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Short communication

A study on boiling heat transfer in three-phase circulating fluidized bed

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Abstract

A vapor–liquid–solid circulating fluidized bed, which is a new type of evaporation boiling means for enhancing heat transfer and preventing fouling, is presented. Experiments were conducted in a 39 mm diameter 2.0 m high stainless steel column, in which the heat transfer coefficient was measured for different superficial velocities, pressure of the heating stream, particle concentration and kinds of particles. The experimental results show that the boiling heat transfer coefficient is enhanced and is about 1.5–2.0 times that of vapor–liquid two-phase flow. The heat transfer coefficient increased with increase in the pressure of the heating stream, but it exhibited a local minimum value with increasing liquid velocity.

Keywords: Boiling heat transfer; Circulating fluidized bed; Three-phase flow

1. Introduction

In recent years, gas–solid circulating fluidized beds have been used extensively for coal combustion and gas–solid reaction [1], but the possibility of using a vapor–liquid–solid three-phase circulating fluidized bed has received no attention.

Fluidized bed heat exchangers for liquid without boiling have been developed for enhancing heat transfer and reducing fouling on the heat transfer surface in various process industries [2–4]. Owing to the increased turbulence caused by the fluidized particles, the values of the heat transfer coefficient in liquid fluidized beds can be up to eight times higher than for single-phase forced convection [5]. Li Xiulin et al. [6] suggested a vapor–liquid–solid three-phase flow boiling heat exchanger in order to solve fouling problems in the boiling process. In this paper, a new type of a vapor–liquid–solid circulating fluidized bed is proposed, which combines a circulating fluidized bed with boiling heat transfer. Compared to traditional fluidized bed heat exchangers, a vapor–liquid–solid circulating fluidized bed heat exchanger has some advantages: the bed can be operated at high liquid velocity, resulting in higher capacities, and can easily be controlled; a high degree of turbulence can be achieved, providing better heat transfer; big bubbles can be broken into several little bubbles by the particles, so that the bed can be operated more stably; particle circulation can clean the fouling on the heat transfer surface, so that continuity of operation can be maintained. It can thus both enhance heat transfer and prevent fouling on heat transfer surfaces. The aim of the present investigation is to study heat transfer and the reduced fouling effect of this heat exchanger type.

2. Experimental equipment

Experiments were carried out in a stainless steel column (0.039 m ID×2 m height) as shown in Fig. 1. Steam was used as the heat source. The particles were recovered in a particle separator and returned to the bottom of the test bed. Liquid was supplied by a pump and the flow rate was measured by a calibrated rotameter. A butterfly valve was located midway in the particle downcomer. The local wall temperatures and the fluid temperatures at the inlet and outlet of the bed were measured by thermocouples.

The heat transfer coefficient was determined by Eq. (1) from the knowledge of the amount of heat supply and the mean temperature difference between the column surface and the fluidized bed:

$$h_{\mathrm{fb}} = \frac{q}{T_{\mathrm{W}} - T_{\mathrm{B}}} \tag{1}$$

The heat transfer surface temperature can be calculated using the heat flux and the thermocouple temperature:

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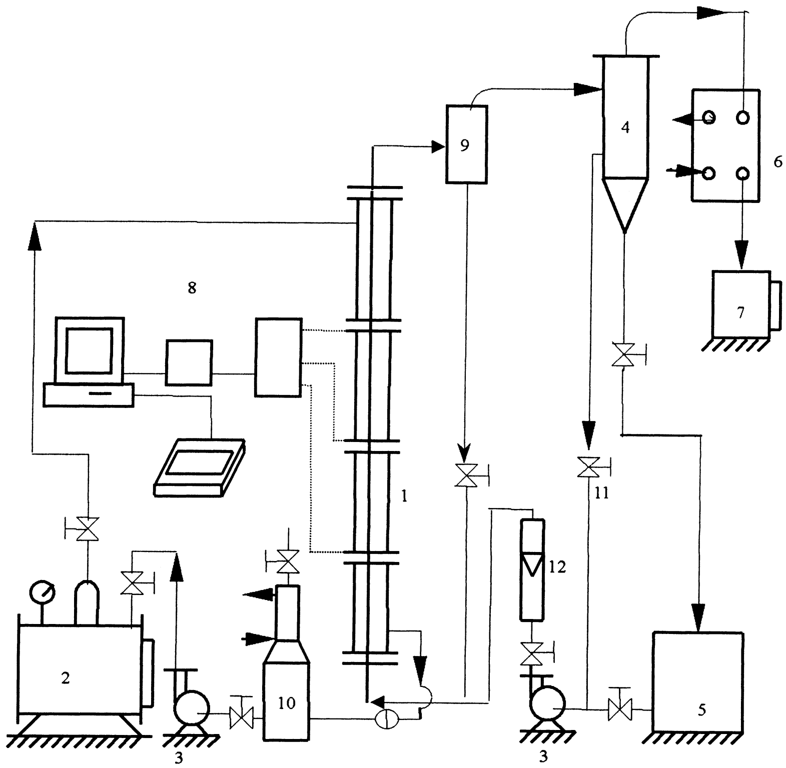

