EFFECT OF FOULING ON NUCLEATE POOL BOILING IN MICROGRAVITY AND EARTH GRAVITY

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ABSTRACT

Nucleate pool boiling of water on clean and fouling surfaces was conducted in microgravity and earth gravity. The microgravity experiments were conducted in 8 s JAMIC drop shaft in Hokkaido of Japan. Platinum wires of 0.2 mm in diameter with or without fouling scale were used to provide uniform heat flux and measurement of the mean temperature of wires. The generated bubble volume was measured with high-speed video or CCD images.

The more vigorous bubbling was observed on the fouling wire compared to that on the clean wire at a same heat flux both in earth gravity and microgravity. The enhancement of the bubbling was associated with the fact that the hydrophilic porous structure in the fouling scale provided the sufficient number of active sites for bubbling nucleation. The wettability of the surface with the fouling scale was much higher than that of the clean bare surface. The bubble departure diameter on the fouling wire was smaller due to the high wettability than that on the clean wire. The latent heat transportation ratio to the total heat flux was calculated with the generated bubble volume measured with high-speed video or CCD images. The ratio was approximately the same at the clean and fouling wires in spite of the apparent difference in bubbling behavior, but it was significantly affected with the gravity level. The ratio increased with an increase of the heat flux in the earth gravity but it remained at the smaller value in the microgravity. The nucleate heat transfer coefficient on the bare surface did not depend on the gravity levels although the bubbling behavior strongly affected with the gravity level.

As the wire radius is small compared to the capillary length scale in microgravity, a growing and coalescing bubble sometimes completely covered the clean wire, evaporating all liquid in contact with the surface and inducing a transition to film boiling. However, on the fouling wire, many small bubbles were generated and sprang from the surface in various directions in microgravity. The spring out action of bubbles suppressed the transition to the film boiling on the fouling wire in the present experimental range.

NOMENCLATURE

c_d: bubble drag coefficient
c_{pL}: specific heat
c_{sf}: constant in Rohsenow's correlation
d_d: bubble departure diameter
f: bubble departure frequency
g: acceleration due to gravity
h_{LG}: latent heat
Pr: Prandtl number [$= \nu / \kappa$]
q: heat flux
r_w: radius of platinum wire
T: temperature
ΔT_{sat}: superheat
δ: thickness of scale
κ: thermal diffusivity
λ: heat conductivity
μ: viscosity
ν: kinematic viscosity
ρ: density
σ: surface tension

subscript
G: steam, L: liquid, SC: scale, W: wall

INTRODUCTION

The nucleate boiling heat transfer is considered to be one of the most important heat transfer process due to its high heat transfer coefficient. However, the heat transfer is significantly reduced with a fouling on the heat transfer surface. Scale formation in boiler and plants leads to the lower efficiency because of the reduction in heat transfer rates. Overheating and tube failures may result, and often the high cost of chemical cleaning may be entailed. For the other disadvantage of the fouling, Osakabe and Isono(1996) reported that the fouling scale in the hot water relief valve significantly reduced the critical flow rate. It was considered that the fouling scale enhanced the boiling in the flashing flow and reduced the nonequilibrium. The typical constituents of scales and deposits in boilers are calcium carbonate, calcium sulphate, calcium phosphate, magnesium hydroxide, magnesium phosphate, complex silicates of magnesium, iron, sodium, calcium and aluminum. The salts of calcium and magnesium are the major source of scale problems.

