Study on dynamic measurement of fouling thermal resistance in a boiler

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Abstract. A fouling thermal resistance method is introduced, for evaluating water quality in real time through measuring fouling thermal resistance on heat transfer surface. A simple device as a boiler heat transfer model was designed for measuring the deposition of dirt by the fouling thermal resistance method. The change in the thermal resistance of the fouling was measured with regard to samples with different water quality. The temperature-time curves were plotted with respect to the measured data of various temperatures over the whole process of temperature rise and fall to examine the feasibility of the method in evaluating the thermal resistance of the fouling contributed by the hardness of the water, finding that the fitted curve can characterize the fouling deposition of high hardness water. It has been shown that this experimental device can be improved further in the hope of being applied in practical use.

1. Introduction

Fouling is an undesirable substance (sediment) accumulated on the surface of heat exchanger. From the basic point of view, fouling can be described as a comprehensive transfer problem of unsteady heat, mass and momentum of heat exchanger fluid and surface, which is closely related to the operating conditions of heat exchanger. Undesirable substances may be crystals, sediments, inorganic salts, biological growth and corrosion products [1, 2]. Fouling is usually invisible from the outside of the processing equipment and can only be reflected by its significant influence on the equipment [3], such as, an increases in the pressure drop, a reduction the heat transfer efficiency. Investigation of fouling dynamics is of great importance since the deposit layer grows with time and may not develop a steady layer having a certain thickness. It is fairly difficult to measure the rate of growth of fouling layers directly due to their soft and readily deformable nature [4] and the challenge in immobilizing a measurement tool in the flow.

The gravimetric method and the direct measurement of thickness most commonly used to measure the degree of fouling are discontinuous or invasive in nature [5]. The gravimetric method evaluates the degree of fouling by weighing the amount of fouling deposited on the heat transfer surface. Without corrosion on the heat transfer surface, preferably the surface state is consistent [6], otherwise there is no point in evaluating in view of nonrepeatability of the test data. The thickness measurement method uses a high-frequency sound wave to pass through the material [7] to measure the wall thickness, with measuring the time when the echo returns to the probe, or recording the amplitude generated when the resonance is produced as a signal source. This method is often adopted to detect the internal defect, the corrosion damage, and the wall thickness of the equipment and piping, however, the disadvantage of
which is difficult tracking changes in the recorded wall thickness for lack of sufficient sensitivity.

In the study of fouling thermal resistance, a commonly adopted approach is to measure the heat transfer performance of the system and then to relate changes in the thermal resistance to the amount of fouling or properties of the deposit such as its thickness and thermal conductivity. An analytical model and monitoring device is put forward in this paper, which is used to simulate the actual operation process of boiler and monitor the change of temperature caused by fouling thermal resistance, thereby determining the degree of scaling. This analytical model based on a simple concept of heat transfer resistance can accurately simulate the deposition process without the assistance of highly sensitive and expensive measurement sensors. Therefore, this device is highly suitable for boiler industry, to monitor the degree of scale formation degree of in a boiler.

2. Experiments

2.1 Configuration of device
Dynamic monitoring device for fouling thermal resistance mainly includes a heating pipe, a temperature controller and a thermometer. The heating pipe is made of stainless steel to eliminate the corrosion effects caused by the open system during the temperature control process, simulating the fouling process in the boiler. As shown in figure 1, the temperature controller is connected with the u-shaped heating pipe and Pt1000 temperature probe, which are all placed into a beaker with 2L water to be tested. The heating pipe is vertical relative to the liquid level and positioned at a fixed depth. Another thermometer is fixed on the wall of the u-shaped heating pipe to measure the wall temperature.

![Figure 1 Dynamic monitoring device for fouling thermal resistance](image)

2.2 Process of measurement
The test water sample was prepared with a standard concentration of calcium chloride solution, adjusting the hardness. Two liters of experimental water was added into the beaker, marking the liquid level. The experiment was performed with the designed fouling resistance measuring device (Figure 1), and the experimental temperature was set to 80 °C. The heating pipe and the temperature probe for the water sample were fixed in position, and the other temperature probe was fixed in the pipe wall groove to measure the wall temperature. An experimental water sample was added every 1 hour to supplement the loss of water by evaporation. The change of temperature was recorded every 2 hours. As the device is an open system, the temperature controller has a limited sensing range of temperature with sensitivity of the sensor. The temperature controller starts up to heat from its lowest temperature. The heating does not stop until the water temperature reaches its highest temperature. Thus, the whole experiment is a process of temperature change via a cycle of from heating up to cooling down. Therefore, the actual temperature control range of the temperature controller is 80 ± 1 °C. The minimum wall temperature and the maximum wall temperature were recorded at 2-hour intervals and the period of time for heating and cooling (the liquid level was kept consistent whenever the temperature was recorded). According to the heat transfer model described in 3.1, the change of the thermal resistance
of the fouling was calculated, and then the degree of fouling was evaluated.

