FORMATION OF CRYSTALLINE SCALES IN EVAPORATORS

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The formation of crystalline scales from falling liquid films on horizontal tube bundles in heat exchangers is poorly understood. The main purpose of this research work was to study the influence of fluid dynamics and heat transfer on scale formation on horizontal tubes. The fluid film thickness and the heat transfer affect the local supersaturation of the solution and thus the crystallization process.

1. INTRODUCTION

Scale formation on heat transfer surfaces is one of the biggest problems in heat exchangers. Scaling is mainly caused by crystallization of inversely soluble salts. The scale invariably reduces plant performance and efficiency.

Fundamentals of falling films on horizontal tube banks like fluid dynamics and mass transfer are quite well known, but the influence of variation of fluid dynamic parameters and heat transfer on scale formation has scarcely been investigated and given little attention in literature. This paper will discuss the impact of fluid dynamics and heat transfer on temperature changes leading to crystalline scale formation on horizontal tubes.

2. FUNDAMENTALS OF FLUID DYNAMICS AND HEAT TRANSFER

The fluid distribution on a trickled horizontal tube can be divided into three flow patterns: Drops, jets and a fluid curtain. The trickling rate, physical characteristics of the fluid and geometric parameters of the tube bank determine the flow pattern between the tubes. The developed flow pattern affects the thin fluid film along the tube (Armbruster (1997)). The trickling rate is defined as the mass flow rate per unit tube length.

$$\dot{\Gamma} = \frac{\dot{m}}{L} \tag{1}$$

The local film thickness obtained by the Nusselt solution depends on the trickling rate and the angle at circumference.

$$\delta(\varphi) = \sqrt[3]{\frac{3\ \dot{\Gamma}\ \eta}{2\ g\ \rho^2\ \sin\varphi}} \tag{2}$$

Equation 2, which neglects inertia forces, predicts the film thickness sufficiently well for low Reynolds numbers, while at increasing mass flow rates and Reynolds numbers inertia effects cannot be ignored (Mitrovic (1990)).
The fluid film thickness on a tube has got a crucial impact on the heat transfer and as a result of this on the crystallization process. Rogers (1981) presented the following correlation for the local Nusselt number around a horizontal tube. The definition of the local heat transfer coefficient α in *Equation 3* is based on the difference between the wall temperature and the mean fluid temperature.

$$Nu = \frac{\alpha}{\lambda_L}\left(\frac{\nu_L^2}{g}\right)^{1/3} = 1.043\ Re_L^{1/9}\ \ Pr^{1/3}\ \ Ga^{-1/9}\ \left(\frac{\sin\varphi}{P(\varphi)}\right)^{1/3} \tag{3}$$

The term $P(\varphi)$ is equal to an integral that describes the temperature in the fluid film as a function of the angle at circumference. This integral has to be solved numerically. Values for different angles are given by Drögemüller (1998).

3. EXPERIMENTAL SETUP

Figure 1 shows the flow chart of the test rig that is used for crystallization experiments with inversely soluble salts (e.g. $CaCO_3$, $CaSO_4$). The formation of crystalline scales (see *Figure 2*) from falling films on horizontal tubes will be studied in the test rig.

