in the months of April and October is equal to 23°C and 31°C, respectively as seen in Figure 7.6, whilst the average ambient air temperature in the months of April and October is 25°C and 28°C, respectively.

Therefore, one should be aware of when to operate the EAHE system. This generally should be limited to the time period between the beginning of May to the end of September. Table 7.3 shows the values for the May-September period only.

Thus, the total annual heat removal rate from the building being cooled by air-conditioning alone and that with air-conditioning and EAHE assistance is 5583kWh and 3851kWh respectively, after deducting April and October’s energy consumption figures from the total summer seasonal energy consumption. This gives a total energy saving of 1732 kWh (see Table 7.3). It is evident from Table 7.3 that energy saving
increased after applying this (relatively coarse, but simple) time control for operation of the EAHE.

Figure 7.3: Monthly total energy consumption for the example building with and without the assistance of the EAHE system.

Figure 7.4: Monthly average energy consumption for the example building with and without EAHE assistance.
Figure 7.5: Heat removal from the example building by the air conditioning during hours from May-September with and without the assistance of the EAHE system
Table 7.2: The seasonal cooling energy requirement for the example building with and without assistance of EAHE for the period beginning of April to the end of October.

<table>
<thead>
<tr>
<th>Months</th>
<th>Monthly total cooling capacity without EAHE (kWh)</th>
<th>Monthly total cooling capacity with EAHE (kWh)</th>
<th>Monthly saving due to EAHE assistance (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>April</td>
<td>77.8</td>
<td>14</td>
<td>64</td>
</tr>
<tr>
<td>May</td>
<td>703</td>
<td>348</td>
<td>355</td>
</tr>
<tr>
<td>June</td>
<td>1050</td>
<td>641</td>
<td>409</td>
</tr>
<tr>
<td>July</td>
<td>1310</td>
<td>897</td>
<td>413</td>
</tr>
<tr>
<td>August</td>
<td>1520</td>
<td>1110</td>
<td>410</td>
</tr>
<tr>
<td>September</td>
<td>1000</td>
<td>855</td>
<td>145</td>
</tr>
<tr>
<td>October</td>
<td>344</td>
<td>449</td>
<td>-106*</td>
</tr>
<tr>
<td>Seasonal</td>
<td>6005</td>
<td>4314</td>
<td>1690</td>
</tr>
</tbody>
</table>

*Minus sign indicates that example building energy consumption increases with use of the EAHE system than without.

Table 7.3: The seasonal cooling capacity for the example building alone and that with assistance of EAHE for the period beginning of May to the end of September

<table>
<thead>
<tr>
<th>Months</th>
<th>Total cooling capacity without EAHE (kWh)</th>
<th>Total cooling capacity with EAHE (kWh)</th>
<th>Saving due to EAHE assistance (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>703</td>
<td>348</td>
<td>355</td>
</tr>
<tr>
<td>June</td>
<td>1050</td>
<td>641</td>
<td>409</td>
</tr>
<tr>
<td>July</td>
<td>1310</td>
<td>897</td>
<td>413</td>
</tr>
<tr>
<td>August</td>
<td>1520</td>
<td>1110</td>
<td>410</td>
</tr>
<tr>
<td>September</td>
<td>1000</td>
<td>855</td>
<td>145</td>
</tr>
<tr>
<td>Seasonal</td>
<td>5583</td>
<td>3851</td>
<td>1732</td>
</tr>
</tbody>
</table>
Figure 7.6: The average ambient air temperature and the EAHE outlet air temperature during the time period beginning of April to the end of October.

Table 7.4: Electricity savings kWh/m² of the example building with and without the assistance of EAHE

<table>
<thead>
<tr>
<th>Case No</th>
<th>Peak energy consumption W</th>
<th>Peak energy consumption W/m²</th>
<th>Annual energy consumption MWh</th>
<th>Annual energy Consumption kWh/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Example building with air conditioning</td>
<td>3430</td>
<td>41.8(1)</td>
<td>6.005</td>
<td>73(2)</td>
</tr>
<tr>
<td>alone</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Example building</td>
<td>2020</td>
<td>24.6</td>
<td>4.3</td>
<td>52.4</td>
</tr>
<tr>
<td>with air conditioning and EAHE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The example building area is 82m²

---

(1) Peak energy consumption divided by building area (W/m²)
(2) Annual energy consumption divided by building area (kWh/m²)
7.5 Results and Conclusions

In this chapter a simulation of an air-conditioned Kuwaiti prototype domestic building has been investigated for the case of the air-conditioning operating alone and with EAHE assistance. The EAHE system was remodelled to include fan operating energy in the system. The results and conclusions are summarised as follows:

1. For the time period April to October, the total heat energy reading to be removed (the air conditioning load) from the example building being cooled by air-conditioning alone is equal to 6005kWh, while that with air conditioning and EAHE system assistance is 4314kWh. This gives a total seasonal energy saving equal to 1690kWh.

2. Time controlled use of the EAHE system (i.e. operation from May to September only) can be more energy efficient. In this case, the total annual heat removal rate from the example building being cooled by air-conditioning alone and with EAHE assistance is equal to 5583kWh and 3851kWh, respectively, with a total energy saving of 1732kWh.

3. It is concluded that the use of an EAHE system to assist air-conditioning in typical Kuwaiti residences can offer energy savings and merits further investigation.

In the next chapter, the cost-effectiveness of the EAHE system is investigated.
Chapter eight: Cost Effectiveness of the EAHE system with the Example Building

8.1 Introduction

New technologies have seldom been adopted in the marketplace unless they were shown to be economically competitive with existing technologies (Kreider and Kreith, 1981). The EAHE system is a technology that requires a reliable estimate of cost-effectiveness over the lifetime of the given system. The EAHE system, described in Chapter Seven, was shown to offer reductions in domestic energy consumption of up to 30% compared with air-conditioning alone. Established economic techniques can be used in life cycle studies, depending on the client’s requirements and special needs to understand and to compare the alternatives. It is possible to perform a sensitivity analysis, determine the payback period, establish a breakdown point between alternatives, determine the rate of return and extra-investment rate of return alternatives, perform a cash flow analysis, and review the benefits and cost (Dell’Isola, 1981). Life cycle costing is not only applied to buildings as a whole but can be applied to two component parts of buildings. It is applied in this work to investigate cost-effectiveness.

Life Cycle Cost (LCC) analysis may be defined as the economical assessment of an item, area, system, or facility, considering all the significant costs of ownership over its economical life, expressed in terms of equivalent dollars ($) (Dell’Isola, 1981; Kirk and Dell’Isola, 1995). Life cycle cost may also be defined as the sum of the present values of all cost components over the life-time of a project, which are considered
important for a 'rational' decision (Kreider, 2001) or decision-making process. One life cycle costing technique commonly used that is helpful to the decision-maker is 'payback period' analysis. For an energy-consuming system, the payback period is the time required for the cumulative fuel saving to equal the initial investment (Simonson, 1984).

ASHRAE (1999) has listed a summary of information that may be used in cost effectiveness analysis for preparing annual budgets, managing assets and selecting design options.

In this chapter an economic assessment of the example building with and without the assistance of an Earth Air Heat Exchanger (EAHE) is presented in terms of its payback period for both the Kuwaiti consumer and government. A period of 25 years is considered in the cost-effectiveness analysis. Some elements of cost-effectiveness analysis need to be illustrated in order to make the concept more clearly understood.

For this reason all relevant costs, including namely capital cost (material and construction costs as an initial cost), maintenance cost, replacement cost and operation cost (or running cost), need to be evaluated to draw reliable conclusions.

The cost-effectiveness analysis will be represented using the Pound (£) and the Kuwaiti Dinnar (KD). In Kuwait the price of electricity for residential buildings is 2 files/kWh (1 KD=1000 files, 1 US $=0.306 KD, 1 Pound=0.500 KD). The Kuwaiti government covers the cost of subsidising electricity, which is 32 files/kWh (Al-Ragom and Al-Ghimlas, 1998; Eltony, 1998).
8.2 Capital cost (or Initial cost)

Capital Cost ($C_C$) or Initial Costs (IC) are defined here as the owner's costs associated with the initial development of a facility and project support (fees, land, real estate, interest, etc.) as well as construction costs.

Material and construction costs for the cases of the air-conditioned example building with and without EAHE assistance are investigated in this section. Construction materials for the building itself are the same in both cases (with and without EAHE assistance) and are shown in Chapter Seven, Table 7.1. The only difference in the construction costs between the two cases is that one has the assistance of the EAHE, see Table 8.1.

The Earth–Air Heat Exchanger system consists of a plastic pipe buried to a depth of 4 m below ground and with a pipe of length 60 metre. A blower fan is used to transport air from the pipe inlet to the pipe outlet. This system is connected to the building located in a hot arid climate like that in Kuwait.

The building materials and construction costs in Kuwait are dependent upon the design and material selections for both the interior and exterior decoration of the buildings. However, an approximate cost for the material and construction of the prototype building for a low-income Kuwaiti family is around £100 (50 KD) per square metre (Ministry of Planning, 1999). Therefore, the total cost of a building space of 10 m x 8.2 m would be around £8,200 (4,100 KD).

