Industry 4.0 – How will the nonwoven production of tomorrow look like?

F Cloppenburg¹, A Münkel¹, Y Gloy¹ and T Gries¹
¹RWTH Aachen University, Faculty of Machinery, Institute for Textile Technology, Otto-Blumenthal-Str. 1, 52074 Aachen, Germany

Email: Frederik.Cloppenburg@ita.rwth-aachen.de

Abstract
Industry 4.0 stands for the on-going fourth industrial revolution, which uses cyber physical systems. In the textile industry the terms of industry 4.0 are not sufficiently known yet. First developments of industry 4.0 are mainly visible in the weaving industry. The cost structure of the nonwoven industry is unique in the textile industry. High shares of personnel, energy and machine costs are distinctive for nonwoven producers. Therefore the industry 4.0 developments in the nonwoven industry should concentrate on reducing these shares by using the work force efficiently and by increasing the productivity of first-rate quality and therefore decreasing waste production and downtimes. Using the McKinsey digital compass three main working fields are necessary: Self-optimizing nonwoven machines, big data analytics and assistance systems. Concepts for the nonwoven industry are shown, like the “EasyNonwoven” concept, which aims on economically optimizing the machine settings using self-optimization routines.

Keywords: nonwovens, industry 4.0, digitalisation, self-optimization

1. Introduction
The term Industry 4.0 stands for the on-going fourth industrial revolution. The first industrial revolution was the mechanisation of work and started with the first mechanical loom in 1784. The second industrial revolution started with the introduction of series production lines based on the division of labor. The third industrial revolution followed the introduction of the first programmable logic controller in 1969. The fourth industrial revolution uses cyber-physical systems to increase the productivity and flexibility of production. A cyber physical system results from the fusion of real objects, like a product or a machine, with information-processing virtual objects. [1]

In a survey of the Institute for textile technology at RWTH Aachen University under German textile engineering companies and textile producers showed, that terms like Industry 4.0, cyber-physical systems or smart factory are not sufficiently known yet. [2] The variety of textile products currently inhibits the textile industry to implement industry 4.0 solutions.

The most advances were made in research and development of industry 4.0 solutions in the weaving industry. For example a self-optimization algorithm for a weaving loom was developed. The self-optimization is based on 4 step routine. First a design of experiment is generated with the loom
settings as the input parameters. Three setting parameters (e.g.: mean warp tension, position of the warp stop motion and machine speed) result in 24 different setups. In the second steps, the test procedure, all setups are run on the loom. Sensors gather information about the warp tension in the different setups. Key values of the warp tension are calculated from the measured, repetitive course of the warp tension. In the third step, the modelling a pure quadratic regression model is used to calculate the the effect of the settings on the key values of the warp tension. A Gauss-Markow-Algorithm is used to calculate the best settings of the machine in the fourth step. [3].

Also a camera based onloom material inspection was developed to skip the manual inspection of the fabric [4]. Several assistance systems have been developed to support the weaver and to teach new personnel the handling of a loom [5].

In the nonwoven production there are currently no efforts of the machine or fabric producers to implement industry 4.0 solutions visible. This work highlights the situation of the nonwoven industry in terms of industry 4.0 and gives an outlook of what has to be developed first to gain the biggest advantages first.

2. Value drivers of the nonwoven production
McKinsey has examined the expected impacts of industry 4.0 in a study called the “digital compass”. The study claims that industry 4.0 will have impact on the eight basic value drivers resource/process, asset utilization, labour, inventories, quality, supply-demand match, time to market and services/aftersales [6]. In order to identify the cost relevant value drivers for the nonwoven industry the cost structure without material costs has to be examined. This leads to a cost distribution, where the biggest shares are personnel, energy and machine costs [7]. The relevant value drivers for the nonwoven industry are therefore resource/process, asset utilization, service/aftersales, labour and quality. Industry 4.0 developments in the nonwoven industry should therefore aim for reducing the share of personnel, energy and machine costs. This can be achieved by using labour efficiently and by increasing the productivity of first-rate quality and therefore decreasing waste production and downtimes. The relevant industry 4.0 technologies are therefore intelligent machines, online machine optimization, smart energy consumption, predictive maintenance, assistance systems for maintenance, repair and operation, automating knowledge work, advanced process control and the use of big data analytics. The expected impact is an increase of 3-5 % productivity, a reduction of 30-50 % of the total machine downtime, an increase of 20-40 % of machine life and an increase of 45-55 % increase of labour productivity. Moreover a reduction of 10-20 % for the costs of quality is expected. [6]

3. Necessary developments to realise industry 4.0 in the nonwoven production
Based on the identified relevant value drivers the first and most important steps for the realisation of industry 4.0 in the nonwoven production are;

- Self-optimizing nonwoven machines in order to reduce the waste production and machine downtime
- Big data analytics to reduce the machine downtime
- Assistance systems to reduce the machine downtime and increase the labour efficiency

A first step for self-optimizing machine is made by ITA with the “EasyNonwoven Concept”, which concentrates on the card as the machine which predominantly determines the quality of the product (see Figure 1). In order to develop a self-optimizing card electronic quality inspections have to be made directly on the unconsolidated web. The quality data and the costs for material, personnel and energy can be used by a self-optimization algorithm which also uses the product data in order to set the revolutions of the card rollers.
Big data is characterized by the four V’s: Volume, Variety, Velocity and Veracity. Big data analytics are Technologies, Concepts, IT-structures and tools capable of analysing and economically use big amounts of data in different formats [8]. Big data analytics offers the chance for constant optimization of the production and maintenance. Furthermore perfect product traceability and fault prevention over company borders is possible. For the nonwoven industry the biggest challenges concerning big data technologies are the save transport of data between companies and the storage and analytic of the data without risking knowledge loss. Therefore the DigiTextil Concepts was developed, which enables a safe data transport and storage of multiple companies in a safe third party cloud. If a product error occurs, the cloud company is able to interconnect the companies if they are both willing to talk to each other. The knowledge of the cloud, which rises the more process chains deliver their data into the cloud, can give advice on how to prevent the error in the future.

Assistance Systems are developed to lead the worker to the correct places and guarantee a quicker reaction to extraordinary behaviour of the machine. Augmented Reality can be used to have the necessary information directly in the field of view. Concerning the nonwoven industry an alarm system would be possible to guide the worker to the correct places along the production line. Therefore errors can be detected earlier and greater damages or waste production is avoided.

4. Conclusion
The relevant value drivers of the nonwoven production were identified using the cost structure of nonwoven producers. Therefore developments should concentrate on solutions that reduce the relative share of labour costs, energy costs and machine costs. This can be achieved by developing self-optimizing machines, safe big data analytics and assistance systems for the nonwoven industry.

