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FOLLOWING THE INTERACTIONS ON THE INNER SURFACE – A STEP TOWARDS FOULING MONITORING

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ABSTRACT

The present work exploits the ability of the Surface Sensor technology to follow the interactions that occurs in the inner surface of the monitoring tubing. Based on the same technology two different tools, resultant from a redesigned and improvement of former versions, and their outputs are discussed. The Diveil Surface Sensor for cooling water treatment processes which has an innovative heating system that creates a heating flux between the bulk fluid and the system wall. It was successfully applied to fouling and cleaning monitoring processes. The Diveil Surface Sensor for quality and process control is highly sensitive version of the technology, which was able to identify differently structured fluids and their cleaning procedures, as well as to quantify the concentration of food oil in hexane.

INTRODUCTION

Biofouling is a ubiquitous problem for aqueous systems and environments! The impossibility to eradicate this phenomenon, demands that the focus should be on its minimization strategies.

Currently a special emphasis is given to the role of biofouling monitoring strategies, which can provide information about the attached layer from earlier stages of formation. An on-line, real-time, non-destructive information about the fouling severity within the process systems, can lead to the implementation of timely, pro-active and adjusted counter-measures and to the assessment (also in real-time) about the efficacy of those actions (Flemming, 2003).

There are several monitoring techniques described in literature (Jancknecht and Melo 2003, Pereira et al, 2009b), but only a small number of them are suited for industrial application. Indeed, the standard methods to monitor biofouling build-up/ removal are still based on the assessment of thermal performance or pressure drop across the processing plants.

A different or complementary (depending on the process) question importance of monitoring tools for online, real-time techniques of product changeover time, can also be a key point to optimize production/ cleaning cycles and in some cases to establish a pre-quality control procedure (Wilson 2005). In some industrial areas, like the ones which deals with non-Newtonian, viscous fluids, monitoring techniques which are able to quantitatively determine the interactions between the fluid and the solid structure (where the fluid flows) can be used as research laboratory tools for the study of cleaning procedures.

The present paper addresses the question of online, real-time monitoring, to assess fouling formation/ removal and to provide information and characterization of the bulk fluids. The results for fouling build-up/removal obtained with the redesigned Diveil Surface Sensor, in laboratory fields will be discussed. Furthermore, it will be demonstrated that based on the Surface Sensor technology, it is possible to identify differently structured fluids (like dish washing liquids) as well as follow their cleaning behavior and quantify concentrations of food oil in hexane, during food oil extraction processes.

BODY

Within the last few years, the technological background behind the laboratorial concept of the Mechatronic Surface Sensor (Pereira et al, 2008, Pereira et al., 2009a, c) – has been redesigned in order to meet some of the most important requirements of an industrial monitoring device for cooling water system. Different analytical parameters have been studied and implemented in order to assess the bulk fluid properties in quality and control operations.

The Diveil Surface Sensor (DSS) includes an actuator (which stimulates the monitoring surface and makes it vibrate) and a sensor, responsible to capture the system vibrating response. The idea behind the Surface Sensor technology is that interactions occurred on the inner surface changes the vibration characteristics of the acoustic wave propagated along this monitoring tubing.

Further information on the functioning principle behind the Surface Sensor technology can be found in Pereira, et.al (2006, 2008, 2009 a, c).

a) Cooling Water Monitoring

The Diveil Surface Sensor for Cooling water systems (DSS_CWT) reflects, major developments, mainly related with the geometry (the laboratorial flow-cell has been replaced by a ½'' Stainless Steel tubing) and with the integration of a heating source system, which creates a heat flux between the bulk fluid and the surface wall, simulating the thermal conditions of the heat exchanger (similar hydrodynamic conditions are also set). The system has the opportunity to operate with or without the heating source, concerning the requirements of the overall process.

The DSS_CWT has a recirculation ring which includes the Sensor Tubing (the piece of Stainless Steel tubing where the sensor and actuator are attached to and the place where the fouling attachment/ removal occurs), a set of instrumentation (bulk and wall temperature measurement, flow meter, heating source system), a recirculation pump and the electronics – see Figure 1.