The previous basic studies have been focuses on the nucleate boiling on surfaces without the fouling and were summarized in the literatures [Carey, 1992 and Tome, 1989]. The nucleate boiling data on surfaces with the fouling are scarce though the actual heat transfer surfaces in boilers and plants are frequently contaminated and covered with the fouling scale. In the previous studies [Osakabe et. al., 1998; Haze et. al., 1999], the nucleate pool boiling on surfaces with a scale of calcium carbonate and silicon coating was conducted. The more vigorous bubbling was observed on the scale and coating surfaces compared to that on a clean mirror-finished copper surface at a same heat flux. The enhancement of the bubbling was associated with the fact that the porous structure both in the scale and silicon coating provided the sufficient number of active sites for bubbling nucleation. The nucleate heat transfer coefficient on the silicon coating of the hydrophobic porous structure was higher than that on the bare surface. In some boiling experiments [Young et. al., 1965 and Vachon et. al., 1969], the enhancement of nucleate boiling heat transfer was observed with the hydrophobic porous structure such as Teflon. It is reasonable that the increase of nucleation density increases the heat transfer. However, the heat transfer coefficient on the scale surface of the hydrophilic porous structure was approximately the same as that on the bare surface in spite of the increase of nucleation density. Liaw & Dhir (1989) reported that the nucleate boiling heat transfer was enhanced with an increase of void fraction near the boiling surface due to a decrease of surface wettability. It was considered that the enhancement due to an increase of nucleation density was strongly affected with the surface wettability.

In the previous study under microgravity, it is believed that the influence of gravity on the nucleate pool boiling is very small [Straub et. al., 1990]. However, very few experiments were made to prove the effect of fouling under microgravity. It is very interesting to investigate the effect of surface wettability under microgravity comparing the boiling behaviors on the bare and fouling surfaces. Nucleate pool boiling on clean and fouling surfaces was conducted in microgravity and earth gravity in the present study.

EXPERIMENTAL APPARATUS AND METHOD

Shown in Fig.1 is schematic diagram of experimental apparatus. Distilled or industrial water was filled in a transparent vessel made of polycarbonate. The wall thickness was 10 mm to reduce the heat loss. The major impurity included in the industrial water was salts of calcium. Platinum wires of 0.2 mm in diameter with or without fouling scale were used to provide uniform heat flux and measurement of the mean temperature of wires. The wire was supported with two SUS poles of 6mm in diameter at an interval of 30 mm. The heat flux was calculated with the measured voltage between the poles and the electric current which was estimated from the voltage drop at a standard resistance of 0.005Ω. The measurement error of heat flux was within ±1%. In the present study, the heat flux was defined at the surface of platinum wire even in the fouling experiments. The mean temperature was determined with the calibrated relation of resistance and temperature of platinum wire.

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 8 s JAMIC drop shaft in Hokkaido of Japan. The generated bubble volume was measured with high-speed video or CCD images.