References


Evaluation of bending rigidity behaviour of ultrasonic seaming on woven fabrics

Ayşe Şevkan Macit and Bahar Tiber
Uşak University, Engineering Faculty, Textile Engineering Department, Uşak-İzmir Yolu, 8. Km 1 Eylül Kampüsü, Uşak/Merkez, Türkiye

ayse.sevkan@usak.edu.tr

Abstract. In recent years ultrasonic seaming that is shown as an alternative method to conventional seaming has been investigated by many researchers. In our study, bending behaviour of this alternative method is examined by changing various parameters such as fabric type, seam type, roller type and seaming velocity. For this purpose fifteen types of sewn fabrics were tested according to bending rigidity test standard before and after washing processes and results were evaluated through SPSS statistical analyze programme. Consequently, bending length values of the ultrasonically sewn fabrics are found to be higher than the bending length values of conventionally sewn fabrics and the effects of seam type on bending length are seen statistically significant. Also it is observed that bending length values are in relationship with the rest of the parameters excluding roller type.

1. Introduction
Apparel industry enhancing the added value of products is one of the sectors which has major importance. Various seaming methods are used in conversion into final product of different fabric surfaces produced by different methods. However, seaming process of some types of textile products which requires functional specifications is in need of alternative seaming methods besides conventional seaming methods. One of these alternative methods is ultrasonic seaming which have been used for almost 20 years and was studied intensively and got attention over the past decade.

Ultrasonic seaming method is not only an energy saving method, but also it can perform sewing process without the need for the materials such as needle, thread that have been used in the conventional seaming methods. Ultrasonic seaming is used in wide range of industries such as technical textiles, medical, filtration and automotive [1, 2].

Many studies related to ultrasonic seaming have been made up to date [3-9]. There are studies examining the bending rigidity in these studies. Bending rigidity is very important property in terms of fabric handle [10]. This property is related to fabric stiffness and they are proportional to each other [11]. In Reddy's (2007) study, the effects of various production parameters and material properties on sewing efficiency and fabric stiffness were examined on ultrasonic seaming and compared with conventional seaming. It has been determined that fabric stiffness is higher in ultrasonic seaming when using 100% polyester, 65/35% polyester/cotton and 100% Spectra as material [12]. Appleby (2009) compared conventional and ultrasonic seaming regarding seam strength and stiffness. 100% polyester fabric was used in the study. It is stated that the stiffness of ultrasonic seaming is higher than the stiffness of conventional seaming. High stiffness can be shown as an advantageous feature in sailing and sportswear [13]. Jevsnik et al. (2015) investigated ultrasonic seaming from an aspect of bond strength, seam thickness, seam stiffness and water permeability properties by comparing conventional
seaming. They observed that conventional seaming had lower stiffness in comparison to ultrasonic seaming [14].

Our study aims to compare ultrasonic seaming and conventional seaming by using woven fabrics coated with polyurethane membrane which are used as blouson. Fifteen types of sewn fabric were gained by changing the parameters of seaming such as roller type and seaming velocity. Bending length values of the sewn fabrics were compared.

2. Material and Method
In this study, conventional seam and ultrasonic seam were applied to three different woven fabrics and fifteen types of sewn fabric were gained. The properties of fabrics and the seam parameters are characterized in Table 1.

<table>
<thead>
<tr>
<th>Fabric code</th>
<th>Weaving structure</th>
<th>Weight in grams per square meter (g/m²)</th>
<th>Thickness (mm)</th>
<th>Raw material</th>
<th>Seam type</th>
<th>Roller / velocity code</th>
<th>Sewn fabric code</th>
</tr>
</thead>
<tbody>
<tr>
<td>F₁</td>
<td>Plain</td>
<td>105</td>
<td>0.366</td>
<td>Polyester</td>
<td>Ultrasonic</td>
<td>r₁v₁</td>
<td>F₁r₁v₁</td>
</tr>
<tr>
<td>F₂</td>
<td>Plain</td>
<td>105</td>
<td>0.366</td>
<td>Polyester</td>
<td>Ultrasonic</td>
<td>r₂v₂</td>
<td>F₂r₂v₂</td>
</tr>
<tr>
<td>F₃</td>
<td>Plain</td>
<td>105</td>
<td>0.366</td>
<td>Polyester</td>
<td>Ultrasonic</td>
<td>r₁v₁</td>
<td>F₃r₁v₁</td>
</tr>
<tr>
<td>F₄</td>
<td>Plain</td>
<td>170</td>
<td>0.432</td>
<td>Polyester</td>
<td>Ultrasonic</td>
<td>r₂v₂</td>
<td>F₄r₂v₂</td>
</tr>
<tr>
<td>F₅</td>
<td>Plain</td>
<td>170</td>
<td>0.432</td>
<td>Polyester</td>
<td>Ultrasonic</td>
<td>r₁v₁</td>
<td>F₅r₁v₁</td>
</tr>
<tr>
<td>F₆</td>
<td>Plain</td>
<td>170</td>
<td>0.432</td>
<td>Polyester</td>
<td>Ultrasonic</td>
<td>r₂v₂</td>
<td>F₆r₂v₂</td>
</tr>
<tr>
<td>F₇</td>
<td>Plain</td>
<td>170</td>
<td>0.432</td>
<td>Polyester</td>
<td>Ultrasonic</td>
<td>r₂v₂</td>
<td>F₇r₂v₂</td>
</tr>
<tr>
<td>F₈</td>
<td>Plain</td>
<td>170</td>
<td>0.432</td>
<td>Polyester</td>
<td>Ultrasonic</td>
<td>r₁v₁</td>
<td>F₈r₁v₁</td>
</tr>
<tr>
<td>F₉</td>
<td>Plain</td>
<td>170</td>
<td>0.432</td>
<td>Polyester</td>
<td>Ultrasonic</td>
<td>r₂v₂</td>
<td>F₉r₂v₂</td>
</tr>
<tr>
<td>F₁₀</td>
<td>Plain</td>
<td>170</td>
<td>0.432</td>
<td>Polyester</td>
<td>Ultrasonic</td>
<td>r₂v₂</td>
<td>F₁₀r₂v₂</td>
</tr>
<tr>
<td>F₁₁</td>
<td>Plain</td>
<td>170</td>
<td>0.432</td>
<td>Polyester</td>
<td>Ultrasonic</td>
<td>r₁v₁</td>
<td>F₁₁r₁v₁</td>
</tr>
<tr>
<td>F₁₂</td>
<td>Plain</td>
<td>170</td>
<td>0.432</td>
<td>Polyester</td>
<td>Ultrasonic</td>
<td>r₂v₂</td>
<td>F₁₂r₂v₂</td>
</tr>
<tr>
<td>F₁₃</td>
<td>Plain</td>
<td>170</td>
<td>0.432</td>
<td>Polyester</td>
<td>Ultrasonic</td>
<td>r₁v₁</td>
<td>F₁₃r₁v₁</td>
</tr>
<tr>
<td>F₁₄</td>
<td>Plain</td>
<td>170</td>
<td>0.432</td>
<td>Polyester</td>
<td>Ultrasonic</td>
<td>r₂v₂</td>
<td>F₁₄r₂v₂</td>
</tr>
<tr>
<td>F₁₅</td>
<td>Plain</td>
<td>170</td>
<td>0.432</td>
<td>Polyester</td>
<td>Ultrasonic</td>
<td>r₁v₁</td>
<td>F₁₅r₁v₁</td>
</tr>
</tbody>
</table>

Fabric samples were prepared along the warp direction. Ultrasonic seam process was performed by using Pfaff 8310 ultrasonic sewing machine. Amplitude of the machine was 100% during the sewing process. Two different speeds were performed as 25 dm/min (v₁) and 45 dm/min (v₂). Two rollers were used that across 4 mm (r₁) and 12 mm (r₂) which have the same pattern as shown in Figure 1. Conventional seam process was performed to woven fabrics by using Brother S-7200C-403 electronic lock stitch sewing machine. Stitch length was 2.6 stitches/cm.