Fig. 1. Schematic diagram of experimental system: (1) CFB heat exchanger; (2) boiler; (3) pump; (4) separator; (5) feed tank; (6) condenser; (7, 10) tank; (8) computer system; (9) particle separator; (11) valve; (12) flowmeter.

Table 1
Physical properties of the saturated brine

Boiling point (°C)	Density (kg/m^3)	Viscosity×10^5 (Pa s)	Thermal conductivity (w/m K)	Specific heat (kJ/kg K)
108.8	1163	45	0.572	3.297

$$T_W = T_{th} - q\frac{S}{\lambda_W} \quad (2)$$

Throughout this study, water or saturated brine was used as the continuous phase. Physical properties of the continuous liquid phase are shown in Table 1.

The solid particles were fluidized in boiling brine. Meanwhile, the salt was crystallized and vapor was produced. Then, vapor, liquid and particles were separated in the particle separator. The particles from the downcomer were fed into the bottom of the bed again. Vapor–liquid flowed into a separator in which vapor was separated into the condenser.

Four different kinds of particles were used in the present study, as shown in Table 2.

3. Results and discussion

3.1. Effect of heating stream pressure

Fig. 2 shows the effect of heating stream pressure on the heat transfer coefficient. In the bed, the heat transfer coefficient increases with increase in pressure of the

Table 2
Physical properties of the solid particles

Material	Diameter (mm)	Density (kg/m^3)	Thermal conductivity (w/m K)	Specific heat (kJ/kg K)
Glass ball	3	2520	1.093	0.6699
Steel ball	3	7850	48.85	0.4605
Ceramic ball	3	2350	1.25	0.8370
Titanium cylinder	3×3	4505	31	0.5240

