

Heat Transfer in a Liquid-Solid Circulating Fluidized Bed Reactor with Low Surface Tension Media^{*}

H.R. Jin¹, H. Lim¹, D.H. Lim¹, Y. Kang^{1,**} and Ki-Won Jun²

¹ Chemical Engineering, Chungnam National University, Daejeon, Korea

² Korea Chemical Technology Division, Korea Research Institute of Chemical Technology, Daejeon, Korea

Abstract Heat transfer characteristics between the immersed heater and the bed content were studied in the riser of a liquid-solid circulating fluidized bed, whose diameter and height were 0.102 m (ID) and 2.5 m, respectively. Effects of liquid velocity, particle size, surface tension of liquid phase and solid circulation rate on the overall heat transfer coefficient were examined. The heat transfer coefficient increased with increasing particle size or solid circulation rate due to the higher potential of particles to contact with the heater surface and promote turbulence near the heater surface. The value of heat transfer coefficient increased gradually with increase in the surface tension of liquid phase, due to the slight increase of solid holdup. The heat transfer coefficient increased with the liquid velocity even in the higher range, due to the solid circulation prevented the decrease in solid holdup, in contrast to that in the conventional liquid-solid fluidized beds. The values of heat transfer coefficient were well correlated in terms of dimensionless groups as well as operating variables.

Keywords heat transfer coefficient, liquid-solid, circulating fluidized bed, liquid surface tension, solid circulation rate, particle size

1 INTRODUCTION

Due to the unique features of liquid-solid circulating fluidized beds it has been employed in diverse fields of chemical, biochemical, food processing, renewable energy and environmental processes [1–4]. One of the special attractions of liquid-solid circulating fluidized bed arises from that it can realize the continuous regeneration of deactivated, used and contaminated catalysts, biomedica, ion exchange resin, absorbents or adsorbents efficiently and economically [5–7]. However, in those heterogeneous reacting or contacting processes, the temperature in the system is not uniform and constant owing to the velocity gradient of continuous liquid phase as well as non-uniform contacting and mixing among multiple phases [8–11]. It is understood that the temperature fluctuations in those heterogeneous processes are highly complicated and irregular, since the processes are dynamic and proceed in flow systems.

The heat transfer characteristics in liquid-solid circulating fluidized beds have been studied with limited kinds of liquid. That is, the continuous liquid media were usually water, diluted synthetic wastewater or viscous aqueous solutions [1, 4, 7–12]. The properties of liquid media have been altered variously depending on the treated materials in various kinds of processes. Actually, it has been frequently encountered that the surface tension of continuous liquid media has been relatively low comparing with that of water or aqueous solutions, especially in the fields of wastewater treatment, fermentation or bio-processing engineering

[1–4, 7]. However, there has been little attention on the heat transfer characteristics in the liquid-solid circulating fluidized beds with low surface tension liquid media.

In the present study, the heat transfer characteristics of liquid-solid circulating fluidized beds with relatively low surface tension media were investigated. Effects of operating variables such as liquid velocity, particle size, solid circulation rate and surface tension of continuous liquid media on the overall heat transfer coefficient of the immersed heater in the riser were discussed.

2 EXPERIMENTAL

Experiments were carried out in the riser of a liquid-solid circulating fluidized bed. The system was composed of three main sections: the riser column, liquid-solid separating unit and solid recycle device, as can be seen in Fig. 1. The diameter and height of the main riser column were 0.102 m and 2.5 m, respectively. The liquid distributor, which was a perforated plate, was installed at the bottom of the riser column. The solid particles which were entrained from the riser were separated at the top of the riser and returned to its bottom through the downcomer and the solid recycle device. The solid circulation rate (G_s) was determined by measuring the amounts of solid piled up above the butterfly valve in the solid recycle device, and adjusted by the secondary liquid flow [9, 11, 12]. The glass beads with density of 2500 kg·m⁻³ was used as solid phase, and mixtures of tap water with

Received 2011-11-15, accepted 2012-07-12.

^{*} Supported by Korea Institute of Energy Technology Evaluation and Planning (KETEP) and GTL Technology Development Consortium (Korean National Oil Corp., Korea Gas Corp., Daelim Industrial Co. and Hyundai Engineering Co.) under “Energy Efficiency & Resources Programs” of the Ministry of Knowledge Economy, Republic of Korea.

^{**} To whom correspondence should be addressed. E-mail: kangyong@cnu.ac.kr

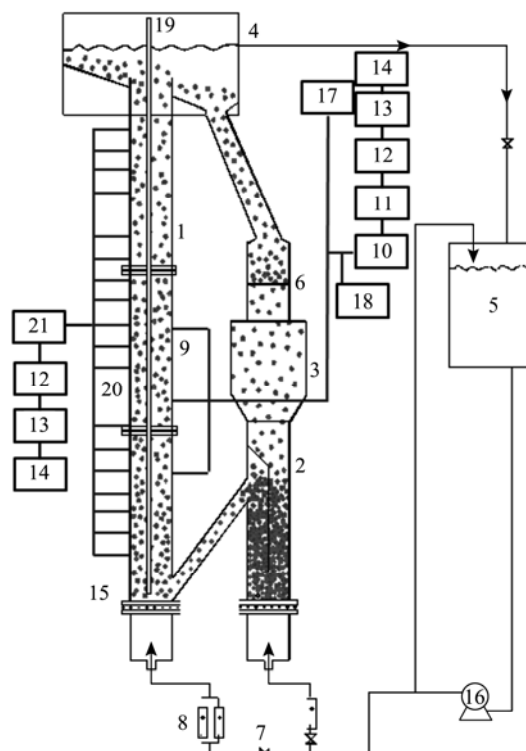


Figure 1 Experimental apparatus

1—riser; 2—down comer; 3—hopper; 4—L/S separator; 5—liquid reservoir; 6—butterfly valve; 7—control valve; 8—flow meter; 9—thermocouple; 10—amplifier; 11—low-pass filter; 12—data acquisition system; 13—A/D converter; 14—computer; 15—liquid distributor; 16—liquid pump; 17—power supply; 18—temperature indicator; 19—heater; 20—pressure tap; 21—pressure sensor