All of the sewn fabrics were washed at 30°C with synthetic washing programme without prewashing by using home laundry machine according to TS 5720 EN ISO 6330:2002 test standard [15]. 4 g/l ECE non-phosphate reference detergent without optical brightening agent was used for washing processes. Washing process was repeated for five times.
Figure 1. a) Roller coded r1, b) Roller coded r2.

Bending rigidity tests were performed to fabrics before and after washing processes with the instrument designed for bending rigidity test method according to TS 1409:1973 [16]. Five samples were prepared from each sewn fabric having dimensions 2.5x15 cm. The samples were conditioned for 24 hours in standard atmospheric conditions (temperature 20±2 °C and relative humidity 65±2%). The conditioned samples were then tested for both faces and both sides. Twenty falling length values were read on the instrument and the average of these twenty values was divided into two to obtain the bending length value for each sewn fabric. Bending rigidity is formulated in TS 1409:1973 as follows:

\[ G = 0.1 W C^3 \]

where:
- \( X \) = Falling length (cm)
- \( C = X/2 \) = Bending length (cm)
- \( W \) = Fabric mass per unit area (g/m²)
- \( G \) = Bending rigidity (mg.cm)

In the standard TS 1409, bending rigidity is calculated according to above equation for a single layer fabric without any seam. However we used sewn fabrics in our study so we have compared the fabrics in terms of bending length values. Test results evaluated considering fabric type, seam type, roller type, seaming velocity and washing process. To evaluate the importance of test results, SPSS 13.0 programme was used with the analysis of variance (ANOVA). In this way the effects of fabric type, seam type, roller type, seaming velocity and washing process on bending length were analyzed.

3. Results
Bending length values of the ultrasonically and conventionally sewn fabrics before and after washing processes were given in Table 2 and Table 3, respectively.

Table 2. Bending length (cm) values of the ultrasonically sewn fabrics before and after washing processes.

<table>
<thead>
<tr>
<th>Fabric</th>
<th>R1V1 Before washing</th>
<th>R1V1 After washing</th>
<th>R1V2 Before washing</th>
<th>R1V2 After washing</th>
<th>R2V1 Before washing</th>
<th>R2V1 After washing</th>
<th>R2V2 Before washing</th>
<th>R2V2 After washing</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>3.94</td>
<td>3.34</td>
<td>3.80</td>
<td>3.27</td>
<td>3.75</td>
<td>3.18</td>
<td>3.55</td>
<td>3.09</td>
</tr>
<tr>
<td>F2</td>
<td>4.82</td>
<td>4.45</td>
<td>4.23</td>
<td>4.30</td>
<td>5.03</td>
<td>4.09</td>
<td>4.97</td>
<td>4.03</td>
</tr>
<tr>
<td>F3</td>
<td>6.02</td>
<td>4.71</td>
<td>6.09</td>
<td>4.43</td>
<td>6.25</td>
<td>4.89</td>
<td>5.85</td>
<td>4.77</td>
</tr>
</tbody>
</table>
Table 3. Bending length (cm) values of the conventionally sewn fabrics before and after washing processes.

<table>
<thead>
<tr>
<th>Fabric</th>
<th>Before washing</th>
<th>After washing</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>3.03</td>
<td>2.92</td>
</tr>
<tr>
<td>F2</td>
<td>3.28</td>
<td>3.20</td>
</tr>
<tr>
<td>F3</td>
<td>3.72</td>
<td>3.62</td>
</tr>
</tbody>
</table>

Considering the obtained bending length values; ultrasonically sewn fabrics’ values are found to be higher than that of conventionally sewn. It is observed that the results obtained from the view point of seam type in this research, are in accordance with the studies about bending rigidity of ultrasonic seaming [12, 13, 14]. Taking into account the highest bending length value observed in the ultrasonic seams for each type of fabrics, the bending length value of conventional seam increased by 30% for the F1 fabric, 53% for the F2 fabric and 68% for F3 fabric before washing processes. After washing processes, the amount of these increments varied by 14%, 39% and 35%, respectively. The results show that the impact level of seam type on bending length values varies according to fabric structure.

It is observed that for both of the seam types, before and after washing processes bending length values of F1, F2 and F3 fabrics increases respectively. F1 fabric is lighter in weight than the others so weight increment has an increasing effect on bending length values. Bending property is in interaction with weight of fabric [17]. F2 and F3 fabrics have same weight in grams per square meter and their constructions are plain and twill, respectively. Twill fabric F3 has higher bending value so fabric structure seems to be effective on bending length. Examining Table 4, the differences of bending length values between fabrics are statistically significant.

Table 4. The effects of fabric type on bending length values (Post Hoc).

<table>
<thead>
<tr>
<th>Fabric type</th>
<th>N</th>
<th>Subset</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>F1</td>
<td>48</td>
<td>3.3798</td>
</tr>
<tr>
<td>F2</td>
<td>49</td>
<td>4.2404</td>
</tr>
<tr>
<td>F3</td>
<td>50</td>
<td>5.0360</td>
</tr>
<tr>
<td>Sig.</td>
<td></td>
<td>1.000</td>
</tr>
</tbody>
</table>

Washing process has a decreasing effect on bending length values for both of the ultrasonically and conventionally sewn fabrics. The effects of washing process, seam type and fabric type are found statistically significant on bending length as seen in Table 5.

Table 5. The analysis of variance table for bending length values of the sewn fabrics.

<table>
<thead>
<tr>
<th>Factor</th>
<th>F</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Washing process</td>
<td>19.098</td>
<td>0.000*</td>
</tr>
<tr>
<td>Seam type</td>
<td>43.699</td>
<td>0.000*</td>
</tr>
<tr>
<td>Fabric type</td>
<td>64.493</td>
<td>0.000*</td>
</tr>
<tr>
<td>Roller type</td>
<td>0.007</td>
<td>0.933</td>
</tr>
<tr>
<td>Seaming velocity</td>
<td>1.362</td>
<td>0.246</td>
</tr>
</tbody>
</table>

*: Statistically significant for α =0.05
From the standpoint of seaming velocity, it is clear that generally bending length values and seaming velocity are inversely proportional for ultrasonic seam. It is known that ultrasonic seam has an increasing effect on fabric stiffness. Fabric exposes to welding longer time at lower ultrasonic seam velocity. Therefore higher bending length values were obtained at lower seam velocity as expected. On the other hand the effect of velocity on bending length is found statistically insignificant for all fabrics as shown in Table 5. Comparing roller type, bending length values of the ultrasonically sewn fabrics don’t demonstrate regular changes between roller types before and after washing processes and the effect of roller is found statistically insignificant for all fabrics (Table 5).

