EFFECT OF ULTRASONIC VIBRATIONS ON SCALE FORMATION

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Results are shown of an experimental study concerning the effect of ultrasonic vibrations on scale formation on a heat-transfer surface. It is shown that an amplitude of flexural vibrations in excess of 3 μ ensures almost a scalefree performance of a heat-transfer surface.

In various branches of industry the water used for cooling systems or distillers has a high mineral content. The use of brines and salted water involves scale formation on the heat-transfer surface, a material whose thermal conductivity is low [1]. In order to develop effective countermeasures, studies are made concerning the mechanism of scale formation, the kinetics of salt precipitation, and the effect of various physicochemical factors on the scale formation: ultrasonic vibrations, magnetic fields, electrohydraulic shock, crystallization seeders, various complex compounds, etc. Most effective seem to be nonreactive methods such as, for instance, the acoustic method.

Several hypotheses have been proposed concerning the mechanism by which ultrasonic vibrations affect the scale formation, but so far there is little experimental evidence which would explain the physical aspects of this phenomenon [2]. Countermeasures against scale formation may be based on either of two different in nature mechanisms of acoustic vibration:

1) Acoustic cavitation, which occurs during the propagation of acoustic waves through water, may, on the one hand, cause the scale to crumble and spall but, on the other hand, also facilitate the formation of many crystallization centers throughout the volume and thus unsupersaturate the solution. The resulting fine-disperse sediment is removed from the system by blowthrough [3-5].
2) Mechanical fatigue spalling of the scale on a heat-transfer surface due to vibrations excited in the latter. Basically this mechanism was examined in our study.

All tests were performed with boiling supersaturated solutions of calcium sulfate in a large volume under atmospheric pressure and a heat load from 0.09 to 0.2 MW/m^2. The test apparatus was a stainless steel tube, 8 mm in diameter and 160 mm long with a wall thickness 0.2 mm, placed in a horizontal position and heated electrically. The ends of the tube were extended into special bulky hermetically sealed current leads with holes for bringing out thermocouples welded to the inside tube surface 1 by the capacitor method. The test segment was immersed in a stainless steel vessel containing a supersaturated solution of calcium sulfate. The temperature of the solution was measured with two Chromel–Copel thermocouples. Ultrasonic vibrations at a frequency of about 19 kHz were transmitted to the test tube from a model BAR sound generator through a transducer and a waveguide, the latter silver-soldered to the tube at the center. The vibration amplitudes in such tubes of various diameters and wall thicknesses were varied from 1 to 3 μ and were measured in air under a microscope.

The measurements were made by the temperature method based on the following principle. The temperature drop across a uniform layer of scale 3 deposited on the outside tube surface 2 under a uniformly distributed heat load was determined according to the equation

$$T_2 - T_3 = \frac{q_2 d_2}{2\lambda_{sc}} \ln \frac{d_3}{d_2} . \qquad (1)$$

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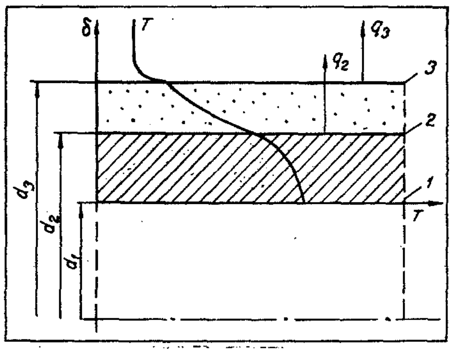

Fig. 1. Schematic diagram of the temperature field in a test tube.

The designations in Fig. 1 are self-evident. The mean scale thickness across a given section was determined as follows:

$$\delta = 0.5\,(d_3 - d_2) = 0.5d_2\left[\exp\frac{2\lambda_{sc}\,(T_2 - T_3)}{q_2 d_2} - 1\right]. \qquad (2)$$

The mean rate of scale formation during a certain time interval is

$$I = \frac{m}{F_2\Delta\tau} = \frac{\rho_{sc}\,(d_{i+1}^2 - d_i^2)}{4d_2(\tau_{i+1} - \tau_i)} = \frac{\rho_{sc}\,d_2}{4(\tau_{i+1} - \tau_i)}$$
$$\times\left[\exp\frac{4\lambda_{sc}\,(T_2 - T_3)_{i+1}}{q_2 d_2} - \exp\frac{4\lambda_{sc}\,(T_2 - T_3)_i}{q_2 d_2}\right]. \qquad (3)$$

The scale density was taken as equal to 2.6 g/cm^3, according to the data in [1], and its thermal conductivity was determined on the basis of its mean temperature $T_m = 0.5(T_2 + T_3)$ from Fig. 2. The heat load and the temperature at the inside scale surface T_2 were determined during the test by establishing the trends of the scale formation process. The temperature of the heat emitting surface T_3 was determined from from the wall-temperature versus heat-load curve which had been plotted on the basis of calibration tests with distillate.

