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Study on boiling heat transfer in liquid saturated particle bed and fluidized bed

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Abstract

An investigation on the effects of solid particles on boiling heat transfer enhancement is performed. The range of particle diameter is from millimeter to nanometer. The experimental results show that boiling heat transfer can be enhanced greatly by adding the solid particle into the liquid whether in fixed particle bed or in fluidized particle bed. The boiling enhancement is closely related to the particle size, the initial bed depth and the heat flux applied. The experiments show that boiling characteristics are greatly changed when a particle layer is put on the heated surface. The major effects of fixed particle bed on nucleate pool boiling heat transfer are the nucleation, bubble moving and thermal conductivity effect. A boiling heat transfer correlation is obtained to predict the boiling heat transfer coefficients in a liquid saturated porous bed. A volumetric convection mechanism of boiling heat transfer enhancement by fluidized particles is proposed. The calculated results from the model suggested in this paper agree reasonably with the experimental values.

Keywords: Boiling; Solid particle; Heat transfer enhancement; Fluidization

1. Introduction

Boiling heat transfer enhancement is an object of intensive study in recent years owing to the cooling requirement of high heat flux surface under small temperature difference between the surface and cooling media. Many effective techniques of boiling enhancement are available and have been applied to some areas of thermal engineering [1–3]. However, all these techniques have some disadvantages, such as, complication in manufacture, fouling of heat transfer surface and serious boiling hysteresis. Therefore, a new method to enhance boiling heat transfer is of courage to investigate.

It has been reported repeatedly in literature that when a proper amount of solid particles is introduced into boiling liquid the pool boiling heat transfer can be greatly enhanced and the boiling hysteresis would be partly or even completely removed [4–8]. With its simplicity it seems to be an attractive boiling augmentation technique to be applied in engineering. However all the reported results dealing with this enhancement technique are still not enough to clear the mechanism of this boiling enhancement and it lacks a systematic study on the influence of particle sizes and initial particle loading on boiling heat transfer.

On the other hand, boiling heat transfer in a liquid saturated porous bed is also an interested object for many thermal engineers. It is encountered in many important applications, such as heat pipe, geothermal energy system and post-accident heat transfer performance in liquid cooled nuclear reactor.

In this work a systematic experimental study is made to understand the influences of solid particles in liquid on boiling heat transfer and the mechanisms of boiling heat transfer enhancement in liquid saturated particle bed and fluidized bed are analyzed respectively.

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Nomenclature

B	constant in Eq. (8)
C_0	constant in Eq. (7)
C_p	specific heat [J/kg K]
d_p	particle diameter [m]
D_d	departure diameter of bubble [m]
E	dimensionless particle diameter
F	factor of fin-like effect
f_b	departure frequency [s^{-1}]
f_p	displacement frequency [s^{-1}]
h_{fg}	latent heat of vaporization [J/kg K]
H_p	bed height [m]
Nu	Nusselt number
Pr	Prandtl number
q	heat flux [W/m^2]
Re	Reynolds number
S	two-phase flow parameter
T	temperature [°C]
U_b	vapor speed [m/s]
V	volume [m^3]
Greek symbols	
λ	thermal conductivity [W/m °C]
σ	surface tension [N/m]
ε	porosity
μ	viscosity [Pa s]
ρ	density [kg/m^3]
ξ	influence factor of bubble departure diameter
Subscripts	
b	bubble
L	liquid
p	particle

2. Experimental study

2.1. Experimental apparatus and procedure

The experimental apparatus is shown in Fig. 1. It is consists of an inner pyrex tube 90 mm in diameter and 150 mm in height. A guard heater around the inner tube is used to keep the test liquid with different initial particle bed depth in saturated temperature. To prevent fluidization of particles in the test of saturated particle bed (fixed bed), a thick punched brass plate was used on bed surface. Meanwhile an initial unconfined particle layer was used in the test of fluidized particle bed. The test section is consists of a cylindrical copper block, a 1 kW film heater and six 0.1 mm chromel–alumel thermocouples positioned at three levels of centerline in the copper block. The heat transfer surface is 60 mm in diameter. The surface temperature was estimated by extrapolating the temperature distribution obtained by thermocouples. The heat flux to the top surface of the cylindrical block was determined from thermocouple measurements of the temperature gradient in the block.