4. Conclusion
In this study, ultrasonic and conventional seaming were performed to polyester woven fabrics coated with polyurethane membrane which are used as blouson. The effect of ultrasonic seaming parameters and fabric structure on bending property were investigated. The following conclusions can be drawn on the basis of the study:

- Our study demonstrated that bending length values of the ultrasonic seams are higher than the conventional seams in polyester woven fabrics coated with polyurethane membrane.
- In ultrasonic seam process, bending length values decreased with the increase of seaming velocity but no generalization could be made for roller type.
- It is clear from the results that bending length values decreased with reducing of fabric weight. On the other hand, these values in twill structure are superior to plain structure at equivalent weight in grams per square meter. Therefore it can be concluded that fabric structure affected bending length values.
- In addition, bending length values decreased after washing process for both ultrasonic seam and conventional seam.
- After all, the effects of fabric type, seam type and washing process on bending length are found statistically significant, but the effects of roller type and seaming velocity on this property are found statistically insignificant for all fabrics.

Acknowledgments
This study has been supported by Uşak University Scientific Research Project under grant [2015/MF005]. I would like to thank to Prof. Dr. M. Çetin Erdoğan and Dr. Serkan Boz at the Textile Engineering Department in Ege University for using ultrasonic sewing machine.

References


[16] Turkish Standard 1973 Stiffness determination of woven textiles TS 1409

Development and testing of a relay nozzle concept for air-jet weaving

A Münkel¹, Y S Gloy¹ and T Gries¹

¹Institut für Textiltechnik der RWTH Aachen University, Otto-Blumenthal-Str. 1
527074 Aachen, Germany

andreas.muenkel@ita.rwth-aachen.de

Abstract. The textile industry is an energy intensive branch of industry. Increasing energy
costs are a challenge for textile manufacturers as well as for the developers of textile
production machines [1].
Air jet weaving is the most productive method to produce woven fabrics. However, air-jet
weaving machines have a significantly higher level of energy consumption compared to other
weaving machines. Approximately 80% of compressed air is consumed by the relay nozzles.
Therefore, there are different approaches to reduce the consumption of compressed air and to
increase the energy efficiency of air-jet looms [2] At the Institut für Textiltechnik der RWTH
Aachen University, Aachen new relay nozzle concepts have been developed. Based on
Computational Fluid Dynamics (CFD) the concepts were further developed with the result of
an energy-efficient relay nozzle concept. The simulations have shown the potential energy
savings up to 60% compared to conventional relay nozzles.
Furthermore, practical validations of these simulation results were done. The velocity,
stagnation pressure and volume flow were measured in the reed canal. The optimal position
regarding the injection angle and high, as well as the distance between two relay nozzles were
identified with the results of the measurements.
In addition, the relay nozzles were tested in the industrial environment. These tests have shown
a low error rate which is comparable conventional relay nozzle concepts. Furthermore, exergy
savings up to 49% has been measured.

1. Introduction
The textile industry is an energy intensive industry. Increasing energy costs are a challenge for textile
manufacturers as well as for the developers of textile production machines. As example, air-jet
weaving is the most productive but also most energy consuming weaving method [5]. In the air-jet
weaving process the weft yarn is inserted into the shed with compressed air by the use different
nozzles types. Figure 1 shows a schematic view of the weft insertion components.
Figure 1. Schematic view of air-jet weft insertion system [1]

Current state of the art air-jet weaving machines employ a tandem and main nozzle combination at the purpose to provide the initial acceleration to the weft yarn, and a series of relay nozzles along the reed channel to keep constant yarn velocity of about 55 – 80 m/s. A profiled reed provides guidance for the air. At the end of the insertion process a nozzle catches and stretches the yarn at the right side of the machine. A cutter is used to cut the yarn when the insertion is completed and the beat-up movement complete the fabric production process [4].

The air-jet weaving machine combines high performance (see Table 1) with low wear, because no mechanical parts are directly involved in the weft insertion process [1].

Table 1. General characteristics of air-jet weaving machine [3],[4]

<table>
<thead>
<tr>
<th>Air Jet weaving machine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weft Insertion rate</td>
</tr>
<tr>
<td>Average Specific Energy consumption</td>
</tr>
<tr>
<td>(kWh/kg of woven fabric)</td>
</tr>
</tbody>
</table>

However, the main drawback regarding of the technology is the very high energy consumption (see Table 1) due to the compressed air usage which is required during the weft insertion process. Since the cost of energy has a systematic increasing trend, power consumption is still a challenging issue. In particular, power consumption is the limiting factor in countries, with high energy and manufacturing cost. An overview of the manufacturing cost of a woven fabric can be seen in Table 2 [6].

For instance, in Italy, the total manufacturing cost is 0.665 USD/m of woven fabric and power cost corresponds to 23.5% (0.156 USD/m). In other countries, such as India or China, the total manufacturing costs are less, respectively 0.235 USD/m and 0.274 USD/m, but on the other hand the power consumption is responsible respectively for 27% (0.064 USD/m) and 34% (0.092 USD/m) of the entire value.
Table 2. Overview of the manufacturing costs of a woven fabric [6]

<table>
<thead>
<tr>
<th></th>
<th>Brazil</th>
<th>China</th>
<th>Egypt</th>
<th>India</th>
<th>Italy</th>
<th>Korea</th>
<th>Turkey</th>
<th>USA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste</td>
<td>0.006</td>
<td>0.008</td>
<td>0.007</td>
<td>0.005</td>
<td>0.008</td>
<td>0.006</td>
<td>0.006</td>
<td>0.006</td>
</tr>
<tr>
<td>Labour</td>
<td>0.047</td>
<td>0.036</td>
<td>0.016</td>
<td>0.009</td>
<td>0.244</td>
<td>0.120</td>
<td>0.053</td>
<td>0.146</td>
</tr>
<tr>
<td>Power</td>
<td>0.085</td>
<td>0.092</td>
<td>0.028</td>
<td>0.064</td>
<td>0.156</td>
<td>0.064</td>
<td>0.057</td>
<td>0.036</td>
</tr>
<tr>
<td>Auxiliairy material</td>
<td>0.037</td>
<td>0.042</td>
<td>0.050</td>
<td>0.048</td>
<td>0.094</td>
<td>0.054</td>
<td>0.059</td>
<td>0.033</td>
</tr>
<tr>
<td>Depreciation</td>
<td>0.077</td>
<td>0.072</td>
<td>0.058</td>
<td>0.065</td>
<td>0.132</td>
<td>0.064</td>
<td>0.062</td>
<td>0.099</td>
</tr>
<tr>
<td>Interest</td>
<td>0.060</td>
<td>0.024</td>
<td>0.039</td>
<td>0.044</td>
<td>0.031</td>
<td>0.018</td>
<td>0.031</td>
<td>0.022</td>
</tr>
<tr>
<td>Total costs</td>
<td>0.312</td>
<td>0.274</td>
<td>0.198</td>
<td>0.235</td>
<td>0.665</td>
<td>0.326</td>
<td>0.268</td>
<td>0.342</td>
</tr>
</tbody>
</table>