ASHRAE Application Handbook (1999) shows a representative checklist for some of the initial costs. These costs are often referred to as the first costs. Cost items
associated with the initial development of the facility may include design, consulting, legal and other professional fees; construction costs, including all furnishings, equipment; land costs; and construction phases financing (Dell’Isola, 1981). Additional costs will be included for (I) excavation and backfill and (II) installation of the EAHE system. These are calculated as follows:

I) Excavation and backfill costs are calculated by multiplying the width, depth and length of the hole needed for the EAHE system, which may be equal to 0.5 m (width) x 4 m (depth) x 60 m (length) with total soil excavation and backfill volume equal to 120 m³. The estimated cost at the Kuwaiti market price for the excavation is £ 9.46/m³ (4.73 KD/m³) and for backfill is £ 2.12/m³ (1.060 KD/m³), adding up to a total of £11.58/m³ (5.79 KD/m³) (Ministry of Public Works, Specifications and Estimations Book of Road and Sanitary Works).

II) Installation of the EAHE system costs (supplying duct (pipe) and fitting at Kuwaiti market price) are estimated (based on the Ministry of Public Works, Specifications and Estimations Book of Road and Sanitary Works) in Kuwaiti Dinari per unit length of pipe (m) to be 5.88 KD/m, which is equivalent to £11.76/m.

Table 8.1 shows the construction cost of an EAHE installed in Kuwait as the sum of the excavation and backfill costs + supplying and duct-fitting cost + fan (and accessories) cost, which is equal to a total of £2,417. This may give an estimate price for the complete installation of an EAHE system per pipe unit length (pounds (£)/m) equal to £40.3/m (20.14 KD/m). For both cases of the example building with and without the assistance of EAHE the total initial costs are summarised in Table 8.2.
Table 8.1 The capital cost (initial cost) of installing EAHE (at Kuwaiti market price).

<table>
<thead>
<tr>
<th>Type of Cost</th>
<th>Cost (£)</th>
<th>EAHE System (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excavation and backfill per cubic metre (120 m³)</td>
<td>£11.58/m³</td>
<td>£1,411.2</td>
</tr>
<tr>
<td>Supplying and duct-fitting/ per metre length (60 m)</td>
<td>£11.76/m</td>
<td>£705.6</td>
</tr>
<tr>
<td>Fan and accessories</td>
<td>Piece</td>
<td>£300*</td>
</tr>
<tr>
<td><strong>Total initial costs of EAHE</strong></td>
<td></td>
<td><strong>£2,417</strong></td>
</tr>
</tbody>
</table>

*(PERRY VIDEX).*

Table 8.2 Total capital cost (initial costs) of the example building alone and that with EAHE system.

<table>
<thead>
<tr>
<th>Type of Cost</th>
<th>Cost (£)</th>
<th>Building Alone (£)</th>
<th>With EAHE (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building Construction cost (includes materials and labour)</td>
<td>£100/m²</td>
<td>8,200</td>
<td>8,200</td>
</tr>
<tr>
<td>Excavation and backfill per cubic metre (120 m³)</td>
<td>£11.58/m³</td>
<td>-</td>
<td>£1,411.2</td>
</tr>
<tr>
<td>Supplying and duct-fitting/ per meter length (60m)</td>
<td>£11.76/m</td>
<td>290</td>
<td>290</td>
</tr>
<tr>
<td>A/C system unit</td>
<td>Piece</td>
<td>290</td>
<td>290</td>
</tr>
<tr>
<td>Fan (with accessories)</td>
<td>Piece</td>
<td>£300</td>
<td></td>
</tr>
<tr>
<td><strong>Total initial costs</strong></td>
<td></td>
<td><strong>£8,490</strong></td>
<td><strong>£10,906.8</strong></td>
</tr>
</tbody>
</table>
Since the capital cost (initial cost) of the example building is common to both cases (with and without EAHE) the capital cost (initial cost) of the EAHE system alone is the only cost that will be considered in the cost-effectiveness analysis.

8.3 Maintenance Cost (MC)

Maintenance Cost (MC) is the cost of regular custodial care and repair, annual maintenance contracts and salaries of staff performing the maintenance tasks. Usually replacement items, having less than a 5-year cycle, are also included in the cost (Kreider, 2001).

Annual maintenance cost for a building (residential) is approximately £1/m² (0.5 KD/m²) to £2/m² (1 KD/m²) per gross square meter, depending on the complexity of the building (Dell’Isola, 1983, 1981; Kirk and Dell’Isola, 1995). Thus, the annual maintenance cost for the example building may be approximately equal to £1/m², which would be required to be spent once every 15* years.

The maintenance cost of an EAHE system (£ per pipe unit length) is in the range of £0.2/m to £0.5/m. This would need to be spent every year due to the cleaning of the pipe’s pathway from the collection of dust and the growth of insects (this figure was quoted by Ministry of Public Works, Maintenance Division in Kuwait based on a similar works to main holes cleaning).

Therefore, the annual maintenance cost for the EAHE system would be £0.2/m for a period of 25 years, while the example building’s maintenance cost is required once every 15 years. Hence, for a cost-effectiveness analysis period of 25 years, the

* Although building maintenance is excluded, this was added for a conservative estimate.
example building maintenance cost may be included once in that period of time (see Table 8.3 and Table 8.5).

**Table 8.3 The total maintenance costs of example building with and without EAHE system.**

<table>
<thead>
<tr>
<th>Type of Maintenance</th>
<th>Maintenance Cost</th>
<th>Period Year</th>
<th>Maintenance Cost (£)</th>
<th>Maintenance Cost (accounted for inflation rate of 3%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Example building</td>
<td>£1/m²</td>
<td>15</td>
<td>£82</td>
<td>£127.75</td>
</tr>
<tr>
<td>EAHE</td>
<td>£0.2/m</td>
<td>Annually</td>
<td>£12</td>
<td>£12.4</td>
</tr>
</tbody>
</table>

\[ £_{m罕n} = £_0 \times (1 + r_{infl})^n \] (Kreider 2001) \(r_{infl} = 0.03\)

### 8.4 Replacement Costs (RC)

Replacement Cost (RC) is the cost of replacing equipment or other facility element. Some of these elements specify a short-term replacement (such as electrical bulbs, etc.); others specify long-term replacement (such as A/C units, roofing insulation, etc.) (Dell'lsola, 1981). The analysis period of the equipment’s service life has a great effect on the cost-effectiveness analysis. The time period of an equipment’s service life is the time during which a particular system or component remains in its original service application (ASHRAE Application Handbook, 1999). Based on data provided from the ASHRAE Application Handbook (1999) an estimate of the service life of various system components is given (e.g. HVAC system, fan, ductwork, cooling tower, dampers, coils etc). Residential air-conditioning service life is in the range of 10 to 15 years; air blower service life (EAHE fan) is in the range of 15-25 years and ductwork service life is 30 years. However, for a cost-effectiveness analysis period
taken as 25 years, an A/C system* should be replaced once in that period of time. The two cases under consideration have similar items for replacements except for items that make up the EAHE system. Therefore, based on the figures for service life stated above, no replacement cost need be added, assuming the equipment’s service life of EAHE is 25 years, where the EAHE system is maintained annually to a high standard.

8.5 Operating Cost (OC)

The operating cost is the cost of fuel, electricity and salaries required to operate the facility (Dell’Isola, 1981). Energy consumption cost would be included in this cost (Table 8.4). For the example building, case 3 (Chapter 6) was selected to be used with the EAHE system due to its energy efficient performance compared with the other cases. The annual energy consumption of the example building without EAHE assistance is 5593kWh while that with EAHE assistance is 3851kWh – a saving of 1732kWh (see Table 8.4).

Referring to Table 8.4, the true electricity price in Kuwait is 0.034 KD/kWh (£0.068/kWh) where customer needs to pay 0.002 KD/kWh (£0.004/kWh) and 0.032KD/kWh (£0.064/kWh) is subsidised by the government to meet the true or actual cost of the electricity.

8.6 Analysis Technique

To analyse the real payback period of the EAHE installation the standard technique of Net Present Value (NPV) was used (Helcké, 1983; Halldane, 1989). Net Present

* Addition to that, A/C is excluded from the EAHE system equipment.
Value (NPV) is defined as the difference between the Present Value (PV) and the aggregate cost saving due to its operation (running cost) and capital cost (initial cost). Present Value (PV) is defined by Helcké (1983) and Halldane (1989) as follows in Equation (8.1) and Equation (8.2):

\[
PV = \frac{E_1}{(1 + i)} + \frac{E_2}{(1 + i)^2} + \frac{E_3}{(1 + i)^3} \ldots + \frac{E_n}{(1 + i)^n} \quad (8.1)
\]

Therefore Equation (8.1) may be expressed as follows:

\[
PV = \sum_{n=1}^{N} \frac{E_n}{(1 + i)^n} \quad (8.2)
\]

where

- \(i\) = interest rate (\%).
- \(n\) = \(n^{th}\) year after investment.
- \(N\) = number of years.
- \(PV\) = Present Value (£).
- \(E_n\) = amount of the annual energy saving expected after \(n^{th}\) year (£).