3. Analysis and discussion

3.1 Heat transfer model

According to Chao Shen's uncertainty analysis on the design of the heat exchanger fouling experimental device, higher surface heat transfer performance and low water flow rate are beneficial to reduction in the uncertainty of the device. The fouling deposition has little effect on the heat flux density of the water [8]. The design is simplified to static scaling, minimizing the effect of heat transfer at the flow rate.

For the sake of calculation of the effect of fouling on heat transfer efficiency, the following assumptions are made:

1. The presence of fouling on the heat transfer surface has negligible effect on the convective heat transfer coefficient of the wall and fluid;
2. The heating pipe power is constant and the heating is a continuous process;
3. The effect of hardness on specific heat capacity of the water to be measured can be ignored.

According to the heat transfer theory, the total fouling thermal resistance of the surface of the heating pipe during the whole experiment is [9]:

\[ R_f = \frac{1}{U_f} - \frac{1}{U_c} \]  \hspace{1cm} (1)

Where \( U_f \) and \( U_c \) are the total heat transfer coefficient in the presence of fouling on the heat transfer surface and in the clean state, respectively. According to Fourier's law, the thermal conductivity \( k \) can be expressed as [10, 11]:

\[ k = \frac{|q|}{\partial T/\partial x} \]  \hspace{1cm} (2)

Where \( q \) is the heat flux on the heat transfer surface, \( \partial T/\partial x \) is the temperature gradient in the continuous temperature field (projection in the x direction). When the position of the heating pipe is fixed, the temperature field is fixed and, the heat flow field is also fixed during the whole heating-cooling process, and then the temperature becomes a function of space. Then the heat \( Q \) flowing over the area \( A \) through a certain point at \( t \) time can be written as:

\[ Q = \int_0^t \int_A k |\text{grad} T| dA \]  \hspace{1cm} (3)

During the experiment, the temperature of the heating pipe is measured by a thermometer. It is assumed that only one side of the heat transfer surface is fouled. The amount of water is constant every time the wall temperature is recorded. The amount of water required to rise from the lowest temperature to the highest temperature is constant, that is, the total heat flux during the heating time is constant, which can be regarded as a constant heat flux model [12, 13]. As shown in Figure 2, \( T_l \) is the temperature of the experimental water sample in the beaker, and \( T_w \) is the wall temperature of the heating pipe. In the distance between \( x=0 \) and \( x=a \), there is a temperature gradient \( \text{grad} T \) between \( T_w \) and \( T_l \), and the heat transfers from the heating pipe to the water sample. As the degree of fouling continues to increase and the deposit of fouling on the wall of the heating pipe causes the temperature of the pipe wall to rise, the thermal resistance of the dirt at any one time is:

\[ R_f (t) = \frac{1}{U_f (t)} - \frac{1}{U_c} = \frac{T_w (t) - T}{q_c} - \frac{T_w (t = 0) - T}{q_c} = \frac{T_w (t) - T_w (t = 0)}{q_c} \]  \hspace{1cm} (4)

Where \( T_w (t) \) is the average wall temperature during the temperature rise and fall for any measurement time, \( T_w (t = 0) \) is the initial wall temperature, and \( q_c \) is the heat flux which is a constant for the experimental device. According to equation (4), the thermal resistance of the fouling at each measurement point is calculated directly from the measured wall temperature.
Figure 2 Constant heat flux heat transfer model

During the experiment, by comparing the thermal resistance of the different experimental water samples with regard to the same fouling time, the degree of fouling can be determined, as shown in equation (5):

$$\eta = \frac{R_{fa}(t)}{R_{fb}(t)} = \frac{T_{wa}(t)-T_{wa}(t=0)}{T_{wb}(t)-T_{wb}(t=0)}$$ (5)

Where $\eta$ is the ratio of the degree of fouling of the $a$ experimental water sample to the $b$ experimental water sample at the fouling time $t$, and $R_{fa}(t)$ and $R_{fb}(t)$ are the thermal resistance of the fouling during the scaling time. The remaining terms are the same as equation (4).