In order to decrease the energy consumption and to increase the energy efficiency, air-jet weaving machines are under constant development. At the Institut für Textiltechnik der RWTH Aachen University (ITA), Aachen, Germany, a novel method based on exergy balances has been applied at the purpose of reducing the power costs while keeping constant fabric quality. The study focused on the air flow field of the relay nozzles [1], [2]. A picture of the position of the relay nozzles and the profiled reed is shown in the following Figure 2.

Figure 2. Detailed view of the relay nozzle and the profiled reed [2]

Finally, the result of the research led to the development of a new geometry of the relay nozzle which can provide the same value of propulsive force to the weft yarn at a lower operating pressure level. This new concept of relay nozzle is able to work at 2 bar inlet overpressure in place of 5 bar, as relay nozzles available on the market [6]. In such a way, the productivity is kept constant and the costs associated to the compressors to pump up the air are decreased.
2. Methods
For the design of the new nozzle concept, different flow simulations have been carried out. The simulations are done with the Computational Fluid Dynamics (CFD) simulation tool ANSYS Fluent from ANSYS, Inc., Canonsburg, USA. The simulations are based on the following assumptions:

- Compressible flow field
- Ideal gas
- Steady state flow

With these assumptions, a CFD model was set up and a CAD-model was integrated into this model. Behind the nozzle outlet a free flow field with ambient pressure is modulated. At the inlet of the nozzle 1 bar overpressure was set as a boundary condition. The reed is not considered because of the complex geometry which increases the calculation time for the simulation uneconomically. The CFD model with the simulated flow field is shown in Figure 3.

![Figure 3. Simulated flow field of the new nozzle concept.](image)

The results of the simulations proof, that the nozzle produces a is very compact (e.g. low divergence flow, no shock waves) free stream and a small blowing angle of 6-8 degree. In agreement with the convergent nozzle theory, it can be drawn from the simulation that sonic conditions are achieved at the outlet surface ($M = 1, c = 343$ m/s). The nozzle is in choking condition and the mass flow density rate reaches the highest possible value which the outer surface can allow, considering the initial boundary conditions of pressure and temperature. Moreover, the expansion of the flow occurs outside of the nozzle by means of dumped oscillations. In Figure 4 the simulated velocity of the air stream, up to 130 mm behind the nozzle, is shown. The Figure 4 shows on the vertical axes the velocity of the air and on the horizontal axes the distance downstream the nozzle. The nozzle is located in the origin.
3. Testing
The simulation showed the potential of up to 60% energy savings compared to the conventional relay nozzles. For testing the newly designed nozzles prototypes were produced with a 3D-printer using a lamination thickness of 0.05 mm. This lamination thickness provides a very detailed print with a very even surface which is needed for meaningful test results.

The nozzles were tested under different conditions using different weft materials and machines for about two weeks each. Table 3 shows the overview of the test series compared the results of a test with the conventional nozzles. It can be seen, that the new nozzle concept lowers the operating pressure up to 3.5 bar and saves up to 26.4% of energy. The difference between the calculated efficiency and the validated efficiency is justified in the interaction with the profiled reed which was not considered in the simulations. The reed produces additional losses which lowers the effect of the newly designed nozzles.

4. Conclusions
At the Institute for Textile Technology of RWTH Aachen University, Aachen, Germany, a novel method has been developed to identify potentials in saving energy of textile production processes [1]. The air-jet weaving process is the most productive but also the most energy intensive weaving process while the pneumatic components of the machine can be identified as biggest energy consumer.

Based on a theoretical model of the weft insertion, a new concept for the relay nozzle has been drawn. The new nozzle operates with only 2.3 bar pressure in place of 5 bar, as commonly used in the state of the art machines. By means of CFD simulations, the potential of the nozzle is shown and an energy reduction up to 60% is possible. Nevertheless, the simulation includes a faithful reproduction of the free flow field of the relay nozzle, without considering the interaction with the profiled reed. The simulations were validated by testing under industrial environment and showed energy savings of about 27% depending on the yarn which was used while production.
Table 3. Test series with industrial environment

<table>
<thead>
<tr>
<th>Nozzle pressure [bar]</th>
<th>Normed volume flow [Nm³/h]</th>
<th>Nozzle pressure [bar]</th>
<th>Normed volume flow [Nm³/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference test</td>
<td>Test with the new nozzle concept</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.5</td>
<td>125</td>
<td>3.0</td>
<td>92</td>
</tr>
<tr>
<td>Weft material: cotton</td>
<td>Machine: LWV 4/E, Lindauer Dornier GmbH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.8</td>
<td>93</td>
<td>2.3</td>
<td>76</td>
</tr>
<tr>
<td>Weft material: Polyester 167 f36 texturized</td>
<td>Machine: OmniPlus Summum, Picanol N.V.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.5</td>
<td>118</td>
<td>3.5-3.2</td>
<td>100</td>
</tr>
<tr>
<td>Weft material: 34/1 PES OE</td>
<td>Machine: OmniPlus Summum, Picanol N.V.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.5/6</td>
<td>102-104</td>
<td>3.5-4</td>
<td>98-100</td>
</tr>
<tr>
<td>Weft material: PA6.6 235 Z75 type 632</td>
<td>Machine: LWV 4/S, Lindauer Dornier GmbH</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Acknowledgement
The project VIP0477 is in the form of assistance “Validierung des Innovationspotenzials wissenschaftlicher Forschung - VIP” supported by the Federal Ministry for Education and Research. The European Commission is gratefully acknowledged for its support of the Marie Curie program through ITN EMVeM project, Grant Agreement N° 315967.

References
‘Spacer stitching’, an innovative material feeding technology for improved thermal resistance

H Saeed¹, H Rödel¹, S Krzywinski¹ and L Hes²

¹Technical University of Dresden, Faculty of mechanical engineering, Institute of textile machinery and high performance material technology, Dresden, Germany
²Technical University of Liberec, Czech Republic

E-mail: hassan.saeed@tu-dresden.de

Abstract. This paper investigates the problems associated with heat loss occurring at the points of needle insertion. The insulation material at stitching points is compressed by sewing thread tensions and consequently the air entrapped is forced to leave its structure. It results in poor thermal insulation at the points of needle insertions. An innovative material feeding technology, ‘Spacer stitching’ is developed which addresses the state of the art of cold spots with a simpler and much efficient method. A comparison of sewing samples of conventional sewing technology with the spacer stitching is carried out in this research paper to study the improvement in thermal properties.

