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Clean or not clean - Detecting fouling in heat exchangers

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Abstract:
Fouling describes unwanted deposits on heat transferring surfaces leading to reduced heat transfer and increased heat transfer resistance. Hence, fouling is a severe issue particularly in food processing because product quality and safety cannot be ensured, and plant efficiency is reduced. As a result, cleaning is performed which limits processing time and increases plant downtime as well as costs because usually it cannot be adapted to amount and type of fouling present. Monitoring of cleaning and fouling requires high demands for measuring and analysing systems in heat exchangers being closed systems. A short overview is given over different monitoring methods in heat exchangers which can be applied both for fouling detection and cleaning supervision and, in a next step, adaption. Several experimental (pressure drop, temperature, heat transfer parameters, electrical parameters, acoustics) and computational methods are presented and compared. Primary focus of presented methods is acoustic methods.

Key words: Fouling, monitoring methods, heat exchangers, cleaning supervision

Introduction

Monitoring of processes is common practice to ensure product safety and to minimse risks. Monitoring of fouling in heat exchangers is a demanding task because fouling occurs in a closed system (heat exchanger) and cannot be easily detected. Fouling in food processing resembles unwanted deposits which decrease heat transfer to product and increase costs due to product loss and cleaning. Cleaning is necessary and usually designed for the worst case. It cannot easily be adapted to fouling type/amount present.

To improve understanding of fouling different models were developed where [1] gives an overview. Also, a huge amount of different methods were developed to detect fouling and, in a next step, to monitor its cleaning success. An overview over selected experimental and numerical methods is given here. This overview is not comprehensive.

Fouling

Fouling is classified into different types from which in dairy industry chemical reaction fouling at pasteurization temperatures and scaling at ultra-high temperature processing occurs mainly. First is often classified as type A or protein fouling and consists mainly of proteins (β-lactoglobulin), later is named type B or mineral fouling and is mainly made of salts [2, 3, 4]. Because processing of safe dairy products is diminished due to fouling cleaning is conducted to ensure a safe product [5].

Pressure Drop

Pressure is measured between inlet and outlet of a heat exchanger and monitored regularly. Fouling reduces the mean square area of a flow channel and introduces a pressure drop at constant flow rate. Pressure measurements are standard and can be used as input parameters for methods e.g. based on neural networks for fouling detection [6]. Pressure drop is often combined with temperature and heat transfer. Unfortunately pressure drop is not sensitive to thin fouling layers and only averages over the whole heat exchanger i.e. exact place of fouling is unknown.

Temperature and Heat Transfer Parameters

Product temperature at inlet and outlet, respectively, is measured to monitor success of process, e.g. if pasteurization temperatures were reached. Fouling introduces an increased heat transfer resistance and thus leads to reduced heat transfer to the product. Necessary temperature for safe product cannot be ensured anymore. Often, outlet temperature is fixed and heating temperature is increased automatically if outlet temperature decreases. This can be used for determination of fouling presence but has the same drawbacks as pressure drop.

Temperature can be used for monitoring fouling and estimating fouling development in heat exchangers [7, 5] or to develop computational models for controlling milk sterilization [8]. Also other parameters like heat transfer coefficient, heat flux, or thermal resistance can be used. For this, either calculations are done with measured temperature and pressure data or heat flux sensors are applied [9, 10]. Not only heat transfer can be monitored but also fouling thickness can be determined directly using a transient fouling probe which compared heat exchangers under fouling and no fouling conditions [11].

Electrical Parameters

Electrical parameters can only be used when electric heating is applied. This is often not the case yet in laboratory scale these parameters showed to be very sensitive to very thin fouling layers even if implanting electrodes is invasive. Usually electrical resistance and/or conductivity are used or temperature/power consumption of heating electrode is monitored. [12] for example developed a sensitive method which linked electrical and thermal resistance (heat flux) see eq. (1) with a, b as constants.

$$R_{th} = aR_{el} + bR_{el}^2 \qquad (1)$$

Electrodes measured electrical resistance and thermal resistance was determined using a heat flux sensor and temperatures at backside of fouled wall and fluid bulk temperature. Fouling build-up as well as cleaning could be monitored with high sensitivity.

