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Scale Formation on Heat Transfer Surface and Removal of Deposited Scale by Adding Glass Beads

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ABSTRACT

A simple laboratory apparatus was developed to observe the mechanism of scale formation in seawater processes and to evaluate the prevention methods such as scale-inhibiting agents and particle abrasion. The apparatus was composed of a tank 300 mm in diameter with a temperature regulator and a rotating drum immersed in it. A test piece 10 mm wide was attached to the drum.

Loop tests were also carried out by operating a double tube type heat exchanger with test tube of Ø 18 x 250 mm. Both tests could sufficiently monitor the formation mechanism of calcium sulfate scale and verify the quantitative effectiveness of the particle abrasion method for scale removal.

INTRODUCTION

Seawater is a severe material for heat exchangers. The dissolved salt often causes scale formation and troublesome corrosion. Various methods have therefore been developed to overcome its severity (Takahashi, 1988). This study was initiated to meet the demand for a simple apparatus to observe the mechanism of scale formation and to evaluate or screen scale-inhibiting agents (Fukumoto et al., 1991).

Another motivation was the interest in the fluidized bed evaporator which was proposed by European desalination groups (Klaren and Windt, 1978; Veenman et al., 1978). The fluidized bed evaporator was developed as a scale-free desalination plant with high heat transfer capability due to the turbulence and abrasion of fluidizing particles, but its quantitative effectiveness has not yet been sufficiently clarified.

The purpose of the study is to propose a laboratory test apparatus which enables simple evaluation or screening of scale-inhibiting agents and to prove the quantitative effectiveness of fluidizing particle abrasion for scale removal.

EXPERIMENTAL STUDIES OF ROTATING CYLINDER METHOD

Many attempts have been proposed for testing methods of scale formation or evaluating scale prevention (Ma and Epstein, 1981; Epstein, 1983; Meijer, 1983; Bohnet, 1985) but they are not always simple enough to correlate mutual relationships between many factors.

The laboratory apparatus studied here (Fig. 1) aims to meet the demand for simplifying the test. The rotating steel cylinder with a diameter of 100 mm is immersed in the small tank 300 mm in diameter. The tank is filled with a calcium sulfate solution as a representative foulant of seawater. The lower part of the cylinder is covered with 70/30 cupronickel plate to keep the temperature of the cylinder

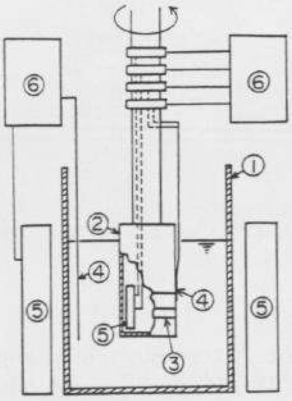

Fig. 1. Laboratory test apparatus of scale formation and removal. 1. Thermostatic tank. 2. Test cylinder. 3. Test section. 4. Thermocouples. 5. Heater. 6. PID regulator.

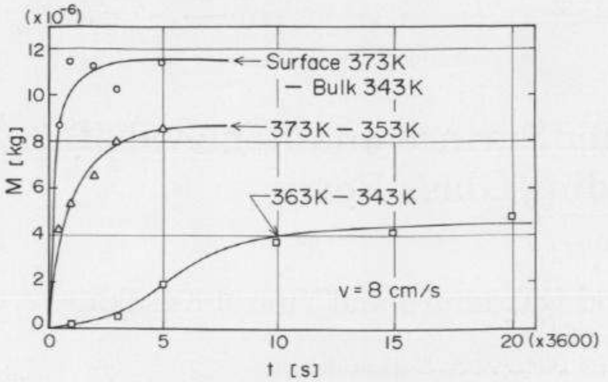

Fig. 2. Fouling curves obtained by the rotating cylinder method (peripheral velocity v_d = 0.08 m/s).