However, it is appropriate to compare the Present Value (PV) of an investment’s total earning with its Capital cost \((C_c)\) (Kenneth, 1998). Thus, the difference between the Present Value (PV) and the Capital cost is called Net Present Value (NPV) (Helcké, 1983) and this is expressed as follows:

\[
NPV = -C_c + \frac{E_1}{(1 + i)} + \frac{E_2}{(1 + i)^2} + \frac{E_3}{(1 + i)^3} \ldots + \frac{E_n}{(1 + i)^n} \quad (8.3)
\]
Therefore Equation (8.3) may be expressed as follows:

\[
NPV = -C_c + \sum_{n=1}^{N} \frac{E_n}{(1 + i)^n}
\]  
(8.4)

where

\[
NPV = \text{Net Present Value (£)}
\]

\[
C_c = \text{Capital cost (£)}
\]

When the inflation rate (r) is included in the calculation the PV then becomes:

\[
PV = \sum_{n=1}^{N} E_n \left( \frac{(1 + r)}{(1 + i)} \right)^n
\]
(8.5)

and Equation (8.4) becomes:

\[
NPV = -C_c + \sum_{n=1}^{N} E_n \left( \frac{(1 + r)}{(1 + i)} \right)^n
\]  
(8.6)

where

\[
r = \text{annual inflation rate (%)}
\]

Equation (8.6) is used to calculate Net Present Value (NPV) inclusive of the inflation rate (r) and interest rate (i).

As can be seen from Equation (8.6) and results in Table 8.5, when the NPV value becomes positive that means the system has paid for itself. The larger the Net Present Value the greater the cost-effectiveness is considered be.
In Equation (8.6), it is necessary to insert the appropriate value of inflation and interest rate. Inflation rate (or escalation rate) is defined as the rate of inflation above the general devaluation purchasing power of the dollar (Dell’Isola, 1981).

The inflation rate has a great effect on the fuel market price, which is in direct relationship with politics (the increase of cost escalation is clearly feasible when fossil fuel prices increased sharply over the period between 1973-1980) (Markus and Morris, 1980).

Based on the Central Bank of Kuwait (CBK) (2001), the Kuwait inflation rate figure in the twenty-ninth annual report for the fiscal year 2000/1 is shown as an average value of 3%. The interest rate (discount rate) is 3% (Ahmad et al, 1996). These values were used in the analysis.

### 8.7 Cost Effectiveness of the EAHE System

Analysis carried out in Chapter 7 showed that an energy saving of 1,732 kWh was obtained due to the use of the EAHE system with net annual savings as shown in Table 8.4, based on the electricity consumer price and the government electricity price, respectively.

The cost-effectiveness analysis (carried out using 'real payback' period which accounts for the effect of interest and inflation, whilst a simple payback period does not account for interest and inflation rate) from the viewpoint of the consumer and the government is calculated using Equation (8.6) and is described next.
8.7.1 Cost benefit from viewpoint of the consumer

The low-income Kuwaiti citizen has two privileges from the government. The first privilege is that he can earn a house from the government through the National Housing Authority programme; this programme involves certain rules regarding salary, number of family members, etc. The consumer starts to pay back the government for the property from the first day of occupying the house. This must be paid back to the government completely in about 25 years. The second privilege is a very low electricity tariff price of £0.004 per kWh.

As a result, the government has to subsidise the rest of the money that is needed to meet the actual cost of the electricity (which is £0.068 per kWh) and hence continue the scheme. The amount of subsidy is £0.064 per kWh. The analysis, shown in Table 8.5, of a ‘real’ payback period for the Kuwaiti consumer using the EAHE system is observed to be unattractive within the corresponding period of 25 years, which cannot be considered as cost-effective. It can be seen from the analysis in Table 8.5 that the Net Present Value (NPV) for the consumer will not become positive even after 50 years. This means that money invested in this system (EAHE) has not been paid back; after 25 years, the consumer will have only paid £174 of the total capital cost of £2,417. As a result of the low electricity price, the Kuwaiti consumer as an investor would have little incentive to implement the EAHE system in his house.

8.7.2 Cost benefit from viewpoint of the Kuwaiti Government

The Government of Kuwait has to subsidise an amount of £0.064/kWh to meet the actual cost of electricity in Kuwait. For the Kuwaiti government, by using the EAHE system with consideration of Kuwaiti interest and inflation rates yields a
corresponding ‘real’ payback period of 22 years that may be considered as cost-effective. It can be seen from the analysis in Table 8.5 that the Net Present Value (NPV) for the Kuwaiti government will become positive after 22 years. This means that money invested in this system (EAHE) has been paid back after 22 years; after 25 years, the system can attain a profit of £344. The EAHE system may be considered as cost-effective for the Kuwaiti government as an investor when it is applied through the National Housing Authority programme (NHA). However, the profitability of the system may be dependent on the life span of the Kuwaiti buildings. Buildings built through the NHA can be considered to have a life span of 25 to 35 years.

Despite this, the question whether the EAHE system may be considered as cost-effective for the Kuwaiti government (with the current energy price (£ 0.064 per kWh) and with a capital cost of 100%** subsidised within a payback period of 22 years) is a matter of debate. It is possible that the widespread use of the system may not yet be sufficiently attractive for the Kuwaiti government to implement.

In this situation, the following section present a number of differing scenarios together with effect on payback period, as guidance to aid decision-making by policymakers and consumers.

### 8.8 Discussions and possibilities

As mentioned in the previous sections, applying the EAHE system from the consumer’s viewpoint to the example building under the consumer’s electricity price,

** Capital cost is paid in whole by the Kuwaiti Government.
is at the present time not cost-effective, whilst for the Kuwaiti government the system may be considered cost effective depending on the building’s life span. However, in recent years, the Kuwaiti government has considered measures and policies on several fronts to reduce inefficiency and waste in energy consumption. One of the government’s efforts to conserve energy is by setting higher energy prices. Therefore, policy makers are currently considering raising the price of domestic energy (Eltony, 1998). In view of this, and to assist policy makers in Kuwait, the cost-effectiveness analysis was repeated for the following four economic scenarios (in each scenario the inflation and interest rate are kept the same):

1. First scenario is for the consumer with different electricity prices, which is applied assuming electricity price increases of 0% (£0.004 per kWh), 100% (£0.008 per kWh), 300% (£0.016 per kWh), 600% (£0.028 per kWh) and 900% (£0.04 per kWh), 1000% (£0.044 per kWh), 1100% (£0.048 per kWh) and 1200% (£0.052 per kWh).

2. Second scenario is for the consumer with no changes in electricity price, but government subsidise installation of the EAHE by 0% (£2417), 10% (£2175), 20% (£1934), 30% (£1692), 40% (£1450), 50% (£1209), 60% (£967), 70% (£725), 80% (£483), 90%, (£242) and 100% (£0) (cost to consumer in brackets).

3. Third scenario is for the consumer to pay an electricity price equal to £0.048 per kWh (i.e. 1100%) increase (this is the British average electricity price, 2002 taken here for comparison) , and for the Kuwaiti government subsidises 50% of the EAHE capital cost.

4. The Fourth scenario is for the Kuwaiti government to maintain the current electricity price subsidised (i.e. £0.064 per kWh for the government and
£0.004 per kWh for the consumer), but to provide an EAHE system subsidy* of 50%.

The cost effectiveness analysis of the EAHE system was repeated with the example building based on the four economic scenarios, and the results are shown in Figure 8.1, Figure 8.2, Table 8.6 and Table 8.7. The results of applying these four economic scenarios result in several important facts that may be helpful to policy makers and consumers in Kuwait:

1. In first scenario, as shown in Figure 8.1, from the consumer’s viewpoint the electricity price increase would not have a significant effect on the payback period until it reaches an electricity price increased by 1000% (£0.044 per kWh). Only then does the EAHE system start to have a payback period of 29 years (comparable with life of the property).

2. In second scenario, the EAHE system subsidy has a direct relation to payback period, see Figure 8.2. As seen from Figure 8.2, increase of EAHE system subsidy leads to decrease in payback period. This would have an effect on the payback period for the consumer’s viewpoint when the subsidy reaches 94% giving a payback period of 20 years. Furthermore, a payback period of 17 years could be obtained when the EAHE system capital cost subsidy reaches 95%, and this may be considered as cost effective by the consumer.

3. From third scenario, as seen from Table 8.6, from the consumer viewpoint, the payback period of the EAHE system cost is 15 years, which may be considered as cost effective by the consumer.

* Subsidy in this context means government subsidy.
4. From the fourth scenario, as seen in Table 8.7, the use of EARE system would be more attractive and cost effective for the Kuwaiti government with payback period of 11 years.

In view of the above results, together with data in Table 8.6, Table 8.7, Figure 8.1 and Figure 8.2, it can be observed that, in both cases, electricity price increase and subsidy of the EABE capital cost could influence the decision to proceed with such installations in Kuwait. These findings can be used to aid the decision-making process. Furthermore, the use of the EABE system would be more attractive to the consumer, if the government was to subsidise 50% of the EABE system cost and to set an electricity price equal to £0.048 per kWh, (the average British electricity price, 2002 for comparison). On the other hand, the EARE system, based on scenarios four, could be more attractive for the government, as government subsidises only 50% of EABE capital cost. This would make the EABE system to be considered as cost-effective with a payback period equal to 11 years.

A full optimisation analysis beyond the scope of this work, but the approach taken can provide useful guidance. The Kuwaiti government can benefit from the EABE system through the NHA programme by considering the above discussion. However, applying EABE system with normal case (i.e. current electricity price with 100% subsidy) would not of-course reduce careless or wasteful use of energy consumption in Kuwait (due to its lower cost), but would help to reduce the total energy consumption of the country.