Growth rate of fouling and reversely cleaning success can be monitored using electrical conductivity [13]. Here, influence of Reynolds number and calcium concentration of whey protein concentrate could be linked with structure and volume of fouling layer via deposit electrical conductivity. These results helped to understand bad cleaning success because cleaning agent could not penetrate fouling layer sufficiently if layer structure was very tense.

Using ohmic heating fouling was found to introduce not only a thermal resistance but also an electrical resistance [14]. This resistance leads to increased energy consumption due to energy dissipation. Fouling and non-fouling fluids differ significantly due to this extra resistance. Temperature of electrode increases due to energy dissipation and can be used for monitoring fouling and cleaning.

Acoustic Methods

Many different acoustic parameters can be used for monitoring fouling and cleaning success. Here, ultrasonic and vibrational methods, guided waves, and Quartz microbalances are presented.

Ultrasonic and vibrational methods are often focused on time of flight measurements and the determination of signal amplitude and its temporal behaviour (damping, eq. (2)).

$$A(t) = A_0 \exp(-\alpha x) \qquad (2)$$

Also, characteristic acoustic impedance can be used. Different acoustic and signal parameters from ultrasonic signals of a piezoceramic were combined in an artificial neural network and a support vector machine. Fouling was determined and cleaning success was monitored [15]. Thereby cleaning time could be shortened which was confirmed by experimental results.

Nano- and microvibrations were excited by a piezoceramic and measured an acceleration sensor and used as mechatronic surface sensor monitors signal amplitude [16, 17]. Damping factor varied with elasticity of fouling which makes it possible to distinguish between different fouling kinds. Besides, cleaning of hair shampoo was monitored and determined cleaning end was validated with different visual inspection methods. Cleaning was successfully determined even when different cleaning procedures were used.

Acoustic methods based on piezoceramics can easily be adapted to different heat exchanger geometries non-invasively. Yet, temperature compensation has to be undertaken and only punctual investigations can be made if not several actuators at different places are combined.

Quartz crystal microbalances (QCM) are very sensitive to very thin layers and also to different fouling build-up but are invasive, sensitive to temperature, and also only punctual. QCM is based on the quartz oscillator principle where resonance frequency f changes dependent on deposited material mass m, see eq. (3).

$$\Delta m = S \Delta f \qquad (3)$$

Even though QCM is not as easily attached to already existing heat exchangers it can be used for monitoring removal of β-lactoglobulin [18]. Differences between different fouling layers dependent on used foulant were found.

Also, energy dissipation can be monitored (QCM-D) where dissipation is related with rigidity of layer. This can be used for monitoring the adsorption process of β-lactoglobulin on surfaces which may help to develop fouling models and to understand fouling removal [19].

Frequency changes were dependent on pH and protein concentration whereas dissipation and visco-elastic behavior depended only on protein concentration.

In contrast to already presented methods guided waves travel along a structure and not through it. They can easily used non-invasively but may give only an overall overview. Fouling could be successfully monitored in tubes using Crisco vegetable oil as foulant [20]. Amplitude drop was determined and found to be independent on load behind fouling layer (water, air). Non-leakage waves were used.

Fouling causes non-stationary distortion which can be detected using wavelet transform for analysis [21]. Tubes became non-homogeneous due to fouling which caused a decrease in energy spectrum due to signal leakage into the fouling layer. This can be in principle also be used to determine cleaning success.

Computational and Numerical Methods

Computational and numerical methods can be used to determine and estimate fouling in heat exchangers and also to adapt heat exchangers better. Advantageous of these methods is that they can use already measured parameters, easily updated during process time if applied online, and be very sensitive if appropriate features and models are used. However ill-chosen features or models may give false results and validation with experimental methods has to be done first.