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

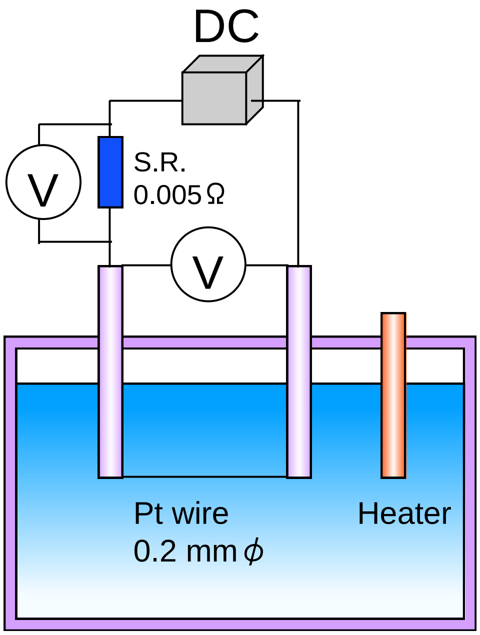

Fig. 1 Schematic of experimental apparatus

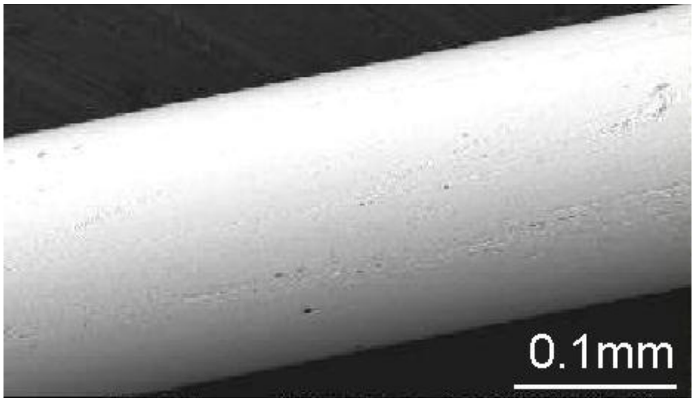

Fig. 2 Electron micrograph of bare surface

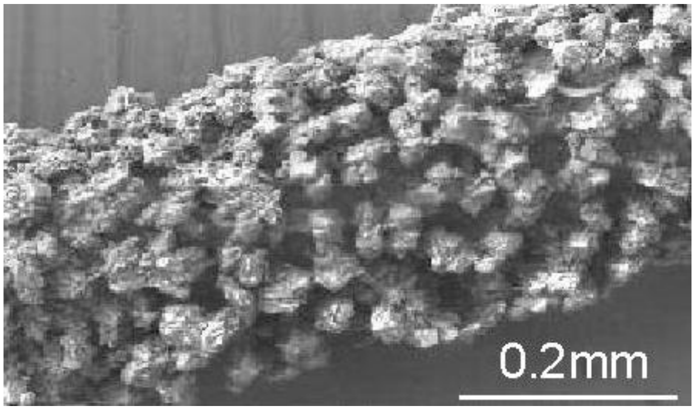

Fig. 3 Electron micrograph of scale surface

Table 1 Major component of scale except carbon and oxygen

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

Shown in Table.1 is the measured component with a x-ray diffractometer 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 present scale mainly consists of calcium carbonate.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Experiments under earth gravity

Shown in Figs.4 and 5 are boiling behaviors on the bare and scale surfaces, respectively, at the same heat flux of 0.2 MW/m^2 under earth gravity. The more vigorous bubbling was observed on the scale surface compared to that on the bare surface at the same heat flux. The enhancement of the bubbling was associated with the fact that the hydrophilic porous structure in the fouling scale provided the sufficient number of active sites for bubbling nucleation. The wettability of the scale surface was much higher than that of the clean bare surface. The bubble departure diameter on the fouling wire was smaller due to the high wettability than that on the clean wire.

Based on an analogy between the bubble release process and natural convection, Zuber(1963) suggested the following relation between bubble departure frequency, f, and diameter , d_d :

$$fd_d = 0.59\left[\frac{\sigma g(\rho_L - \rho_G)}{\rho_L^2}\right] \quad (1)$$

The inverse of the frequency is the time period associated with the growth of each bubble. The time periods are equal to the sum of the waiting period and the time required for the bubble to grow to its departure diameter.

Fig. 4 Boiling behavior on bare surface at heat flux of 0.2 MW/m^2 under earth gravity

Fig. 5 Boiling behavior on scale surface at heat flux of 0.2 MW/m^2 under earth gravity

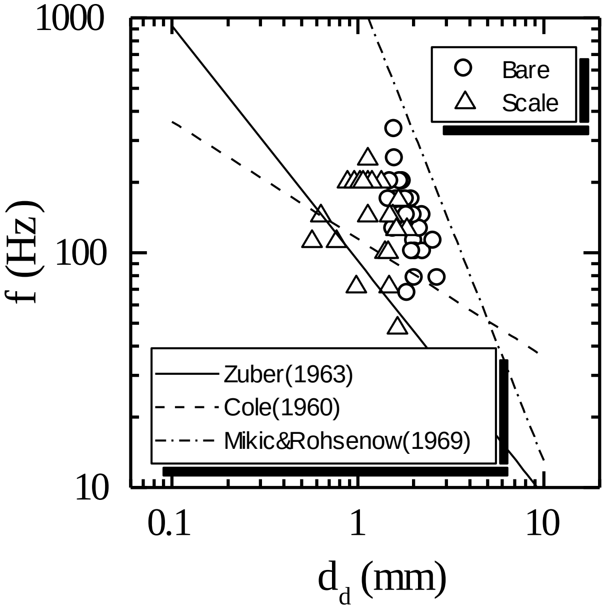

Fig. 6 Relation of bubble departure frequency and diameter on bare and scale surfaces.