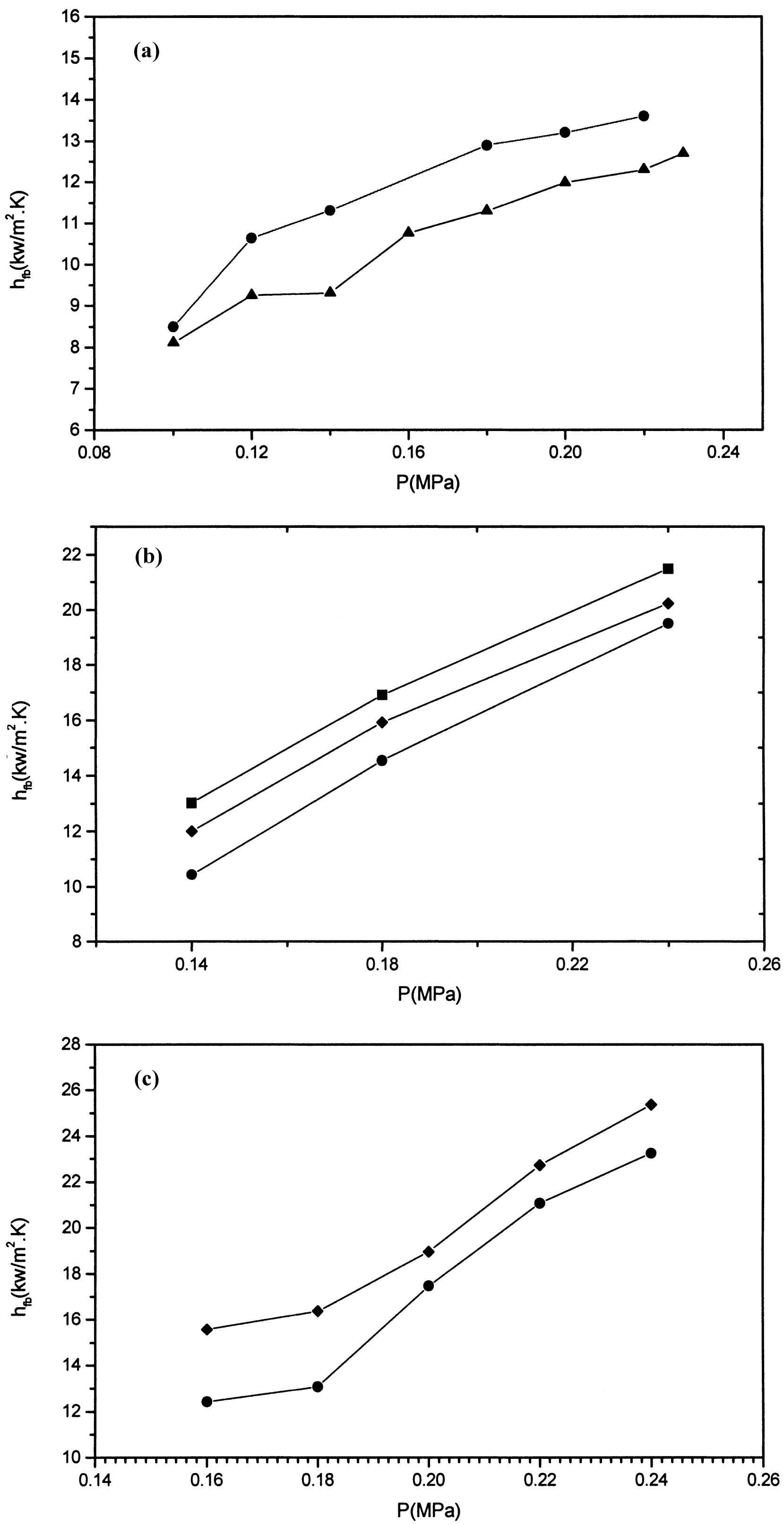

Fig. 2. (a) Glass ball C=20%; (b) titanium particle C=8%; (c) effect of heating vapor's pressure on the heat transfer coefficient U_l (m/s): (▲) 0.41; (●) 0.61; (◆) 0.71; (■) 0.79.

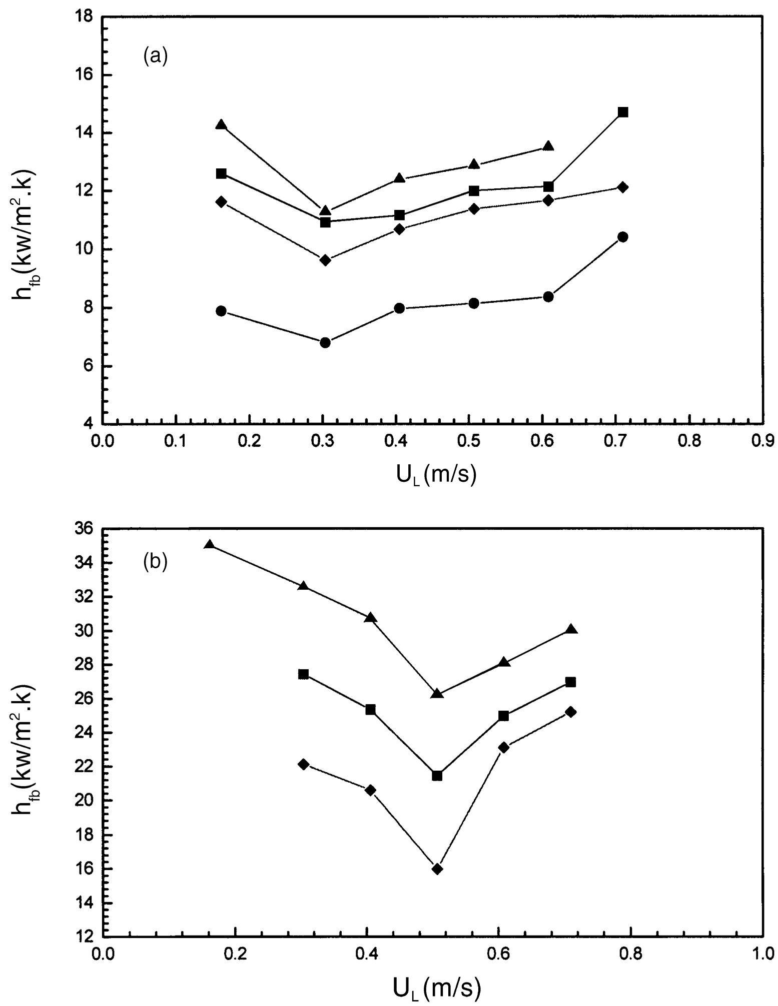

Fig. 3. (a) Glass ball C=12%; (b) effect of liquid flow rate on the heat transfer coefficient P (MPa): (●) 0.10; (◆) 0.16; (■) 0.20; (▲) 0.24.

heating stream. This is in agreement with two-phase flow boiling. Thus, the major contribution to heat transfer is made by the temperature drop or heat transfer driving force. With increase in the heat transfer driving force and heat flux, three-phase superficial velocity and vapor fraction increase, as result of which the heat transfer coefficient increases.

