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The Effect of Fouling on Nucleate Pool Boiling of Small Wires

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Pool boiling experiments with small diameter wires were conducted in earth gravity and microgravity conditions. Bare wire and fouled wire with a scale deposition of calcium carbonate was used. The wettability on the scale wire was higher than that on the bare wire. Though more vigorous bubbling was observed on the scale wire when compared to that on the bare wire at the same heat flux, the boiling curve for the scale wire was approximately the same as that on the bare wire. However, the critical heat flux (CHF) on the scale wire was higher than that of the bare wire. On the scale wire, the departure diameter of bubbles was relatively smaller than that on the bare wire. The smaller diameter of bubbles detaching from the scale wire is considered to be due to the high wettability and high nucleation site density. As the result, the coalescence of bubbles near the wire was prevented, and the CHF was delayed and increased on the scale wire when compared to that on the bare wire. Heat Trans Asian Res, 33(5): 316–329, 2004; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/htj.20016

Key words: wettability, fouling, microgravity, small cylinder, CHF, pool boiling

1. Introduction

Nucleate boiling heat transfer is widely used in industrial applications due to its higher heat transfer coefficient among the various heat transfer processes. Recently higher heat flux and more density has been required in heat transfer components such as electronic equipment or heat exchangers for energy saving. It is very important to understand the boiling heat transfer in the small heat transfer area to increase the density.

The boiling experiments using small heat transfer areas, such as wires of small diameter, have been conducted by various researchers after Nukiyama [1] found the boiling curve on small diameter wire. Bakhru and Lienhard [2] indicated the "patchy boiling," where the maximum point (CHF point) and the minimum point (MHF point) disappear on the boiling curve. This took place when the non-dimensional diameter of wire r' was less than 0.01. When the heat transfer size is smaller than the capillary length of two-phase, the whole heat transfer wire is easily covered with vapor bubbles and film boiling is established immediately at the initiation of boiling. However the effects of a fouling scale on these boiling behaviors have not been clarified.

The scale increases the heat resistance and the number of nucleate sites because of its hydrophilic porous structure that changes surface wettability and decreases the surface heat conductivity.

In the present study, fouling scales were generated on wires of various small diameters by pre-boiling for long durations in industrial water containing various minerals, and the effects of scale on bubbling behavior and heat transfer were experimentally investigated in earth gravity. In a microgravity condition, the effect of wire wettability becomes significant due to the lack of buoyancy force and the peculiar phenomena on small diameter wires are emphasized because the capillary length of two-phase becomes large. As these results in microgravity were expected to be useful to understand the effects of wire diameter and fouling scale in earth gravity, microgravity experiments were conducted in the drop shaft in Hokkaido of Japan.

Nomenclature

c_p:	specific heat (J/(kg · K))
c_{sf}:	constant in Rohsenow's correlation (= 0.013)
g:	acceleration due to gravity (= 9.80665 m/s^2)
h_{LG}:	latent heat (J/kg)
Pr:	Prandtl number [= ν/κ]
q:	heat flux (W/m^2)
$q_{CHF,\ Bare}$:	average CHF on bare wire (W/m^2)
$q_{CHF,\ Scale}$:	CHF on scale wire (W/m^2)
$q_{CHF,Z}$:	CHF predicted by Zuber's correlation (W/m^2)
r:	radius of wire (m)
r':	non-dimensional radius of wire [= $r/\sqrt{\sigma/g(\rho_L-\rho_G)}$]
T:	temperature (K)
ΔT_{sat}:	superheat (K)
κ:	thermal diffusivity (m^2/s)
λ:	heat conductivity [W/(m · K)]
μ:	viscosity (Pa · s)
ν:	kinematic viscosity (m^2/s)
ρ:	density (kg/m^3)
σ:	wire tension (N/m)

Subscripts

G:	steam
L:	liquid
S:	scale
W:	wall

2. Experimental Apparatus and Methodology

Shown in Fig. 1 is a schematic diagram of the experimental apparatus. Distilled or industrial water was filled in a transparent vessel made of polycarbonate, and used for the bare and scale wires experiments, respectively. The major impurity included in the industrial water was salts of calcium. The wall thickness of the vessel was 10 mm to reduce the heat loss. Platinum wires of 0.005 mm, 0.01 mm, 0.015 mm, 0.025 mm, 0.05 mm, and 0.1 mm in radius with or without fouling scale were used