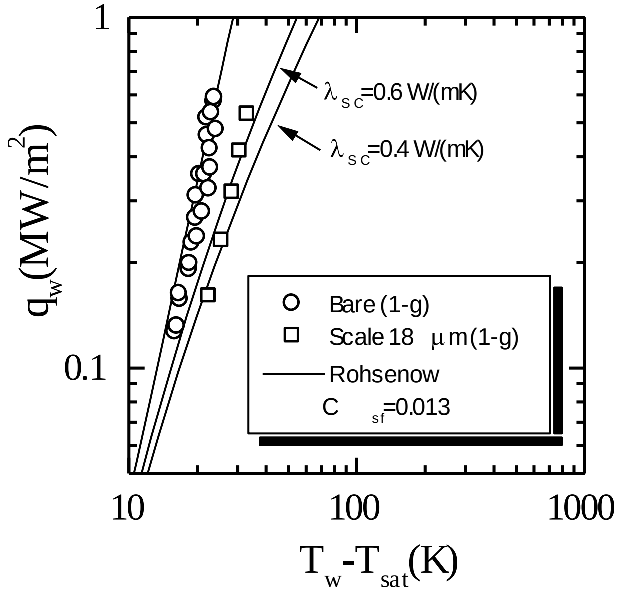

Fig. 7 Boiling curves for bare and scale surfaces under earth gravity

Ivey(1967) proposed the two kinds of relation corresponding to the regime of bubble growth as,

$f^2 d_d = \text{const}$ for inertia controlled growth

$f^{1/2} d_d = \text{const}$ for heat transfer controlled growth

It is considered that the inertia associated with the induced water flow due to the bubble growth tends to pull the bubble away from the surface. For the inertia controlled growth, Cole(1960) proposed the relation as,

$$f^2 d_d = \frac{4g(\rho_L - \rho_G)}{3C_d \rho_L} \tag{2}$$

where C_d: bubble drag coefficient (approximately 1 for water at atmospheric pressure). For the heat transfer controlled growth, Mikic and Rohsenow(1969) proposed the relation as,

$$f^{1/2} d_d = 0.83 \frac{\Delta T_{sat} c_{pL} \rho_L}{\rho_G h_{LG}} \sqrt{\pi \kappa_L} \tag{3}$$

Shown in Fig.6 is the relation between bubble departure frequency, f, and diameter , d_d on the bare and scale surface. The relation on the bare surface is close to the correlation for the heat transfer controlled growth by Mikic and Rohsenow (1969). The departure diameter on the scale surface is slightly smaller than that on the bare surface. Some data on the scale surface tend to agree well with the correlation for the inertia controlled growth by Cole(1960). It is suggested that the high wettability on the scale surface induces the water flow to pull the bubble away and the relation tends to agree well with the correlation for the inertia controlled growth.

Numerous experiments of the nucleate boiling heat transfer has been conducted to understand the transport mechanism. Rhosenow's model(1952) is based on the assumption that the bubble growth and release induces motions of surrounding water that facilitates the convective heat transfer. When the wire of r_w in radius is covered with the scale of thickness δ, the well-known Rohsenow's correlation becomes,

$$q_w = \mu_L h_{LG} \sqrt{\frac{g(\rho_L - \rho_G)}{\sigma}} \left(\frac{c_{pL} \Delta T_{sat}}{c_{sf} h_{LG}} \right)^3 Pr_L^{-5.1} (1 + \delta / r_w) \tag{4}$$

Through the present study including the above Eq.(4), the heat flux is defined at the surface of platinum wire. The value of c_{sf} is recommended for different liquid-solid combination. A value of 0.013 is recommended as a first approximation. The heat resistance of scale gives the following relation between the wire surface temperature, T_w, and the scale surface temperature, T_{SC}.

