Eco-intelligent monitoring for fouling detection in clean-in-place

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Abstract

Clean-in-place (CIP) is a widely used technique applied to clean industrial equipment without disassembly. Cleaning protocols are currently defined arbitrarily from offline measurements. This can lead to excessive resource (water and chemicals) consumption and downtime, further increasing environmental impacts. An optical monitoring system has been developed to assist eco-intelligent CIP process control and improve resource efficiency. The system includes a UV optical fouling monitor designed for real-time image acquisition and processing. The output of the monitoring is such that it can support further intelligent decision support tools for automatic cleaning assessment during CIP phases. This system reduces energy and water consumption, whilst minimising non-productive time: the largest economic cost for CIP.

1. Introduction

Food and drink production is the largest manufacturing sector within the UK and uses approximately 430 mega litres of water per day (1) equating to about 10% of all industrial water consumption. Additionally the industry is also the fourth highest industrial energy user in the UK, consuming 37 TWh with an associated 11 MT of CO_2 produced in 2010 (2).

Furthermore it is estimated that between 9 and 30% of the site energy used by a food processing plant is for cleaning (3,4), as reported in Fig. 1, whilst between 7 and 33% of a production site's water is utilised by the cleaning process (5,6). The usual procedure for cleaning equipment in the food industry is the Clean-in-Place (CIP) system that avoids the need for equipment disassembly.

CIP is a complex operation which typically involves a warm water rinse, washing with alkaline and/or acidic solution, and a clear rinse with warm water to flush out residual cleaning agents (7).

CIP is an important component in guaranteeing food safety in food processing plants. Successful cleaning between production runs avoids potential contamination and products that fail to meet quality standards. Carrying out CIP correctly – from design to validation – ensures secure barriers between food flows and cleaning chemical flows (8).

The current standard for CIP is not to utilise real time monitoring but to establish, during system commissioning, the worst case scenario for material fouling (e.g. material type, condition) and to determine, by invasive techniques, the appropriate time required to clean the system.

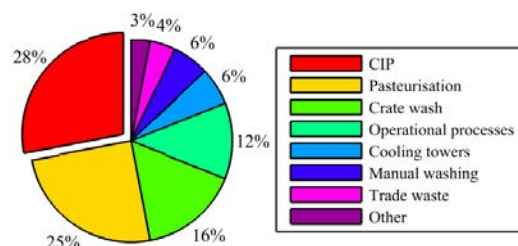This procedure is then routinely used for all CIP cycles,

Fig. 1.Water use of a milk processor (4)

regardless of actual fouling level. This precautionary approach results in systematic over-cleaning, which has considerable economic and environmental impact from excess water, cleaning chemicals and energy consumption during the cleaning process (9).

The purpose of this research is to establish the feasibility of an optical system for real-time surface fouling detection within openable components (i.e. tanks and vessels).

This paper undertakes a review of the state of the art on modern fouling detection methods.

The experimental setup of the optical system and the procedures for novel real-time CIP monitoring systems are described, along with the validation of the results in laboratory environment.

The paper concludes with a summary of discussions and implications for future of CIP.

2. Modern CIP

Cleaning food deposits, which contain both proteins and minerals, is a complex process that involves interactions between surface, deposits and detergent. It requires a multistage process, having many steps that may be controlled by shear stress, mass transfer, and chemical reaction (10). These cleaning stages can be described as follows:

- Diffusion of the cleaning solution from the bulk into deposit;
- Chemical reactions start and the deposited materials are broken;
- Dispersion of the deposit material into the cleaning solution by the shear action.

The most common CIP treatment is a two-stage process: a first stage using alkali (commonly NaOH) and second stage using acid base (nitric or phosphoric), usually separated by a water rinse step. The alkaline is used first to remove the protein and fat deposits and expose the thin minerals layer which is then dissolved by the acid step (11).

Since any cleaning time is downtime (i.e. non-productive time) it is also important that CIP is carried out effectively and efficiently, contributing to an overall low total cost of ownership.

Applying real time monitoring technologies represent some benefits such as reducing the amount of water which saves money in water supply charges of industry. In most cases, it will also have the effect of reducing the volume of wastewater discharge effluent, which will also reduce trade effluent charges. Savings in water are not the only benefit: for example the Carbon Trust reports that the UK brewing sector could save 4,600 tCO_2 (or 1% of total brewery sector carbon) by implementing real time cleaning verification systems (12,13). Such a monitoring technology would lead to an eco-efficiency improvement in industrial processes, reducing the consumption of resources, reducing the impacts on the natural environment, and increasing the product or service value (14).