1. Introduction
Earth has very diverse climatic conditions. Humans have survived in extreme weather and temperatures for tens of thousands of years. As the most evolved species on the planet, humans have developed ways to keep themselves comfortable in even the harshest surroundings. To supplement what little body hair modern humans have left, our species relies on clothing, as one of the critical threats to our health and safety is extremely cold weather. In rural Oymyakon in Eastern Russia, temperatures often drop below -50 °C, making it one of the coldest permanently inhabited places in the world [1]. Such places exist on almost all continents. The optimum comfortable conditions for the human body rely on the skin maintaining a temperature of 33 °C to 35 °C. The core temperature of the human body cannot deviate from 37 °C by more than 0.2 K [2,3]. Suitable clothes prevent the harmful effects of the temperature difference between the body and its environment.

With the invention of the sewing machine by Elias Howe (1819-1867) [4], and further innovations in sewing technology with ever increasing speeds in the 20th century, mass production in the clothing industry was realized. The industrial sewing machine became more robust and specialized industrial versions of sewing machines are capable of working at higher sewing speeds. The combination of advanced automation technology and higher sewing speeds is utilized on clothing for the production of goods of longer runs, and labour-intensive work is reduced [5], [6]. Various types and forms of clothing i.e. jackets, sweaters, gloves, and sleeping bags are used to protect human beings living in extremely cold weather conditions. They are produced at mass production scale worldwide. With the advances in fabric technologies, insulating materials, and scientific knowledge of clothing comfort, these products are getting warmer and more functional than ever before.
The flow of heat through clothing is a complex process involving conduction, convection and radiation. Perceptible heat is exchanged through not only the fabric itself but also through its interstices as well as through small and large apertures of the clothing [7]. The air, which itself acts as an insulator, plays a very important part in clothing insulation systems [8], [9].

In clothing products to be used in extreme weather conditions, layers of textile materials are combined with suitable insulation materials and are held together with sewing. Sewing is important to keep the insulation material at its designated place. Lockstitch is one stitch type used widely for combining layers of insulation materials with textile fabrics. The thread systems in lockstitch pull each other to locate the point of knotting in the sandwich structure of fabrics and insulation material. During the stitch formation, the outer and inner layers of textile material are brought close together during by tensions of sewing threads. Therefore, the insulation material, sandwiched between the extreme layers of fabric is compressed along the stitch line, causing a thin spot at each point of needle insertion.

![Figure 1](image1.png)

**Figure 1.** Graphical illustration of cold spots

Figure 1 shows a graphical illustration of cross-section of conventional lockstitch and the formation of cold spots. These thin spots, commonly known as ‘cold spots’, are responsible for heat loss from the human body to its outer climate. These cold spots reduce the overall insulating value of the material [11]. Due to compression along the stitch line, the air trapped inside the insulation material is forced to leave its porous structure. The thermal resistance which depends upon the thickness of insulation material and primarily on the volume of air trapped in it [12] is reduced due to localized compression at the points of needle insertions along the stitching line. The insulation materials do not exhibit their optimum performance along stitch line as in the rest of the product’s surface [13], [14]. The combination of these factors causes heat loss from the points of needle insertion. The greater the number of stitch lines, the more heat would be lost through them.

![Figure 2](image2.png)

**Figure 2.** Heat loss through cold spots on stitching line [15]
Figure 2. Error! Reference source not found. shows a thermal image of person wearing a jacket, revealing the heat loss through these cold spots [15]. In situation of extreme weather conditions, heat loss through clothing system is critically important in directing the precious body heat to escape and these cold spots present along the stitching line act as bridges between the internal climate of the body and its external climate.

The traditional manufacturing methods especially with manmade insulation materials, suffer from the disadvantages of stitching lines due to formation of cold strips in the material. This is due to the fact that the thickness of the insulation along the lines of stitching is reduced merely to that of the two sheets of material. In both natural insulating materials and manmade nonwoven batting, at the point of needle insertions where the thread systems pull each other, the insulation material is compressed and heat loss occurs at these points.

The cold spots are accepted as a by-product phenomenon, inherited by sewing machine mechanisms in clothing industry. There are a number of patents registered worldwide by individuals and by renowned clothing manufacturers that counter the problem of cold spots [9], [10], [13], [14], [16], [17], [18], [19]. Most of the patents are resolving the problem with numerous material handling methods that cover the stitch line. These patents examples from the 20th and 21st century explain that the problem of cold spots and its negative impacts on product performance are well known to textile and clothing technologists. The design patents submitted by global brands until very recently prove that the problem persists despite complex material handling techniques proposed, and that a machine-based solution is not yet available.

2. Development of Spacer Stitching

The concept of spacer stitching is inspired by the spacer fabric where two parallel layers of fabric are joined to each other with the constituting fabric yarns itself and maintaining a distance between them. The concept of spacer stitching is first implemented with lockstitch sewing technology. In spacer stitching, sewing thread also join two or more layers of sewing material like any other. An innovative material feeding concept is used to maintain the distance between the extreme layers of textile material which does not compress the insulation material. Spacer stitching should not be confused with any form of loose stitches. This material feeding concept can be mounted on machines of other stitch classes. The concept is created on two level material feeding system by introducing an extra raised stitch plate, on top of original stitch plate. Lower textile layer and insulation material is fed between the raised stitch plate and lower (original) stitch plate, while the upper textile material is fed on top of raised stitch plate. The graphical illustration of spacer stitch can be seen in Figure 3.

Figure 3. Graphical illustration of spacer stitching (left) and sample prepared with lockstitch (right)
The prototype was designed and mounted on conventional lockstitch sewing machine at Institute for Textile Machinery and High Performance Materials (ITM) of Technical University of Dresden. There are certain limitations in material transport while working with conventional sewing machines that will be improved in the next phase of research. The distance of raised stitch plate from machine base is flexible and it is adjusted according to required stitch height and thickness of insulation material to be sewn. The final stitch height depends on the sewing threads tensions, sewing thread type, distance between stitch plates and thickness/bulkiness of insulation material. A patent is already applied.

3. Study of heat loss through stitching
The clothing industry and garment engineers are aware of the problem presented by cold spots, yet there is lack of research available which specifies the degree of heat loss occurring through the stitch lines. There is no research work in the literature discussing the quantification of this well-known problem in detail. Historically, the clothing industry has focused on devising new material handling techniques to neutralize the problem of cold spots [20], [21]. These techniques cover the cold spots in one way or another, aiming to stop/hinder the heat passage through the weak link of stitching by adopting complex and time consuming manufacturing methods.