The Government of Kuwait has built a number of residential buildings through the National Housing Authority (NHA) programme. The number of houses built prior to
this study of the EAHE system is over 42,000 houses (Al-ragom et al, 1998). Thus, the Kuwaiti government, based on the cost-effectiveness analysis of a normal case (i.e. current electricity price with 100% subsidy) (see Table 8.5), would gain a profit of £344 per house after a period of 25 years. Using figure, for the 42,000 houses built, the Kuwaiti government would have yielded a total of £14 million at the end of 25 years. There would be further savings for the government if the cost-effectiveness analysis were applied in terms of the fourth scenario for the number of houses built. This would have yielded a total of 65.5 million at the end of 25 years, see Table 8.7 and Figure 8.3.

Figure 8.3 shows the Net Present Value (NPV) cash flow distribution diagram for an EAHE system over a period of 25 years from the viewpoint of the Kuwaiti government if installed throughout the NHA programme of 42000 houses.

Table 8. 4 Annual energy consumption cost for the example building, with and without EAHE, paid by a customer

<table>
<thead>
<tr>
<th>Type of Cost</th>
<th>Electricity Price (£/kWh)</th>
<th>Annual Energy saving (kWh)</th>
<th>Annual saving investment (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Example building (£) with EAHE (consumer price)</td>
<td>0.004(^{(1)})</td>
<td>1732</td>
<td>7</td>
</tr>
<tr>
<td>Example building (£) with EAHE (Government price)</td>
<td>0.064(^{(2)})</td>
<td>1732</td>
<td>111</td>
</tr>
</tbody>
</table>

\(^{(1)}\) 0.002KD=£0.004
\(^{(2)}\) 0.032KD=£0.064
Table 8.5 Net Present Value (NPV) analysis for the EAHE system applied by the Kuwaiti government and consumer.

<table>
<thead>
<tr>
<th>Year Number (N)</th>
<th>Maintenance Cost (£)</th>
<th>Present Value (£)</th>
<th>NPV (£)</th>
<th>Present Value (£)</th>
<th>NPV (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Government</td>
<td>Government</td>
<td>Consumer</td>
<td>Consumer</td>
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<td>1</td>
<td>12.4</td>
<td>111</td>
<td>-2319</td>
<td>7</td>
<td>-2422</td>
</tr>
<tr>
<td>2</td>
<td>12.7</td>
<td>222</td>
<td>-2207</td>
<td>14</td>
<td>-2416</td>
</tr>
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<td>3</td>
<td>13.1</td>
<td>333</td>
<td>-2096</td>
<td>21</td>
<td>-2409</td>
</tr>
<tr>
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<td>443</td>
<td>-1985</td>
<td>28</td>
<td>-2403</td>
</tr>
<tr>
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<td>554</td>
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</tr>
<tr>
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<td>42</td>
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<td>25.9</td>
<td>2882</td>
<td>455</td>
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<td>-2263</td>
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<td>699</td>
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<td>3436</td>
<td>1008</td>
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<td>2244</td>
<td>314</td>
<td>-2461</td>
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</tbody>
</table>
Table 8. 6 Results of applying third scenario.

<table>
<thead>
<tr>
<th>Electricity price (£)/kWh</th>
<th>Period</th>
<th>NPV 3rd scenario (£)</th>
<th>Payback period (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.048</td>
<td>25</td>
<td>+845</td>
<td>15</td>
</tr>
</tbody>
</table>

Positive sign indicates money earning

Table 8. 7 Results of applying fourth scenario.

<table>
<thead>
<tr>
<th>Electricity price (£)/kWh</th>
<th>Period</th>
<th>NPV 4th scenario (£)</th>
<th>Payback period (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.064</td>
<td>25</td>
<td>+1554</td>
<td>11</td>
</tr>
</tbody>
</table>
Figure 8.1 The effect of electricity price increase on payback period of the EAHE (first scenario).

Figure 8.2 The effect of EAHE installation subsidy on the payback period (second scenario).
Figure 8.3 Cash flow diagram on the Net Present Value (NPV) for EAHE system applied to 42000 houses of the NHA, based on the fourth scenario showing system payback in the eleventh year and continued increase in profit.

8.9 Summary and Conclusion

In this chapter, the cost effectiveness of applying an EAHE system to a typical Kuwaiti domestic building (example building) has been presented using life cycle costing techniques. One of the life cycle techniques is payback period analysis using Net Present Value (NPV). Based on the Kuwaiti consumer’s current electricity tariff, a cost-effectiveness analysis conducted over a 25-year period shows that installation of an EAHE system is a poor investment for the Kuwaiti consumer. Therefore, such a system is not cost-effective using the current electricity tariff. However, because electricity price subsidises, the Kuwaiti Government may consider such a system to be cost effective depending on the building’s life span, with a payback period of 22
years. However, the use of the EAHE system for both the Kuwaiti consumer and
government may become more attractive based on the following circumstances:

1. The EAHE system becomes acceptable from the Kuwaiti consumer’s viewpoint
   (as an investor) when the price of electricity increases by 1000% over the current
   price. Furthermore, the EAHE system become more attractive and more profitable
   when the electricity price becomes £0.048 per kWh and a subsidy of 50% of the
   EAHE capital cost is made by the government. In this case, the Kuwaiti consumer
   would consider the system as cost-effective with a payback period of 15 years.

2. Further attraction for EAHE system, when the Kuwaiti government maintain the
   current electricity price (£0.064 per kWh), but to provide an EAHE system
   subsidy of 50%. This would result in a payback period of 11 years.

Thus, the Kuwaiti government in the normal case (i.e. current electricity price with
100% subsidy) would gain a profit of £344 per NHA house at the end of 25 years.
With this profit and for 42000 houses built, the Kuwaiti government would have
yielded a total of £14 million at the end of 25 years. Furthermore, the Kuwaiti
government at the current electricity price with 50% of the EAHE system capital cost
subsidies would have yielded a total of 65.5 million at the end of 25 years. Thus, This
could offset the need to build ‘more’ power stations.

Notwithstanding the proceeding economical arguments, with widespread installation
of EAHE system in Kuwait would of course reduce national energy consumption and
correspondingly reduce carbon dioxide emission (electricity usage being displaced).
Chapter nine: Conclusions and Future studies

9.1 Summary of the research

Economic and industrial development in countries which have a hot, arid climate has led to increasing demand for electricity, much of which is consumed in air conditioning systems to meet the high peak summer demand for cooling caused by high external dry-bulb temperatures and solar radiation. In Kuwait, domestic air conditioning is generally deployed between the beginning of April and the end of October. The highest air temperatures occur in July and August, with an average afternoon maximum value of 45°C. Domestic air conditioning accounts for between 70%-80% of electricity power consumption, despite the fact there is a reduction in population in summer. The government of Kuwait, through the Kuwait Institute for Scientific Research (KISR), has tried to reduce energy consumption using a number of methods (thermal insulation, windows orientations, etc). One way to reduce energy consumption in domestic buildings is to couple the building with the soil environment, i.e. direct contact with ground (underground buildings). In this approach, building an the underground structure increases the capital cost of a dwelling, which will have a significant impact on the housing programme (NHA) and which in turn will exacerbate this situation. The concept of an EAHE system is that of a pipe which is buried in the ground and where the outdoor ambient air is drawn from the pipe inlet. The air passing through the pipe exchanges heat along the length of the pipe walls with the surrounding underground environment. The outlet air from the buried pipe serves to ventilate the building indoor environment, resulting in reduced building cooling loads.
This system has been investigated in this thesis. The main conclusions may be summarised as follows:

- The subsoil environment has been investigated in terms of soil properties, and the subsoil temperature has been predicted using Labs model. The subsoil temperature model requires values for certain parameters. Values for these parameters have been determined for Kuwait subsoil, giving values for mean annual surface temperature ($T_m$), annual surface temperature amplitude ($A_s$), phase constant ($t_o$), and soil thermal diffusivity ($\alpha$), equal to $25.6^\circ C$, $13.3^\circ C$, 552 hours, and $0.0038m^2/hr$, respectively.

- Kuwaiti soil thermal diffusivity ($\alpha$) plays an important role and has been highlighted as a key parameter in being able to predict accurately subsoil temperature with respect of other parameters. The thermal diffusivity value was found to be best approximated as $0.0038 \text{ m}^2/\text{h}$ using the Direct Amplitude Method (DAM), which falls within the expected experimental results for Abrams' soil thermal diffusivity. Abrams soil diffusivity value is in the range of $0.00093$ to $0.00465 \text{ m}^2/\text{h}$ see (Mac Donald et al. 1985).

- Soil properties of Kuwait was investigated in two different locations, desert and coastal with an average value of soil thermal conductivity and soil density, equal to $0.86W/m \, ^\circ C$ and $1874.5 \text{ kg/m}^3$ respectively. All the preceding soil property values are available for use in soil temperature prediction model.

- A subsoil temperature model (Labs, 1989) applicable to Kuwait was validated with measured soil temperature data (Kuwait International Airport 1983) and showed good agreement within an accuracy of $\pm1^\circ C$. Thus, the subsoil temperature model presented can be used for prediction of the hourly predicted subsoil temperature at any depth below ground surface.
• The degree-day approach was used to estimate the cooling/heating potential of the subsoil environment. Results for a base temperature of 24.5 °C gave a total subsoil degree-days of 754.5, compared to the atmospheric value of 1804 during the period between April to October. This demonstrates the ground cooling potential for this region when operating an EAHE system.

