

Research on the Characteristics of CaCO₃ Crystallization Fouling on Enhanced Heat Transfer Tubes

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Abstract. Enhanced heat transfer tubes are widely used in heat exchangers, and the characteristics of heat transfer and fouling are focused. Four kinds of tubes were tested at different temperature, initial concentration and velocity to study heat transfer and fouling characteristics. The results show that: the initial growth rate and final fouling resistance of fouling resistance decreases as velocity increases. But the influence of velocity gradually reduces when velocity is higher than some certain value. The fouling layer is compact and thin at high velocity, but thick and fluffy at low one. The fouling resistance does not always increase when concentration increases. Although the initial concentration is different, the concentration is similar after 8 hours. The final fouling resistance is similar at different concentration, but the morphology is different. The fouling resistance increases as the temperature increases. There is no fouling on the groove of ribs at low temperature, but opposite at high temperature. There is most fouling on the SOFT, more than PT. The scale inhibition performance of WSOF is best and lest fouling. The NSOF has a similar fouling resistance with PT.

Introduction

The oblique fin tubes are widely used in compact heat exchangers, especially in double pipe heat exchanger and shell and tube heat exchanger. Fouling is an important factor to the coefficient of enhanced heat transfer as the same with spirally corrugated tube, corrugated pipe and convergent-divergent tube. Dan Yu^[1] et al did the heat transfer experiments of six kinds of spirally corrugated tubes at different conditions, such as water hardness, temperature, screw pitch and groove depth. And not only the water quality parameters, but also the tube parameters effect the fouling was found. Zhiming Xu^[2~6] et al researched heat transfer and flow resistance of spirally corrugated, corrugated pipe, arc line, transversally corrugated and convergent-divergent tubes at clean and fouling conditions, and found that all enhanced tubes have higher rate of enhanced heat transfer at clean and fouling condition, but the rate decreases significantly at fouling condition, and the fouling resistance of different kind of tubes has a big difference. Yemei Gu^[7] et al found that the induction period shortened and deposit rate increase significantly when concentration of foulant raise. And when concentration is more than some value, the induction period is almost 0.

The fouling characteristics of CaCO₃ crystallization fouling on plain tube (PT) and four kinds of enhanced heat transfer tubes (Straight Oblique Fin Tube (SOFT), Transversally Corrugated Fin Tube (TCFT), Wide Saw-tooth Oblique Fin Tube (WSOF) and Narrow Saw-tooth Oblique Fin Tube (NSOF)) have experimental researched. The temperature of hot water, initial foulant concentration, and flow velocity and so on are changed. The fouling resistance and morphology of fouling of the five kinds of tubes are got.

Experimental setup and methods

According to the definition of fouling resistance, the growth of fouling and the impact on heat transfer enhancement of enhanced heat transfer tubes is measured by fouling resistance.

$$R_f = 1/U_f - 1/U_0 \quad (1)$$

R_f is the fouling resistance, m^2K/W ; U_f is the total heat transfer coefficient at scaling condition, W/m^2K ; U_0 is the total heat transfer coefficient at clean condition, W/m^2K .

Because of extremely low concentration of $CaCO_3$, the density of $CaCO_3$ aqueous solution is almost equal to distilled water and the wall thickness and thermal resistance of inner tube can be ignored. Therefore, the total heat transfer coefficient at clean and fouling conditions at different conditions and the fouling resistance were got. According to Newton cooling formula and the heat balance equation, the physical quantities need to measure are: the hot water temperature of the inlet and outlet and flow rate of the inner tube, and the temperature and flow rate of the inlet and outlet of the solution. The experimental setup as shown in Fig.1 is including a double-pipe tubes, hot water thermostat tank and $CaCO_3$ solution thermostat tank, the cooling system and electric heater to maintain the constant temperature of the two tanks, circulating pump and circulating water-pipes, pt100 platinum resistance temperature sensor and Agilent data acquisition instrument^[8].