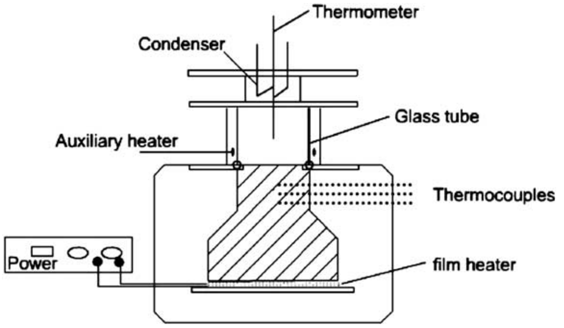

Fig. 1. Experimental apparatus.

Distilled water was tested. Glass beads ($\lambda = 0.74$ W/m °C) with diameter from 0.5 to 3 mm, steal balls ($\lambda = 45$ W/m °C) of 0.5 mm in diameter and fine sand ($\lambda = 0.3$ W/m °C) of 1.6 μm in average diameter and Al_2O_3 particles ($\lambda = 46$ W/m °C) of 26 nm were used as test solid particles. Starting with pool boiling of water without particles, the experiments were carried out at saturation conditions for different particles and initial bed depth. By use of measured surface temperatures and corresponding heat fluxes, the boiling curves were obtained for different boiling conditions.

The boiling processes in particle layer (for fixed bed) and above the heating surface (for fluidized bed) were visually observed through the glass wall.

The experimental uncertainty in surface temperature is less than 1.78%, the uncertainty in surface heat flux are about 1.95%. The measuring uncertainly of particle diameter for 0.5–3 mm range is less than 0.05 mm. The diameters of fine sand and Al_2O_3 are within the size ranges: 0.5–1.6 μm with 90% of 1.6 μm sand particles and 20–30 nm. The uncertainty of the calculated heat transfer coefficients is estimated within 5%.

2.2. Experimental results and discussion

The experimental results show that the boiling behavior is much different from the ordinary water pool boiling and the boiling heat transfer can be enhanced greatly for both the fixed particle bed and fluidized bed. The visually observation shows that there are more nucleation sites existed in the gaps of particles and heated surface. The incipient boiling temperature is much lower than in the case of pure water boiling, especially for fixed particle bed. Boiling hysteresis phenomena almost disappear in all the boiling cases tested. The experimental observation also shows that the average bubble sizes in nucleate pool boiling with solid particles are generally greater than that without particles, especially if the solid particles are in the static state on the heated wall (that is, in fixed bed) or not been fully fluidized and the bubble sizes are usually between 10 and 20 mm in diameter for water boiling on the copper surface under atmosphere pressure.

2.2.1. Hydrodynamic behavior of vapor–liquid-particle near the heated surface

When a layer of unconfined particles is put on the heated wall submerged in the liquid pool during the boiling, the observed motion states of vapor, liquid and solid particles are shown in Fig. 2. At lower heat flux the vapor bubbles grow at one or more nucleation sites on the heated surface and somewhere they are coalescing as they grow. The buoyancy of the bubbles or the coalesced vapor patches do not overcome the resistance of the overlying particle layer, the particle bed is fixed in this time as shown in Fig. 2a. The heat transfer from the heated surface to liquid is mainly governed by the convection of the liquid located in the gaps of the particle bed and the heat conduction of particles themselves.