3.2. Effect of superficial velocity

Boiling heat transfer coefficients in the three-phase circulating fluidized bed have been measured for particles of glass and steel. The experimental results are shown in Fig. 3 as plots of heat transfer coefficient versus liquid velocity.

According to Fig. 3, at the same heating stream pressure, the heat transfer coefficient exhibits a local minimum with an increase in U_l, but when the velocity increases further, the heat transfer coefficient increases gradually again.

The reason why the bed heat transfer coefficient exhibits its local minimum with increasing U_l can be attributed to the liquid velocity and particle concentration. The change from fluidized regime to circulating fluidized regime is accompanied by a sharp drop in the heat transfer coefficient. The reduction results from particles which are carried away from the bed and do not part in circulation, which decreases the effect of particles in the bed. After this point, increase in the heat transfer coefficient is due to particle circulation and the increase in velocity which makes the fluidized bed a circulating fluidized bed, in which the fluid velocity and the presence of fluidized particles enhance the heat transfer at the same time.

3.3. Effect of particle concentration

Measured boiling heat transfer coefficients for glass balls and steel balls are plotted against particle concentration in Fig. 4. The particle concentration is found to be a dominant factor influencing the heat transfer coefficient in the bed.

The heat conduction from clusters is much higher than that from the liquid and the gas. On the other hand, the

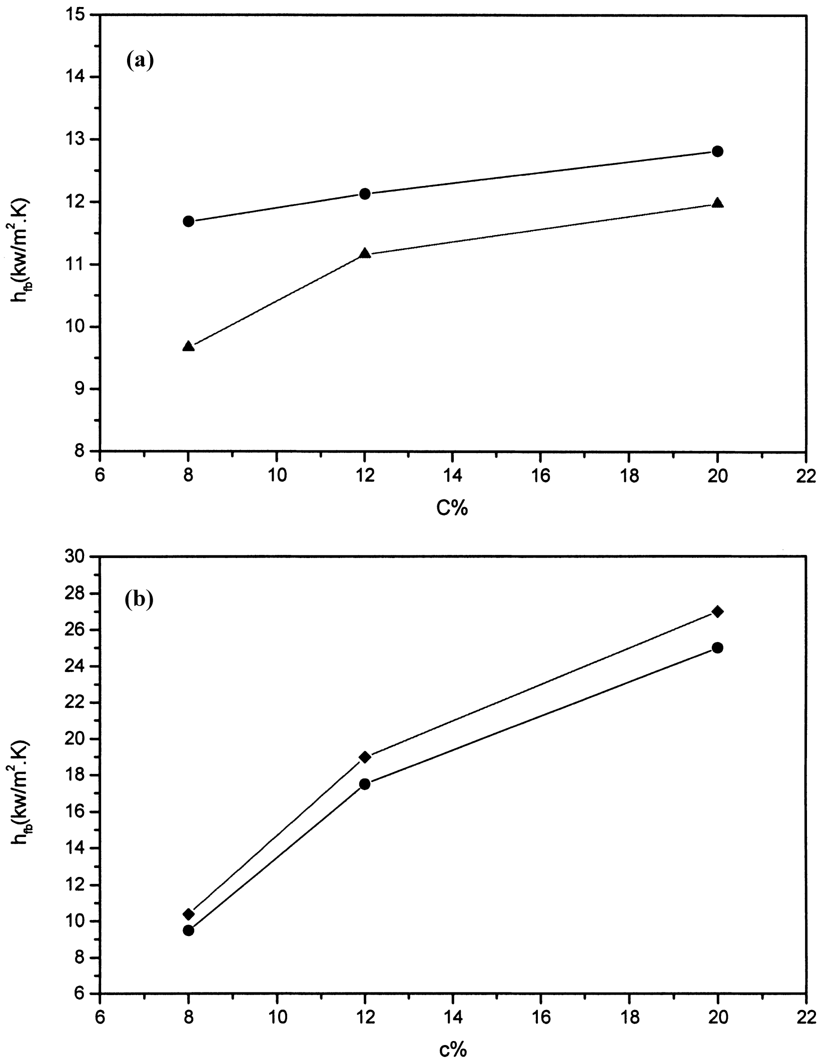

Fig. 4. Glass ball P=0.2 MPa; (b) effect of particle concentration on the heat transfer coefficient U_l (m/s): (▲) 0.41; (●) 0.61; (◆) 0.71.