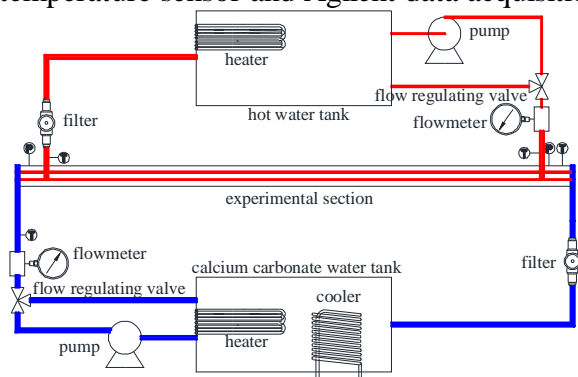


Fig.1 Experiment setup of $CaCO_3$ scaling

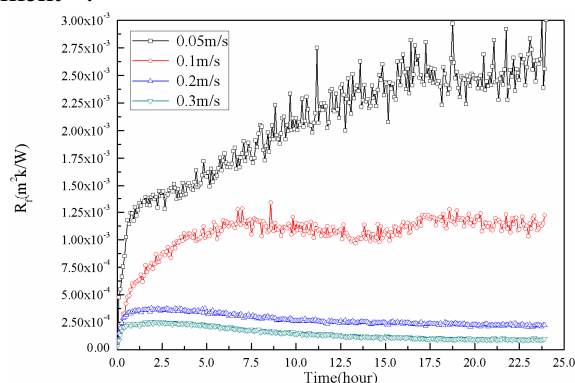


Fig.2 Fouling resistance of SOFT

Tab.1 Geometrical parameters of heat transfer tubes

Tube	Out Diameter	Fin Height	Fin Number	Helix Angle	Enhanced Tube Thickness	Tube Thickness
SOFT	12.7mm	0.65mm	1339/m(39/inch)	45°	0.7 mm	1.0mm
WSOFT	12.7mm	0.60mm	1812/m(46/inch)	45°	0.7 mm	1.0mm
NSOFT	12.7mm	0.65mm	1339/m(39/inch)	45°	0.7 mm	1.0mm
TCFT	12.7mm	0.48mm	1812/m(46/inch)	0°	0.7 mm	1.0mm
PT	12.7mm					1.0mm

Experimental results and analysis

According to the definition of fouling resistance, the growth of fouling and the impact on heat transfer enhancement of enhanced heat transfer tubes is measured by fouling resistance.

Fouling characteristics at different velocities. The flow velocity is 0.05m/s, 0.1m/s, 0.2m/s and 0.3m/s, respectively. When the concentration of $CaCO_3$ is 1.0mmol/l, the fouling resistance is reduced significantly as the velocity raises from 0.05m/s to 0.1m/s, but the fouling resistance decreases little as the velocity raises from 0.2m/s to 0.3m/s. So, as flow velocity increase, the impact to the fouling resistance gradually decrease as shown in Fig.2.

In the progress of $CaCO_3$ crystallization fouling, the effect of flow velocity is dual and complicated. From Fig.7 and Fig.8, it can be found the flow velocity has an influence on the three stages of fouling, transport progress, attachment progress and denudation progress. High velocity can not only raise the transport amount of particle to tube surface which is good for scaling, but also make the flow scour the fouling better, and denudation shear stress bigger, which is good for scaling denudation.

Fouling characteristics at different initial $CaCO_3$ concentration. Fig.3 shows that no matter how many the initial $CaCO_3$ concentration, the concentration of Ca^{2+} decrease rapidly. When the initial $CaCO_3$ concentration is 0.5, 1.0 and 2.0mmol/l, the concentration of Ca^{2+} decreased to about 0.25mmol/l after 5, 6 and 8 hours, respectively. So the more initial concentration, the more descending

rate and final concentration stable later. Fig.4 shows the fouling resistance of SOFT raised most fast and maximum peak value at 1.0mmol/l. And the fouling resistance is second at 2.0mmol/l while smallest at 0.5mmol/l. It can be found the fouling resistance will gradually reduce after the peak value, but the final fouling resistances are almost the same among different initial concentration.