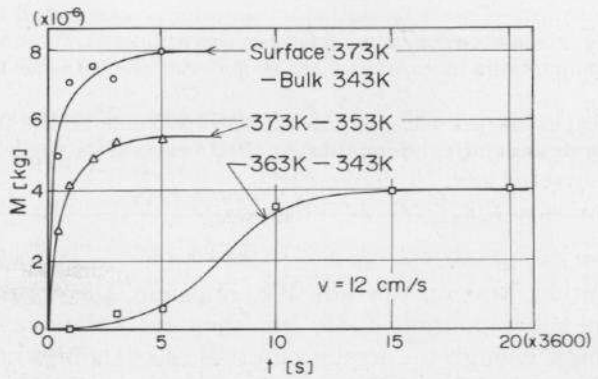

Fig. 3. Fouling curves obtained by the rotating cylinder method (peripheral velocity v_d = 0.12 m/s).

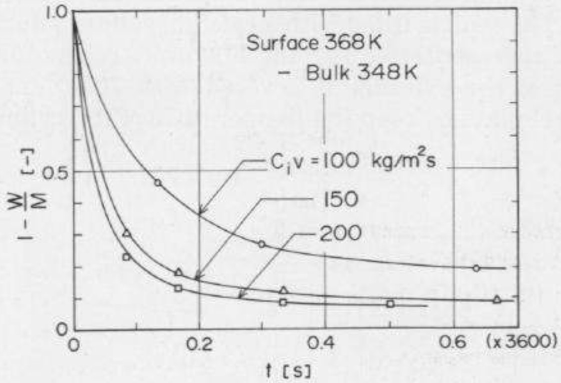

Fig. 4. Removing curves obtained by measuring the weight of residual scale.

surface constant. A test piece of the same material with a width of 10 mm was wound. The test piece is easily removable and subjects to observation. Temperatures of the cylinder surface and the bulk solution are kept constant with a P.I.D. regulator. The scale formation process was observed by measuring the weight of the test piece at various rotational speeds and temperatures of the cylinder surface and the bulk solution.

Typical fouling curves are shown in Figs. 2 and 3. The abscissa is the time in seconds and the vertical axis indicates the deposited scale M kg when peripheral velocities of the drum are 0.08 and 0.12 m/s. Each curve respectively approaches an equilibrium value which depends on the temperature and the peripheral velocity. The figures show that the rate of scale formation increases with an increase of surface temperature of the drum and also temperature difference between the surface and the bulk solution. The tendency agrees with the data for calcium sulfate solution reported by Amjad (1988). The difference in the rate of scale formation at the initial stage suggests that the scale formation is controlled by solute crystallization with vaporization in the case of surface temperature at 373°K and by generation of nuclei in the case at 363°K.

The particle abrasion method to remove the scale was tested by the same apparatus as that shown in Fig. 1. Glass beads of average diameter 0.2 mm were mixed with the bulk solution. A set of baffle plates was installed inside the tank to homogenize the particle concentration. The peripheral velocity of the drum with a test piece was varied from 1 to 2 m/s and the particle concentration was from 50 to 100 kg/m^3.

A result of the removing test is shown in Fig. 4. Where the parameter C_iv kg/m^2 s denotes the particle load to the test piece which is transferred here from an idea in the field of dust collection. The figure shows that the particle load in a range between 100 and 200 kg/m^2 s is suitable for mild cleaning of the surface. The concentration is very low as compared with the operating condition of the fluidized bed evaporator proposed by a European group (Veenman et al., 1978).

Removing curves by abrasion are of apparently asymptotical decrease as shown in Fig. 4 but they do not attain any equilibrium value until complete removal of the scale. Hashimoto (1974) characterized the effect of abrasion by the gradient n in a logarithmic plot of the removing curve. A logarithmic plot of the data is shown in Fig. 5. The values of n are an order of 1.0–1.5 and the straight lines are shifted to the right with an increase of the particle load C_iv. This tendency agrees with the characterization proposed by Hashimoto (1974).