The study could be tentatively divided into four stages:

1. Obtaining calibration curves for the temperature of the heat emitting surface as a function of the heat load and of the bulk water temperature, during the boiling of distillate in and without an acoustic field, respectively.
2. Obtaining kinetic curves for the temperature T_2 during the boiling of aqueous calcium sulfate solutions; in this stage we determined the density, the thermal conductivity in the radial direction, and the crystal content of the scale [1];
3. Obtaining kinetic curves for the temperature-difference ΔT_{sc} buildup across the scale, the scale-thickness δ-buildup, and the rate of scale formation – all by comparison of test data obtained in the first and the second stage;
4. Comparing the kinetic curves for temperature-difference buildup, scale-thickness buildup, and scale formation rate in and without an acoustic field, respectively.

In Fig. 3 are shown the kinetic curves representing the change in scale thickness at various amplitudes of flexural vibration. An analysis of these relations indicates that, at an amplitude of the order of 1 μ, the scale thickness throughout the test did not differ from the scale thickness built up in the absence of ultrasonic vibrations. An effect of ultrasonic vibrations at such small amplitudes was in evidence only when the scale had loosened from the metal of the heating surface.

At amplitudes of the order of 2 μ there appeared a periodic spalling of the scale, the maximum scale thickness for steady spalling being 1.2 mm; at amplitudes of the order of 3 μ this maximum thickness was 0.4 mm.

The scale thickness at which steady spalling occurs has been called the critical scale thickness.

The critical scale thickness decreased as the amplitude of flexural vibration excited in the tube increased: at an amplitude of 3 μ it was 0.4 mm, at an amplitude of 2 μ it was 1.2 mm, and at an amplitude at 1 μ it probably exceeded the maximum scale thickness (4 mm) obtained in our experiment.

It is to be noted that the process of scale breakdown has fatigue characteristics. Generally, therefore, the critical scale thickness should depend not only on the amplitude but also on the number of cycles and on the crystallization rate. The higher the crystallization rate is, the sooner will the fatigue cracks in the scale "close up."

Most tests were performed with the sound generator turned on permanently, but an intermittent turn-on at 1350 min after the beginning of the test resulted in the breakdown and the spalling of a scale which had been formed on the test tube for days in the absence of ultrasonic vibrations (Fig. 3). Just before the sound generator was turned on, the scale thickness was approximately 4 mm or several times the critical scale thickness.

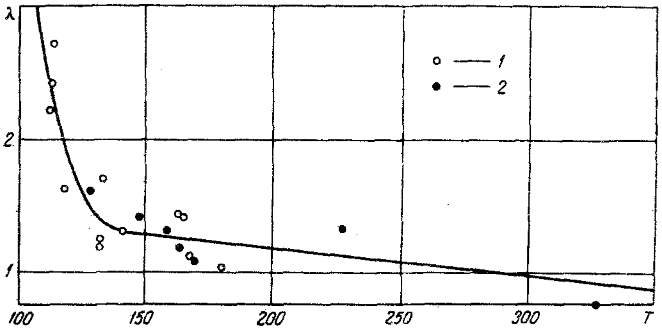

Fig. 2. Radial component of thermal conductivity of sulfate scale: 1) according to the data in [1]; 2) according to the data of this study. Temperature T (°C); thermal conductivity λ (W/m · deg).

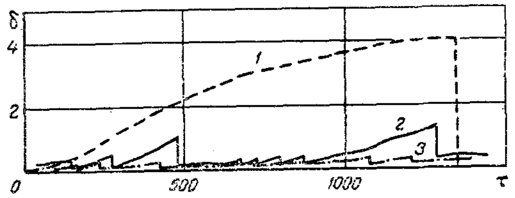

Fig. 3. Kinetic curves for the scale thickness at various vibration amplitudes: 1) 0 and 1 μ; 2) 2; 3) 3.

As far as the amplitude of flexural vibrations affects the scale spalling off the heat-transfer surface of a tube, it is interesting to analyze the profile of scale thickness and temperature difference across the scale along a tube. The results of two typical tests are shown in Fig. 4, both having been performed under similar conditions on the same test tube. The only difference between them was that the sound generator was turned on in the first test (a) and turned off in the second test (b). On the same diagram is shown the amplitude distribution of flexural vibrations and the locations of thermocouples along the left-hand half of the test tube. The amplitude of flexural vibrations was about 3 μ at the coupling to the waveguide and 2 μ at the section through thermocouple No. 1.