Fouling in a cross-flow heat exchanger can be detected offline modeling temperatures and mass flow rate [22]. For this Kalman filtering was used to determine model parameters. Fouling determination was found to be reasonable and consistent.

Combining experimental results (features were heat flux and Ca_4SO concentration) and artificial neural networks (ANN) initial fouling deposition under pool boiling conditions were investigated [23]. The ANN could determine the experimental determined results with high accuracy where higher heat fluxes led to higher accuracies.

Summary

Different methods for detecting and modeling fouling in heat exchangers were presented. Most experimental methods can also be used for monitoring cleaning success making them very interesting for different applications. Dependent on process and requirements different methods may have more advantages than others and have to be chosen accordingly.

One single method covering all needs seems to be implausible because combining different methods and switching between them is more practical. Objectives for using different methods may be beside others:

- Determining exact place of fouling.
- Determining exact amount/thickness of fouling.
- Determining only overall values (is fouling present or absent).
- Monitoring and adapting cleaning processes (cleaning has to be conducted for what time).
- Monitoring fouling development (starting/when is it gone, i.e. successful cleaning).

Combining different methods enhances detection stability and objectives will be more easily reached. Thus, first objectives have to be defined, limits of methods and processing parameters have to be known.

Industry requires non-invasive, fast, reliable, robust, and reasonable methods. Most presented methods do not fulfill all of these requirements but only some, e.g. being very sensitive but invasive or being already used but being not very sensitive. Also, combination of different methods will increase reaching the needs. Here, applicability of the different methods is briefly summarized

- For determining fouling presence, pressure drop and temperature measurements are sufficient.
- For information of amount and place of fouling heat transfer parameters can be monitored.
- When electrical heating is used heater performance can be monitored.
- If e.g. cleaning shall be adapted acoustic methods are suitable which are all sensitive enough. Here, a decision has to be made if single spots (ultrasonic sensors) or broader overview (guided waves) are of more interest. Temperature correction has also to be included.
- For deciding if a heat exchanger is fouled and how long cleaning shall be conducted numerical methods are useful. They can also be updated with different measured parameters during the process.

Table 1 gives an overview over advantages, limitations, and possible fields of application for presented methods.

Finding suitable methods for monitoring of fouling and cleaning in closed systems depends on a variety of conditions. Due to many different possible methods a suitable procedure customized to the needs can be found. In future, combing different approaches, switching between them, and including numerical and modeling methods seems to be a good way. In this manner adaption to changing process parameters (different products on the same line) and enhancing product quality will be easier.

Tab. 1: Overview over advantages, limitations, fields of applications for presented methods

Method	Short description	Advantages	Limitations
Pressure drop	Pressure between inlet and outlet is measured	No extra equipment Usually measured Caution of excessive pressure	Not very sensitive Fouling place unknown Thin layers not monitored
Temperature	Product outlet/heating medium temperature is measured	No extra equipment Usually measured	Not very sensitive Thin layers not monitored Fouling place unknown
Heat transfer parameters	Heat flux, heat transfer coefficient, thermal resistance is measured	No extra equipment (besides heat flux) Flow/temperature is usually measured	Certain thickness necessary Heat flux sensors cannot be used at high temperatures
Electrical parameters	Electrical resistance, conductivity is measured Electrical behaviour of heater monitored	Very sensitive to thin layers Fouling thickness can be determined	Invasive Electrical heating needed (not popular)
Acoustic/ Ultrasound/ QCM/QCM-D	Acoustic parameters are measured Frequency change and energy dissipation monitored (QCM-D)	Non-invasive Very sensitive to material change, (very) thin fouling Fouling and cleaning monitored Movable clamp-on sensor	Scattering can occur Parameters temperature dependent One transducer: only one point QCM/QCM-D invasive (integration in new design)
Numerical methods	Clean/fouled heat exchangers modelled Parameters combined	No extra equipment Very sensitive if appropriate parameters and models used	Parameters can insert errors First, validation with other methods necessary

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