3.2 Temperature measurement with three-point method

The whole experiment is a process of warming and cooling. With a random number of points at the same interval, it is hard to accurately describe the wall temperature change caused by fouling of the heating pipe, but it is easy to record the temperature value on the temperature detector by a simple device. In the course of the experiment, every two hours, the extreme point of the temperature rising and cooling process, that is, the initial temperature $T_0$ at which the temperature rise starts, the highest temperature $T_1$ for temperature rise, and the lowest temperature $T_2$ for temperature drop are recorded. At the same time, the time $t_1, t_2$ taken by the temperature rise and temperature drop is recorded by a stopwatch. Due to the assumption in (2) of 3.1, the measured data are fitted into the time-temperature curve $T(t)$ by Newton interpolation, and then the function curve is time-integrated. The integrated area is proportional to the heat flux, and then the temperature integral is averaged. The number represents the temperature value during this time period. This method measures three temperature values, referred to as the three-point method, as shown in equation (6) [14]:

$$\bar{T} = \frac{\int_{t_1}^{t_2} T(t) \, dt}{t_2-t_1}$$ (6)

Deepening of the degree of fouling, will affect the heat transfer efficiency of the heat transfer surface. In the heating and cooling processes, the wall temperature of the heating pipe will change due to the change of the thermal resistance of the fouling. Therefore, the average temperature value obtained by this calculation method is related to the heat flux during the whole time period, for which the thermal resistance of the fouling is responsible. The average temperature matches up with the temperature that causes a change in the temperature rise and temperature fall process.

3.3 Evaluation of device stability

The deionized water was subjected to a 24-hour temperature test on the designed device. The stability of the device was verified in accordance with to the wall temperature curve (Figure 3) in the clean state of the heating pipe.
In terms of the data of the measured deionized water, the temperature change in the temperature-time curve is smooth. The temperature peak fluctuates around 1°C, and the temperature fluctuates between 6 and 7°C during the whole experiment. It has shown that the device has good stability for the impurity-free deionized water test. The temperature data of the long-term scaling experiment were integrated and calculated to obtain the following table 1.

![Temperature-time curve of deionized water](image)

**Figure 3 temperature - time curve of deionized water**

| Water sample             | Water hardness (mmol/L) | Mean heating time (s)/ Standard deviation | mean highest temperature (°C)/ Standard deviation | Fitted slope of the line(*10⁻²) |
|--------------------------|-------------------------|-------------------------------------------|---------------------------------------------------|-------------------------------|
| Deionized water          | 0                       | 94/13.19                                  | 88.28/0.41                                        | 0.07                          |
| Municipal water supply   | 1.43                    | 119/26.54                                 | 84.91/1.06                                        | 0.58                          |
| Formulation water sample | 3.00                    | 107/29.75                                 | 85.13/1.12                                        | 1.39                          |

As can be seen from the above table 1, the average heating time obtained for deionized water as the experimental water sample is 94 seconds, which is less than the heating time for scaling precipitation. The reasons are that scaling leads to the reduction in heat transfer coefficient, and in turn the heat transfer efficiency decreases, with taking more of time. The comparing between the standard deviation of the highest temperature and the slope of the fitted curve, has displayed that the temperature rise-fall process of the device in the clean state is basically the same, with good stability.

### 3.4 Measurement and feasibility analysis of fouling thermal resistance

A scale thermal resistance test was performed using a municipal water with a hardness of 1.43mmol/L and a water with a hardness of 3.00mmol/L on a fouling thermal resistance measuring device. Assuming that the wall temperature of the heating pipe rises evenly during the heating period, and using the average value of the integral of each set of temperature data over time as the average temperature within the two hours, all the temperatures of the entire test are plotted and then curve-fitted. Figure 4 shows the variation of the wall temperature of the heating pipe caused by the
thermal resistance of the fouling:

![Figure 4 Fouling temperature curve (left: municipal water; right: a water with a hardness of 3.00mmol/L)](image)

Seen from the left figure, the fouling time of municipal water is within 100 hours. The figures show that the temperature fluctuates little, and thus temperature rises slowly. It is learned from this group of temperature data that in a relatively short period of time (within 100 hours), the degree of fouling does not exert a significant effect on temperature, It is noted that the degree of scaling becomes greater as the concentration of calcium ions in the water sample increases, and the temperature changes significantly. The temperature rises and falls sharply at a higher temperature in the later stage. After 200 hours of temperature control, the municipal water used in the experiment is gradually concentrated with evaporation, and the hardness ions gradually increase. The concentration of chloride ion in the final concentrated water sample is 0.0141 mol/L, and the chloride ion concentration of Municipal water is $6.31 \times 10^{-4}$ mol/L. This indicates that the water sample was concentrated by a factor of 22 during the experiment. The high concentration of hardness ions contributes to the scale driving force to a certain extent, facilitating the process of fouling. This also explains that the temperature changes obviously after 100 hours.

