EFFECT OF FOULING ON NUCLEATE POOL BOILING AND CRITICAL HEAT FLUX

Yusuke FUKADA, Ikuya HAZE, Sachiyo HORIKI and Masahiro OSAKABE

Tokyo University of Mercantile Marine, Koutou-ku, Tokyo 135-8533, Japan
Phone & FAX +81-3-5245-7404
E-Mail osakabe＠ipc.tosho-u.ac.jp

Keywords: Wettability, Fouling, Micro Gravity, Pool boiling

ABSTRACT

Pool boiling experiment with a platinum wire was performed in earth and micro gravity. Bare surface and fouling surface with scale of calcium carbonate was used. The wettability on the scale surface was higher than that on the bare surface. The critical heat flux (CHF) was measured and movies of the bubbling were taken with a high-speed video camera. The more vigorous bubbling was observed on the scale surface compared to that on the bare surface at the same heat flux. The scale surface became thermal resistance and the boiling curve on the scale surface eventually shifted to the right side of that on the bare surface. However, the critical heat flux on the scale surface was higher than that on the bare surface. On the scale surface, the departure diameter of bubbles is relatively smaller than that on the bare surface. The smaller diameter of bubbles detaching from the scale surface is considered to be due to the high wettability. As the result, the coalescent of bubbles near the surface was prevented and the CHF was delayed and increased on the scale surface compared to that on the bare surface.

NOMENCLATURE

c_p: specific heat
c_{sf}: constant in Rohsenow's correlation
d: diameter of cylinder
g: acceleration due to gravity
h_{LG}: latent heat
Pr: Prandtl number [$= \nu / \kappa$]
q: heat flux
$q_{CHF,Z}$: critical heat flux predicted by Zuber's correlation
r_w: radius of platinum wire
T: temperature
ΔT_{sat}: superheat
κ: thermal diffusivity
λ: heat conductivity
μ: viscosity
ν: kinematic viscosity
ρ: density
σ: surface tension

subscript
G: steam, L: liquid, 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, when the layer of the scale is formed on the heated surface, the heat transfer coefficient decreases rapidly and sometimes results as a burnout. Therefore some kinds of water treatment are conducted for boilers and thermal plants. The previous studies have been focused on the thermal resistance of scale but the boiling characteristics on the scale surface has not been investigated in detail.

The scale increases the heat resistance and the number of nucleate sites because of its porous structure, which changes surface wettability and decreases the surface heat conductivity. 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 Thome, 1989]. The nucleate boiling data on scale 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., 1997; 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 the previous study under micro gravity, 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 micro gravity. It is very interesting to investigate the effect of surface wettability under micro gravity comparing the boiling behaviors on the bare and fouling surfaces. Nucleate pool boiling on clean and fouling surfaces was conducted in micro gravity and earth gravity in the present study.

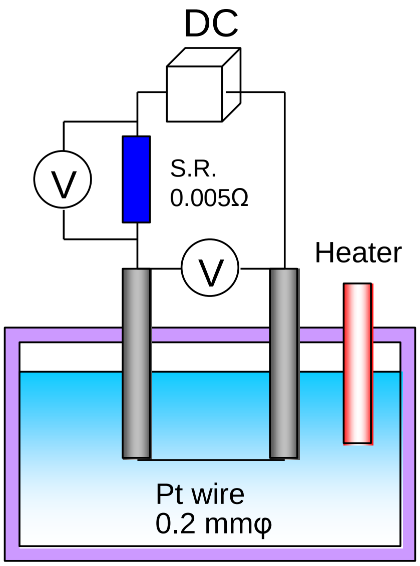

Fig. 1 Schematic of experimental apparatus

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 6 mm in diameter at an interval of 30 mm.

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 0.005Ω. The measurement error of heat flux was within ±1%. In the present study, the heat flux was defined at the surface of platinum wire or scale surface. The average temperature was determined with the calibrated relation of resistance and temperature of platinum wire. The variation between the time-averaged and instantaneous temperature of wire was within ±2.5 K.