With increase of wall heat flux, the buoyancy of cumulated vapor is getting large enough and can overcome the resistance of the particle bed, the vapor flows upward and fluidizes partially the particle layer as shown in Fig. 2b. At middle heat flux the nucleation sites increase rapidly, the permanent vapor columns are present on the heated surface and the upward vapor flow causes the particle to be fluidized completely. The particles move up and down with the upward vapor flow and downward liquid flow as shown in Fig. 2c. An upward particle from the heated surface like a departing vapor bubble draws a portion of the superheated liquid in its wake. When the heat flux increases to a critical value, the upward vapor cushion would hinder the downward motion of particles and thus the direct contact of the particle with the heated surface would be prevented (Fig. 2d).

2.2.2. Effect of particle diameter

The effect of particle diameter on boiling heat transfer in a fixed particle bed and fluidized bed is different. For a fixed bed Fig. 3 shows that at a given heat flux the boiling heat transfer rate increases with increasing the particle diameter. This can be explained by the effect of the flow resistance to bubbles and liquid, because their motions in porous bed are restricted and resisted. The smaller is the particles, the larger the flow resistance.

For a fluidized bed with a given initial bed depth H_p, the heat transfer rate decreases with the increasing of particle diameter if the particle diameters are in the same order of magnitude with bubble diameter as shown in Fig. 4. This is because the additional volumetric convection caused by smaller particles in liquid pool would be stronger than larger particles, which will be discussed in the next section of this paper. Fig. 5 shows the boiling heat transfer results of water with fine suspension particles in it. It can be seen that when the particle diameter

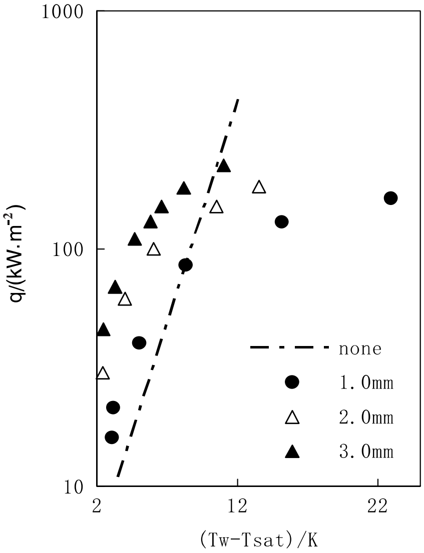

Fig. 3. The effect of particle diameter for fixed particle bed (glass beads, $H_p = 40$ mm).

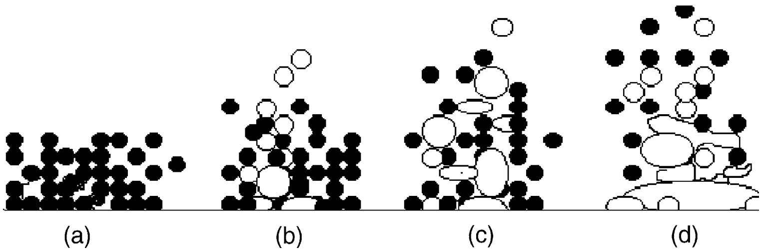

Fig. 2. The hydrodynamic states of vapor–liquid-particles.

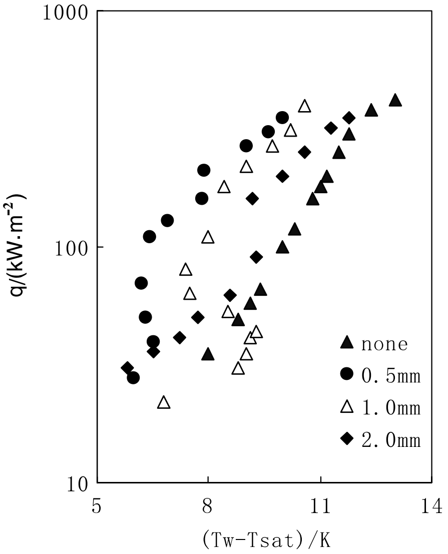

Fig. 4. The effect of particle diameter for fluidized particles (glass beads, $H_p = 4.8$ mm).