Rapid *in situ* industrial methods for determining fouling levels in process equipment include Adenosine Triphosphate (ATP) swabs, which cause photoluminescence of protein and microbes, to determine cleanliness of tank/pipework inner surfaces.
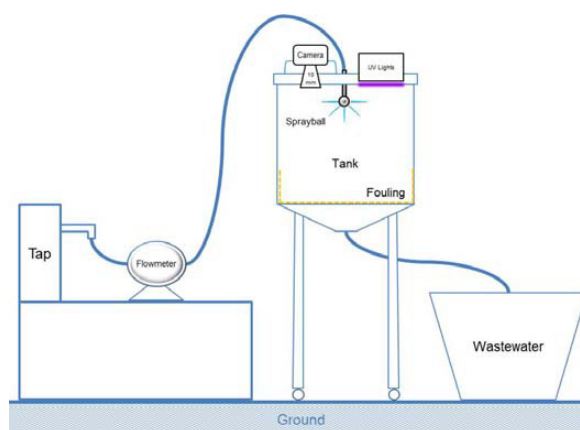

Fig.2. Experimental setup general scheme

Fig. 3. Methodology flow chart

This technique requires the system to be opened in several places where a swab is physically wiped over the inner surface which is time consuming, opens up the opportunity for contamination, introduces the risk of damage to the equipment, and requires a clean, before and after the procedure.

Alternatively, UV light detection methods, are particularly used for the detection of residual cells and soiling on industrial surfaces (15).

Microscopy *in vitro* methods include Scanning Electron Microscopy (SEM) (16), and Epifluorescent microscopy (17).

Optical methods have been used for the detection of food fouling: UV illumination is a widely recognised method for detecting food soil, with little change in findings when microorganisms are included. Performance can be improved in certain circumstances by altering the wavelength (15).UV light (353 nm) can also be used for the detection of residual cells and soiling on industrial surfaces (18). The molecular configuration of organic material allows some organic residues to fluoresce when illuminated by UV light (19). Thus, UV light may be used to detect residual soil when work surfaces are illuminated by an appropriate wavelength; highlighting areas in an industrial plant that need be cleaned more intensively. Unlike ATP bioluminescence, UV light detection methods do not require direct contact with the surface.

3. Experimental setup

In this work, an image based methodology for optical fouling detection has been developed. The methodology consists of 5 main steps as illustrated in Fig. 3.
Each step of this procedure is described in detail in this section, along with the description of the equipment utilised for the experimental campaign.

The purpose of the experimental campaign is to reproduce a CIP system in laboratory scale, in order to verify the capability of a monitoring system to detect surface fouling within the tank.

A stainless steel brewing tank, diameter 62 cm and a usable volume of 100 litres (Fig. 2) endowed with exit tap was used for the design and implementation of the proposed CIP monitoring system. The lid was modified in order to allow the installation of the sprayball, the camera and the UV lights set.

3.1. Fouling application

In order to carry out the experimental campaign it was necessary to produce artificial layers of fouling. Three different fouling agents were individually utilised for these experiments:

- A riboflavin solution in water (20) was prepared according to the following proportions: Riboflavin 0.2 g/l and dextrose: 40 g/l used to help the riboflavin bind to the tank surface. The quantity of riboflavin fouling applied was 80 ml for each test.
- Yoghurt: density = 1050 g/l, viscosity = 1100 mPa·s, amount of fouling for each test = 125 g.
- Vanilla flavoured ice cream: density = 548 g/l, viscosity = 300 mPa·s, amount of fouling for each test = 250 g.

For the present experimental procedure, without access to industrial scale processing of food products, a manual application method was used. Riboflavin, yoghurt and ice cream were placed inside of the tank and manually applied in the bottom and side surfaces, this in order to simulate actual conditions of a tank after a batch of industrial production .

3.2. Washing

In this experimental campaign, the washing cycles were carried out using a static SSH spray ball, with a 180° downward coverage. The spray ball was positioned in the tank lid and straightened so the water flow coming out covered the tank uniformly. Inlet and outlet water flows were measured using a Cole Palmer FR4L71BVBN – CP flowmeter.

Detergent was applied in the tank cleaning process using two different methods: a) introduction of the required quantity directly in to the wash water hose, and b) applying the detergent directly on to the surface inside of the tank where the fouling had been applied.