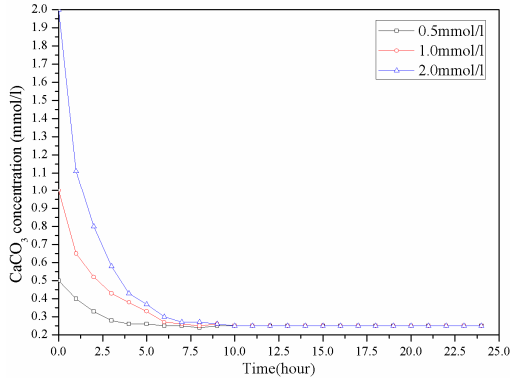


Fig.3 The change of CaCO_3 concentration

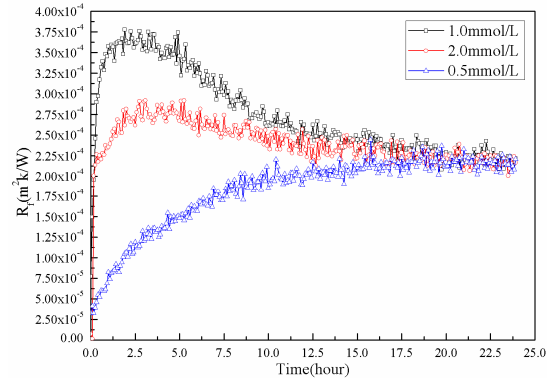


Fig.4 Fouling resistance of SOFT at 0.2m/s

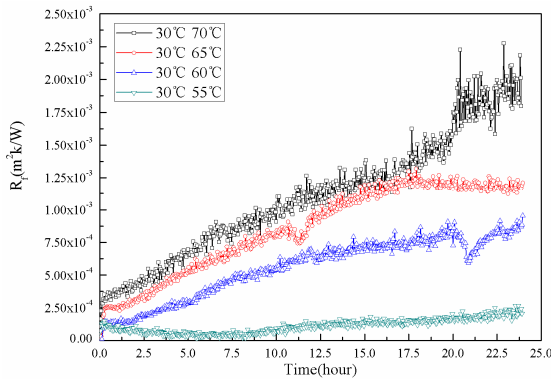


Fig.5 Fouling resistance of TCFT

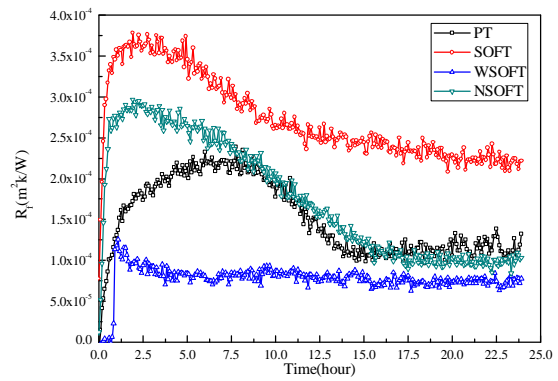


Fig.6 Fouling resistance at 0.2m/s

It's also found that the fouling resistance rate and fouling resistance is not increasing as the concentration increases from Fig.7 and Fig.8. There is a most optimum concentration that make the most fouling and most fouling resistance. In the experiments, the fouling rate is the biggest when CaCO_3 concentration is 1.0mmol/l at the same other parameters. And when the concentration raises to 2.0mmol/l or reduces to 0.5mmol/l, the fouling rate decreases. So 1.0mmol/l is the most optimum concentration in the experiments. Because the fouling rate is depend on the deposit rate and the denudation rate. At 0.5mmol/l, the deposit rate of fouling is lower, so the fouling resistance increasing rate, but the formed fouling is dense and the particle is smaller. And at 2.0mmol/l, the deposit rate is higher, but the structure of fouling layer is fluffy and can be taken away by flow easily, so the denudation rate is higher. In some condition, the denudation rate is higher than deposit rate. So, at the same condition, higher concentration makes the bigger fouling resistance increasing rate and peak value, but smaller final fouling resistance. Altogether, at the most optimum concentration, that is 1.0mmol/l in the experiments, the deposit rate is higher and the fouling formed on the tubes is compact, so hard to scour, which make the fouling deposit rate maximum and the denudation rate minimum so as to the most fouling and biggest fouling resistance^[9].