$$q_w = \frac{\lambda_{SC}(T_w - T_{SC})}{r_w \ln(1 + \delta / r_w)} \tag{5}$$

Previous study(Japan Boiler Association, 1984) for the calcium carbonate scale as same as the present study showed its heat conductivity was approximately 0.6~0.4W/(mK). In the calculation for the scale surface, heat conductivity of scale was assumed as 0.6~0.4W/(mK) and the wall superheat in the Rohsenow's correlation was defined as,

$$\Delta T_{sat} = T_{SC} - T_{sat} \qquad (6)$$

Shown in Fig.7 is the boiling curves for the bare and scale sufaces under earth gravity. The thickness of the scale was 18μm in the experiment. The heat flux on the bare surface agrees well with the Rohsenow's correlation in which the constant c_{sf} is assumed as 0.013. When the heat resistance of scale is considered with Eqs. (5) and (6), the prediction by the Rohsenow's correlation shifts to the right side as shown in Fig.7. The prediction taking account of the heat resistance agrees well with the experimental data. The previous study showed that the nucleate heat transfer coefficient on the silicon coating of the hydrophilic porous structure was higher than that on the bare surface. However, the nucleate heat transfer coefficient on the scale surface of the hydrophobic porous structure was approximately the same as that on the bare surface. The present results also indicate that the boiling heat transfer on the scale surface is approximately the same as that on the bare surface in spite of the increase of the nucleation density.

Experiments under microgravity

The microgravity experiments were conducted in JAMIC drop shaft in Hokkaido of Japan with a drop height of 500m and a 8 second drop time. The quality of the microgravity was approximately 10^{-5}g. Before and during the microgravity condition, the water temperature was kept at the saturation temperature by using a back-up heater. After the drop initiation, the boiling experiments were conducted with increasing the heat flux of platinum wire step by step.

Figures 8 and 9 show the boiling behaviors on the bare and scale surfaces, respectively, under microgravity. The generated bubbles remain and move horizontally with coalescent on the bare surface. But, on the scale surface, the generated bubbles immediately detach from the surface without coalescent.

The capillary length scale, L, is defined as,

$$L = \sqrt{\frac{\sigma}{g(\rho_L - \rho_G)}} \qquad (7)$$

In the present platinum wire, the non-dimensional radius r_w/L is approximately 0.04. For the small wire compared to the capillary length, the initial bubble generated on the wire grows and spreads until the wire is partially blanketed with a vapor patch. Bakhru and Lienhard(1972) concluded that the local minimum and maximum observed in the usual boiling curve vanish for $r_w/L<0.01$. They referred to this as "patchy boiling". As the wire radius is small compared to the capillary length scale in microgravity, it is possible that a growing and coalescing bubble sometimes completely covers the wire and results as the low heat flux burnout.

Fig. 8 Boiling behavior on bare surface at heat flux of 0.12 MW/m^2 under microgravity

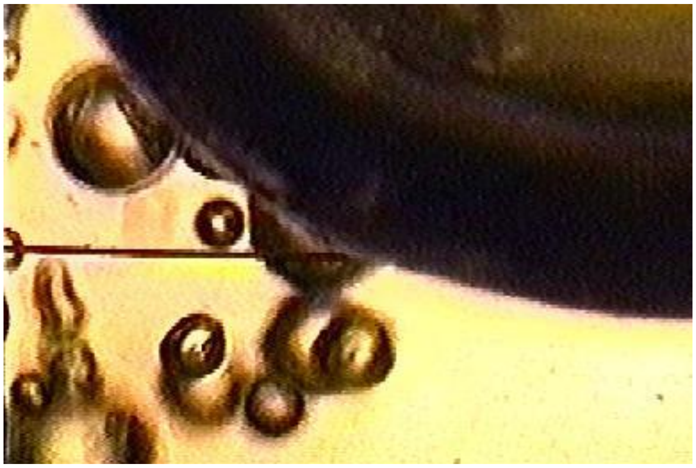

Fig. 9 Boiling behavior on scale surface at heat flux of 0.12 MW/m^2 under microgravity