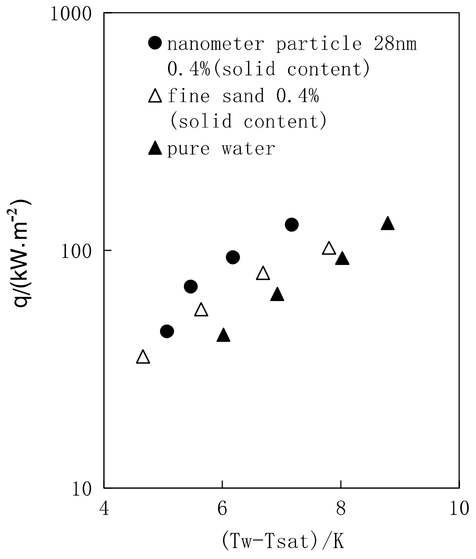

Fig. 5. The boiling curves for fine sand and nanometer particle.

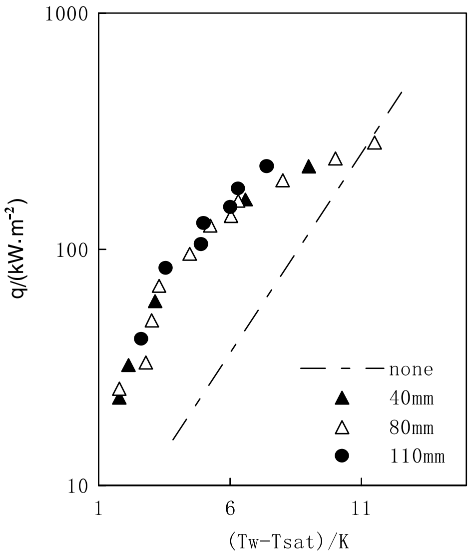

Fig. 6. The effect of initial bed depth (glass beads, $d_p = 3.0$ mm).

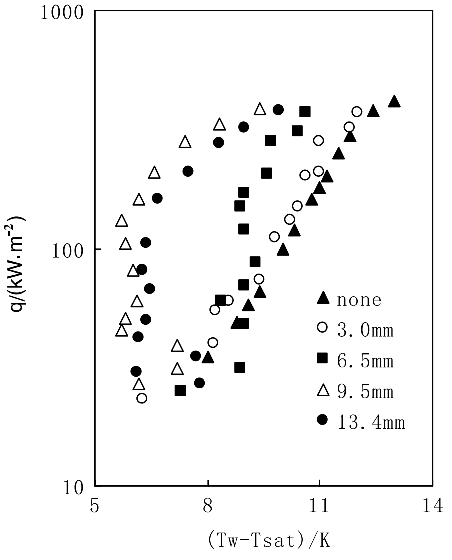

Fig. 7. The effect of initial bed depth (glass beads, $d_p = 1.0$ mm).

is far smaller than that of the departure bubble, the enhancement of boiling heat transfer will decrease by comparing with larger particle case as indicated in Fig. 4. But for nanometer particles the boiling heat transfer can be improved owing to the higher thermo-conductivity of water-particle mixture (called as nanometer fluid [9]).

2.2.3. Influence of initial bed depth

The effect of bed height on boiling heat transfer for fixed particle bed is shown in Fig. 6. In the particle size range tested in this work, no obvious effect of initial bed depth was found on the boiling heat transfer rate. This means that the boiling heat transfer rate is mainly determined by the process existed in the comparatively thin layer of the particle bed near the heated surface. Contrarily the effect of initial bed depth for a fluidized bed is somewhat different. For a given particle diameter, if the initial bed depth is relatively small, the boiling heat transfer increases with increasing initial bed depth as shown in Fig. 7. But if the initial bed depth is large