Considering the amount of fouling to apply in every test, the size and proportion of the tank and the water flow it was decided that 40 ml of detergent is a sufficient volume to be used within these experimented. The water temperature was set to 20°C for all the tests.

3.3. Image acquisition

For the acquisition of images, a Nikon D3100 digital camera and a set of 18 W 370 nm fluorescent UV lights were installed in the lid of the tank (Fig. 4)
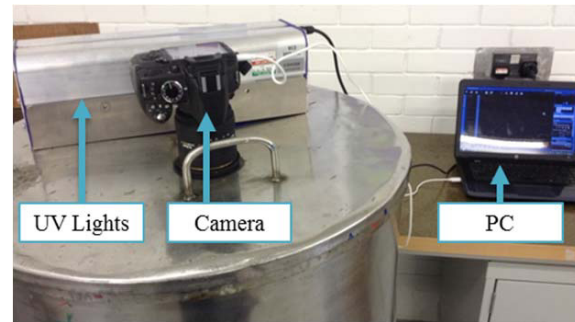

Fig. 4. Image acquisition system

The digital camera was placed with a 7° inclination angle to improve the field of view within the tank for its given geometry.

In order to maximise the tank surface included in a single image, a wide angle Sigma 10-20 mm zoom was used on the digital camera. Considering that the UV light set is the only source of light in the tank, it was not necessary to apply a UV filter on the lens. The campaign of experimental tests was carried out using a time-lapse technique.

Time-lapse photography is a technique whereby the frequency at which film frames are captured (the frame rate) is much lower than that used to view the sequence seconds (21). The digital camera was tethered to a computer using the digiCamControl software for the remote acquisition of images. This software allows the control of ISO, shutter speed, aperture, white balance, exposure, compression and metering mode, while acquiring digital images.

The time lapse tool was used during the experimental procedure for time lapse settings and for the numbers of images required in every time lapse.

4. Experimental programme

Clean-in-place process monitoring experiments were carried out according to the procedure described in this section. The duration of each test varies according to the level of cleaning detected, i.e. the tests end either when the tank results clean or when the washing no longer improves cleanliness.

Table 1. Experimental campaign programme

Test ID	Fouling Agent	Time lapse (s)	Water Flow (l/min)	Cleaning agent
R01	Riboflavin	5	8	Water
R02	Riboflavin	3	8	Water
R03	Riboflavin	3	8	Water
R04	Riboflavin	3	8	Water
Y01	Yoghurt	5	5	Water
Y02	Yoghurt	5	8	Water
Y03	Yoghurt	5	5/8	Water
Y04	Yoghurt	5	5/8	Water +Detergent
Y05	Yoghurt	5	5/8	Water +Detergent
Y06	Yoghurt	5	5/8	Water +Detergent
Y07	Yoghurt	5	5/8	Water +Detergent
I01	Ice Cream	3	5/2/8	Water
I02	Ice Cream	5	5/2	Water
I03	Ice Cream	5	5/8	Water +Detergent
I04	Ice Cream	5	5/2	Water +Detergent

Different values in the same water flow field for a test indicate a special input water flow configuration for the experiment. Detergent was applied through the input pipe, using 40 ml per test. Only in the Y05 test the same amount of detergent was applied directly on the inner surface of the tank before starting the washing cycle.

5. Image processing

The RGB image appears as a 4608 x 3072 x 3 elements matrix, where the first two dimensions (4608 x 3072) represent the image resolution, and the third dimension (3) is represented by the three colours channels red, green and blue respectively. An example of RGB image is reported in Fig 5.

Due to the reaction to the UV light, in the RGB image, the fouling appears as a series of cyan-like coloured stains (Fig. 5), while the tank surface is blue-purple. In order to isolate the fouling image, it was necessary to isolate the green channel (G) of the image, as reported in the image below.

After this transformation, the green channel image corresponds to a 4608x3072 matrix whose elements values range from 0 (black) to 255 (white) and it appears as a grayscale image (see Fig. 6). The RGB to grayscale transformation allows the visualisation of the fouling on the tank surface.

In order to be able to quantify the amount of fouling and its removal rate over time, it is necessary to transform the grayscale image into a black and white (BW) image.

This transformation requires the computation of the global threshold which was computed according to the Otsu's method [20] which chooses the threshold to minimise the infraclass variance of the black and white pixels.

The output binary BW image replaces all pixels in the input image with luminance greater than the threshold with the value 1 (white) and replaces all other pixels with the value 0 (black). An example of a BW image is reported in Fig. 7.