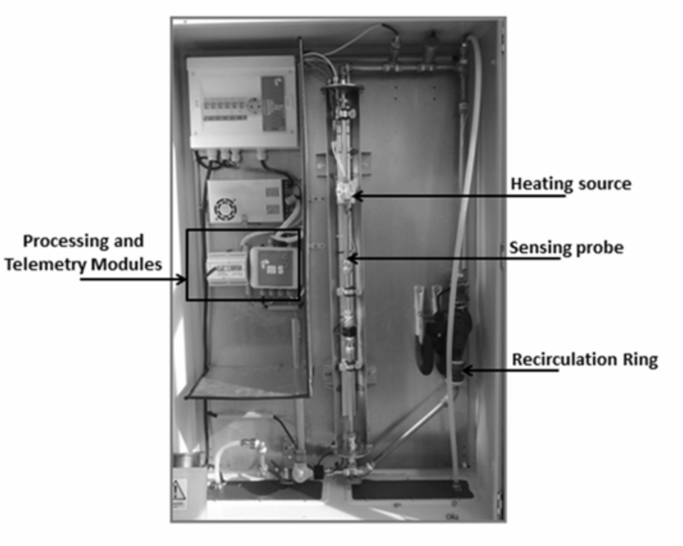

Fig 1: photography of the DSS_CWT system

The whole system, is controlled by dedicated electronics modules which are responsible for: a) performing the actuation of the monitored surface and collect the vibration response to that actuation (output wave); b) mathematically process the output wave and provide the result; c) control the temperature within the recirculation ring (after achieving a given wall temperature the water is blow-down, allowing the entrance of fresh water/ solutions); d) the acquired data, including temperatures and flow rates, is available at a web based platform, specific design to interact and present information about DSS_CWT system.

The DSS_CWT has been laboratory and industrially tested, however only the laboratorial results will be discussed. In laboratorial experiments fouling from Simulated Milk Ultrafiltration solutions (SMUF) has been induced on the monitored surface. In the recirculation ring (parallel to the Sensor Tubing), a set of 4 coupons (also made of Stainless Steel and with ½'' diameter) was included and used to assess the fouling quantity.

The first set of tests included the evaluation of the DSS_CWT output signal over time, at different experimental conditions: SMUF precipitation, water recirculation, SMUF precipitation, water recirculation and cleaning with Nitric acid at 0.5%.

The second set of trials comprised similar fouling formation experiments with SMUF, which has been carried out and stopped at different times, after the addition of the foulant solution (this corresponds to different stages of fouling formation, based on the information gathered in the first set of lab trials). At the end of each experiment the coupons have been removed from the experimental rig and the dry mass per unit of area have been determined. The output signal of the DSS_CWT at the stoppage point has been related with the average value of the dry mass determined in the coupons.

The operational conditions of the two set of experiment previously described has been carried out at the following average values: a) wall temperature: 55 ºC; b) bulk temperature: 40 ºC; c) flow velocity: 0.5 m/s (turbulent flow); d) retention time within the recirculation ring: 10 minutes.

b) Quality and Process Control

A different setup and mathematical approach has been implemented in order to evaluate if the Surface Sensor technology is able to distinguish different products or products concentrations during production cycles. The Diveil Surface Sensor for quality and process control (DSS_QPC) configuration is much simpler than the DSS_CWT one. It basically consists of the Sensor Tubing, and instrumentation for bulk temperature and flow measurement. Besides the physical constraints inherent to this new configuration, it takes advantage of an innovative mathematical procedure, which increases the system sensitivity regarding the interactions at the monitored surface.

These trials have been done in laboratorial scale, and consist on monitoring the DSS output signal for different tested fluids.

Within the scope of quality and process control the DSS output response has been monitored in two distinct 'processes', in order to evaluate the ability to:

i) distinguish differently structured dish washing liquids and water. Two differently structured dish washing liquids (commercially available at supermarket) have been tested. Each of these fluids have been pumped to the DSS_QPC system with a peristaltic pump (flow velocity: 0.003 m/s (laminar regime); T: 23 ºC), let to recirculate for 3 h, and then cleaned with water at 55 ºC (until the standard DSS value for water was achieved). The DSS_QPC output response for each of the fluids corresponds to an average value of the 4 runs, with 12 measurements each. In spite of the goal for this trial, the cleaning procedure for one of the tested liquids has also been monitored.

ii) determine the concentration of food oil in hexane. The main goal of this trial is to determine a relation between the DSS_QPC output response and the fraction of food oil in hexane. A similar procedure to the one described in i) was implemented. The solutions with different concentrations of food oil have been (randomly) pumped to the DSS_QPC system. During the recirculation period the output response of the DSS was measured. Between each fluid run, the system was cleaned with water at 55 ºC. The output response is the average value of 4 runs, with 12 measurements each.