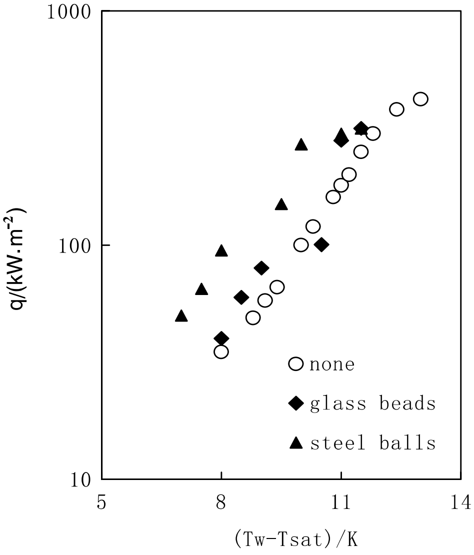

Fig. 8. The effect of particle thermal conductivity ($d_p = 0.5$ mm, $H_p = 0.3$ mm).

(larger than 9.5 mm in this work), the boiling heat transfer decreases with increasing initial bed depth. This indicates that there exists a saturated initial particle loading for boiling heat transfer enhancement in liquid fluidized bed.

2.2.4. Effect of particle thermal conductivity

The experimental data indicate that for the same particle diameter the higher heat transfer rate belongs to the particles with larger thermal conductivity for both fixed and fluidized bed as shown in Fig. 8.

3. Mechanisms of boiling heat transfer enhancement by adding solid particles into the liquid

The experimental results show that the boiling heat transfer would be greatly enhanced by adding the solid particles into the boiling liquid and the boiling behavior is much different for the fixed particle bed and fluidized bed. Therefore the different mechanism of boiling heat transfer enhancement for different particle status could be expected. In following text the mechanisms of boiling heat transfer enhancement will be analyzed for two typical particle regimes: fixed particle bed and fluidized particle bed.

3.1. Boiling heat transfer in fixed particle bed

The boiling characteristics are greatly changed when a fixed particle layer is put on the heated surface. The major effects of particles on nucleate boiling heat transfer can be analyzed as follows.

Firstly, according to the visual observation in the test, the additional active nucleation sites would be provided on the heated surface due to existence of particles being contacted with the surface, for example, it was observed that only 4–6 nucleation sites were appeared on the smooth copper surface for pure water alone at heat flux $q = 2 \times 10^4$ W/m^2, while there have more than 10 nucleation sites existed in the gaps for glass beads bed of 20 mm depth at the same heat flux. For pool boiling at low heat flux the required wall superheat ΔT_s decreases as the nucleation site density n increases [10], therefore at the same heat flux the wall superheat for boiling in particle layer will be smaller than that for the ordinary pool boiling and the boiling heat transfer enhancement by solid particles is obvious. The experiments also show that the nucleation site density n increases as the particle diameter d_p decreases. One can assume that the increase of nucleation sites is proportional to the contact points of particles with the heated surface, that is, proportional to the particle diameter. Thus the particle diameter can be considered as a mainly important parameter to this boiling heat transfer enhancement.

On the other hand, it is obvious that the presence of solid particles will certainly impede the bubble motion, and thus influence bubble detachment. The observations shows that the average bubble sizes with solid particles are larger than that without particles. This indicates that the bubble diameter is increased if the particles are added into the boiling liquid. As we know that the increase of bubble departure diameter means the decrease of bubble frequency, and the higher the bubble frequency the stronger the boiling heat transfer. The larger bubble diameter means the heat transfer resulted from bubble formation process is weakened due to the presence of solid particles. Thus the bubble departure diameter can be considered as another mainly important parameter to this boiling heat transfer descent.