• A mathematical model has been presented of a circular ground cooling pipe as a cross-flow heat exchanger (EAHE) with one fluid unmixed (i.e. air). The pipe wall assumed to have negligible thermal resistance. An external thermal resistance was assumed to be provided by a concentric cylinder of earth of arbitrary thickness, which was exposed to an undisturbed subsoil temperature as a boundary condition.

This EAHE model was validated against three other studies: Mihalakakou et al (1995), Dhaliwal et al (1984), and Shingari (1995). The validation process showed that predictions from the proposed EAHE model agree with those from all of the three other models with respect of the input parameters given. The EAHE model presented is therefore considered to be appropriate to simulate the thermal behaviour of an earth air heat exchanger.

• The EAHE model (Type264) together with the model to predict Kuwait subsoil temperatures (Type262) were operated together within the TRNSYS-IISIBAT simulation program (Klein et al 1996). These two models are capable of being used for parametrical studies examining the thermal performance of the EAHE system.

• An extensive sensitivity analyses (5 cases) were performed. The variables influencing the thermal performance of EAHE system (pipe length, airflow rate in the pipe, depth of the buried pipe below ground surface and subsoil thermal
conductivity) were investigated. For each variable, sensitivity analysis was carried out taking continuous values for each case and keeping other variables as constant. EAHE system parameters that were used to help improve its performance are namely: pipe length, airflow rate in the pipe, depth of the buried pipe below the ground surface and the soil thermal conductivity are equal to 60m, 100kg/hr (0.023 m³/s), 4m and 0.86W/m°C respectively.

- A similar parametric analysis was performed on the design of typical Kuwaiti buildings. Among the building cases examined one was identified as being the most energy-efficient from amongst those investigated; this case was used to assess the benefit of the EAHE / building system using the TRNSYS simulation program. In addition, some guidance to aid further housing design in Kuwait has been furnished.

- The effectiveness of the Earth-air heat exchanger in reducing cooling loads in the Kuwaiti domestic building (example building) was evaluated by simulation. These results showed that annual energy consumption of the example building being cooled by air-conditioning alone is equal to 5583 kWh, while that with air conditioning and EAHE system assistance is 3851 kWh. This represents a total energy saving of 1732 kWh during the time period from May to end of September with a reduction of about 30% in energy consumption. This shows that the EAHE system is a worth while mentioned for energy saving in hot desert climate like that of Kuwait.

- The cost effectiveness of applying an EAHE system to a typical Kuwaiti building (example building) has been presented using the payback period analysis technique. Based on the Kuwaiti consumer’s current electricity tariff, a cost-effectiveness analysis conducted over a 25-year period showed the EAHE system
to be a poor investment for the Kuwaiti consumer. However, because of the subsidised cost electricity paid by the state, Kuwaiti Government may consider the system to be cost effective (depending on the building’s life span) with a payback period of 22 years. In view of this, a number of different economic scenarios were applied from the viewpoint of the Kuwaiti government and the consumer with regard to electricity price and EAHE system subsidy. The results obtained show that the EAHE system becomes a more attractive investment when the electricity price rises to £0.048 per kWh and a subsidy of 50% of the EAHE capital cost is applied. In this case, the EAHE system from the viewpoint of the Kuwaiti consumer would be considered as cost-effective with a payback period of 15 years. For the Kuwaiti government at the current electricity price subsidy, the EAHE system becomes more attractive investment with a subsidy of 50% of EAHE system capital cost, giving a payback period of 11 years.

The Kuwaiti government with the current case (with no scenarios applied) would gain a profit of £344 per house in the NHA programme. With this profit repeated for 42000 houses built, the Kuwaiti government would have saved a total of £14 million at the end of 25 years. Furthermore, Kuwaiti government at the current electricity price subsidy and 50% of the EAHE system capital cost subsidised would have yielded a total of £65.5 million at the end of 25 years. The technique applied and these data are now available to the Kuwaiti government and policy makers to aid future planning and decision-making.
9.2 Further studies

In this thesis, the thermal performance of the subsoil environment in a dry desert climate like that in Kuwait together with use of an earth-air heat exchanger (EAHE) to ventilate a typical Kuwaiti building has proved to be effective in reducing domestic energy consumption.

However, further studies could be carried out for examining the performance of the EAHE system in a dry desert climate but using these following techniques:

9.2.1 Ground shading technique, such as vegetation cover

Experiments done by Kusuda in Washington, D.C. have demonstrated that the average surface temperature of white-painted asphalt was lower in midsummer by about 7°C as compared with the surface of black asphalt. The average surface temperature of the soil covered (and shaded) by grass was lower by about 4°C as compared with bare soil (Givoni, 1993).

Furthermore, in the summer season, the mean monthly surface air temperature of short grass-covered soil shows a reduction of 6°C comparing with the monthly surface air temperature of bare soil (Jacovides et al 1996).

Based on weather data provided by Kuwait International Airport (1983) and the Kuwait Institute for Scientific Research (1995), the difference between the monthly average minimum ambient air temperature on the top of a ground surface covered with short grass and that for a bare ground surface is about 4°C in months of July and August, see Figure 9.1.

As seen from Figure 9.1 it is clear that grass cover or vegetation has affected the monthly average minimum ambient air temperature, with a difference of about 4°C being evident.
In the subsoil temperature model, the mean annual ground surface temperature ($T_m$) is an important variable value, (a main input parameter) which is approximated by using the mean annual air temperature; this influences directly the prediction of the subsoil temperature.

Due to the lack of data for mean annual ground surface temperature for the grass covered ground surface, calculation of the corresponding mean annual air temperature is not possible.

Hypothetically, in view of the data provided in Figure 9.1, when the minimum mean annual surface air temperature ($T_{m}$) is decreased, the mean annual surface air temperature is decreased as well. Thus the subsoil temperature as a result would have better performance, which would increase the performance of the EAHE system.

However, full analysis must take place to confirm and measure the performance of the EAHE under a grass covered ground surface.

![Figure 9.1 The monthly minimum average ambient air temperature on a bare ground surface and that for a surface covered with short grass.](image-url)
9.2.2 The use of Solar Technologies

Solar technologies is basically the use of sun's energy and light to provide heat, light, hot water, electricity, and even cooling, for homes, businesses, and industry. Sunlight-solar energy can be used to generate electricity, for pumps or fans, provide hot water, and to heat, cool, light buildings.

Photovoltaic (solar cell) systems convert sunlight directly into electricity. A solar or PV cell consists of semi-conducting material that absorbs the sunlight. The solar energy knocks electrons loose from their atoms, allowing the electrons to flow through the material to produce electricity. PV cells are typically combined into modules that hold about 40 cells. About 10 of these modules are mounted in PV arrays. PV arrays can be used to generate electricity for a single building or, in large numbers, for a power plant. A power plant can also use a concentrating solar power system, which uses the sun's heat to generate electricity. The sunlight is collected and focused with mirrors to create a high-intensity heat source. This heat source produces steam or mechanical power to run a generator that creates electricity. PV arrays that generate electricity may be coupled with fans of the EAHE to reduce further electricity consumption, (which is the only EAHE energy expenditure) of the example building that equipped with EAHE system.

9.2.3 The use of combined open/closed system for EAHE

There are two types of earth cooling pipe system, open loop system or the closed loop system. The difference between the two systems is in the manner in which cooling air is circulated. The open loop system (which has been adapted in this work) draws fresh outdoor air into the pipes, cools it, and delivers it to the building interior, where the pipe inlet is open to the outside atmosphere and the pipe outlet is inside the building.
The closed loop system, however, recirculate air from the building rather than taking in outdoor air. Here, air flows from the building interior through the earth cooling pipes and back to the building interior. The closed loop system may perform well as regards reducing the amount of cooling required in buildings, but no fresh ventilation air is introduced into the building, which in turn may create a health problem in the long term. Furthermore such a system, if used with an open loop system may increase the EAHE system performance and energy reduction, allowing indoor air in close system to be mixed with fresh ventilation air, which is eventually introduced into the building, see Figure 9.2.

Further increase in EAHE performance may be investigated with use of other techniques such as the use of different type of pipe materials.

Figure 9.2 Earth cooling pipe with combination of Close/ Open loop system.
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>EAHE</td>
<td>Earth-Air Heat Exchanger</td>
</tr>
<tr>
<td>COP</td>
<td>Coefficient Of Performance</td>
</tr>
<tr>
<td>ASHRAE</td>
<td>American Society of Heating, Refrigeration and Air-conditioning Engineers, Inc., USA.</td>
</tr>
<tr>
<td>Hp</td>
<td>Horsepower</td>
</tr>
<tr>
<td>W</td>
<td>Watt</td>
</tr>
<tr>
<td>kWh</td>
<td>Kilowatt hour</td>
</tr>
<tr>
<td>MW</td>
<td>Megawatt hour</td>
</tr>
<tr>
<td>TRNSYS</td>
<td>Transient System Simulation Program</td>
</tr>
<tr>
<td>KISR</td>
<td>Kuwait Institute for Scientific Research</td>
</tr>
<tr>
<td>CDD</td>
<td>Cooling Degree-Days</td>
</tr>
<tr>
<td>CDH</td>
<td>Cooling Degree-Hours</td>
</tr>
<tr>
<td>HDD</td>
<td>Heating Degree-Days</td>
</tr>
<tr>
<td>HDH</td>
<td>Heating Degree-Hours</td>
</tr>
<tr>
<td>LCC</td>
<td>Life Cycle Costing</td>
</tr>
<tr>
<td>PV</td>
<td>Present Value</td>
</tr>
<tr>
<td>NPV</td>
<td>Net Present Value</td>
</tr>
<tr>
<td>OC</td>
<td>Operating Cost</td>
</tr>
<tr>
<td>MC</td>
<td>Maintenance Cost</td>
</tr>
<tr>
<td>RC</td>
<td>Replacement Costs</td>
</tr>
<tr>
<td>NHA</td>
<td>National Housing Authority</td>
</tr>
<tr>
<td>CBK</td>
<td>Central bank of Kuwait</td>
</tr>
</tbody>
</table>
NOMENCLATURE

\( A_s \) Annual surface temperature amplitude \( (^\circ C) \)

\( C_p \) Specific heat at constant pressure of air \( (J/kg \cdot K) \)

\( d \) Pipe diameter \( (m) \)

\( k \) Soil thermal conductivity \( (W/m \cdot K) \)

\( k_{air} \) thermal conductivity of air \( (W/m \cdot K) \)

\( L \) Pipe length \( (m) \)

\( m \) Mass flow rate of air \( (kg/s) \)

\( Pr \) Prandtl number.