The experiments were conducted at the saturated temperature of atmospheric pressure in micro and earth gravity. A back-up heater was used to maintain the saturation temperature.

The micro gravity experiments were conducted in JAMIC drop shaft in Hokkaido of Japan. The drop time is 10 seconds and the quality of the micro gravity is approximately 10^{-4} g. 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. The surface temperature of scale was estimated with the average thickness and the heat conductivity.

Shown in Table.1 is the measured component 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 present scale mainly consists of calcium carbonate.

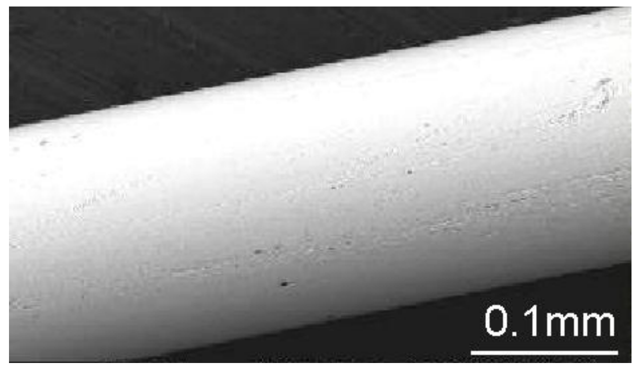

Fig. 2 Electron micrograph of bare surface

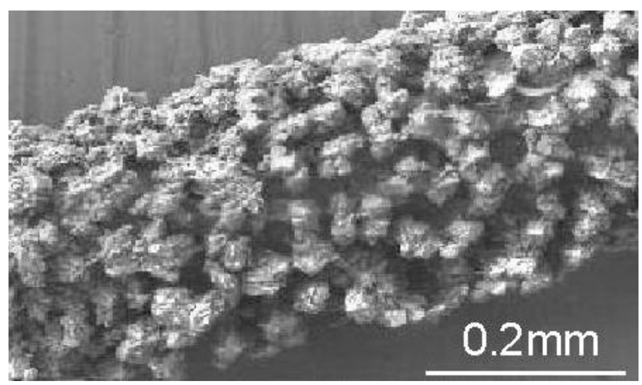

Fig. 3 Electron micrograph of scale surface

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

EXPERIMENTAL RESULTS AND DISCUSSIONS

Experiments under earth gravity

Shown in Fig.4 and Fig.5 are boiling behaviors on the bare surface and scale surface at a same heat flux under earth gravity, respectively. The more vigorous bubbling was observed on the scale surface compared to that on the bare surface. 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.

Shown in Fig.6 and Fig.7 are photograph for burnout of the bare surface and the scale surface, respectively. On the bare surface, a part of heated surface was covered with bubbles and burnout gradually. On the scale surface, a growing and coalescing bubbles completely covers the wire and burnout. The scale surface did the burnout at short time compared with the bare surface.

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

Shown in Fig.8 are the boiling curves for the bare and scale surfaces under earth gravity. The average platinum wire temperature or the scale surface temperature corrected with the average thickness of scale is used in the boiling curves for the scale surface. The solid line in Fig.8 is Rohsenow's correlation (1952) shown as,

$$q_w = \mu_L h_{LG}\sqrt{\frac{g(\rho_L-\rho_G)}{\sigma}}\left(\frac{C_{pL}\Delta T_{sat}}{C_{sf}h_{LG}}\right)^3 Pr_L^{-5.1} \qquad (1)$$