Therefore one can expect that the ratio of two diameters, that is, particle diameter d_p and bubble departure diameter D_d should be a important controlling parameter for this boiling enhancement, that is

$$E = d_p/D_d = d_p/(\xi + (1 + \xi^2)^{1/2})D_{d0} \quad (1)$$

where D_{d0} is Fritz bubble departure diameter, $D_{d0} = f_4(\theta)(\sigma/g(\rho_L - \rho_V))^{1/2}$, ξ, a factor to reflect the influence of solid particles on bubble departure and derived in our previous work [11] as

$$\xi = \frac{3H_p(\rho_p - \rho_L)}{4D_{d0}(\rho_p - \rho_L)}(1 - \varepsilon)$$

Secondly, all bubbles formed on the heated surface will grow up within particle gaps. Heat is transferred to bubbles not only from wall directly but from particles. The bubble growth rate would be increases if the thermal conductivity of the liquid lower than the conductivity of the particles and this were often the case. Thus the boiling heat transfer would be enhanced. This can be considered as a fin-like effect. Having considered the effect of thermal conductivity of liquid, Lorenz et al. [12] suggested that for a given heat flux the wall superheat ΔT_s satisfied the relationship $\Delta T_s \propto \lambda_L^{-n}$, for the case of boiling in particle bed, the same relationship might be expected as

$$\Delta T_{sp} \propto \lambda_e^{-n} \quad \text{or} \quad \left(\frac{q}{\Delta T_{sp}}\right) \propto \lambda_e^n \tag{2}$$

where λ_e is a equivalent conductivity of liquid-particle mixture, calculated by $\lambda_e = \varepsilon\lambda_L + (1-\varepsilon)\lambda_p$ in which ε is porosity of the particle bed. Thus the dimensionless term $F = \lambda_e/\lambda_L$ can be chosen to describe the fin-like effect of the particle bed on boiling enhancement.

Thirdly, the bubble and liquid motion in the particle bed should be restricted and resisted. The suppression of the liquid–vapor exchange would cause the boiling heat transfer decreasing. The flow in particle bed can be considered as a flow passing through a set of capillary tubes. The basic dimensionless parameter which describes the two-phase annular flow in capillary tube of the porous bed is $S = \mu_L U_b/\sigma$ [13], thus it can be selected as a correlation parameter to describe the influence of particles on the motion of liquid and vapor in the bed as well as on boiling heat transfer. The vapor speed U_b in boiling case has the form of $U_b = q/\rho_V h_{fg}\varepsilon$.

Having considered the effects mentioned above and assuming these three effects are independent, the correlation of nucleate pool boiling heat transfer in a fixed particle bed can be expressed by following modified form of ordinary nucleate pool boiling heat transfer correlation as

$$Nu = CRe^{n1}Pr^{n2}E^{n3}S^{n4}F^{n5} \tag{3}$$

where

$$Nu = qd_p/(\Delta T_s\lambda_e), \quad Re = qd_p/(\varepsilon\mu_V h_{fg})$$
$$Pr = \mu_L C_{pL}/\lambda_L \quad E = d_p/(\xi + (1+\xi^2)^{1/2})D_{d0}$$
$$S = q\mu_L/(\rho_V h_{fg}\sigma\varepsilon) \quad F = \lambda_e/\lambda_L$$

The experimental data of pool boiling in the fixed particle bed are plotted in terms of the dimensionless parameters in Eq. (3) as shown in Fig. 9. A best fit through 105 data points yield the following correlation as

$$Nu = 3.83 \times 10^{-3}Re^{1.14}Pr^{0.33}E^{0.41}S^{-0.81}F^{0.83} \tag{4}$$

in which 90% of data points are correlated within the range of ±30%. This correlation can be used to predict the boiling heat transfer coefficients in particle bed for water, F-11, F113 and ethanol at atmosphere pressure.

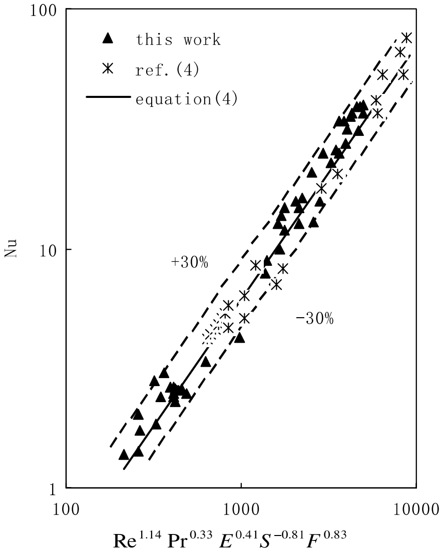

Fig. 9. Correlation of pool boiling heat transfer data in fixed particle bed.