\( NTU \) No of transfer units

\( Nu \) Nusselt number

\( P \) Atmospheric pressure \( (Pa) \)

\( Q_p \) Heat transferred to/from air \( (W) \)

\( R_c \) Thermal resistance between air and pipe inner surface.

\( R_i \) Thermal resistance of earth 'cylinder'

\( Re \) Reynolds number

\( r \) Pipe radius \( (m) \)

\( T_a \) Ambient air temperature \( (^\circ C) \)

\( T_m \) Mean annual ground temperature \( (^\circ C) \)

\( T_e \) Exit air temperature delivered through the pipe outlet \( (^\circ C) \)

\( T_{outlet} \) Exit air temperature delivered through the pipe outlet \( (^\circ C) \) including increased air temperature due to the heat caused fan power \( (^\circ C) \)
\( T_{(z,t)} \) Undisturbed soil temperature (\( ^\circ C \)) at depth \( z \) (m) and time \( t \) (hours).

\( t \) Time of the year (hours)

\( t_0 \) Phase constant, hours minimum surface temperature

\( UA \) Overall conductance of tube (W/m²K)

\( q \) Flow rate of air (m³/s)

\( \dot{V} \) Air velocity in tube (m/s)

\( z \) Depth below grade (m)

\( \alpha \) Thermal diffusivity of the soil (m²/hr)

\( \varepsilon \) Effectiveness of EAHE system

\( \rho \) Density of air (kg/m³)

\( f \) Friction factor for smooth pipe

\( v \) Kinematic viscosity of air (m²/s)

\( DD_{\text{heg}} \) Monthly heating degree-days, (\( ^\circ C \)-days)

\( D_m \) The number of days in the month, (365 days)

\( T_{a,d} \) The daily average temperature, (\( ^\circ C \))

\( A_{1} \) Annual ground temperature amplitude at the first layer. (\( ^\circ C \))

\( A_{2} \) Annual ground temperature amplitude at the second layer. (\( ^\circ C \))

\( z_1 \) The depth of first layer below ground (m)

\( z_2 \) The depth of second layer below ground (m)

\( T_m \) Mean annual ground surface temperature (\( ^\circ C \))

\( t \) Time of the year (hours)

\( t_o \) Phase constant, i.e. the time when minimum surface temperature occurs. (Hours)
\( \alpha \) Thermal diffusivity of soil \( (m^2/\text{hours}) \)

U-value The overall thermal transmittance \( Wm^{-2}K^{-1} \)

\( R \) Thermal resistance \( (m^2kW^{-1}) \)

\( UA \) Overall conductance of tube \( (Wm^{-2}K^{-1}) \)

\( h_v \) Convective heat transfer coefficients at exterior wall surfaces \( (Wm^{-2}K^{-1}) \)

\( h_i \) Convective heat transfer coefficients at interior wall surfaces \( (Wm^{-2}K^{-1}) \)

\( x \) Thickness \( (m) \)

\( \Delta P_i \) Fan total pressure \( (Pa) \)

\( P_f \) Fan air power \( (W) \)

\( P \) Static pressure \( (pa) \)

\( \sum K_i P_r \) Additional pressure loss due to bends, fittings, flow split or flow merge \( (pa) \)

\( P_v \) Velocity pressure

\( \Delta T_f \) Temperature increase of air as it flows through the pipe

\( \eta_{fan} \) Total fan efficiency

\( i \) interest rate \( (%) \)

\( n \) \( n^{th} \) year after investment.

\( N \) number of years.

\( PV \) Present Value \( (£) \)

\( E_n \) amount of the annual energy saving expected after \( n^{th} \) year \( (£) \)

\( NPV \) Net Present Value \( (£) \)

\( C_c \) Capital cost \( (£) \)

\( r \) Annual inflation rate \( (%) \)
amount of annual energy savings expected at commencement of project (£).
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Appendix A

Mihalakakou et al (1995) model for predicting the performance of the earth-air heat exchanger


Mihalakakou et al (1995) model calculates the air temperature at the outlet of the earth-air heat exchanger. A step by step method (from step 1 to 29) is shown in Table A.1.

A.2 Coefficients of polynomials \((a_0, a_1, a_2, a_3)\) for Equations (5-19).

Coefficients of polynomials \((a_0, a_1, a_2, a_3)\) are determined by Mihalakakou et al (1995). These coefficients shown in Table A.2 are used in steps 12, 13, 14, and 15 in Mihalakakou et al (1995) model, Table A.2.

A.3 Coefficients of polynomials \((b_0, b_1, b_2, b_3)\) for Equations (5-20).

Coefficients of polynomials \((b_0, b_1, b_2, b_3)\) are determined by Mihalakakou et al (1995). These coefficients shown in Table A.2 are used in steps 20, 21, 22, and 23 in Table A.3
Table A.1 Mihalakakou et al (1995) simplified method for calculating the air temperature at the outlet of the earth-air heat exchanger.

<table>
<thead>
<tr>
<th>No.</th>
<th>Parameters of the earth air heat exchangers</th>
<th>Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Input length of the Pipe (L)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Input the radius of the Pipe (R)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Input the depth of the pipe (Z)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Input the Air velocity inside the pipe (u)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Input the inlet air temperature (T_in)</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Input ground temperature at the depth of the exchanger</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Calculate the air volume flow rate in the pipe (Q=πr^2u)</td>
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</tr>
<tr>
<td>8</td>
<td>Calculate the parameter P1 = -0.0161896×L</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Calculate the parameter P2 = 0.00019058×L×L</td>
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</tr>
<tr>
<td>10</td>
<td>Calculate the parameter P3 = -0.00000957×L×L×L</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Calculate the dimensionless parameter U = 0.995242 + P1 + P2 + P3</td>
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</tr>
<tr>
<td>12</td>
<td>α_0 (Tables A.2) A parameter as a function of volume flow rate and the pipe's length</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>α_1 (Tables A.2)</td>
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</tr>
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<td>14</td>
<td>α_2 (Tables A.2)</td>
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<tr>
<td>15</td>
<td>α_3 (Tables A.2)</td>
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<td>16</td>
<td>Calculate the Parameter QD_1 = α_1×Z</td>
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<td>17</td>
<td>Calculate the Parameter QD_2 = α_2×Z×Z</td>
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<td>18</td>
<td>Calculate the Parameter QD_3 = α_3×Z×Z×Z</td>
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</tr>
<tr>
<td>19</td>
<td>Calculate the correction parameter for the depth CV_1 = α_0 + QD_1 + QD_2 + QD_3</td>
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<tr>
<td>20</td>
<td>β_0 (Tables A.3) A parameter as a function of pipe depth (Z) and the pipe’s length (L)</td>
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<td>21</td>
<td>β_1 (Tables A.3)</td>
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<td>23</td>
<td>β_3 (Tables A.3)</td>
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<td>24</td>
<td>Calculate the parameter QV_1 = β_1×Q</td>
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<td>25</td>
<td>Calculate the parameter QV_2 = β_2×Q×Q</td>
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<td>26</td>
<td>Calculate the parameter QV_3 = β_3×Q×Q×Q</td>
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<td>27</td>
<td>Calculate the correction parameter for the flow rate CV_2 = β_0 + QV_1 + QV_2 + QV_3</td>
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<td>28</td>
<td>Calculate the corrected value of U_cor = U×CV_1×CV_2</td>
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<td>29</td>
<td>Calculate the air temperature at the outlet of the pipe T_outlet = T_s + U_cor×(T_in - T_s)</td>
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</table>

Next, the coefficients of the polynomials in Equations (5-19) and (5-20) are given in Table A.2 and Tables A.3.
<table>
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<th>$\alpha$</th>
<th>$D_0$</th>
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<td>0.950</td>
<td>0.950</td>
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</tr>
</tbody>
</table>

Table 2: Coefficients for Equation 5.19, $(a_0, a_1, a_2, a_3, a_4, a_5, a_6)$. 