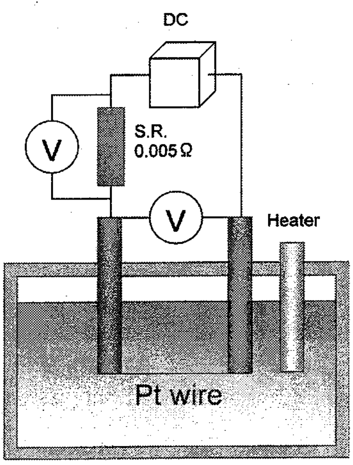

Fig. 1. Experimental apparatus.

to provide uniform heat flux and measurement of the mean temperature of wires. The wire was welded to two SUS poles of 6 mm in diameter fixed to the lid of vessel at an interval of 30 mm.

The boiling experiments were conducted by increasing electric current and heat flux step-by-step and finally burnout was confirmed. The heat flux was calculated with the measured voltage between the poles and the electric current that was estimated from the voltage drop at a standard resistance of 0.005 Ω. The measurement error of heat flux was within ±1%. In the present study, the heat flux was defined at the surface of platinum wire or scale. The wire mean temperature was determined with the extrapolation of the calibrated relation of resistance and temperature of platinum wire between 0 and 100 °C. The radial temperature distribution in wire was considered to be negligible in the current experiments. The measurement error of temperature was within ±0.3%. The experiments were conducted at the saturated temperature of atmospheric pressure in microgravity and earth gravity. A back-up heater was used to maintain the saturation temperature.

The microgravity experiments were conducted in JAMIC drop shaft in Hokkaido of Japan. The drop time was 10 s and the quality of the microgravity is approximately 10^{-5} g.

Figures 2 and 3 are microscopic photographs for the bare and scale wires, respectively, obtained using a scanning electron microscope (SEM). The bare wire was cleaned with Aceton before the experiment. Small cavities with a mouth radius less than 10 μm can be recognized in the micrograph. The fouling scale was generated with the pre-boiling in industrial water for approximately 10 hours. The scale consisting of a hydrophilic porous structure can be seen in Fig. 3. The average thickness of scale was determined with an enlarged photograph such as Fig. 3.

Shown in Table 1 are the measured components with an x-ray diffract meter for the scale generated in the present experiment. The measurement indicated the major component of the scale except carbon and oxygen. It is estimated that the p scale mainly consists of calcium carbonate.

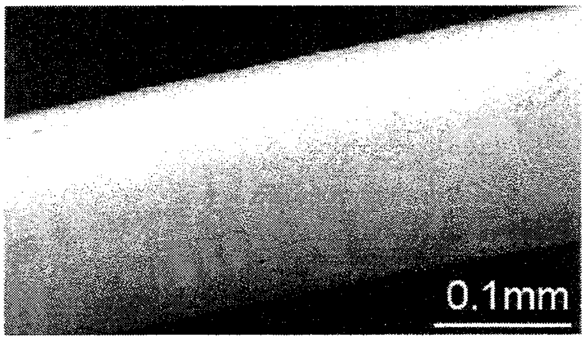

Fig. 2. Electron micrograph of bare wire ($r = 0.1$ mm).

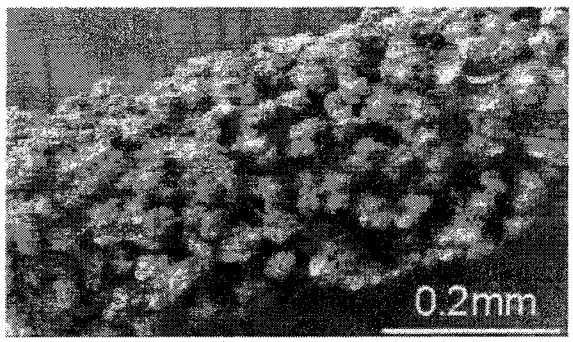

Fig. 3. Electron micrograph of scale wire ($r = 0.1$ mm).