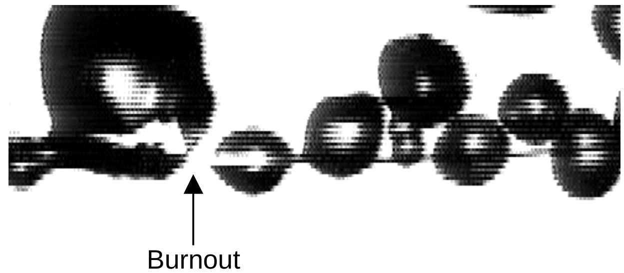

Fig. 6 Burnout of bare surface

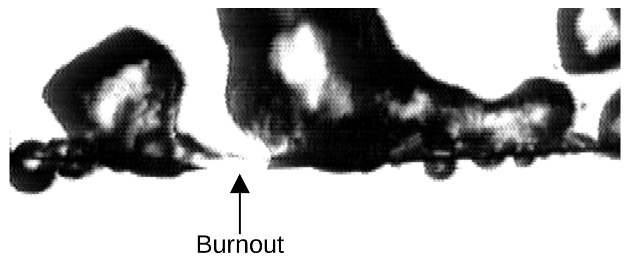

Fig. 7 Burnout of scale surface

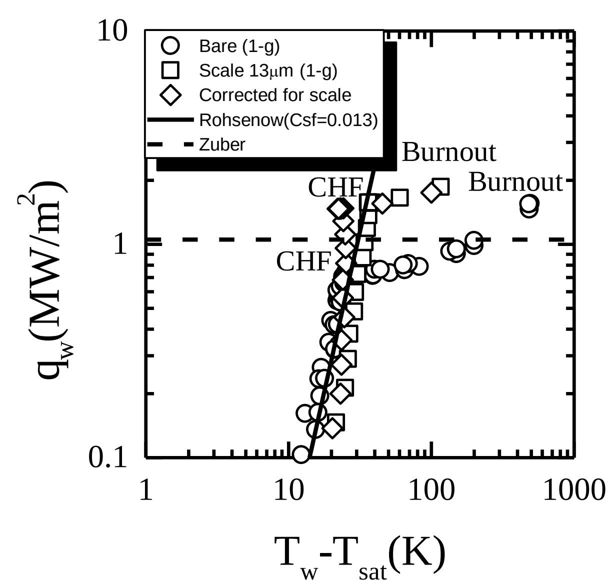

Fig. 8 Boiling curve on for bare surface and scale surface under earth gravity

The boiling curve on the bare surface agrees well with Rohsenow's correlation in which the constant c_{sf} is assumed as 0.013. The scale surface became thermal resistance and the boiling curve on the scale surface eventually shifted to the right side of that on the bare surface.

In the previous study (Haze et al., 2000), the heat conductivity of the scale made of calcium as a main component was approximately 0.7W/(mK). When the heat flux and the superheat on the actual scale surface were calculated with the average scale thickness and the heat conductivity of 0.7W/(mK). The boiling curve on the actual scale surface almost agrees with on the bare surface.

The dashed line in Fig.8 is Zuber's correlation (1958) shown as,

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

Although a platinum wire was used in the present study, Zuber's correlation for the critical heat flux of a horizontal flat plate was compared as a reference. The critical heat flux was defined at DNB (Departure from Nucleate Boiling). The critical heat flux on the bare surface was lower than Zuber's correlation. The critical heat flux on the scale surface was higher than that on the bare surface though the scale became the thermal resistance. It is considered that the higher critical heat flux on the scale surface than that on the bare surface is caused by the smaller diameter of bubbles detaching from the scale surface. The detaching bubbles prevent the coalescent of bubbles near the surface and delay the CHF. The smaller diameter of bubbles detaching from the scale surface is considered to be due to the high wettability.

Experiments under micro gravity

The micro gravity experiments were conducted in JAMIC drop shaft in Hokkaido of Japan with a drop height of 500m and 10-second drop time. The quality of the micro gravity was approximately 10^{-4}g. Before and during the micro gravity 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 9 and 10 show the boiling behaviors on the bare and scale surfaces, respectively, under micro gravity. The generated bubbles remain and move horizontally with coalescence on the bare surface. But, on the scale surface, the generated bubbles immediately detach from the surface without coalescence.

The capillary length scale, L, is defined as,

$$L = \sqrt{\frac{\sigma}{g(\rho_L - \rho_G)}} \quad (3)$$

In the present platinum wire, the non-dimensional radius r_w/L is approximately 0.04 in earth gravity. 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 micro gravity, it is possible that a growing and coalescing bubble sometimes completely covers the wire and results as the low heat flux burnout.