After this transformation, the fouling is represented by the black pixels while the background is white.

The total amount of detectable surface fouling can be then computed by summing all the black pixels within each image. On the other hand, white pixels show that the fouling is below the detection level. In order to establish whether the non-detected fouling is below the cleanliness threshold, an investigation correlating the output of the optical detection system with industry standard for cleaning detection through the ATP swabbing technique is required.

The detection capability is influenced by the following parameters: lens characteristics, camera resolution, fouling thickness and light set characteristics. In order to correlate the size of the stains on the digital image to the real size of the stains in the tank, an experimental test was carried out. A series of eight UV fluorescent calibrated samples of 1 cm^2 each were placed in different positions within the tank.

An image was acquired in order to measure the extension in pixel of the pieces of paper. For this work, the value of 2000 pixel has been chosen for 1 cm^2 of fouling. This implies that, for the current configuration, the sensitivity of the system, being 1 pixel corresponds to 0.05 mm^2 of surface fouling.
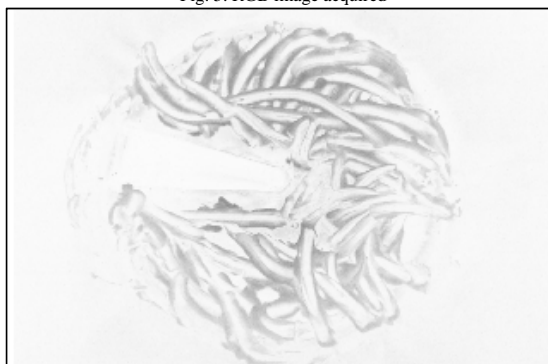

Fig. 5. RGB image acquired

Fig. 6. Green channel grayscale representation

Fig. 7. BW image

6. Results and discussion

In this section, an instance of Riboflavin, Yoghurt and Ice cream tests results is illustrated in terms of test specifications and a chart reporting surface fouling level and water flow vs time.

6.1. Riboflavin tests

The experimental and the image acquisition parameters are reported in Table 2. Water flow was set to 8.0 l/min during the experiment with the exit tap of the tank wide open during the whole washing cycle.

An initial variation in the amount of fouling can be seen in the first 12 seconds of the test, this is due to the low viscosity of the Riboflavin solution.

Table 2. Test R03 specifications

Parameter		Value
Test ID		R03
Fouling agent		Riboflavin
Fouling quantity		80 ml
Water Temperature		20 °C
Detergent		None
Camera configuration	Exposure	1/100 sec.
	F-stop	f/4
	ISO	1600
	White balance	Manual
	Time Lapse	3 s

Table 3. Test Y03 specifications

Parameter		Value
Test ID		Y03
Fouling agent		Yoghurt
Fouling quantity		125 g
Water Temperature		20 °C
Detergent		None
Camera configuration	Exposure	1/80 sec.
	F-stop	f/4
	ISO	3200
	White balance	Manual
	Time Lapse	5 s

Table 4. Test I02 specifications

Parameter		Value
Test ID		Ice cream
Fouling agent		250 g
Fouling quantity		125 g
Water Temperature		20 °C
Detergent		None
Camera configuration	Exposure	1/100 sec.
	F-stop	f/4
	ISO	6400
	White balance	Manual
	Time Lapse	5 s

Fig. 8. Fouling removal in test R03

Fig. 9. Fouling removal in test Y03

Fig. 10. Fouling removal in test I02

Fig. 8 illustrates the results of the test R03. As soon as the washing cycle starts (12-15 s), the apparent surface fouling value increases, this is due to the water flow which removes part of the fouling allowing it to float on the water surface since the inlet flow (8.0 l/min) is higher than the drain flow (2.0 l/min).As the washing cycle continues, the amount of surface fouling decreases as it is drained, and after 33 seconds, the tank results appear clean according to the system sensitivity.

6.2. Yoghurt tests

The experimental and the image acquisition parameters are reported in Table 3.Water flow was set to 8.0 l/min during the experiment with the exit tap of the tank wide open during the whole cycle. Fig. 9 illustrates the results of the test Y03.