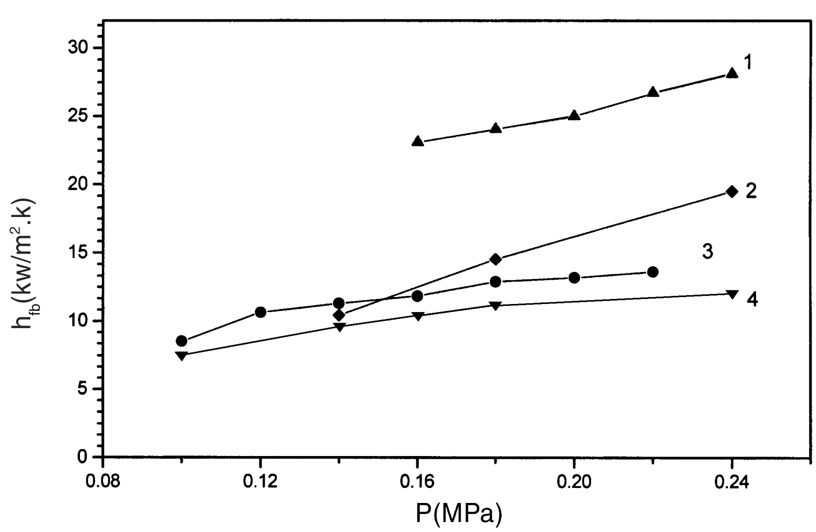

Fig. 5. Effect of particle materials on the heat transfer coefficient: (1) steel ball; (2) titanium particle; (3) glass ball; (4) ceramic ball; U_l=0.61 m/s, C=20%.

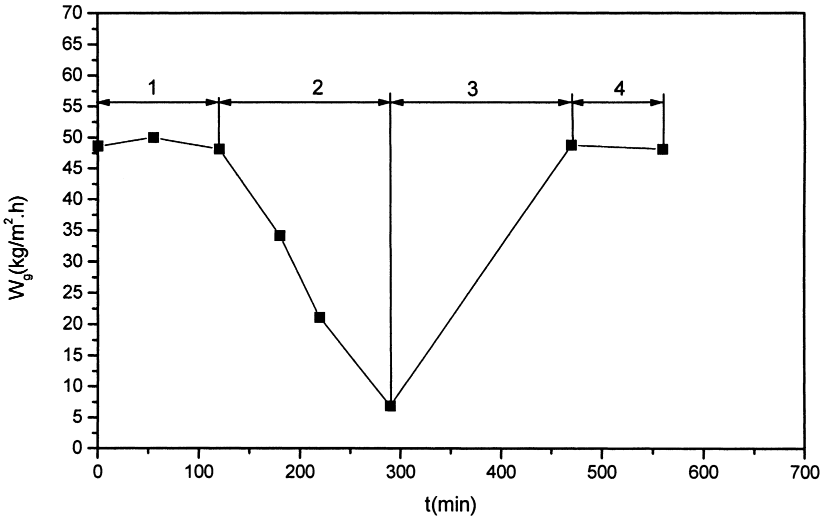

Fig. 6. Relation of evaporation intensity with time: (1) CFB stable operating zone; (2) two-phase flow boiling zone; (3) CFB starting zone; (4) CFB stable operating zone; U_l=0.41 m/s, P=0.18 MPa.

particles have more of a chance of colliding with the wall when the concentration increases. The motion of the particles near the wall may increase the number of nucleation sites on the wall and help to sweep away bubbles on the heating surface, which shortens the time of growth of the vapor bubbles. All of this enhances the boiling heat transfer. There is also a higher slip velocity between the particles and the bubbles. When the particles penetrate into the big bubbles, they will be divided into a large number of small bubbles that can promote the turbulence. Therefore, the heat transfer coefficient increases with increase in the particle concentration, but as the particle concentration increases with further, the heat transfer coefficient will increase only slowly as shown in Fig. 4.