\( D_n = \sum_{k=0}^{n} a_k D_{n-k} \)
<table>
<thead>
<tr>
<th>$D$</th>
<th>$b_1$</th>
<th>$L = 10$</th>
<th>$L = 20$</th>
<th>$L = 30$</th>
<th>$L = 40$</th>
<th>$L = 45$</th>
<th>$L = 50$</th>
<th>$L = 55$</th>
<th>$L = 60$</th>
</tr>
</thead>
<tbody>
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<td>0.994852</td>
<td>0.999135</td>
<td>0.999610</td>
<td>0.999922</td>
<td>0.999969</td>
<td>0.999995</td>
<td>0.999999</td>
</tr>
<tr>
<td>0.75</td>
<td>0.964251</td>
<td>0.978206</td>
<td>0.986906</td>
<td>0.992153</td>
<td>0.99478</td>
<td>0.997116</td>
<td>0.998039</td>
<td>0.999043</td>
<td>0.999999</td>
</tr>
<tr>
<td>1</td>
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<tr>
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<tr>
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<td>0.960558</td>
<td>0.966829</td>
<td>0.972943</td>
<td>0.978967</td>
</tr>
<tr>
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</tr>
<tr>
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<td>0.907264</td>
<td>0.912152</td>
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<td>0.920204</td>
<td>0.923531</td>
<td>0.926486</td>
<td>0.929199</td>
</tr>
<tr>
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</tr>
</tbody>
</table>

**Note:** The table continues with similar entries for various values of $D$. For more detailed information, please refer to the specific source or context of this data.
D

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L= 10

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4.50

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-0.47602
0.141876

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APPENDIX B

APPENDIX B-1

Degree-day Evaluation

The monthly heating –degree can be calculated as

\[ DD_{htg\cdot m} = \sum_{d=1}^{D_m} (T_{a\cdot d} - T_{bas}) \]  

(B.1)

Where:

- \( DD_{htg} \) = Monthly heating degree-days, \(^\circ\)C-days.
- \( D_m \) = The number of days in the month, (days).
- \( T_{a\cdot d} \) = The daily average temperature, \(^\circ\)C.

Monthly cooling degree-days are calculated in a similar manner as:

\[ DD_{c\cdot m} = \sum_{d=1}^{D_m} (T_{a\cdot d} - T_{bas}) \]  

(B.2)

Where:

- \( DD_{c\cdot m} \) = Monthly cooling degree-days, \(^\circ\)C-days.
- \( D_m \) = The number of days in the month, (365 days).
- \( T_{a\cdot d} \) = The daily average temperature, \(^\circ\)C.
- \( T_{bas} \) = The base temperature (environment temperature) used for calculating cooling and heating degree-days. The base temperature values which are recommended for Kuwait by ISO Standard 7730 (1984) are:
  - Winter heating: base temperature 20.0 \(^\circ\)C
  - Summer cooling: base temperature 24.5 \(^\circ\)C
APPENDIX B-2

Ground cooling and heating degree-day values are calculated in a similar manner having the same values of base temperature for winter and summer season, except that $T_{a,d}$ will be replaced by $T_{z,t}$. However, the values for ground temperature are on an hourly basis; therefore, $T_{z,t}$ will be averaged on monthly basis to calculate heating/cooling degree-day in the same manner.

$$SSDD = \sum_{i=t}^{D_m} (T_{z,t} - T_{Bas})$$  \hspace{1cm} (B.3)
APPENDIX C

TYPE 262 & TYPE 264 PROGRAMS AND SIMULATION

Unlike many other programs TRNSYS is a modular system simulation program that gives program flexibility, as explained in chapter 3. An additional of two components (models) were added to the TRNSYS-library. These components are Kuwait Subsoil environment model, which called Type 262 and Earth-Air Heat Exchanger (EAHE) model, which called Type 264. TRNSYS-IISiBat was selected to run both components models.

C.1 Kuwait Sub-soil environment model (TYPE 262)

Subsoil temperature and cooling/heating degree hours predicted (see chapter 4) using a program called “Type 262”. Type 262 modelled using a Fortran subroutine, which then developed using TRNSYS/IISiBat inside the TRNSYS environment. The Fortran source code is shown in section C.1.1 and PARAMETERS, INPUTS and OUTPUTS of the component are shown in Table C.1 and Table C.2.

TRNSYS/ IISiBat with its graphical connections with other TRNSYS-subroutine models provided in IISiBat-library (such as Type 56 (Multi-building simulation, Type19 single building simulation, etc) makes the use of type 262 is significant and supportive to other TRNSYS components. Figure C.1 shows Type 262 (subsoil temperature) and other TRNSYS subroutines configuration.
Figure C.1 Component configuration of TRNSYS–Subroutines with model Type262.

Table C. 1 The user definable PARAMETERS for the Sub-Soil temperature

Type (262)

<table>
<thead>
<tr>
<th>Type 262 user definable PARAMETERS</th>
<th>(m)</th>
<th>(°C)</th>
<th>(hrs)</th>
<th>(m²/hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>* Depth below ground surface</td>
<td>(z)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>* Mean annual ground surface</td>
<td>(T_m)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>* Annual surface temperature amplitude</td>
<td>(A_s)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>* Phase constant</td>
<td>(t_o)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>* Thermal diffusivity of soil</td>
<td>(α)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

C-2
Table C. 2 Type262 variables of INPUTS/OUTPUTS.

<table>
<thead>
<tr>
<th>The INPUTS/OUTPUTS variables for Type262</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Time of the year</em></td>
</tr>
<tr>
<td>(t)</td>
</tr>
<tr>
<td>(hours)</td>
</tr>
<tr>
<td><em>Sub-soil Temperature at depth z and at time t</em></td>
</tr>
<tr>
<td>(T_{z,t})</td>
</tr>
<tr>
<td>(° C)</td>
</tr>
<tr>
<td><em>Subsurface degree day (cooling/heating)</em></td>
</tr>
<tr>
<td>(SSDD)</td>
</tr>
<tr>
<td>(° C-days)</td>
</tr>
</tbody>
</table>

C.1.1 Fortran Source code for model (TYPE 262):

SUBROUTINE TYPE262 (TIME, XIN, OUT, T, DDTDT, PAR, INFO, ICNTRL, *)

C THIS SUBROUTINE MODEL IS Simple model of ground Temperature .
C Assuming the soil is undisturbed soil and degree days.

REAL Tm, z, As, to, a, Pi, t, Tg, F, P, Ti
DOUBLE PRECISION XIN, OUT
INTEGER*4 INFO
DIMENSION XIN (1), PAR (6), OUT (2), INFO (15)

CHARACTER*1TRNEDT,PERCOM, HEADER, PRTLAB, LNKCHK,
PRUNIT, IOCHEK, PRWARN
CHARACTER*3 YCHECK (1), OCHECK (2)

COMMON /LUNITS/ LUR, LUW, IFORM, LUK
COMMON /SIM/ TIME0, TIMEF, DELT, IWARN
COMMON/ CONFIG /TRNEDT, PERCOM, HEADER, PRTLAB,
LNKCHK, PRUNIT, IOCHEK, PRWARN

C PARAMETERS
C z  PAR(1) Depth below grade (m)
C Tm PAR(2) mean annual Temperature (c)
C a  PAR(3) soil thermal diffusivity (m^2/day)
C to PAR(4) Phase constant (days)
C As PAR(5) Temperature Amplitude (c)
C Ti Par(6) maintained indoor temperature

C INPUT VARIABLES
C t XIN (1) Time of the year

C OUTPUT VARIABLES
C Tg OUT (1) Ground temperature (c)
z=PAR(1)
Tm=PAR(2)
a=PAR(3)
to=PAR(4)
As=PAR(5)
Ti=PAR(6)
t=XIN(1)

49 FIRST CALL
IF (INFO(7). EQ.-1) THEN
   NP=6
   NI=1
   ND=0
   CALL TYPECK (1,INFO, NI, NP, ND)
   DATA YCHECK/\'DY1','DY1'/
   DATA OCHECK/'TE1'/
   CALL RCHECK (INFO, YCHECK, OCHECK)
END IF

Pi=3.14159

P=EXP (-z*(Pi/(8760*a))**.5)
D=cos (3.1)

F=cos ((2*3.14159/8760)*(t-to- (z/2)*(8760/(3.14159*a))**.5))
Tg=(Tm)-(As*P*F)
SSDD=t*(Tg-Ti)
OUT (1)=Tg
OUT (2)=SSDD
RETURN 1
END
C.2 Earth-Air Heat Exchangers (EAHE) model (Type 264)

Earth Air Heat Exchanger (EAHE) was modelled for predicting the outlet air temperature of EAHE (see chapter 5) using a program called ‘Type 264’. ‘Type 264’ modelled using a Fortran subroutine, which then developed using TRNSYS/II SiBat inside the TRNSYS environment. The Fortran source code is shown in section C.2.1 and PARAMETERS, INPUTS and OUTPUTS of the component are shown in Table C.3 and Table C.4.

TRNSYS/ II SiBat with its graphical connections with other TRNSYS-subroutine models (e.g. TRNSYS-Type9, Sky-Temperature TRNSYS-Type 69, TRNSYS-Type16 and TRNSYS-Type56, TRNSYS-Type 25) can assist ‘Type 264’ together with subsoil temperature model (Type 262). ‘Type 262’ assists EAHE model ‘Type 264’ with hourly subsoil temperature, as shown Figure C.2. Referring to Figure C.2, a complete TRNSYS-components configuration is showing the graphical connections to/from TRNSYS-Type56 with other TRNSYS-components. TRNSYS-Type9 for weather data using Kuwait Typical Meteorological Year (TMY), Sky-Temperature TRNSYS-Type 69 for determining a fictitious sky temperature, TRNSYS-Type16 for solar radiation and TRNSYS-Type56, TRNSYS-Type 25).