The temperature difference between the test piece and the bulk solution remarkably affects the removing curve, as shown in Fig. 6. The effect depends on the stiffness of the scale originating from the formation mechanism at different conditions. To verify the dependence, the removing rate at the initial stage of

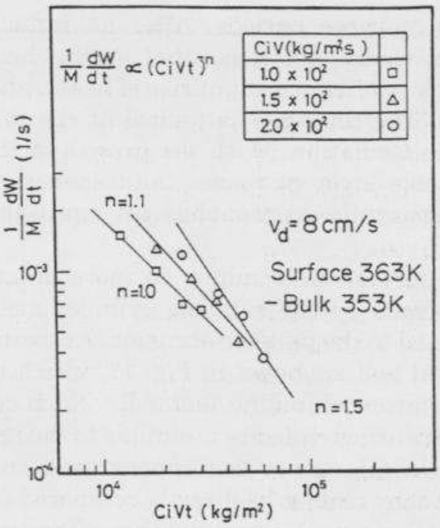

Fig. 5. Relationship of the removal rate to the overall particle load.

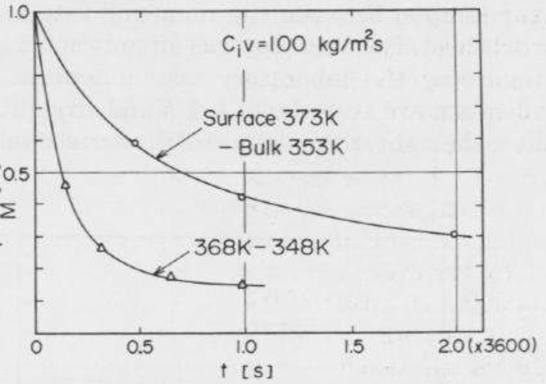

Fig. 6. Effect of the temperature difference between the test piece and bulk solution on the removing curve.

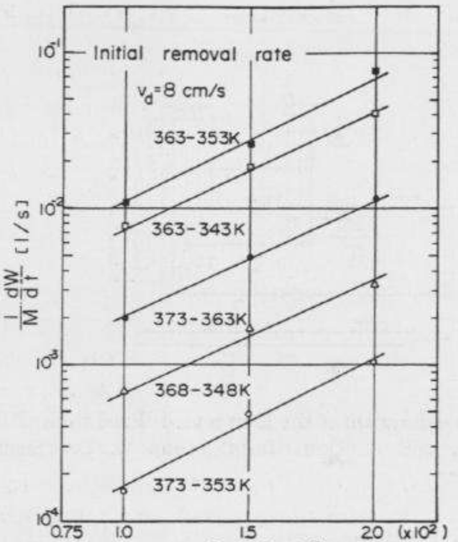

Fig. 7. Relationships between the removing rate at the initial stage and the particle load.

each curve is plotted against the particle load C_iv in logarithmic values as shown in Fig. 7. The figure shows a linear relationship with each temperature condition. It also shows that the removing rate of the deposited scale decreases with an increase of the surface temperature and/or the temperature difference between the surface and the bulk solution. The result suggests that the scale stiffness is more dependent on the temperature at the heated surface than on the temperature difference. In the case of a surface temperature of 373°K, for instance, the removal rate at a temperature difference of 10°K is approximately ten times as high as that of 20°K, while at a surface temperature of 363°K, the ratio is only two to one. Testing times in this study were rather short as compared with practical cases but the idea would be applicable to monitor the mechanism of scale formation and evaluate scale prevention methods such as screening of scale-inhibiting agents and particle abrasion.

LOOP TEST WITH A DOUBLE TUBE HEAT EXCHANGER

An annular geometry heat transfer tube with indirect electric heating was tested to observe scale formation and cleaning processes in more practical conditions (Knudsen, 1981). In referring the report, a double tube heat exchanger was studied for a loop test.

The flow diagram of the loop is shown in Fig. 8 and a schematic cross-section of the test tube is shown in Fig. 9. The transition length is 25 times the equivalent diameter of the annular duct, which follows the heated section of the concentric rod with a length of 250 mm. The thermocouples embedded in the wall of the concentric core allow determination of the surface temperature and measurement of the local fouling resistance as the wall temperature rises with time. They are located 9 equivalent diameters from the upstream end of the heated section. At this location, the thermal boundary layer will not be completely developed, but the temperature gradient in the fluid adjacent to the wall and hence the local heat transfer coefficient will be almost constant in the flow direction (Knudsen, 1981). The following experimental conditions were determined here to form the more practical scale layers and to test at a reasonable range of the surface temperature:

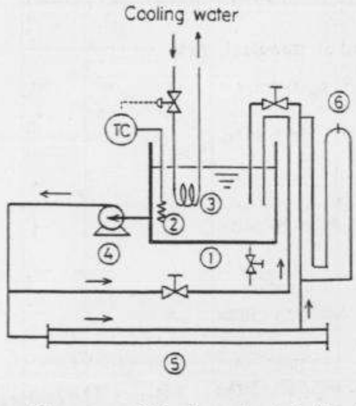

Fig. 8. Flow diagram of the loop test. 1. Feed tank. 2. Heater. 3. Cooling coil. 4. Centrifugal pump. 5. Test section. 6. Manometer.