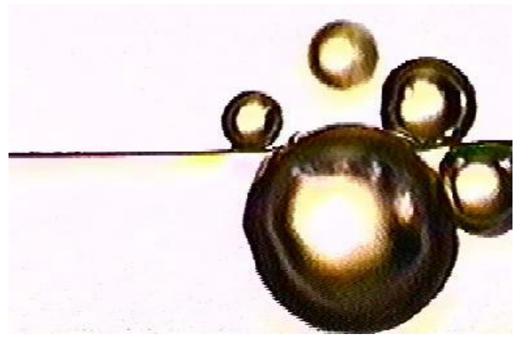

Fig. 9 Boiling behavior on bare surface at heat flux of 0.12 MW/m^2 under micro gravity

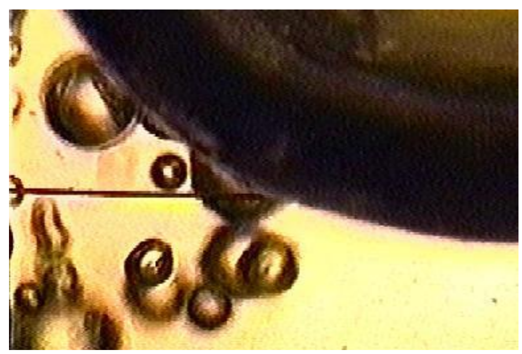

Fig. 10 Boiling behavior on scale surface at heat flux of 0.12 MW/m^2 under micro gravity

Shown in Fig.11 is the relation of heat flux and the time after drop. The electric current was increased every 2s by 0.5A with a DC power supply. 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 3 s after the drop. The generated heat increased due to the increase of temperature and electric resistance of wire under a constant electric current. The temperature excursion point at 3 s was defined as the critical heat flux (CHF).

The corresponding photographs for the bare surface are shown in Fig.12. 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 covered with the large bubbles. However, on the fouling wire, many small bubbles were generated and sprang from the surface in various directions in micro gravity. The spring out action of bubbles suppressed the transition to the film boiling on the fouling wire in the present experimental range.

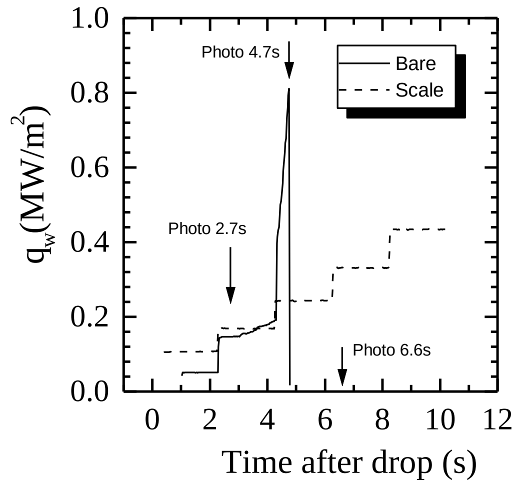

Fig. 11 Low heat flux burnout of bare wire under micro gravity

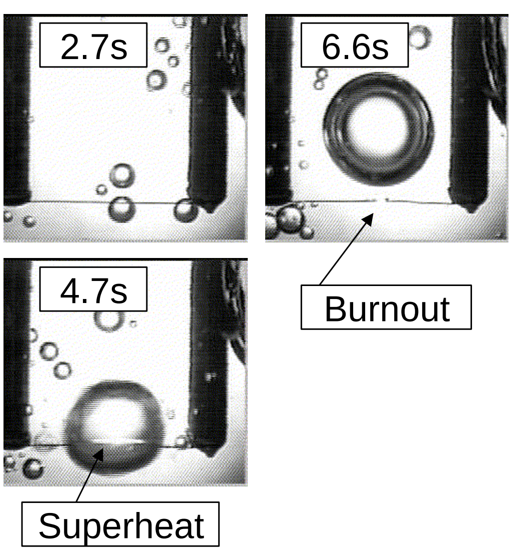

Fig. 12 Photographs for low heat flux burnout of bare wire under micro gravity

Shown in Fig.13 is the boiling curves for the bare and scale surfaces under micro gravity. 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 micro gravity 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 surface did not depend on the gravity levels although the bubbling behavior strongly affected with the gravity level.