3.2. Boiling heat transfer in fluidized particle bed

The experimental results show that the boiling heat transfer can be enhanced by the fluidized particles in liquid. For saturated pool boiling the total heat transport from a heated wall to the liquid can be considered to be the sum of three principal components: the microlayer evaporation of the liquid sub-layer under the growing bubbles, sensible heat transfer by the wake flow of the departure bubbles and the natural convection. It is thought that the main mechanism of the boiling enhancement by the fluidized particles is the increase of the sensible heat wake flow caused by the upward particles from the heated surface. It is proposed that a upward fluidized particle has analogy to a rising bubble departed from the heated surface during nucleate boiling. Thus a new heat transfer model for the fluidized particle bed can be developed. Assuming that a upward fluidized particle can be treated like a rising spherical bubble as shown in Fig. 10. To obtain the wake volume of a rising particle of diameter d_p from the surface, a single bubble rising in an infinite liquid is analyzed first. Komasawa et al. [14] found that for a bubble of diameter D_b with velocity U_b rising in an infinite liquid the ratio of wake volume V_w to bubble volume V_b increases with the bubble Reynolds number as

$$\frac{V_w}{V_b} = Re_b^{0.66} \quad (Re < 200)$$
$$Re_b = D_b U_b/\nu_L \tag{5}$$

For a bubble rising from a heated wall, its wake volume is less than that in the infinite liquid owing to the

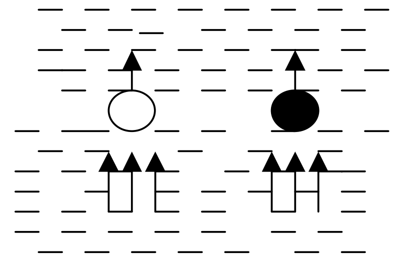

Fig. 10. Rising particle—vapor bubble analogy in boiling liquid.

hindering effect of the wall. By use of the measured wake volume of a departure bubble from the boiling surface [15], Eq. (5) can be modified to its final form which can be used to calculate the wake volume of a rising particle from the heated surface, it is

$$\frac{V_w}{V_p} = 0.3Re_p^{0.66} \qquad (6)$$

where V_p is a particle volume, Re_p is particle Reynolds number defined as $Re_p = d_pU_p/\nu_L$, U_p approximately equals to bubble velocity at given heat flux as $U_p = q/h_{fg}\rho_V$.

Thus the total convective sensible heat transfer by the all particle wakes can be calculated by

$$q_p = C_0 n C_{pL}\rho_L V_w f_p \overline{\Delta T_s} \qquad (7)$$

where C_0 is a coefficient related to the interaction between particle and particle as well as particle and bubble. This interaction causes the upward particles to decrease, thus $C_0 \leqslant 1$. C_{pL}, ρ_L are specific heat and density of the liquid respectively, $\overline{\Delta T_s}$, an average superheat of the rising liquid wake, $\overline{\Delta T_s} = 0.5(T_w + T_s)$, n, the number of rising particles per unit area of the heat surface. f_p, the displacement frequency of particles on the surface. It can be calculated as follows. Since the detaching motion of one bubble will cause far more than one particles to move up, therefore f_p should be greater then the departure frequency of bubble in nucleate pool boiling f_b. Assuming that the rising motion of particles is resulted from the bubble detachment and that the bubble space is actually occupied by particles prior to bubble nucleation. Thus it is reasonable to assume that f_p is proportional to f_b and the ratio of bubble and solid particle projected area, that is

$$f_p \propto f_b(S_b/S_p)$$

If bubble and solid particle are both spherical, then

$$f_p \propto f_b(D_d/d_p)^2$$

where D_d is the departure diameter of bubble.