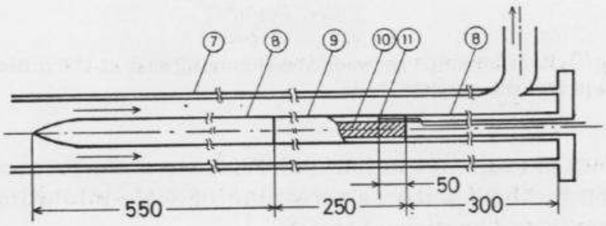

Fig. 9. Schematic cross-section of the test tube. 7. Outer tube (I.D. 40 mm). 8. Inner tube (O.D. 18 mm). 9. Heat section (copper tube). 10. Resistance heater. 11. Thermocouple.

velocity of the foulant: 1.0–1.5 m/s
heat flux: $1.4 \times 10^5\ W/m^2$
temperature of the foulant: 316°K
temperature of the heated surface: 336°K

Calcium sulfate solution was also used in the loop test.

The observed fouling curves are shown in Fig. 10. Where, heat transfer resistances in m^2K/W are plotted in the vertical axis. A fouling process generally consists of three periods. After an induction time, several nuclei are generated at the heated surface, which results in a slight rise of heat transfer performance. The tendency is typical at the initial stage of scale formation. With the growth of these nuclei, the scale layer increases the thickness and then asymptotically approaches an equilibrium value.

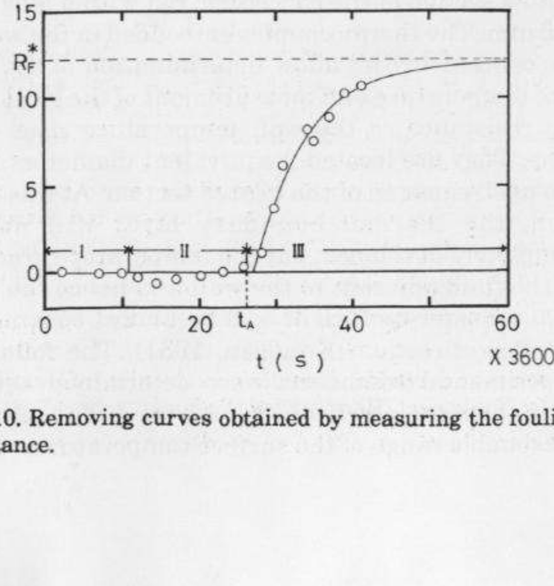

Fig. 10. Removing curves obtained by measuring the fouling resistance.

The scale formed here might be more practical than that formed by the rotating cylinder method and is subjected to the particle abrasion. An example of the removal test is shown in Fig. 11, which indicates the variation of fouling factor R_F. Each curve for a different surface velocity is similar to the result obtained by the laboratory test apparatus as shown in Fig. 4, but they cannot be directly compared since the scale removal was determined there from measuring the weight of the test piece. Data in Fig. 11 were then plotted in logarithmic values as shown in Fig. 12. The figure shows that the removal process of fouling is characterized by the gradient of each linear relation between the removing rate and the particle load. The tendency was already noted in Fig. 6 regarding the laboratory test apparatus. Both gradients n are an order of 1–1.5 and straight lines shift to the right with increase of the surface velocity.