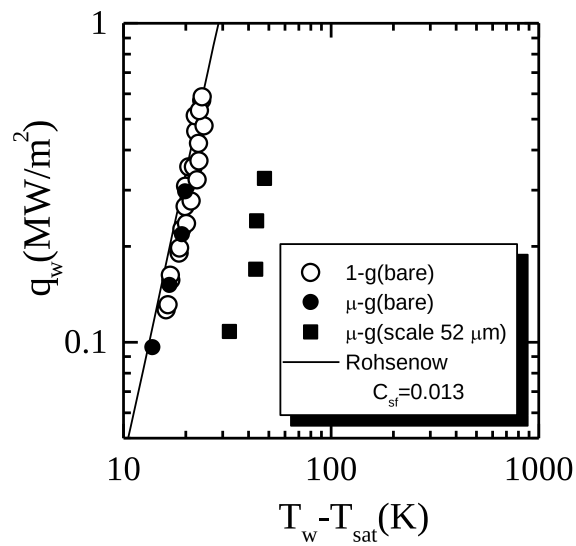

Fig. 13 Boiling curves on bare and scale surface under micro gravity

Straub et al. (1990) also reported that the nucleate boiling heat transfer on a platinum wire of 0.2 mm in diameter under micro gravity obtained in a parabolic flight of airplane agreed well with that under earth gravity.

The thickness of the scale was 52μm in the micro gravity experiment. Due to the heat resistance of scale, the experimental data for the scale surface shift to the right side as shown in Fig.13. However the burnout could not be observed in the present experiment.

Shown in Fig.14 is the effect of heated surface size on the critical heat flux for the bare and scale surfaces under earth and micro gravity. The solid line and the dashed line are the correlations by Sun&Lienhard and Haramura&Katto, respectively. The correlation by Sun&Lienhard (1970) is,

$$\frac{q_{CHF}}{q_{CHF,Z}} = 0.89 + 2.27\exp\left(-3.44\sqrt{R'}\right) \qquad (R' < 3.47) \tag{4}$$

$$\frac{q_{CHF}}{q_{CHF,Z}} = 0.894 \qquad (R' > 3.47) \tag{5}$$

where $q_{CHF,Z}$ is the predictive critical heat flux by Zuber. The correlation by Haramura&Katto (1983) is,

$$\frac{q_{CHF}}{q_{CHF,Z}} = \left(\frac{\sqrt{3}}{R'}\right)^{1/16} \left\{1 + \frac{1}{2(R')^2}\right\}^{1/32} \times \left\{1 + 0.156\left(\frac{\rho_G}{\rho_L}\right)^{0.4}\left(1 + \frac{\rho_G}{\rho_L}\right)\frac{1}{R'\left(q_{CHF}/q_{CHF,Z}\right)^2}\right\} \tag{6}$$

The non-dimensional radius, R', is defined as,

$$R' = (d/2)/\sqrt{\sigma/g(\rho_L - \rho_G)} \tag{7}$$

In the present platinum wire, the non-dimension radius R' is approximately 0.04 in earth gravity and 0.00012 in micro gravity. Sun and Lienhard concluded that the q_{CHF} data started deviating from their prediction and scattered widely on the $q_{CHF}/q_{CHF,Z}$ vs. R' coordinates for R'<0.15. In Fig.14, the data of Sun and Lienhard, Siegel and Howell tend to be below the predictions. Also in the present study, the critical heat flux on the bare surface under earth and micro gravity is below the prediction. As the wire radius is small compared to the capillary length scale, it is possible that a growing and coalescing bubble sometimes completely covers the wire and results as the low heat flux burnout.