Shown in Fig.10 is the relation of heat flux and the time after drop. In the scale surface experiment, the heat flux is increased step by step successfully. However, in the bare surface experiment, the heat flux suddenly tends to increase at approximately 4.4 s after the drop. The corresponding photographs for the bare surface are shown in Fig.11. At 4.7 s after the drop, a growing and coalescing bubble completely covers the clean bare wire, evaporating all liquid in contact with the surface and inducing a transition to film boiling. Photograph at 4.7 s shows the superheated wire in the large bubbles. However, on the fouling wire, many small bubbles were generated and sprang from the surface in various directions in microgravity. The spring out action of bubbles suppressed the transition to the film boiling on the fouling wire in the present experimental range.

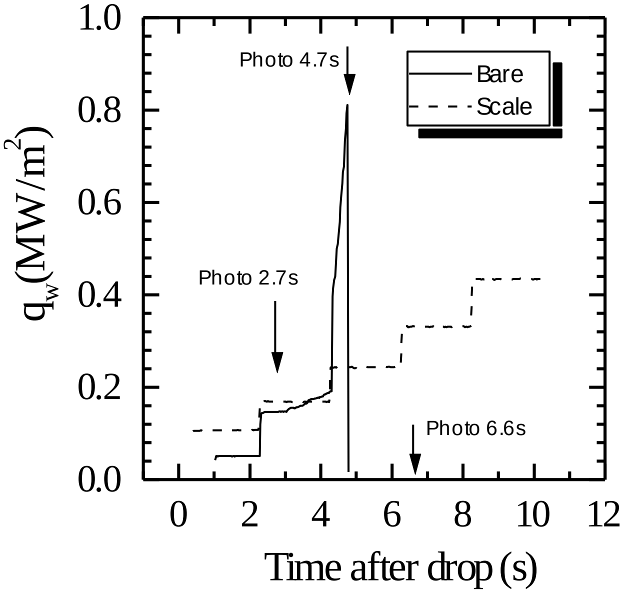

Fig. 10 Low heat flux burnout of bare wire under microgravity

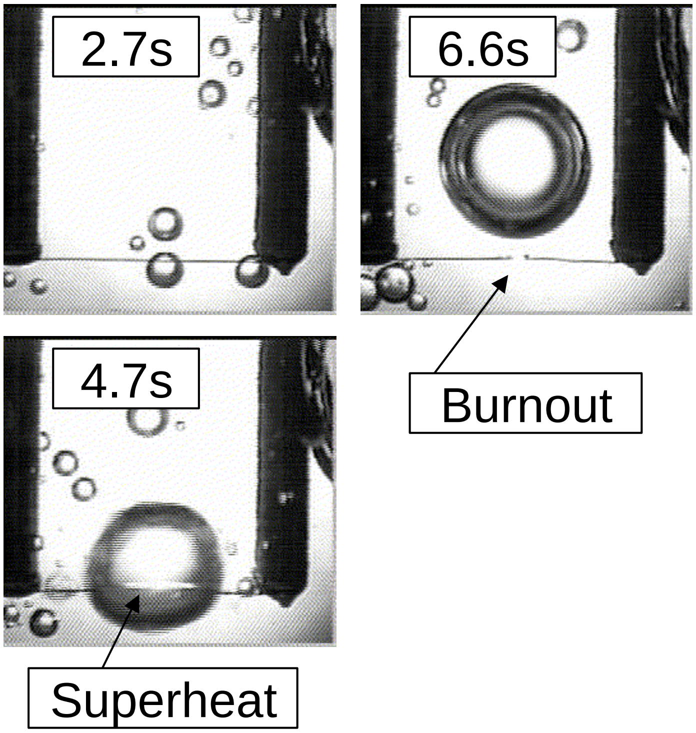

Fig. 11 Photographs for low heat flux burnout of bare wire under microgravity

Shown in Fig.12 is the boiling curves for the bare and scale surfaces under microgravity. The data under earth gravity are also included in the figure for the comparison. The heat flux data on the bare surface under earth gravity and microgravity agree well with the Rohsenow's correlation in which the constant c_{sf} is assumed as 0.013. The nucleate heat transfer coefficient on the bare surface does not depend on the gravity levels although the bubbling behavior strongly affected with the gravity level. Straub et. al. (1990) also reported that the nucleate boiling heat transfer on a pratinum wire of 0.2 mm in diameter under microgravity obtained in a parabolic flight of airplane agreed well with that under earth gravity.