Table 1. Major Components of Scale Except Carbon and Oxygen

Scale component	Molar fraction(%)
Ca	78.4
K	5.8
Fe	4.5
Cl	3.4
Zn	2.9

3. Experimental Results and Discussions

3.1 Earth gravity experiments

Shown in Figs. 4 and 5 are boiling behaviors on the bare platinum wires of 0.025 mm and 0.01 mm in radius, respectively. A decrease of nucleation site density per unit length of wire can be observed with decreasing the wire radius at the same heat flux. The nucleation site density per unit area is also decreasing.

Shown in Figs. 6 and 7 are boiling behaviors on the bare and scale wires of 0.1 mm in radius at the same heat flux, respectively. The more vigorous emission of small bubbles was observed on the scale wire compared to that on the bare wire [3]. The enhancement of the bubbling was associated with the fact that the hydrophilic porous structure in the fouling scale provided a sufficient number of active sites for bubbling nucleation. It was reported that the wettability of the scale wire was much higher than that of the clean bare wire [4]. The bubble departure diameter on the fouling wire was smaller than that on the clean wire due to the higher wettability. When the wire radius is less than 0.05 mm, a significant difference on the boiling behavior at the relatively low heat flux region could not be recognized but the more vigorous emission of small bubbles from the scale wire compared to that on the bare wire was observed at the relatively high heat flux region near the burnout.

Shown in Fig. 8 are the boiling curves of bare wires of different radius. Nucleate boiling was maintained at the lower superheat region but the wire was gradually covered with vapor bubbles and departed from the nucleate boiling with increasing superheat. The solid line in Fig. 8 is Rohsenow's correlation [5] shown as,

$$q_w = \mu_L h_{LG} \sqrt{\frac{g(\rho_L - \rho_G)}{\sigma}} \left(\frac{C_{pl} \Delta T_{sat}}{C_{sf} h_{LG}} \right)^3 \mathrm{Pr}_L^{-5.1} \quad (1)$$

where the constant c_{sf} is empirically determined with the combination of boiling liquid and surface material. In the present study, the constant c_{sf} of 0.013 for platinum surface and water was used.

The dashed line in Fig. 8 is Zuber's correlation [6] for the burnout heat flux expressed as

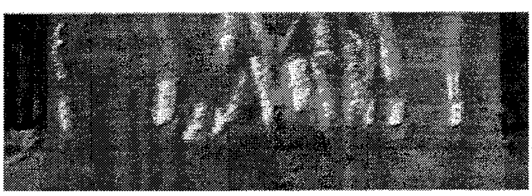

Fig. 4. Boiling behavior on bare wire of r = 0.025 mm at heat flux of q = 0.48 MW/m^2 and in earth gravity.

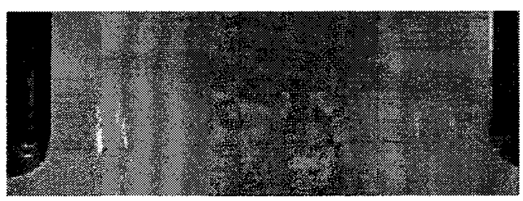

Fig. 5. Boiling behavior on bare wire of r = 0.01 mm at heat flux of q = 0.49 MW/m^2 and in earth gravity.

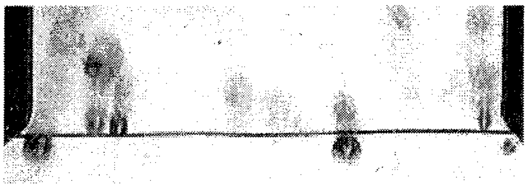

Fig. 6. Boiling behavior on bare wire of $r = 0.1$ mm at heat flux of $q = 0.2$ MW/m^2 and in earth gravity.

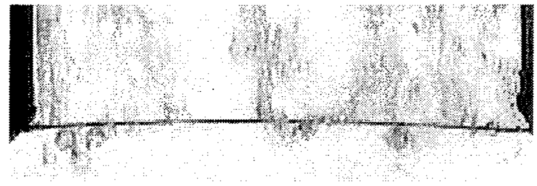

Fig. 7. Boiling behavior on scale wire of $r = 0.1$ mm at heat flux of $q = 0.2$ MW/m^2 and in earth gravity.

$$q_{CHF,Z} = 0.131 \rho_G h_{LG} \left(\frac{\sigma g(\rho_L - \rho_G)}{\rho_G^2} \right)^{1/4} \tag{2}$$

Although platinum wires were used in the present study, Zuber's correlation for the CHF of a horizontal flat plate was compared as a reference.