3.4. Effect of material of the particles

Fig. 5 shows the effect of particle material on the heat transfer coefficient. We found that, for a given bed voidage, the particles whose density and thermal conductivity are high have a higher heat transfer coefficient than the particles whose density and thermal conductivity are low. With increase in the particle density, clusters of particles can be formed easily. Meanwhile, the higher density particles can disturb the boundary layer of the heat transfer more strongly. The higher the thermal conductivity that the particles have, the faster they receive heat from the heating surface, so that equilibrium between solid and liquid can be reached quickly. The particles whose thermal conductivity is higher promote the occurrence of nucleate boiling heat transfer [7].

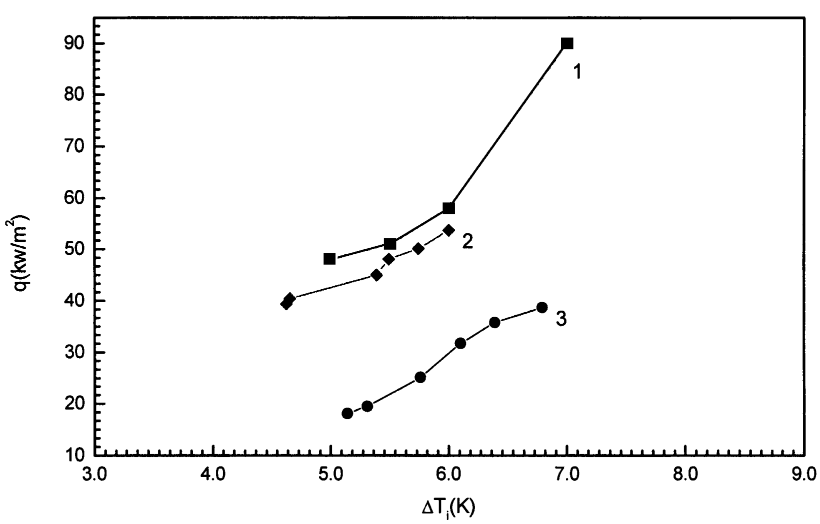

Fig. 7. Relation of heat flux with temperature drop: (1) non-circulating three-phase fluidized bed boiling; (2) CFB boiling; (3) two-phase flow boiling.

3.5. Cleaning and preventing fouling

Fouling may cause discontinuity in industrial processes. For example, in a saltworks plant, the workers have to halt the operation to remove the fouling in the tubes of brine evaporators every 8 h or shorter in China. But in the three-phase circulating fluidized bed experimental apparatus, we operated for more than 1000 h in boiling mode without fouling.

Fig. 6 shows that the heat transfer coefficient dropped quickly without the particles in the bed when we closed the circulating valve. This shows that the heating surface had been covered by a fouling layer. When we opened the valve to make particles circulate in the bed, the heat transfer coefficient gradually recovered its former level. This shows that the particles cannot only prevent fouling but also clean the fouling that has already occurred.

3.6. Comparison of two-phase flow boiling and three-phase circulating fluidized bed boiling

Fig. 7 shows the variation in evaporation with surface superheat for water. For comparison, the control run with or without the presence of solid particles (glass balls) is included. It is clear that heat transfer in a three-phase circulating fluidized bed boiling is higher than that in two-phase flow boiling. The experimental results show that the circulating fluidized bed boiling heat transfer coefficient is about 1.5–2.0 times that of vapor–liquid two-phase flow boiling.

4. Conclusions

1. The boiling heat transfer coefficient in a three-phase circulating fluidized bed is about 1.5–2.0 times that of two-phase flow boiling.
2. In a circulating fluidized bed, the particles whose density and thermal conductivity are high can result in a higher heat transfer coefficient for a given particle concentration.
3. The circulating fluidized bed can not only enhance heat transfer but also clean and prevent fouling.

5. Nomenclature

C	particle concentration (v/v)
q	heat flux (w/m^2)
P	pressure of heating steam (MPa) (gauge pressure)
S	distance between thermocouple location and inside wall surface of the tube (m)
ΔT	temperature difference (K)
ΔT_i	temperature drop between tube wall and boiling point inside wall, $T_W - T_B$ (K)
T_B	the boiling temperature (°C)
T_W	the heat surface temperature inside tube (°C)
T_{th}	the thermocouple temperature (°C)
U	superficial velocity of liquid (m/s)
W	the evaporation intensity of fluidized bed heat exchanger (kg/m^2 h)
t	operating time (min)

Greek symbol

λ	thermal conductivity, w/m.K

Subscripts

exp	experiment
fb	average
g	vapor
i	inside of tube
l	liquid
w	wall

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