Fouling characteristics at different hot water temperature. Fig.5 is the fouling resistance of 1.0mmol/L, 0.1m/s, calcium carbonate tank temperature 30°C, and hot water temperature 55°C, 60°C, 65°C and 70°C. The fouling resistance gradually increases as the hot water temperature increases and the temperature difference between hot water and cold water increases. The foulant particle motion aggravates as the temperature increases, so the supersaturation and the diffusion coefficient at the boundary layer. The homogeneous nucleation rate of CaCO_3 in solution increases as the temperature increases. And because of the negative solubility characteristics, the solubility decreases as the temperature increases, and the CaCO_3 crystallization more and faster^[10].

In Fig.9, it can be found that scaling is made with small particles on the top of ribs at 30°C. When the temperature raises up, the amount of fouling increases significantly. And when the temperature rises to 70°C, almost the whole surface is covered by fouling. There is almost no fouling cover on the groove between ribs at 30°C, but a lot of fouling cover on the groove at 70°C. The particle of fouling forms more and denser as the temperature increases.

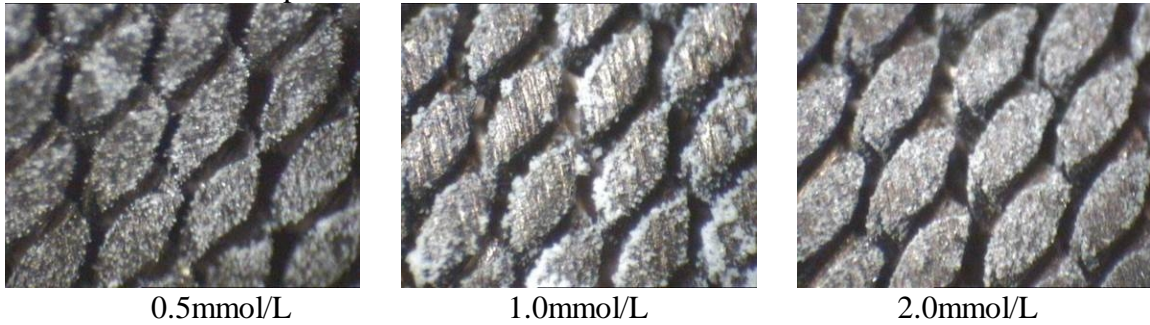


Fig.7 Morphology of scaling on SOFT at 0.1m/s and different concentration

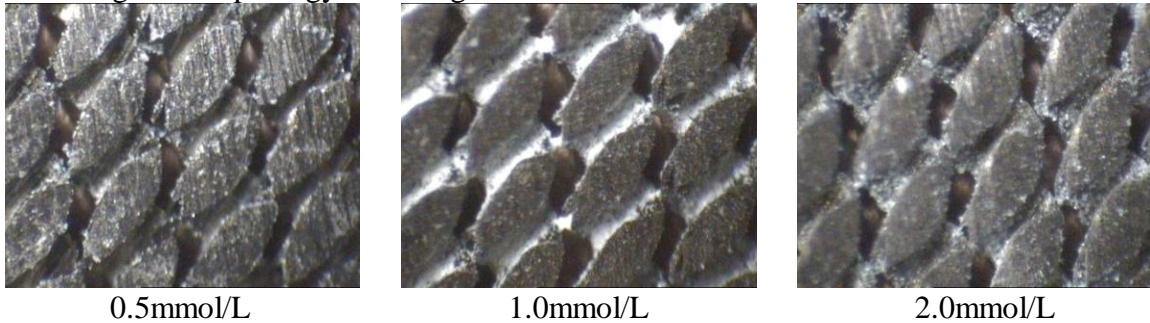


Fig.8 Morphology of scaling on SOFT at 0.2m/s and different concentration

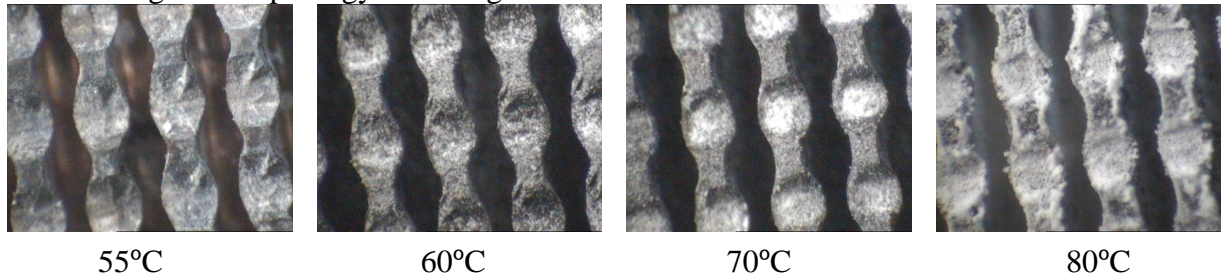


Fig.9 Morphology of scaling on TCFT at different temperature of hot water

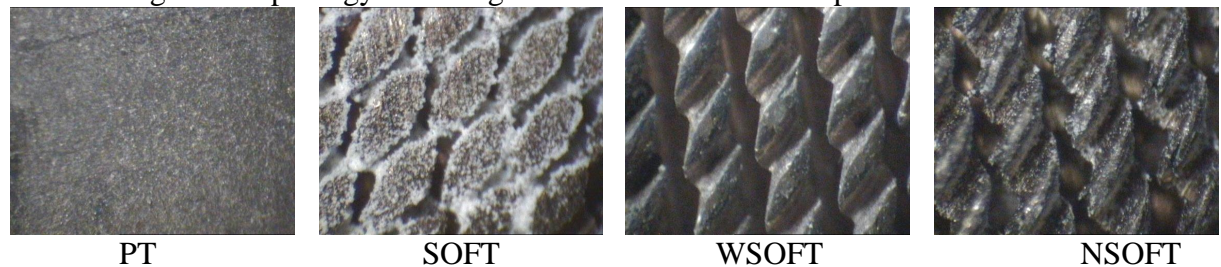


Fig.10 Morphology of scaling on different tubes at 0.2m/s

Fouling characteristics at different kinds of tubes. The fouling resistance of WSOF is the smallest, and smaller than PT, so its anti-fouling performance is the best. And the fouling resistance of SOFT is the biggest, and bigger than PT, so its anti-fouling performance is the worst. The fouling resistance of PT and NSOF is similar, so their anti-fouling performance is similar too.