As shown in Fig. 8, the experimental data tend to shift left with decreasing the radius of wire and disagree with Rohsenow's correlation at the lower superheat conditions. This is considered to be due to the increasing contribution of convection heat transfer with decreasing the radius. The data agrees well with Rohsenow's correlation when the radius is larger that 0.05 mm.

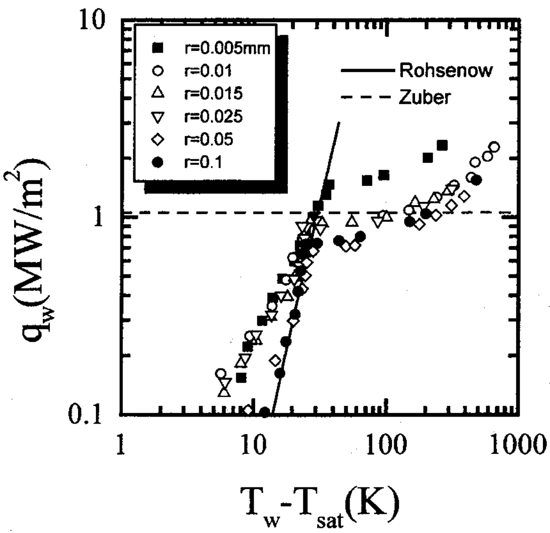

Fig. 8. Boiling curves on bare wire of different diameters in earth gravity.

Figure 9 shows the effect of fouling scale on the boiling curve of wire of 0.1 mm in radius. Three kinds of data for the bare wire, scale wire and corrected scale wire are shown. The thickness of scale was 6.5 μm, and the relation of the wire mean temperature covered with the scale and the heat flux defined at the wire surface is plotted as the scale data in the figure. The scale wire data sift left when compared to that of bare wire. This is considered to be due to the scale, as a heat resistance increases the wire mean temperature. The corrected scale wire data shows the relation of heat flux and temperature defined at the scale surface. These are calculated with the measured thickness of scale and its heat conductivity. The heat conductivity of $\lambda = 0.7$ (W/(m · K)) recommended by Haze et al. [7, 8] for the scale mainly consisting of calcium carbonate, was used in the calculation. Though the heat conductivity was measured at a non-boiling condition, it is assumed that it can be used also in the boiling condition as a first approximation. The data on both the bare and scale wires agree well with Rohsenow's correlation in the nucleate boiling region but a departure from the nucleate boiling occurs at the lower heat flux on the bare wire. In the present study, the CHF was defined at the departure from nucleate boiling (DNB).

Figure 10 shows the effect of a fouling scale on the boiling heat transfer for a wire of 0.015 mm in radius. The data for the bare wire, scale wire and corrected scale wire at the lower heat flux region disagree with Rohsenow's correlation but gradually approach it with increasing heat flux. This difference is considered to be due to the significant contribution of convection heat transfer in the smaller wire, though the bubble emission was confirmed even at the low heat flux region as indicated with the incipient boiling. A significant difference for the bare and scale wires in the nucleate boiling region cannot be observed but the departure from the nucleate boiling occur at the lower heat flux on the bare wire for a 0.1 mm wire.