The critical heat flux on the scale surface under earth gravity agrees with the prediction. In the present experimental range, the burnout on the scale surface under micro gravity was not observed. On the scale surface, the departure diameter of bubbles is relatively smaller than that on the bare surface. The smaller diameter of bubbles detaching from the scale surface is considered to be due to the high wettability. As the result, the coalescent of bubbles near the surface was prevented and the CHF was delayed and increased on the scale surface compared to that on the bare surface.

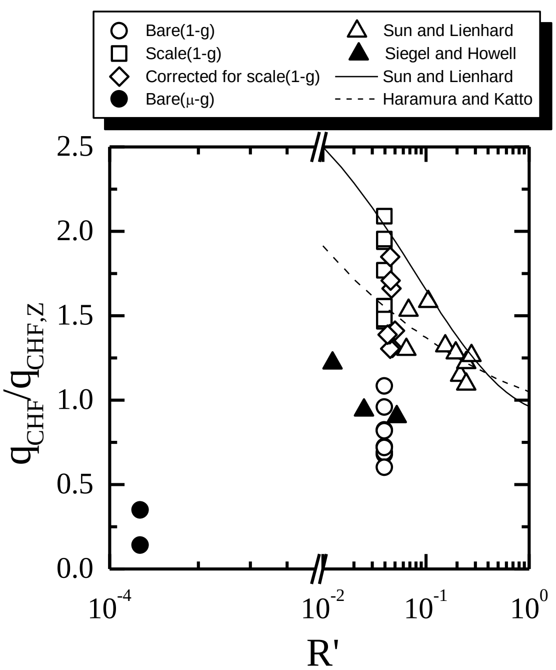

Fig. 14 Effect on heated surface size on bare and scale surface under earth gravity and microgravity

CONCLUSION

Nucleate pool boiling of water on clean and fouling surfaces was conducted in micro 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 the same heat flux both in earth and micro gravity. 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 though the bubbling behavior strongly affected with the gravity level.
3. As the wire radius is small compared to the capillary length scale, the critical heat flux data deviate from the prediction based on the experimental data for the large surface and scatter widely. It is possible that a growing and coalescing bubble sometimes completely covers the small wire and results as the low heat flux burnout.
4. On the scale surface, the departure diameter of bubbles is relatively smaller than that on the bare surface. The smaller diameter of bubbles detaching from the scale surface is considered to be due to the high wettability. As the result, the coalescence of bubbles near the surface was prevented and the CHF was delayed and increased on the scale surface compared to that on the bare surface.

REFERENCES

Bakhru,N. and Lienhard,J.H., 1972, "Boiling from small cylinders", *Int. J. Heat Mass Transfer*, 15, 2011-2025.

Carey,V.P., 1992, *Liquid-vapor phase-change phenomena*, Hemisphere Publishing Corp..

Haramura,Y. and Katto,Y., 1983, "A new hydrodynamic model of the critical heat flux, applicable widely to both pool and forced convective boiling on saturated liquids", *Int. J. Heat Mass Transfer*, 26, 389-399.

Haze,I., Tomemori,H., Motoya,D. and Osakabe,M., 1999, "Effect of surface properties on nucleate pool boiling", *Proc. of 5th ASME/JSME Joint Thermal Eng. Conf.*, AJTE99-6397.

Haze,I., Motoya,D. and Osakabe,M., 2000, "Effects of gravity and surface property on nucleate pool boiling", *Proc. of Boiling 2000*, 1, 391-405.

Rohsenow,W.M., 1952, "A method of correlating heat-transfer data for saturated boiling of liquids", *Trans. ASME*, 74, 969-976.

Straub,J., Zell,M. and Vogel,B., 1990 "Pool boiling in reduced gravity field", *Int. Heat Transfer Conf.*, Jerusalem, Israel, 91-112.

Sun,K. and Lienhard,J.H., 1970, "The peak boiling heat flux on horizontal cylinders", *Int. J. Heat Mass Transfer*, 13, 1425-1439.

Thome,J.R., 1989, *Enhanced boiling heat transfer*, Hemisphere Publishing Corp..

Zuber,N., 1958, "On the stability of boiling heat transfer", *Trans. ASME*, 80, 711-720.