A comparison of curves 1 obtained 100 min after the beginning of the tests indicates that the scale thickness along the test was smaller than critical. For this instant of time, therefore, it would be difficult to assert any positive effect of ultrasonic vibrations on the breakdown of scale. It could only be noted that the temperature difference across the scale layer was larger at sections corresponding to maximum deflections than at those corresponding to nodes.

After already 500 min (curves 2), however, the effect of ultrasonic vibrations on the scale breakdown and the related reduction of scale thickness (as compared to the scale thickness in the test without sound) become evident. The mean scale thickness in the test with sound was 0.5 mm and the temperature difference was about 30°C. At the same time, in the comparable test without sound the mean scale thickness was 2.0 mm and the temperature difference was 250°C.

At 1200 min after the beginning of the test (curves 3) the scale thickness in the test with sound was from 0.2 mm (within the region of largest amplitudes) to 1.0 mm (within the region of smaller amplitudes) and the temperature difference ranged from 20 to 200°C, while in the comparable test without sound the scale thickness was 3.5 mm and the temperature difference was 400°C under a heat load of 0.14 MW/m^2

After 1460 min (curves 4) the temperature difference was 30°C along the entire tube and the scale thickness was about 0.5 mm. No test with the sound generator off was performed under comparable conditions, because of the prohibitive temperature rise at the tube wall.

An analysis of the mean rate of scale formation during the boiling of supersaturated calcium sulfate solutions has shown that in tests with the sound generator off this rate varied over a wide range, from 200 to 700 $g/m^2 \cdot h$, as a function of the mean supersaturation level. The latter can vary appreciably, depending on the manner in which the volume of boiling solution is maintained: by returning the condensate or by adding a calcium sulfate solution 2 g/liter.

In the tests with the sound generator on, both methods of maintaining a constant level of solution in the vessel yielded a mean rate of scale formation which decreased monotonically with time. The mean rate of scale formation in these tests was almost independent of the supersaturation level, but was determined only by the length of testing time and by the critical scale thickness, the latter depending on the amplitude

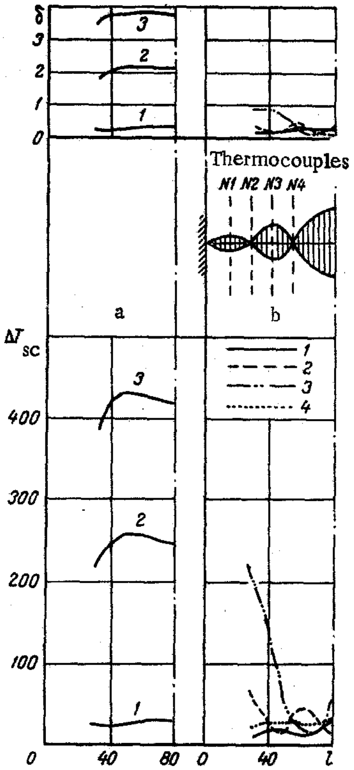

Fig. 4. Profiles of the scale thickness δ (mm) and of the temperature difference T (°C) across the scale, along the tube, at four instants of time after the beginning of tests: 1) 100 min; 2) 500; 3) 1200; 4) 1460; a) without ultrasonic vibrations; b) at a vibration amplitude 3 μ near the waveguide and 2 μ at the section through thermocouple No. 1.

of flexural vibrations. The mean rate of scale formation decreased as this amplitude was increased. The mean rate of scale formation decreased also with longer testing time, at a constant critical scale thickness. Thus, with the sound generator on, the mean rate of scale formation was 80 $g/m^2 \cdot h$ during a 400-min test, 40 $g/m^2 \cdot h$ during a 1000-min test, 20 $g/m^2 \cdot h$ during a 1500-min test, etc.

Thus, ultrasonic vibrations during longer operating periods will ensure an almost scalefree performance of a heat-transfer surface.

NOTATION

d_1, d_2	are the inside and outside diameter of test tube;
d_3	is the outside diameter of scale layer;
δ	is the thickness of scale layer;
T_1	is the temperature at the inside tube surface;
T_2	is the temperature at the outside tube surface;
T_3	is the temperature at the outside scale surface;
ΔT_{sc}	is the temperature difference across the scale;
I, $\bar{I}$	are the instantaneous and mean rate of scale formation;
q_2	is the thermal flux density on the outside tube surface;
q_3	is the thermal flux density on the outside scale surface;
τ	is the time;
l	is the length of tube.

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