3.2 Microgravity experiments

Microgravity experiments were conducted by using wire of 0.1 mm in radius. Figure 11 shows the boiling behaviors on the bare wire at heat flux of 0.12 MW/m^3 under microgravity. The generated

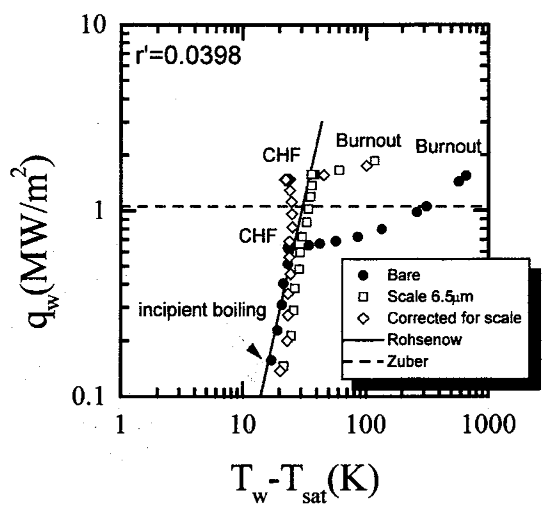

Fig. 9. Boiling curves on bare and scale wire of $r = 0.1$ mm in earth gravity.

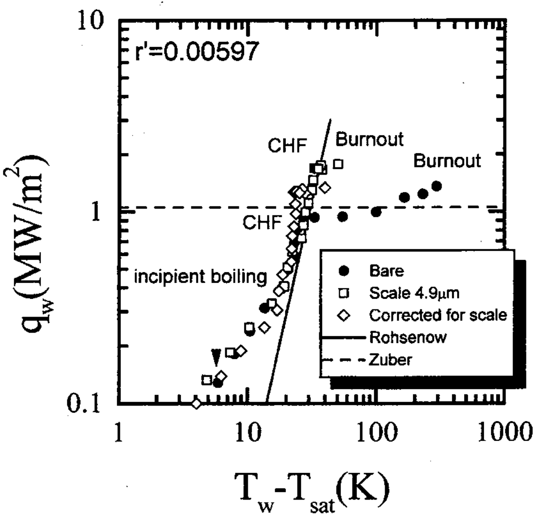

Fig. 10. Boiling curves on bare and scale wire of $r = 0.015$ mm in earth gravity.

bubbles remain on the bare wire due to lack of buoyancy force and move horizontally with the coalescence. Sometimes the coalescing bubbles covered the whole heat transfer surface and finally resulted in burnout. But, on the scale wire shown in Fig. 12, the generated small bubbles immediately detach from the wire without the coalescence. The detaching behavior of bubbles into various directions suppresses the transition to the film boiling on the scale wire.

Shown in Fig. 13 is the relation of heat flux and the time after drop. The electric current was increased every 2 s by 0.5 A with a DC power supply. In the scale wire experiment, the heat flux is increased step-by-step successfully. However, in the bare wire experiment, the heat flux suddenly tends to increase at approximately 3 s after the drop. The generated heat increased due to the increased

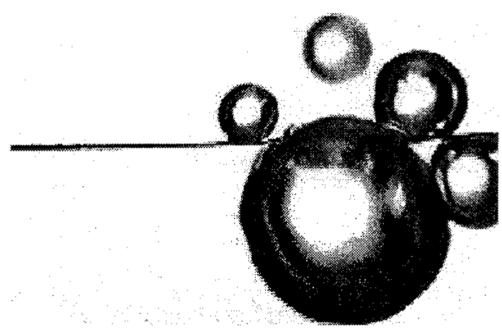

Fig. 11. Boiling behavior on bare wire of $r = 0.1$ mm at heat flux of $q = 0.12$ MW/m^2 in microgravity.

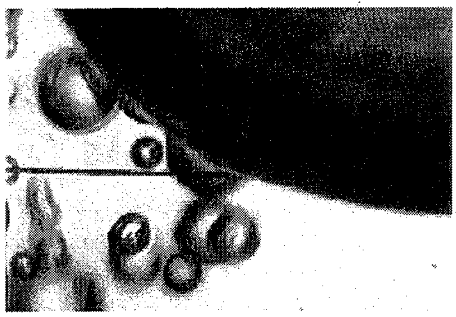

Fig. 12. Boiling behavior on scale wire of r = 0.1 mm at heat flux of q = 0.12MW/m^2 in microgravity.