The two approaches described in sections a) and b) reflect the effort to, based on a same technological principle monitor different processes – fouling/ cleaning and bulk fluid properties. The mathematical processes implemented in the DSS_CWT and in the DSS_QPC lead to different parameters, respectively the Normalized Amplitude and the DSS output response. These two parameters represent different physical measurements at the monitored surface, and being so, they are not inter-related.

RESULTS AND DISCUSSION

1. Monitoring Cooling Water Processes

Mineral fouling formation and removal was assessed with the DSS_CWT. Figure 2, shows the output response of this monitoring device to the different, and sequential, fouling conditions. The experimental procedure started with the establishment of the signal baseline for the clean system (water – period between 0 and 30 h). The addition of Simulated Milk Ultrafiltrate solution – SMUF (which resembles the mineral composition of milk), produces an increase on the Normalized Amplitude for an average value of 0.012 V. Changing the SMUF solutions by water, the DSS_CWT signal decreased and reached an average value of 0.005 V, indicating some removal of the attached layer. Between hour 70 and 75 a new increase on the DSS_CWT output response was observed, due to the second precipitation with SMUF, reaching a similar value to the one observed on the first precipitation. The addition of HNO_3, removed the attached layer of deposit and the signal started to decrease. The ultimate values for water (after cleaning procedure) are similar to the ones obtained for the clean state conditions. The cleaning condition was determined at the end of the experiment, by weighing the coupons and determining the dry mass which was 0.4 mg/cm^2.

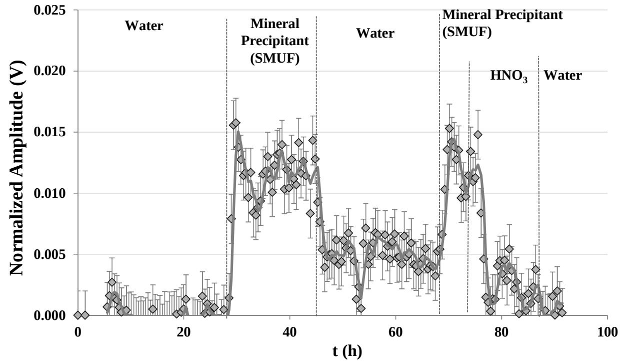

Fig 2: evolution of the DSS_CWT output response (Normalized Amplitude) over time, for different fouling layers (experimental conditions - Wall temperature: 55 ºC, Bulk temperature: 40 ºC, flow velocity: 0.5 m/s)

In order to assess the impact of the deposit formed during SMUF precipitation, different runs have been carried out and stopped at different Normalized Amplitudes, after which the coupons dry mass was determined. Figure 3 shows the variation of the Normalized Amplitude with the amount of SMUF. It can be seen that a very good relation between this two parameter was found (with a correlation coefficient higher than 0.97), and that, for this range of Normalized Amplitude the maximum dry mass is 4 mg/ cm^2. This confirms the data obtained by Pereira et al. (2006), where the authors found, for the flow cell system, dry masses ranging of 2.8 mg/cm^2 for similar Normalized Amplitudes. The main differences observed on the output results rely on the fact that in the DSS_CWT system, the SMUF precipitation reached very fast a constant plateau (in about 1 hour). It seems that this fact might be related with the experimental procedure of the SMUF recirculation ring, which enters (each 10 minutes) at 23 ºC and it heated to until 40 ºC bulk temperature and 55 ºC skin temperature.