By use of the approximate relationship $D_d^2 f_b =$ constant [16], the convective sensible heat transfer by the particle wake can be finally expressed as

$$\begin{aligned} q_p &= C\varepsilon d_p^{-1.34} B(T_w - T_s) \\ B &= (q/h_{fg}\rho_V\nu_L)^{0.66} C_{pL}\rho_L \end{aligned} \qquad (8)$$

where C is a coefficient which can be determined by experiments, ε is the porosity of initial particle bed. B is a complex parameter related with the boiling liquid and boiling process itself.

Eq. (8) shows that q_p is inversely proportional to the 1.34 power of particle diameter at the given initial bed depth H_p. For a given range of particle diameter the boiling heat transfer enhancement increases with decreasing the particle diameter and increasing the initial bed depth. Meanwhile the boiling heat transfer enhancement also depends boiling process itself and under the fully fluidized particle state the boiling enhancement would be more obvious with increasing boiling heat flux. Fig. 11 is the comparison between the boiling heat transfer component calculated by Eq. (8) and experimental data which are obtained by comparing the boiling heat transfer data in the pure water alone with the heat transfer data in pool boiling with fluidized particles. The agreement is satisfactory. It means that the proposed mechanism of boiling enhancement by fluidized particles is realistic and acceptable.

Finally the total heat transfer in boiling with fluidized particles can be expressed as

$$q = q_b + q_p \qquad (9)$$

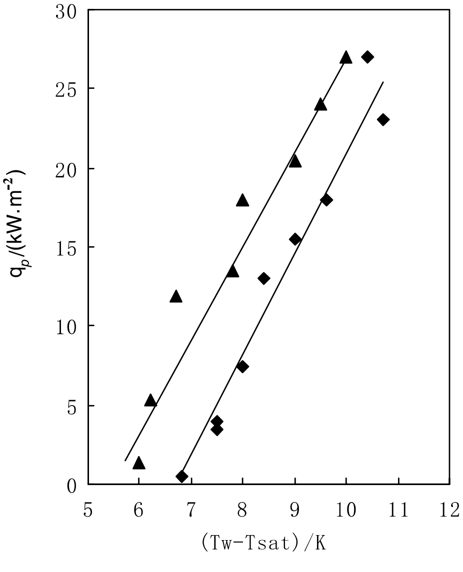

Fig. 11. Comparison between calculated value (Eq. (8)) and experiment data (glass beads–pure water). (◆) $d_p = 1$ mm $H_p = 4.8$ mm; (▲) $d_p = 0.5$ mm $H_p = 4.8$ mm; (—) calculated value.

in which q_b is the boiling heat flux for pure liquid, q_p is the convective sensible heat flux of the upward particle wake calculated by Eq. (8).

4. Conclusions

(1) The boiling heat transfer can be enhanced greatly by adding the solid particle into the liquid whether in the fixed particle bed or fluidized particle bed.

(2) The experimental results show that the boiling heat transfer enhancement is closely related to the particle size, the initial bed depth (in fluidized case) and the heat flux applied.

(3) The boiling heat transfer characteristics are greatly changed when a particle layer is put on the heated surface. The major effects of fixed particle bed on nucleate pool boiling heat transfer are the nucleation effect, bubble moving effect and thermal conductivity effect. The correlation (4) can be used to predict the boiling heat transfer coefficients in a liquid saturated porous bed.

(4) A layer of unconfined solid particle on the heated surface could be fluidized during the boiling process, the fluidized particles in boiling liquid can enhance the boiling heat transfer in lower and middle heat flux range, the mechanism of boiling enhancement by the fluidized particles is the convective sensible heat transfer caused by the particle wake flow.

Acknowledgements

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