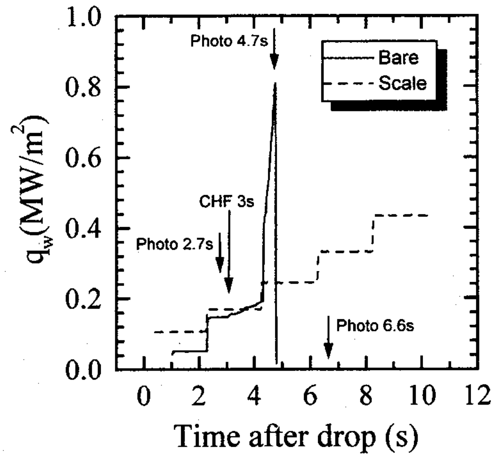

Fig. 13. Heating behavior on bare and scale wire of r = 0.1 mm in microgravity.

temperature and the electric resistance of wire under a constant electric current. The temperature excursion point at 3 s was defined as the CHF.

The corresponding photographs for the bare wire are shown in Fig. 14. At 4.7 s after the drop, a growing and coalescing bubble completely covers the clean bare surface, evaporating all liquid in contact with the surface and inducing a transition to film boiling. A photograph at 6.6 s shows the burnout of the wire. When the coalescing large bubble slightly detaches from the wire, this burnout behavior called "patchy boiling" does not take place. On the other hand, the heat flux of the fouled wire can be increased step-by-step without burnout as shown in Fig. 13. Many small bubbles were

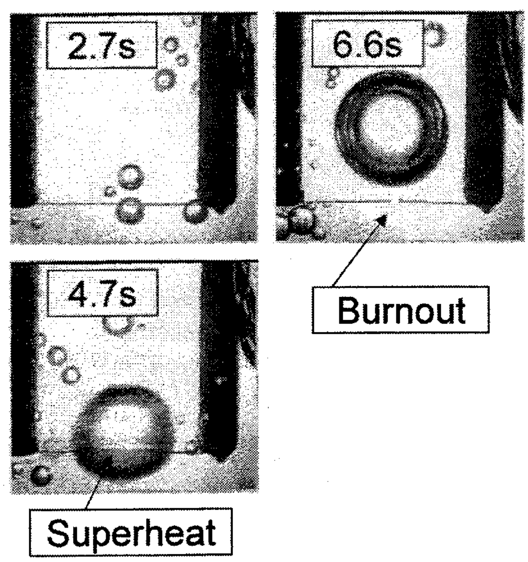

Fig. 14. Burnout behavior on bare wire of r = 0.1 mm in microgravity.

generated and sprang from the scale wire in various directions. The spring out action of bubbles successfully suppressed the transition to the film boiling on the fouled wire in the present experimental range.

Shown in Fig. 15 are the boiling curves for the bare and scale wires in microgravity. The data under earth gravity are also included in the figure for the comparison. The heat flux data on the bare wire under earth gravity and microgravity agree well with Rohsenow's correlation in which the constant c_{sf} is assumed as 0.013. The nucleate heat transfer coefficient on the bare wire did not depend on the gravity levels although the bubbling behavior was greatly affected by the gravity level. Straub et al. [9] reported that the nucleate boiling heat transfer on a platinum wire of 0.1 mm in radius under microgravity obtained in a parabolic flight of an airplane agreed well with those under earth gravity. Due to the heat resistance of scale, the experimental data for the scale wire shift to the right side as shown in Fig. 15. A corrected boiling curve for the scale wire could not be obtained as the thickness of scale was 52 μm and too thick to estimate the heat resistance.

3.3 Effect of wire diameter on critical heat flux

Shown in Fig. 16 is the effect of heated wire size on the CHF ratio, $q_{CHF}/q_{CHF,Z}$. Where q_{CHF} is experimental CHF and $q_{CHF,Z}$ is predictive CHF by Zuber's correlation. The present experimental data for bare and scale wires under earth and micro gravity, data by Sun and Lienhard [10] under earth gravity and data by Siegel and Howell [11] under microgravity are included in Fig. 16. The solid line and the dashed line are the correlations by Sun and Lienhard [10] and Haramura and Katto [12], respectively. The correlation by Sun and Lienhard is

$$\frac{q_{CHF}}{q_{CHF,Z}} = 0.89 + 2.27\exp(-3.44\sqrt{r'}) \quad (r' < 3.47) \tag{3}$$