The thickness of the scale was 52μm in the microgravity experiment. When the heat resistance of scale is considered with Eqs. (5) and (6), the prediction by the Rohsenow's correlation shifts to the right side as shown in Fig.12. The experimental data tend to approach to the prediction taking account of the heat resistance at the high heat flux region. The nucleate boiling heat transfer coefficient on the scale surface of the hydrophilic porous structure was approximately the same as that on the bare surface at the high heat flux region under microgravity. It should be noted that the increase of nucleation density does not results as the increase of heat flux on the high wettability surface such as the fouling scale.

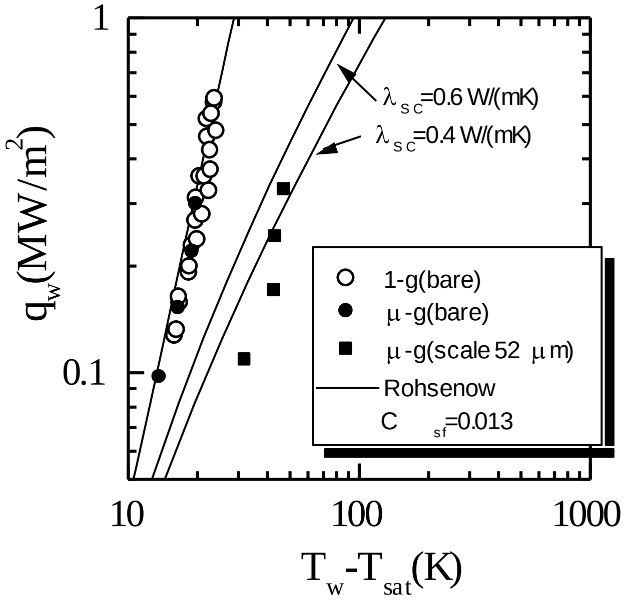

Fig. 12 Boiling curves on bare and scale surface under microgravity

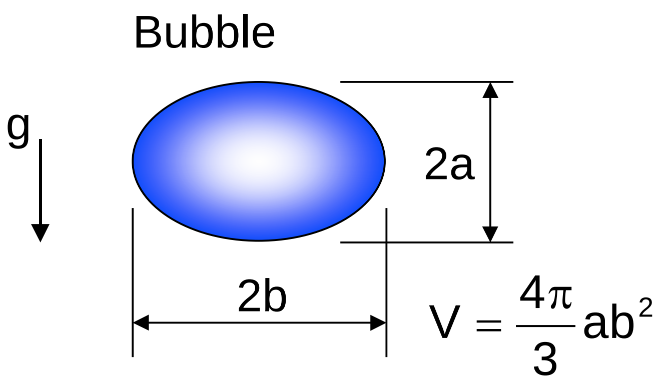

Fig. 13 Calculation model for a bubble volume

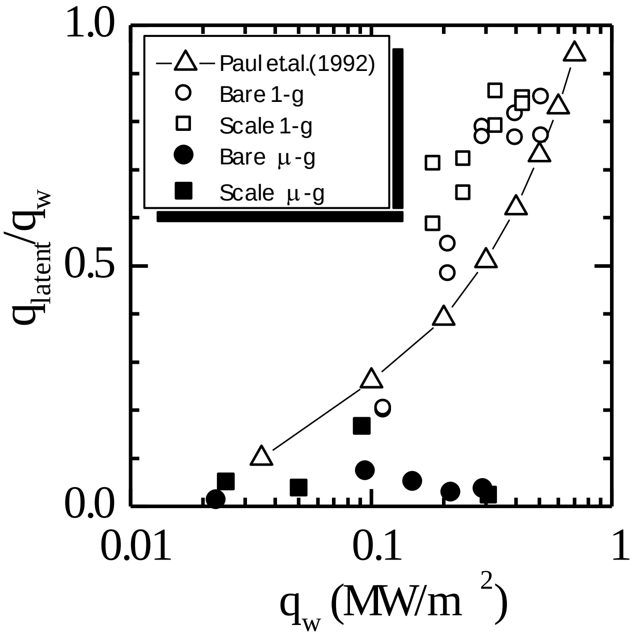

Fig. 14 Latent heat transportation ratios

The latent heat transportation ratio to the total heat flux was calculated with the generated bubble volume measured with high-speed video or CCD images. A bubble was assumed as an ellipsoid as shown in Fig.13. The measured horizontal and vertical distances give the generated volume as,

$$V = \frac{4\pi}{3} ab^2 \qquad (8)$$

The maximum errors for the measured volume of a typical bubble are ±3% in earth gravity experiments and ±30% in microgravity experiments if the error due to the deformation from the ellipsoid is neglected. The latent heat transportation heat flux is defined as,

$$q_{latent} = \frac{h_{LG}}{A} \frac{1}{t} \int_0^t V dt \qquad (9)$$

where A is the heat transfer area. The time duration to take an average was typically 1s in the microgravity experiment and 0.2s in the earth gravity experiment.

Shown in Fig.14 are the latent heat transportation ratios to the wall heat flux on the bare and scale surfaces under earth gravity and microgravity. The measured data by Paul et. al. (1992) were obtained on a bare platinum wire of 0.3 mm in diameter under earth gravity. The ratio was approximately the same at the clean and fouling wires in spite of the apparent difference in bubbling behavior, but it was significantly affected with the gravity level. The ratio increased with an increase of the heat flux in the earth gravity but it remained at the smaller value in the microgravity. These results indicate that the heat transfer mechanism on the scale surface is approximately the same as that on the bare surface, but the mechanism under microgravity is different from that under earth gravity in spite of the same boiling curve. It is considered that the sensible heat transportation plays a more important role on the nucleate boiling heat transfer under microgravity.