In this test, the hardness of the experimental water (3.00mmol/L) is more than two times that of the municipal water (1.43mmol/L). From the figure on the right, it can be observed that after 60 hours temperature control, the temperature curve shows a steep climbing pattern. The temperature data of the whole temperature control process were fitted into a straight line with a slope of 0.0139, which was remarkably higher than the fitted slope of 0.0058 for the municipal water as experimental water. In the time of 160 hours of fouling, the ratio of the two fitted slopes in the two experiments was 2.398 adequately reflected the change in the degree of fouling based on formula (5) during in the same period of time with different water samples. According to the theoretical model of fouling thermal resistance, this is the direct evidence of the increase in fouling thermal resistance. This test has demonstrated that this designed method can be used to predict the degree of fouling by dynamically monitoring the wall temperature change caused by the thermal resistance of the boiler.

According to the above study of the thermal resistance of the boiler by the wall temperature method, the degree of fouling in the boiler can be measurably detected by the change in the wall temperature of the boiler. However, for the temperature-time curve of the experimental water sample with a hardness of 3.00mmol/L, the temperature changes over the later period greatly. As the amount of water in the temperature control system is constant, the heat flux of the heating pipe has a certain range for maintaining the temperature of system in the temperature range of from 79 °C to 81 °C. As the thermal resistance increases, the heat transfer efficiency decreases, resulting in a longer heat transfer time. The system heat transfer is slow, causing the wall temperature of the heating pipe to rise with the increase in the degree of fouling, characterized by the temperature rise and fall process overtime. However, such phenomenon of temperature rise and fall is strictly subject to the nature of the test system. According to equation (3) in 3.1, the heat required to maintain 2L water at 80 °C is constant. When the
temperature continues to increase due to the increase in the thermal resistance of the fouling, the temperature difference between the heating pipe at a higher temperature and the experimental water sample at a temperature of 80 °C will keep heat transferring on. Thus, the period of time for temperature rise becomes shorter over the whole heating-cooling process, while the period of time for the temperature drop remains constant, or becomes longer. In short, the change of the temperature curve at the latter stage is not as obvious as the earlier and middle stages. Moreover, the fouling thermal resistance device was designed as a static scaling mode for simplicity, and the temperature was controlled at 80 °C. In this circumstance, due to the influence of various factors, including, among other things, bubbling, heat flow, will cause the entire experimental system to reach a certain degree of fouling, finally striking a sediment-desorption balance of the scale \([15, 16]\), and making it difficult to continue to increase the scale.

Taking into account the amount of water and the degree of fouling, the device, designed to determine the fouling thermal resistance of a boiler by simulating the fouling of a boiler has its limitations. When the temperature reaches a certain limit, it is difficult to further increase due to the deposition of the scale. However, for an industrial boiler, a higher temperature limit is allowable depending on the heat amount of the boiler and its mode of operation. Compared to the simulated device designed in this experiment, the boiler wall temperature in practice is relatively easy to measure. Thus, in actual application, it is only necessary to determine the slope of the temperature-time curve or the wall temperature change arising out of a certain degree of fouling to watch over scale formation in the boiler for the purpose of avoiding any safety accident by taking timely actions of cleaning.

4. Conclusion
The device designed for fouling thermal resistance in this experiment has good stability and can simulate the operation of a boiler to some extent. The proposed three-point wall temperature method has succeeded in measuring the thermal resistance of the fouling and the fitted slope by data analysis can roughly reflect the temperature change in a scaling process. The measurement of fouling thermal resistance for the designed device has its own restrictions, determined by the total heat required to maintain a certain temperature of the system as the entire experimental system to reach a sediment-desorption balance of the scale. Compared with the simulation equipment used in the experiment, it is of great significance in industry that the degree of scale formation in a boiler can be simply monitored by recording different temperatures of the system as a larger measurable temperature rise can be expected during the actual operation.

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