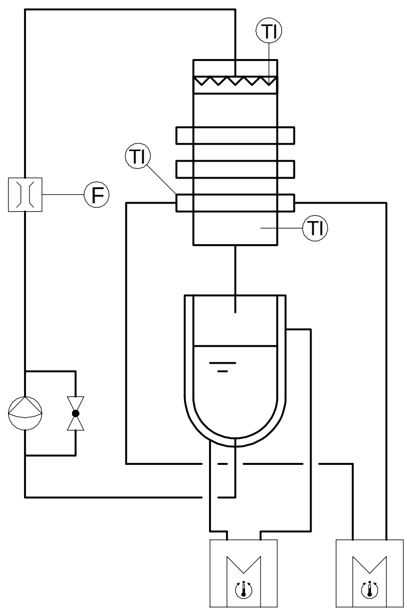

Fig. 1: Flow chart of the experimental test rig

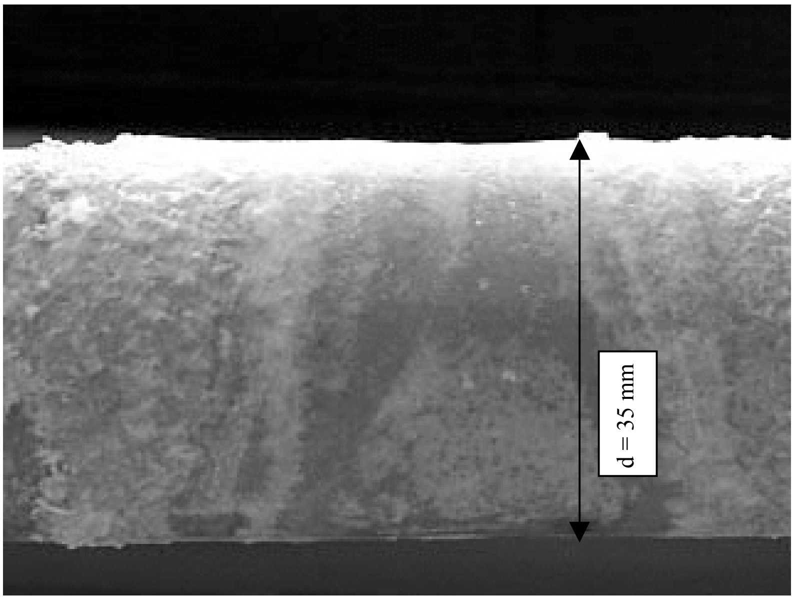

Fig. 2: Crystalline scale around the tube circumference

The main part of the test rig is made up of three horizontal tubes one below the other (length: 250 mm / diameter: 33.7 mm). The first two tubes homogenize the flow pattern and are made out of acrylic plastic, whereas the bottom one (stainless steel) is heated by the heating fluid.

The test solution is trickled on the top tube and the trickling rate is controlled by the volume flow rate. After leaving the heating tube, the solution flows back into the storage tank. A thermostat cools down the test solution before it is recirculated. A second thermostat controls the temperature of the heating fluid. The temperature of the test solution is measured before it flows over the first tube (trickling temperature) and after leaving the heated tube (drain off temperature). Also the surface temperature of the heating tube is monitored. The inlet temperature of the heating fluid, the trickling temperature of the test solution at the tube bank as well as its volume flow rate are kept constant during each of the experiments.

4. RESULTS AND DISCUSSION

The solubility of inversely soluble salts such as $CaCO_3$ and $CaSO_4$ decreases with increasing temperature. For this reason the temperature rise in heat exchangers has a strong impact on the degree of supersaturation, as shown in *Figure 3*.

As shown in *Table 1*, the trickling rate, depending on the volume flow rate, influences the overall temperature change of the test solution and hence the degree of supersaturation. The inlet temperature of the heating fluid was kept constant at 80.2 °C.

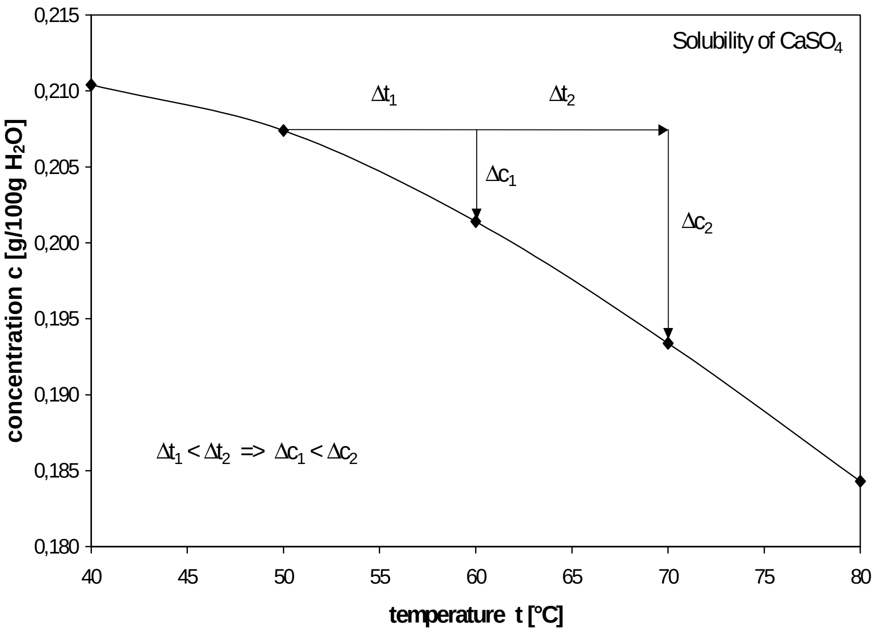

Fig. 3: Saturation curve of an inversely soluble salt (calcium sulfate)(CRC2002).

Table 1: Overall temperature change by variation of volume flow

volume flow (l/h)	trickling rate (kg/s m)	trickling temp. (°C)	drain off temp. (°C)	temperature diff. (K)
30	0.0414	40.2	58.1	17.9
40	0.0552	41.1	56.2	15.1
60	0.0827	46.9	56.4	9.5
80	0.1103	47.4	56.2	8.8
100	0.1379	48.3	56.1	7.8
120	0.1655	49.3	55.4	6.1
150	0.2068	49.7	55.0	5.3
170	0.2344	49.9	54.7	4.8

A closer look at the tube circumference shows the interaction of fluid dynamics and heat transfer and the impact of both phenomena on the march of temperature around the tube. The fluid film thickness along the tube circumference due to *Equation* 2 is plotted in *Figure 4*. The film thickness strongly drops off at the top of the tube, reaches a minimum at the angle of 90° and strongly increases again at the bottom of the tube. In the range from 45° to 135° only a minor change of the film thickness can be seen.