CONCLUSION

Nucleate pool boiling of water on clean and fouling surfaces was conducted in microgravity and earth gravity. The followings are major results.

1. The more vigorous bubbling was observed on the fouling wire compared to that on the clean wire at a same heat flux both in earth gravity and microgravity. The enhancement of the bubbling was associated with the fact that the hydrophilic porous structure in the fouling scale provided the sufficient number of active sites for bubbling nucleation.
2. The nucleate boiling heat transfer coefficient on the bare surface did not depend on the gravity levels although the bubbling behavior strongly affected with the gravity level.
3. As the wire radius is small compared to the capillary length scale in microgravity, a growing and coalescing bubble sometimes completely covered the clean wire, evaporating all liquid in contact with the surface and inducing a transition to film boiling. However, on the fouling wire, many small bubbles were generated and sprang from the surface in various directions in microgravity. The spring out action of bubbles suppressed the transition to the film boiling on the fouling wire in the present experimental range.
4. The relation between bubble departure frequency and diameter on the bare surface is close to the correlation for the heat transfer controlled growth under earth gravity. The departure diameter on the scale surface is slightly smaller than that on the bare surface. Some data on the scale surface tends to agree well with the correlation for the

inertia controlled growth. It is suggested that the high wettability on the scale surface induces the water flow to pull the bubble away and the relation tends to agree with the correlation for the inertia controlled growth.

5. The latent heat transportation ratio was approximately the same at the clean and fouling wires in spite of the apparent difference in bubbling behavior, but it was significantly affected with the gravity level. The ratio increased with an increase of the heat flux in the earth gravity but it remained at the smaller value in the microgravity. It is considered that the sensible heat transportation plays a more important role on the nucleate boiling heat transfer under microgravity.

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