These components (all together with subsoil environment model Type262 and EAHE model Type 264 will link as an INPUTS connection to TRNSYS-Type56 at regular time interval) were conducted with a TRNSYS/II SiBAT program to investigate thermal characteristics and energy savings of an example building located in Kuwait climate or similar desert climate. Results and performance of EAHE Type 264 will be shown using TRNSYS-ONLINE PLOTTER Type 65 and Type25 (TRNSPRED).
C.2.1 Fortran Source code for EAHE model (TYPE 264)

SUBROUTINE TYPE264 (TIME, XIN, OUT, T, DTDT, PAR, INFO, ICNTRL, *)

REAL d, L, k, P, Cp, TA, V, TS, pi, r, R2, gas, rho, V1, k1, Re, Tin, Ef, Ec
REAL Nu, hc, Rs, Rc, UA, Mdot, NTU, e, T2, Q, dP, Pf, Tout, Tf, Qnet, COP, CoolP

DOUBLE PRECISION XIN, OUT
INTEGER*4 INFO
DIMENSION XIN (3), PAR (7), OUT (6), INFO (15)

CHARACTER*1 TRNEDT, PERCOM, HEADER, PRTLAB, LNKCHK, PRUNIT, IOCHEK, PRWARN
CHARACTER*3 YCHECK (3), OCHECK (6)

COMMON /LUNITS/ LUR, LUW, IFORM, LUK
COMMON /SIM/ TIME0, TIMEF, DELT, IWARN
COMMON/CONFIG/TRNEDT, PERCOM, HEADER, PRTLAB, LNKCHK, PRUNIT, IOCHEK, PRWARN

C PARAMETERS
C d PAR(1) pipe diameter (m)
C L PAR(2) tube length (m)
C k PAR(3) soil conductivity (W/m-K)
C P PAR(4) atmospheric pressure (Pa)
C Cp PAR(5) specific heat at constant pressure (air) (J/kg-K)
C dK PAR(6) number of fitting in the pipe
C Ef PAR(7) fan effectiveness =0.5

C INPUT VARIABLES
C Ta XIN (1) air temperature
C Mdot XIN (2) air mass flow rate (kg/hr)
C Ts XIN (3) soil temperature

C OUTPUT VARIABLES
C Q OUT (1) heat transferred to/from air kJ/hr
C T2 OUT (2) temperature of air leaving pipe
C dP OUT (3) total pressure drop (pa)
C Pf OUT (4) fan power (kJ/hr)
C Tf OUT (5) Fan temperature (C)
C Qnet OUT(6) net energy (kJ/hr)

d=PAR(1)
L=PAR(2)
k=PAR(3)
P=PAR (4)
Cp=PAR (5)
dK=PAR(6)
Ef=PAR(7)
TA=XIN (1)
Mdot=XIN (2)/3600
TS=XIN (3)

C FIRST CALL
IF (INFO (7). EQ.-1) THEN
   NP=7
   NI=3
   ND=0
   CALL TYPECK (1,INFO, NI, NP, ND)
   DATA YCHECK/E1,'MF1','TE1','TE1'
   DATA OCHECK/E1,'PW1','MF1','PR3','PW1','TE1','PW1','DM1','PW1'/
   CALL RCHECK (INFO, YCHECK, OCHECK)
END IF
pi=3.1416
r = d/2
r2 = 2*r

C % gas constant for air (J/kg-K) gas = 8314.0/28.84

C calculate convective heat transfer coefficient
C assume air properties at inlet temperature
C calculate gas density, kg/m^3

rho=P / (gas*(Ta+273.15))

C kinematic viscosity of air
V1=(1.0E-4)*(0.1335+(0.925*Ta*1.0E-3))

C thermal conductivity of air
K1=0.02442+(0.6992*Ta*1.0E-4)

C air velocity in tube
v=4*Mdot/(rho*pi*d^2)
Re=v*d/V1
Pr=V1*Cp*rho*gas/K1
f=1/(0.79*LOG(Re)-1.64)**2

C Gnieliski (I&dew p 413)
denom=1+12.7*((f/8)**0.5)*((Pr**0.67)-1)
Nu=(f/8)*(Re-1000)*(Pr/denom)
hc=Nu*K1/d

C UA value
Rs = LOG (r2/r)/(2*pi*L*K)
Re = 1/(2*pi*r*L*hc)
UA = 1/(Rs +Re)

C no transfer units
NTU = UA/(Mdot*Cp)
C outlet temperature & heat transfer
\[ e = 1 - \exp(-\text{NTU}) \]

C  output variables - convert Q to kJ/hr
\[ T_2 = T_a - (T_a - T_s)e \]
\[ Q = 3.6 \times \text{Mdot} \times \text{Cp} \times (T_a - T_2) \]

C  Pressure drop (Pv):
\[ P_v = 0.5 \times \rho \times v^2 \]
\[ dP = (4 \times P_v \times f \times L/d) + (dK \times P_v) \]

C 121  Fan effectiveness (Ef) and Fan power (Pf)
\[ Pf = \frac{dP \times (\text{Mdot} \times \rho)}{Ef} \]

C  Fan temperature rise (Tf)
\[ Tf = \frac{dP}{(Ef \times \rho \times \text{Cp})} \]
\[ T_{out} = T_2 + Tf \]
\[ Q_{net} = \text{Mdot} \times \text{Cp} \times (T_a - T_{out}) \]

\[
\text{OUT (1)} = Q \\
\text{OUT (2)} = T_2 + Tf \\
\text{OUT (3)} = dP \\
\text{OUT (4)} = Pf \\
\text{OUT (5)} = Tf \\
\text{OUT (6)} = Q_{net}
\]

RETURN 1
END

Table C.3 The user definable parameters for EAHE model Type264

<table>
<thead>
<tr>
<th>Type 264 user definable PARAMETERS</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>* Pipe diameter</td>
<td>(d)</td>
<td>(m)</td>
</tr>
<tr>
<td>* Pipe length</td>
<td>(L)</td>
<td>(m)</td>
</tr>
<tr>
<td>* Soil conductivity</td>
<td>(k)</td>
<td>(\text{Wm}^{-1}\text{k}^{-1})</td>
</tr>
<tr>
<td>* Atmospheric pressure</td>
<td>(P)</td>
<td>(\text{pa})</td>
</tr>
<tr>
<td>* Specific heat of air at constant pressures</td>
<td>(Cp)</td>
<td>(\text{J/Kg-K})</td>
</tr>
<tr>
<td>* Number of fitting in the pipe</td>
<td>(dK)</td>
<td>-</td>
</tr>
<tr>
<td>* Fan effective</td>
<td>(E_f)</td>
<td>-</td>
</tr>
</tbody>
</table>
Table C.4 The user definable INPUTS/OUTPUTS variables for EAHE model-Type264

The INPUTS variables for Type264

* Ambient air temperature \((T_a)\) \(^\circ C\)
* Mass flow rate \((M_{dot})\) \((Kg/hr)\)
* Sub-soil Temperature at depth \(z\) and at time \(t\). \((T_{(z,t)})\) \(^\circ C\)

The OUTPUTS variables for Type264

* Heat transferred to/from air in the pipe \((Q)\) \((KJ/hr)\)
* Outlet air temperatures leaving pipe \((T_{outlet})\) \(^\circ C\)
* Total pressure drop \((dP)\) \((pa)\)
* Fan power \((P_f)\) \((KJ/hr)\)
* Fan temperature \((T_f)\) \(^\circ C\)

Figure C.2 TRNSYS System configuration for the simulation of building thermal performance.
C.3 Simulation of example building equipped with EAHE model

The simulations were conducted with TRNSYS-IISIBAT program using EAHE (Type264) and Kuwaiti sub-soil model (Type262) which is developed in chapter 5 and chapter 4 respectively, to investigate the thermal characteristics and energy savings of a typical domestic Kuwaiti building. The example building modelled using TRNSYS-PREBID (which creates file that has all building descriptions and information, see chapter 3) TRNSYS-PREBID has the capability to let the user defined in (each zone of) the building model air flowing ventilation as outside ambient air or other. The outlet air from the EAHE (Type264) is discharged into the building and thus taken to “other” as the ventilation supply. This ventilation supply is in terms of “energy rate control” is defined in TRNSYS-Type 56 as an energy gain/loss input where its additional energy being added /subtract to/from the zone, TRNSYS-Type 56 then will adjust the loads accordingly to the entire load. (TRNSYS/PREBID 3.0, Klein et al 1996). TRNSYS configuration of the simulation is shown in Figure C.2. and IISiBat assembly window can be seen in Figure 3.3 (chapter 3).
Appendix D

Publications originated from this work

**Refereed Journal Paper:**

- Al-Ajmi F., Hanby V.I. and Loveday D.L., (2002A)
  "The potential for ground cooling in a hot arid climate."
  Climate Change and the Built Environment,
  International Conference, UMIST, 7th to 9th April 2002

  "Thermal performance of the subsoil environment in dry
desert climate", ASHRAE annual summer meeting,
Hawaii 2002; and will be in ASHRAE Transaction,
Vol. 108, Pt.2, 2002A.

  "A simulation Of an earth air heat exchanger coupled
  with residential air conditioning in a hot desert
  climate"; 6th International conference on System
Simulation in Buildings; Liège, December 16-18,
SSB 2002, Belgium.