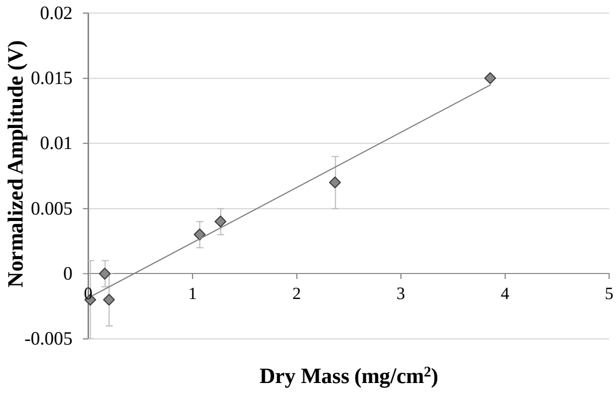

Fig 3: Normalized Amplitude variation with SMUF deposits dry masses

Additionally, the impact of the bulk fluid (water *vs* SMUF solution) on the systems response has been determined. No impact on the Normalized Amplitude was observed when the bulk fluid changed from water to SMUF or vice-versa (for T: 23 ºC).

2. Quality and Process Monitoring

2.1 Distinction between differently structured fluids (Dish Washing Liquids)

With the purpose of evaluating the ability of the Diveil Surface Sensor for Quality and Process Control monitoring (DSS_QPC) system to distinguish differently structured fluids and confirm the new mathematical processing approach, some experiments have been carried out with two dish washing liquids, commercially available (the information about the structural difference between the tested solutions was provided by the manufacturer). The DSS_QPC output response was compared for water and the dish washing liquids – DWL_A and DWL_B - see Figure 4.

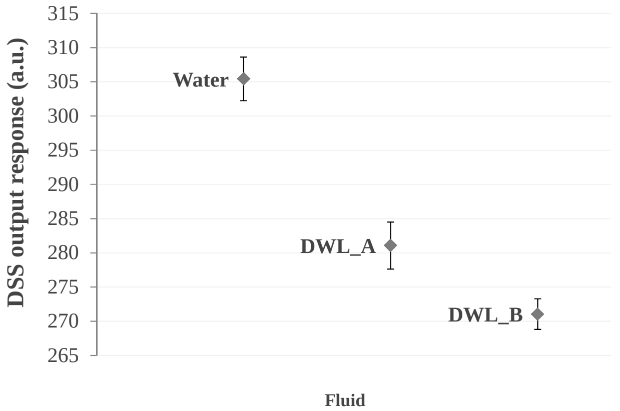

Fig 4: Impact of different fluids (water, two different dish washing liquids – DWL_A and DWL_B) on the DSS output response

These results indicate that the 3 tested fluids have different impact on the vibration of the overall system, enabling from the analysis of the DSS output signal, to distinguish between water and the dish washing liquids, as well as to distinguish between the two DLW. The points and error bars represented in Figure 4, corresponds to the average value and standard deviation of 48 measurements (4 runs with 12 points) of the DSS output response.

2.2 Monitoring cleaning of Dish Washing liquid

Based on the results found in section 2.1, where the DSS output response is clearly different for water and the Dish washing liquids, the cleaning procedure of the DWL_A was monitored over time – Figure 5.

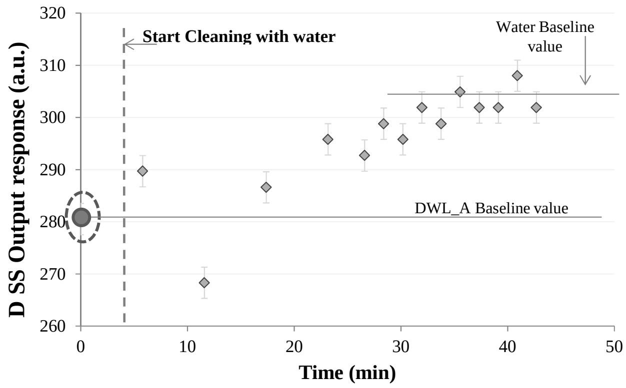

Fig 5: cleaning curve of the DWL A with water at 55 ºC, assessed with the DSS_QPC (DSS Output response)

The DSS output response starts at 280, which is the specific response for the DWL_A. When the cleaning procedure started, the DSS output response shows a non-linear behavior (until time ~ 18 min) which reflects the removal of the bulk fluid. When the DWL_A starts to be removed from the monitored surface (after 18 min) the DSS output response increased towards the water baseline value (~305). This period between 18 min and 40 minutes, corresponds to the removal/ dissolution of the thin layer of DWL_A still present in the inner surface of the tubing. The final values correspond to the water baseline value ~305, which is the output value for the system clean state.