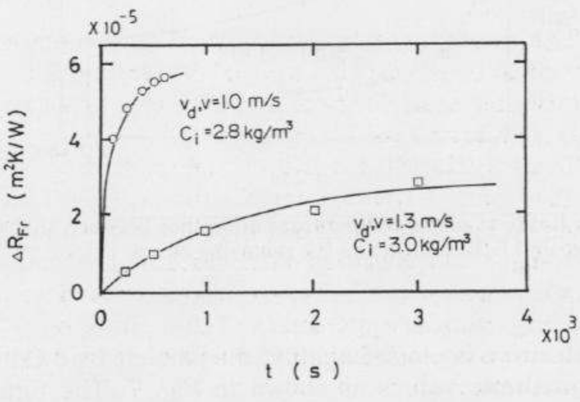

Fig. 11. Removing curves obtained by measuring the fouling resistance.

The removing rate is presumed to be in proportion to the particle concentration and also to kinetic energy of the particle load. The removing rate at the initial stage is then in proportion to the particle load at the power of three. The data shown in Fig. 13, however, indicates that the removing rate at the initial stage is in proportion to C_iv at the power of approximately 1.8. In the case of the figure, the scale was formed at a surface velocity of 1.5 m/s and the scale was then cleaned by particle abrasion with the surface velocity conditions ranging from 1.0 to 3.0 m/s. The difference is attributed to the fact that the

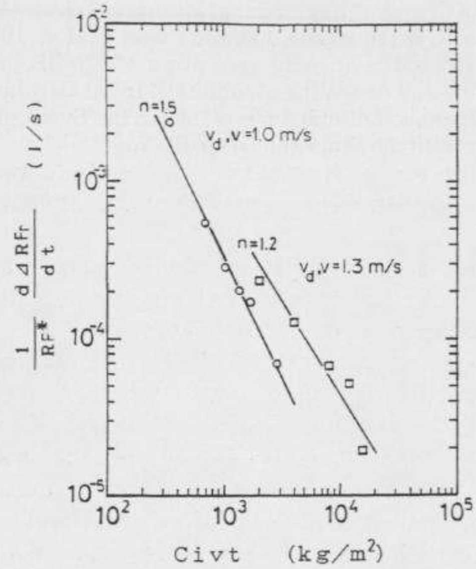

Fig. 12. Relation of the removing rate to the overall particle load.

moving particle loses kinetic energy by mutual collision and the collision angle against the wall is often deflected due to fluid turbulence.

CONCLUSIONS

The rotating cylinder method proposed was proved to be practicable as a laboratory testing apparatus for scale formation or removal by successfully monitoring the processes as follows.

To verify the effectiveness of the rotating cylinder method, scale formation and the removal curve were obtained by using a loop test with a double tube heat exchanger. The observed data indicated that fouling curves were quite similar to those observed in the rotating cylinder apparatus and that stiffness of the scale could be explained by the approaches proposed in this study.

The removal test of the particle abrasion method verified that the fouling factor observed by measuring the weight of residual scale decreased asymptotically in inverse proportion to the overall particle load and also that stiffness of the formed scale was dependent on the surface velocity and temperature conditions. The suitable concentration of particle for mild cleaning was very low as compared with the operating condition of the fluidized bed evaporator.

ACKNOWLEDGMENT

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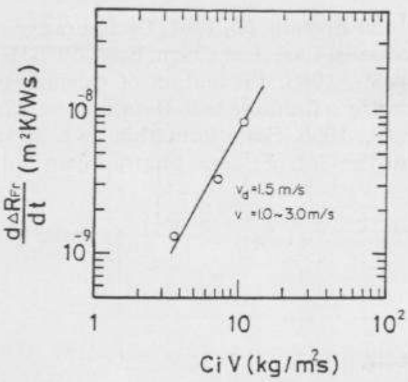

Fig. 13. Relation of the removing rate at the initial stage to the particle load.

NOMENCLATURE

C_i	granule concentration (kg/m^3)
M	amount of formed scale (kg, kg/m^3)
q	heat flux (W)
R_F	fouling factor (m^2 K/W)
ΔR_{FR}	removed fouling factor (m^2 K/W)
T_{WC}	temperature of the heated surface (°K)
T_{WF}	temperature of foulant (°K)
t	time (s)
v	velocity of the fluid at the heated surface in the scale removing experiments (m/s)
v_d	velocity of the foulant at the heated surface in the scale formation experiments (m/s)
W	amount of removed scale (kg, kg/m^3)

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