Fig.10 shows the morphology of scaling on different tubes at calcium carbonate tank water temperature 30°C, hot water tank water temperature 60°C, the concentration of CaCO_3 is 1.0mmol/l, and the flow velocity of calcium carbonate solution is 0.2m /s. There is most fouling on the SOFT, and the whole surface was almost covered by big fouling particles and the fouling was compact, so the

fouling resistance was the biggest. The whole surface of PT was covered by fouling, and a fouling layer was totally formed, and the fouling resistance was big. There is a lot fouling formed on NSOFT surface and well distributed, and the fouling resistance is similar to PT. There is less fouling on the surface of WSOFT and the particles of fouling were sparse, so the fouling resistance is smallest.

Conclusions

Four kinds of tubes were tested at different temperature, initial calcium carbonate concentration and velocity to study their heat transfer and fouling characteristics. The results show that: the initial growth rate of fouling resistance decrease when velocity increases, as well as the final fouling resistance. But the influence of velocity to fouling resistance gradually reduces when velocity is higher than some certain value. The fouling layer is compact and thin at high velocity, but thick and fluffy at low velocity. The fouling resistance does not always increase when the concentration increases. Although the initial concentration is different, the concentration is similar after 8 hours. The final fouling resistance is similar at different concentration, but the morphology is different. The fouling resistance increase as the temperature of hot water increase. There is no fouling on the groove of ribs at low temperature, but at high temperature, the fouling deposits on the groove. There is most fouling on the SOFT, more than pt. The scale inhibition performance of WSOFT is the best and lest fouling. The NSOFT has a similar fouling resistance with PT.

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