In the framework of research various testing methods are used to study the effects of spacer stitching on thermal properties. However, following techniques will be discussed in this research paper.
- Permetest
- Sweat guard hot plate (Skin Model)
- X-Ray Tomography

3.1. Permetest
Permetest is a simpler version of the skin model developed by L. Hes and co-workers [22]. Measurements are expressed in units of $R_{et}$ and $R_{ct}$ as defined in ISO 11092. Its porous surface is continuously heated to a constant temperature. The temperature can be varied, but normally kept at a difference of 10 K to the ambient temperature. Because of this temperature difference the heat flows through the tested material [23,24].

3.1.1. Sample preparation. Testing samples were prepared for thermal resistance testing. Insulation materials of three different densities of nonwovens were used. Samples prepared are divided in 3 categories. In first category came the samples which were not sewn at all. The results from non-stitched samples served as a benchmark for comparison as they were the best case scenario. In second category the sample were prepared with conventional lockstitch. The third category of sample was prepared with spacer stitching. The samples are sewn with stitch density of 3,1 stitches/cm and sewing needle of 80 Nm. The size of sewing thread in needle and in bobbin was 100 tex made of 100 % polyester. The samples with spacer stitching are further categorized in three sub categories based upon the stitch plate distances. Spacer stitching samples were prepared with stitch plate distance (SPD) of 6 mm, 9 mm and 11 mm. A total number of 75 samples were prepared for testing with Permetest. Out of this number, 45 Samples were prepared for spacer stitching with different stitch plate distances, 15 for conventional lockstitch and samples without stitch were prepared for three insulation materials.

<table>
<thead>
<tr>
<th>Insulation Material</th>
<th>HO-108 (Sample 1)</th>
<th>HO-168 (Sample 2)</th>
<th>HO-297 (Sample 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (mm)</td>
<td>24.0</td>
<td>23.0</td>
<td>21.0</td>
</tr>
<tr>
<td>Fabric Mass (g/m²)</td>
<td>200</td>
<td>200</td>
<td>150</td>
</tr>
<tr>
<td>Material (100%)</td>
<td>PES</td>
<td>PES</td>
<td>PES</td>
</tr>
</tbody>
</table>
3.1.2. Measurement and Results. In order to study the role of air entrapped, samples were tested in Permetest in three different compression states i.e. fully compressed, 50% compressed and uncompressed. These states of compressions were developed in combination to thickness of insulation materials and working principle of instrument. The instrument has a lever mechanism that moves testing diaphragm up and down. At first the samples were fully compressed between the movable lever and air flow chamber. The distance of movable measuring head was noted from base of instrument. After that the sample was placed in most uncompressed state possible in a way by making sure that the surrounding air do not get into instrument and disturbs the repeatable measurements. Again, the distance of moveable head was measured from instrument base. From these two values the 50% compression value was calculated by dividing the difference of distances in half. This process was repeated for other two insulation materials separately.

![Figure 4. Thermal resistance (mKm²/W) of sample 1 with Permetest](image)

The results for sample 1 are shown in Figure 4. The tendency of thermal resistance of samples is obvious from results. The tendency of results means that the thermal resistance of samples without stitch always showed the highest thermal resistance, because there were no cold spots present due to absence of any needle penetration. The results from lockstitch showed the worst thermal resistance as expected. The reason is the maximum compression of insulation material at the points of needle insertions by the tensions of needle and bobbin thread systems. The thermal resistance of samples of spacer stitching was in between the sample without stitch and the sample sewn with conventional lockstitch. This tendency of results was also followed by other two insulation materials used in sample 2 and sample 3 in similar pattern.
A gradual increase in thermal resistance was also observed in the samples of spacer stitching with increasing stitch plate distance. With the gradual increase in stitch plate distance the stitch height was increased and so did the amount of air present along stitch line. Therefore, a gradual increase of thermal resistance was observed during measurements. It was also observed that under increasing compression state of testing, the thermal resistance decreased for all of samples. The compression forces the trapped air to leave the structure of insulation material and increase the heat flow. The tendency of compression was similar for all samples sewn or unsewn.

It became obvious from the results of Permetest that the spacer stitching improves the thermal properties of any insulation materials as compared to conventional sewing technology of lockstitch. The results from Permetest were also used for the comparison thermal properties of insulation materials. This comparison of thermal resistance explains that under same testing conditions and sampling parameters for insulation material of sample 1, spacer stitching had shown an increase in thermal resistance of up to 14 % when compared with conventional lockstitch.

3.2. Sweat guard hot plate (Skin Model)

Skin model works as per DIN (BS) EN 31092 and ISO 11092. It is also known as “Sweat Guard Hot Plate”. This device measures thermal properties and water vapour resistance of fabrics and other materials under steady state conditions. Heat and mass transfer process which occurs next to human skin are simulated during the test [25]. A reliable test results require up to 2 hours for one sample.

3.2.1. Samples preparation. The insulation material of sample 1 was studied. The stitching parameters and textile materials mentioned before for Permetest were followed for sample preparation. A total of 15 samples were prepared and tested on Skin Model. The testing methodology was the same as used for testing with Permetest i.e. the samples prepared were divided in 3 categories. In the first category come the samples which are not sewn at all, followed by the sample prepared with conventional lockstitch and spacer stitching. Unlike Permetest where three different stitch plate distances were used, only one stitch plate distance of 11 mm for samples of spacer stitching was used. The dimension of samples prepared was 300 mm * 300 mm. The sample is placed in the testing equipment in free form without any external compressional load except its own weight of gravity.

3.2.2. Measurements and results. The tendency of test results can be seen clearly in results. The thermal resistance of samples without stitch has shown the best thermal resistance. They are followed by the samples sewn with spacer stitching. Conventional lockstitch has shown the least thermal resistance.

![Figure 5. Thermal resistance (Km²/W) of sample 1 with Skin Model](image-url)
3.3. X-ray Tomography

X-Ray computed tomography is a seldom used method for studying textile structures. It is mostly used to study the internal structure of nanomaterials and electronic circuits. The advantage of X-Ray tomography is that a complete 3D internal image of any object is obtained via X-Rays. The 3D data obtained by tomography can be analysed by various imaging software for further studies. At the Center of Micro technical Manufacturing of Technical University of Dresden the ‘Phoenix Nanotom m’ from GE was used for the study.

The sample is mounted on a rotating platform. On one side of this rotating platform is the X-Rays source and on the other side is the detector. When the measurements are started, the sample is rotated on 360° about a vertical axis. The testing time can range between 60 minutes to 240 minutes depending upon precision required.

3.3.1. Sample Preparation. In order to compare the internal structure of lockstitch with spacer stitching, two samples were prepared. In the tested sample the insulation material was 100% polyester, the fabric was polyester/cotton mix and the sewing thread was 100% cotton. Different material composition of sample is later helpful during image reconstruction and distinguishment between materials. The sample measurements are 85 mm*45 mm. The sample is not meant to move during image collection. For this purpose, a frame was printed by 3D printer that can clamp the sewing sample to mount it on the platform of the tomography equipment. The frame was designed in such a way that the insulation material is not compressed.