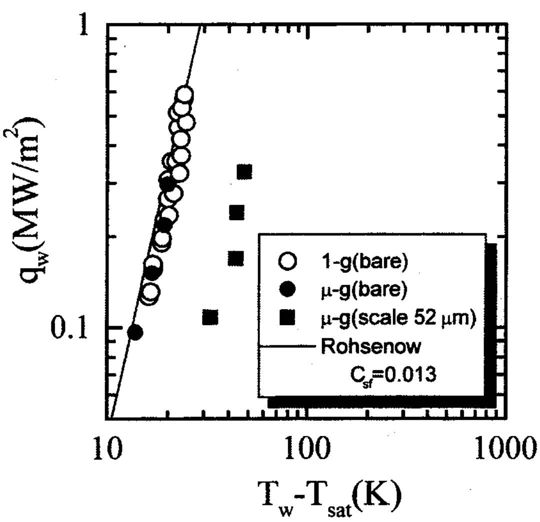

Fig. 15. Boiling curves on bare and scale wire of $r = 0.1$ mm in earth gravity and microgravity.

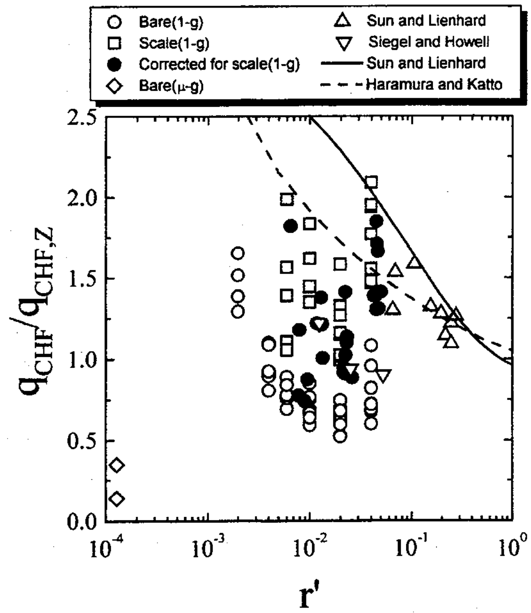

Fig. 16. Effect of wire diameter on CHF.

$$\frac{q_{CHF}}{q_{CHF,Z}} = 0.894 \quad (r' > 3.47)$$

The correlation by Haramura and Katto is

$$\frac{q_{CHF}}{q_{CHF,Z}} = \left(\frac{\sqrt{3}}{r'}\right)^{1/16} \left\{1 + \frac{1}{2(r')^2}\right\}^{1/32} \times \left\{1 + 0.156\left(\frac{\rho_G}{\rho_L}\right)^{0.4} \left(1 + \frac{\rho_G}{\rho_L}\right) \frac{1}{r'(q_{CHF}/q_{CHF,Z})^2}\right\}^{5/16} \tag{4}$$

The non-dimensional radius r' is defined as

$$r' = r/\sqrt{\sigma/g(\rho_L - \rho_G)} \tag{5}$$

In the present platinum wire, the non-dimensional radius r' is between 0.002 and 0.04 in earth gravity. The non-dimensional radius depends on the acceleration due to gravity. The non-dimensional radius of 0.1 mm is approximately 0.04 in earth gravity and is approximately 0.000126 in micro-gravity. In this calculation, the gravity acceleration of 10^{-5} g in microgravity was used.

Sun and Lienhard concluded that the q_{CHF} data started deviating from their prediction and tend to be lower than the predictions for $r' < 0.15$ on the $q_{CHF}/q_{CHF,Z}$ versus r' coordinates. Also in Fig. 16, the experimental data tends to be below the predictions for $r' < 0.15$. Shoji et al. [13] obtained a qualitative relation between CHF and wire diameter from the bubble momentum equation around small wires, similar to those used in the present study, and the stability of the evaporative macro-layer.

The relation indicated that the CHF was maximum at $r' = 0.15$ and decreased with increasing r'. This tendency can be also noticed in the present experimental data including the microgravity data. However the data limited to the bare wire in earth gravity tends to increase at $r' < 0.02$ and the reason needs further investigation.