As soon as the washing cycle starts (8-10 s), the apparent surface fouling value increases, this is due to the water flow which removes part of the fouling allowing it to float on the water surface since the inlet flow (8 l/min) is higher than the drain flow (2.0 l/min).The asymptotic trend of the fouling around 50 cm^2 visible toward the end of the test highlights that the cleaning process was not completely successful. This was attributed to the irregular tank bottom surface which presents some crevices in which the residual yoghurt is not removed by the spray ball.
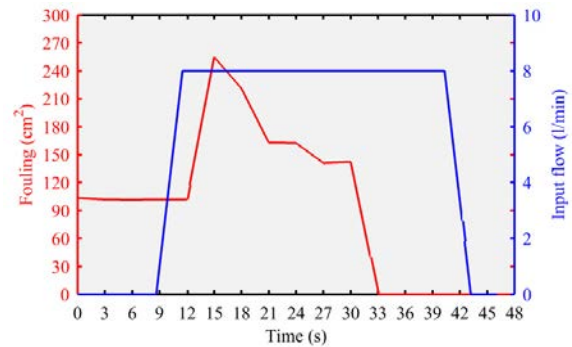
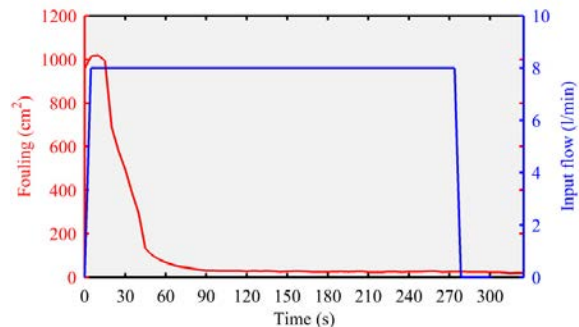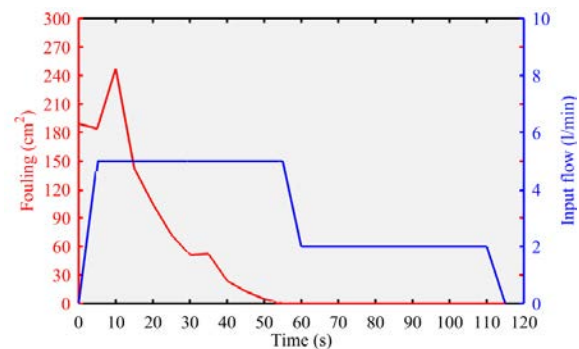Moreover the yogurt has a higher viscosity (1100 mPa·s) and it makes its removal more difficult when constrained in crevices and cracks.

6.3. Ice cream tests

The experimental and the image acquisition parameters are reported in Table 4. Water flow was set to 5.0 l/min for 70 seconds then decreased to 2.0 l/min for the rest of the test. During the experiment with the exit tap of the tank wide open during the whole washing cycle.

Fig. 10 illustrates the results of the test I02. In the first 10 seconds of the washing cycle the apparent surface fouling value rapidly increases, again due to the water flow which removes part of the fouling allowing it to float on the water surface since the inlet flow (5.0 l/min) is higher than the drain

flow (2.0 l/min). As the washing cycle continues, the fouling amount decreases until it reaches zero shortly before 60 seconds. In this case, the tank results clean to the sensitivity of the system.

7. Conclusions

This paper proofs the concept of evaluating the detection system rather than the effectiveness of CIP. An optical monitoring system was set up in order to detect in real-time various types of surface fouling within a stainless steel tank. An image acquisition system endowed with wide zoom camera and UV lights set was built to acquire digital images inside the tank. An image processing methodology was developed to assess the level of detectable fouling at a certain sampling rate.

Results show that it was possible to detect in real time the gradual reduction of surface fouling within openable components via non-invasive optical monitoring system. The resulting benefits include a more efficient and effective resource usage such as water, energy and time.

In future work, the detection system outputs can be inputted to an intelligent decision support system for a more advanced assessment of the cleaning process in terms of self-adaptation of washing parameters.

The sensitivity of the system can be improved by working on two aspects:

- Improving the image acquisition unit: specifically, a high performance camera with higher definition optics can result in more precise measurements. Moreover, further studies will be carried out on the image resolution, which, if reduced can decrease significantly the computation time.
- Light source: diverse fouling types can have different response to different wavelength. A specific wavelength, therefore, will maximise the fouling fluorescence and facilitate the detection.

During the experiments, issues with tank walls and irregular shape of tank were encountered. Regular and smooth surfaces can increase the detectability of fouling

The optical monitoring system described in this paper can be successfully implemented on openable components, while it is not suitable for non openable components such as pipeworks, heat exchangers and valves, for which a sensor fusion approach is requested.

Acknowledgements

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