3.3.2. Measurement and results. After mounting the sewing sample on rotating stage, the recording with X-ray was carried out. The size of one pixel in the image was 10 µm. The equipment’s own imaging software was used to reconstruct the raw data images into a 3D structure. For further processing of images open source softwares from Volume Graphics and Image J were used. By adjusting the gray values obtained, a better contrast between different set of materials/construction was made.

![Figure 6. Cross-sectional view of lockstitch (left) and spacer stitching (right)](image)

The cross-sectional view in Figure 6 shows how much the insulating material is compressed in lockstitch (left) at the points of needle insertions. There is no textile or insulation material present but only the lock formed by two thread systems. Furthermore, apart from the point of two needle insertions, the material present between them is in considerable compact form. Due to this compression, the air pockets are reduced and material along the stitch line behaves more densely than the rest of sandwich structure. The increase in density and removal of air pockets along stitch line lead
to increased thermal conductivity and greater heat loss. The cross-sectional view of spacer stitching (right) indicates that the textile and insulation material are in far more uncompressed state and guarantee additional volume of air in its structure. The lock formed by needle and bobbin thread can be seen near the lower side of textile material.

With X-Ray tomography results, the air trapped even inside the cross-section of sewing thread and the fabric’s individual yarn can be seen. Therefore, a closer estimate of air volume existing in a unit stitch length is conceivable. To estimate the amount of air present in a unit stitch length of conventional lockstitch and spacer stitching, two dimensional images stack of top view of stitch were converted into binary images with the help of imaging software. The black pixels in the binary image mean the absence of material or the air present in material. The white pixels represent the material. This material can be the fabric, the insulation material or the sewing thread. A distance of 3 mm to either side of stitch perpendicular to the direction of stitch length is taken in study for calculation. It was observed that this 3 mm distance exhibits the most of compression. Beyond this distance, the effects of compressions start to diffuse.

![Figure 7. Substacks of lockstitch](image1)

![Figure 8. Substacks of spacer stitch](image2)

It is quite visible from the binary image in the middle of Figure 7 and Figure 8 that the numbers of white pixels are much more in conventional lockstitch than in spacer stitching. This shows that material density in lockstitch is greater than that of spacer stitch in a unit stitch length.

Each image was calculated on the basis of presence and absence of material. The imaging software calculates each pixel present in the 2D image stack one by one. The binary images results were later
combined to calculate the volume of air and material present in a three dimensional image. The conceptual illustration of this calculation process is shown in Figure 9.

![Material calculation for a binary image](image1.png)
![Addition of material calculations of binary images](image2.png)

**Figure 9.** Concept for air and material volume calculation along stitch line

A good insulating clothing system is based not simply on the thermal properties of the textile material, rather it’s the amount of air that it can encapsulate in its structure. The thermal conductivity of air is $0.025 \, Wm^{-1}K^{-1}$ which is 10-20 times less than any textile material [3], [6]. Therefore, the most important factor for maintaining the temperature of human body is the insulating air trapped in fabric and insulation material. The greater the volume of air trapped in its structure, the greater the thermal insulation can be achieved. The relatively uncomprssed stitch formation of spacer stitching offers lesser compression of insulation material and more volume of insulating air for improved thermal insulation. Good thermal insulation material is composed of 90-95 % of its volume of air, and very excellent ones can have more than 99 % of its volume of air in its structure [3].

With the help of imaging software, the volume percentage of material and air in a unit length of stitch was calculated and results are shown in Figure 10. Calculations from X-Ray tomography revealed that in the case of lockstitch, a unit stitch has a volume percentage of 15 % material and 85 % of the volume percentage made up by air. Here, the material includes the fabric layers, insulation material, and the sewing threads between the extreme layers of fabrics. In comparison, the spacer stitch with the same sewing and fabric parameters has volume percentage of material of 4.5 % and of 95.5 % air.

![Lockstitch](image3.png)  ![Spacer Stitch](image4.png)

**Figure 10.** Comparison of volume percentage distribution of air and material in a unit stitch length

### 4. Conclusion

The test samples of specimens without stitch, spacer stitching and conventional lockstitch are tested with different testing equipment and following findings are observed. Three different insulation
materials with three different raised stitch plate distances for spacer stitching were studied with \textit{Permetest}. The best results were achieved from the sample 1 along with a 1.1 cm raised stitch plate distance. Spacer stitch has shown 10-14\% better thermal resistance as compared to lockstitch samples.

Independent testing was carried out in TU Liberec on \textit{Sweat Guard Hot Plate (Skin Model)} and an improvement of 3.6\% thermal resistance is measured from lockstitch to spacer stitch was observed. The purpose of this study is not to compare the thermal resistance values from two different methods of \textit{Permetest} and \textit{Skin Model}, rather is to understand the tendency of results. The trend of results is clear that spacer stitching shows advantage over conventional lockstitch technology. Furthermore, the gradual increase in thermal resistance with increasing stitch plate distances validates that with more uncompressed stitch formation better thermal insulation is attained.

The results from X-Ray tomography give a very clear internal picture of conventional lockstitch and spacer stitch in a unit stitch length. The unit stitch in spacer stitching has up to 10\% more air volume present in its structure compared to lockstitch, when sewn under same conditions. More air volume in an insulation material pledges better thermal resistance.

In outdoor clothing, the insulation material is held along with textile materials with multiple stitch lines. The use of spacer stitching can improve the thermal insulation of products impressively. If one stitch line can improve the thermal resistance up to 14 \% as measured by \textit{Permetest} and 3.6\% by \textit{Skin Model}, more number of stitch lines can make a much greater difference. The invention can offer great prospective in industrial application of insulation. The technology can also be used for the development of advanced filtration processes. It may also be applied for the thermal protection of aircraft bodies. Spacer fabrics can also be sewn with the new technology without local compression to maximize product utilization for its desired final use. Some initial tests with spacer fabrics are by now being carried out with positive results. In the composite industry, spacer stitching can deliver positive results by reducing the localized compression problems in composite parts caused by sewing.

\textbf{Acknowledgment}

The author is grateful to Dr. Scharfenberger from Freudenberg Group, Mr. Oliver Albrecht from TU Dresden and Dr. Mazari from TU Liberec for their material and testing support.

\textbf{References}

[1] Byrne K \textit{Photographer Captures Stunning Scenes From Coldest Inhabited Place on Earth}
[9] Moriarty C 2013 \textit{Thermal insulation structure and producers made therefrom}
[16] Jerald W N 1990 Insulated sleeping bag
[18] Li Y L 2015 Insulating method and product
[19] MaSmallish C S 1934 Sealed quilted material
[21] Tesch G 1993 Quilted bed blanket
[22] Hes L Permetest Manual (Liberec)
[24] Prof. Lubos Hes, PhD. Ds Friendly testing of comfort parameters of functional garments and clothing and its use in marketing