The CHF on the scale wire is larger than that on the bare wire as shown in Fig. 16. The growing and coalescing bubble stays for a longer duration on the bare wire and sometimes completely covers the wire. On the scale wire, the departure diameter of bubbles is relatively smaller than those on the bare wire. The smaller diameter of bubbles detaching from the scale wire is considered to be due to the higher wettability and the higher nucleation site density. As the result, the coalescence of bubbles near the wire was prevented. The CHF was delayed and increased on the scale wire when compared to that on the bare wire. The scale experiments were not conducted for the wires of 0.005 mm and 0.01 mm in radius because the continuous boiling for long duration to form scale on the wires was difficult.

The CHF on the bare wire in microgravity is significantly reduced when compared to that in earth gravity. The growing and coalescing bubble stays on the bare wire due to lack of buoyancy force and sometimes completely covers the wire even at low heat flux. So the CHF data on the scale wire in microgravity are not in Fig. 16. The smaller diameter of bubbles detached from the scale wire even in microgravity due to the higher wettability. As the result, the coalescence of bubbles near the wire was prevented and the CHF was not observed.

4.4 Effect of scale thickness on critical heat flux

In the present study, a thicker scale could be formed on the wires with a larger radius. Shown in Fig. 17 is relation between the CHF ratio and the thickness of scale in earth gravity. The CHF ratio

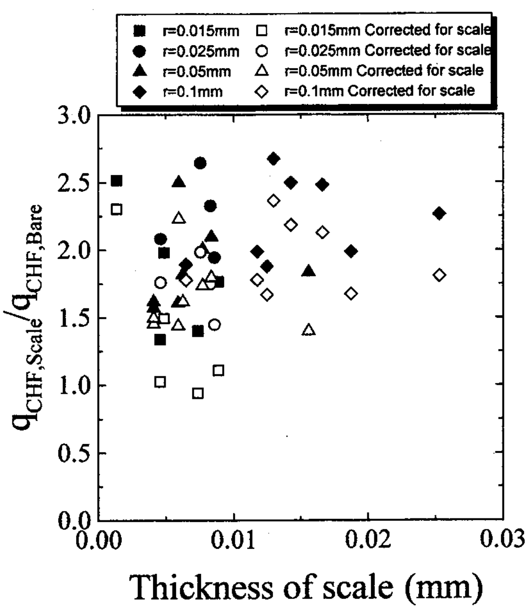

Fig. 17. Effect of scale thickness on CHF.

in the figure is the CHF on the scale wire divided by the average CHF on the bare wire of the same radius. The CHF ratio does not strongly depend on the thickness of scale. Although the data for increases of CHF due to the scale have a wide deviation, it should be noted that the significant increase of the CHF due to the slight formation of scale can be confirmed in the figure. These are considered to be due to the vigorous detaching behavior of small bubbles from the scale wire of high wettability and high nucleation site density.

4. Conclusions

The effects of fouling scale generated with minerals in industrial water on bubbling behavior and boiling heat transfer was experimentally investigated in microgravity and earth gravity. The following are the major results.

1. More vigorous bubbling was observed on the fouled wire compared to that on the clean wire at a same heat flux in earth gravity. The enhancement of the bubbling was associated with the fact that the hydrophilic porous structure in the fouling scale provided a sufficient number of active sites for bubbling nucleation. No significant difference could be observed for the boiling curves of bare and scale wires in spite of the significant difference of the bubbling behavior.

2. The bubbling behavior in microgravity is significantly different from that in earth gravity due to lack of buoyancy force but the nucleate boiling heat transfer coefficient was approximately the same. On the bare wire in microgravity, the growing bubble stayed on the wire and sometimes covered the whole heat transfer wire resulting in burnout even at the low heat flux. However, on the scaled wire, many small bubbles were generated and detached in various directions. As a result, the coalescence of bubbles near the wire was prevented, and the CHF was delayed and increased on the scaled wire compared to that of the bare wire.

3. Also in earth gravity condition, the CHF on the scaled wire is larger than that of the bare wire. The growing and coalescing bubble stay for a longer duration on the bare wire and sometimes completely covers the wire. On the scaled wire, the easy detaching behavior of bubbles resulted as the higher CHF. The significant increase of the CHF due to a slight formation of scale can be confirmed.

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