The cleaning curve shown in Figure 5 reflects the correction of the DSS output response for a temperature of 23 ºC. This correction was based on the prior determination of the impact of the temperature on the systems response (the DSS output response showed a linear relation with the temperature).

The ability of the DSS_QPC to distinguish differently structured fluids, even between Newtonian (like water) and non-Newtonian fluids (like the Dish Washing liquids) was confirmed. This output is very important not only for quality assessment during production cycles (of a vast range of fluids), but also as a research tool. In this latter area, some preliminary trials are being carried out in order to find out which rheological (or other) parameter affects the vibration characteristics of the monitoring system, in each specific circumstance.

2.3 Quantification of food oil in hexane fractions

With the aim of determining online, and in real-time different fractions of food oil in hexane (during the extraction process), solutions with different concentrations of food oil in hexane, was let to recirculate in the DSS_QPC.

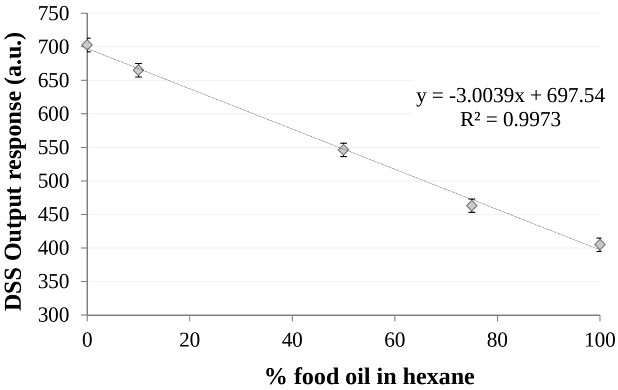

Fig 6: variation of the DSS Output response with different concentration of food oil in hexane

This study is a part of a collaboration work with a food oil producer company, in order to implement the DSS_QPC product in real industrial facilities, to evaluate and optimize the extension of food oil extraction processes.

Figure 6 shows a very good relation between the DSS output signal and the concentration of food oil in hexane. The high correlation coefficient (~ 0.99) between the two variable, as well as the very low standard deviation observed for each average point (both of these measurements include 48 points - 4 runs with 12 acquisition each) demonstrates the potentialities of the DSS_QPC to follow online and in real-time the extraction process of food oil with hexane. The data obtained in this trial points out that the DSS_QPC is able to provide information about the fraction of food oil in hexane with an error inferior of 1.8% of such concentrations.

Additionally, when comparing the DSS output response for the different experiments carried out with the DSS_QPC it is possible to conclude that all the tested fluids/ solutions are distinguishable between themselves: DWL B ~ 270, DWL A ~ 280, water ~ 305 (all in Fig 4), Food oil ~ 400 and Hexane ~700 (the former two in Fig 6). Just for clarification, the water baseline has also been used to assess the cleaning of the system, when cleaning the solutions tested in section 2.3. The baseline for water was in all of the experiments ~305.

CONCLUSIONS

The question of generating valuable information on-line and real-time about fouling formation/ cleaning processes and about the characterization/ quantification of bulk fluids has been addressed on the present work.

The Diveil Surface Sensor, is an online monitoring technology which is able to follow the interactions between the deposit layers or the bulk fluid that occur on the inner surface of the monitoring system. Those interactions change the vibration properties of the acoustic wave propagated along such system.

The redesigned Diveil Surface Sensor has been successfully tested for fouling and cleaning online, real-time monitoring processes. Furthermore, it was demonstrated the potential of the technology for Quality and Process Control, through the identification of differently structured fluids (Dish washing liquids, water, hexane and food oil), and for quantitatively determine the concentration of food oil in hexane.

The DSS for Quality and Process Control can be an important tool for the optimization of the production and of the cleaning cycles, by providing on-line real-time information about such procedures.

NOMENCLATURE

DSS – Diveil Surface Sensor;
DSS_CWT – Diveil Surface Sensor for cooling water systems;
DSS_QPC – Diveil Surface Sensor for quality and process control;
DWL – Dish washing liquids

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