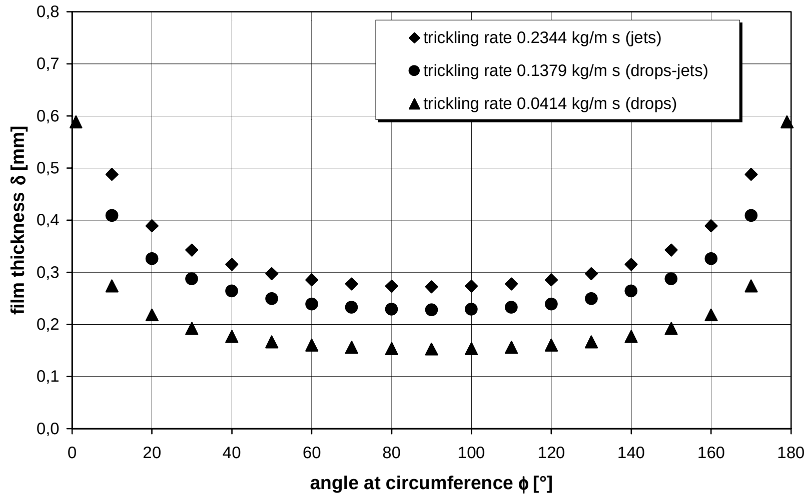

Fig. 4: Fluid film thickness around a horizontal tube depending on the trickling rate

Figure 5 shows the local heat transfer coefficient around a horizontal tube due to *Equation 3*. The heat transfer coefficient is largest at the top of the tube and decreases with increasing angle and finally reaches its lowest value at the bottom of the tube. Correspondingly, the difference between wall temperature and fluid temperature is smallest at the top of the tube and increases with increasing angle and reaches its highest value at the bottom of the tube. Therefore, at this point the starting point of the crystallization may be expected due to the highest local supersaturation of the solution.

In *Figures 4 and 5* the influence of the trickling rate is illustrated. A higher trickling rate leads to an increase of the film thickness and an increase of the heat transfer coefficient.

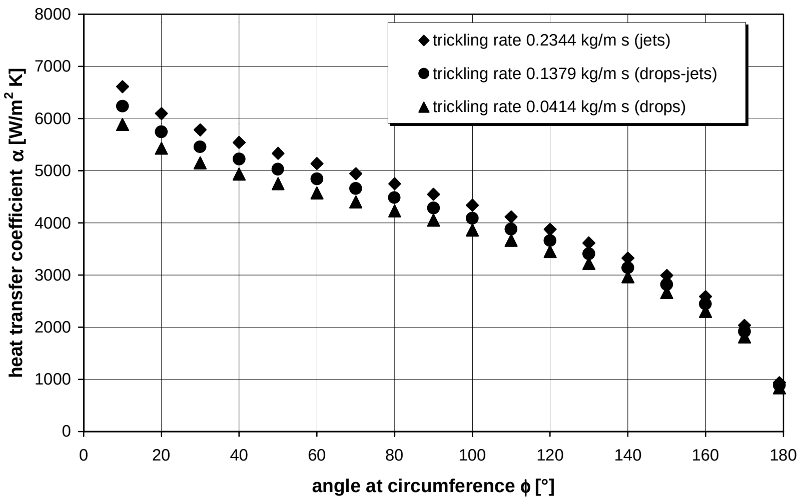

Fig. 5: Variation of the heat transfer coefficient along the circumference of a horizontal tube for different trickling rates

However, the increase of the heat transfer coefficient diminishes by approaching the separation point at 180°.
Thus, the trickling rate does not only affect the overall temperature change from inlet temperature to outlet temperature; it also has an effect on the temperature profile around the tube. The supersaturation of the solution increases on its flow path from the impingement point to the separation point of the tube. Therefore, the scaling tendency increases towards the bottom part of the tube. By adjusting the trickling rate, the scaling tendency may be influenced.

5. CONCLUSIONS

A test rig was installed that allows to study the formation of crystalline scales on horizontal tubes. The fluid dynamics and the heat transfer affect the local supersaturation of the solution and must be considered in further investigations.

6. REFERENCES

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7. SYMBOLS

a	thermal diffusivity (m^2 / s)
d	tube diameter (m)
g	acceleration due to gravity (m / s^2)
L	tube length (m)
$\dot{m}$	mass flow rate (kg / s)
α	heat transfer coefficient (W / m^2 K)
δ	fluid film thickness (mm)
φ	angle at circumference (°)
λ_L	thermal conductivity of fluid (W / m K)
η_L	dynamic viscosity (kg / m s)
ν_L	kinematic viscosity (m^2 / s)
$\dot{\Gamma}$	trickling rate (kg / m s)

$P(\varphi)$	Integral	
Ga	Galilei number	$Ga = \left(\frac{\pi d}{2}\right)^3 \frac{g}{\nu_L^2}$
Nu	Nusselt number	$Nu = \frac{\alpha}{\lambda_L}\left(\frac{\nu_L^2}{g}\right)^{1/3}$
Pr	Prandtl number	$Pr = \frac{\nu_L}{a_L}$
Re_L	Film-Reynolds number	$Re_L = \frac{\dot{\Gamma}}{\eta_L}$