Table 1 Physical properties of liquid phase

Liquid medium	$\mu_{L,app} \times 10^3 / \text{Pa} \cdot \text{s}$	$k_L \times 10^3 / \text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$	$\sigma_L \times 10^3 / \text{N} \cdot \text{m}^{-1}$	$\rho_L / \text{kg} \cdot \text{m}^{-3}$
water	0.960	609.12	72.75	1000
mixture of water & ethanol (2%, by mass)	0.952	600.16	65.18	999.5
mixture of water & ethanol (3%, by mass)	0.948	595.68	60.92	999.0
mixture of water & ethanol (5%, by mass)	0.940	586.71	55.73	998.0

ethyl alcohol were used as a continuous liquid phase. The diameter of solid particles was either 0.5, 1.0, 2.0 or 3.0 mm. The surface tension of continuous liquid phase was in the range of $(55.73\text{--}72.75) \times 10^{-3} \text{ N} \cdot \text{m}^{-1}$. The physical properties of continuous liquid phase were summarized in Table 1, in which the values of thermal conductivity of liquid media were estimated from the relation reported by Assael *et al* [13].

For measuring the pressure drop in the riser, ten pressure taps connected with sensor were mounted flush with the riser wall at intervals of 0.15 m from the inlet of solid recycle. The pressure sensor was semiconductor type (Sensys, Wet Differential Pressure Transducer, Korea). The output voltage signal from the pressure sensor was processed by a data acquisition system (NI cDAQ-9205, National Instruments, Hungary) and a personal computer. The voltage-time signals, corresponding to the pressure-time signals, were sampled at a rate of 1000 Hz. The total data

acquisition time was 30 s having more than 30000 data [14, 15]. The holdups of liquid and solid phases in the test section of the riser were determined by static pressure drop method [5–7] by using Eqs. (1) and (2) from measured values of ΔP .

$$\Delta P/L = (\varepsilon_s \rho_s + \varepsilon_L \rho_L) g \quad (1)$$

$$\varepsilon_s + \varepsilon_L = 1.0 \quad (2)$$

As a heating source, a cone-shaped heater with an outside diameter of 0.03 m and a length of 1.5 m was placed coaxially on the distributor plate at the center of the riser [9, 12]. The heater was made of a copper rod, with an axial hollow space to accommodate a cartridge heater so as to keep the heater surface at the same T . Six thermocouples, which are iron-constantan J-type, were positioned at the surface of the heater 60° apart each other at an elevation of 0.2 m interval from the inlet of the solid recycle, to measure the temperature at the heater surface (see Fig. 2).

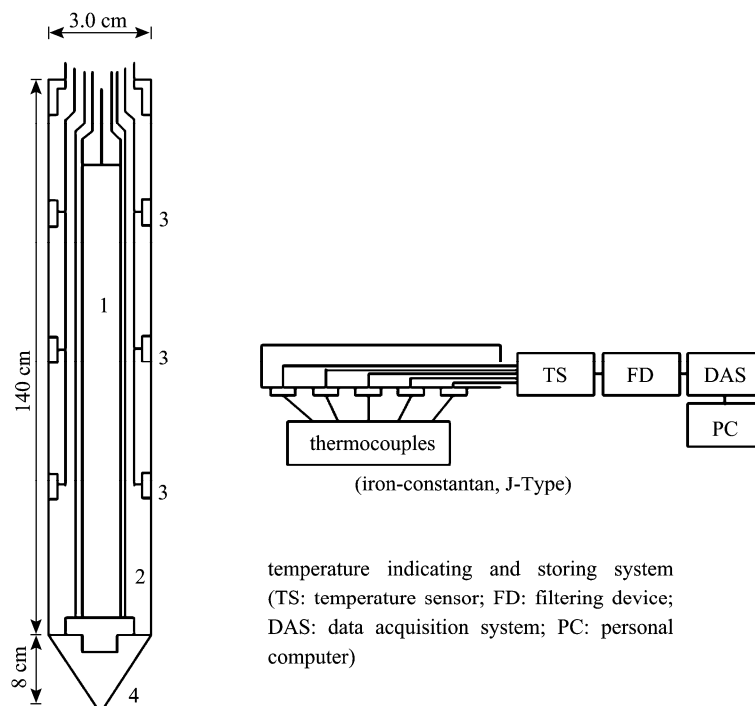


Figure 2 Heater structure & temperature sensing system at the heater surface
1—heater; 2—copper tube; 3—thermocouples; 4—teflon cone

Three sets of five thermocouples were installed in the axial direction with 0.3 m intervals from 0.5 m above the particle recycle part. Each set was composed of five thermocouples which were installed in the radial direction to measure the temperature in the riser content. The probes of thermocouples were connected to a temperature monitoring system, further to a data acquisition system (NI cDAQ-9174) with a filtering device, and then a personal computer to record all temperatures at each point simultaneously and continuously. The cut-off frequency of filtering device was 10 Hz to avoid the noise. To maintain the isothermal condition in the riser at room temperature, the temperature of the liquid phase in the reservoir was controlled. The temperature-time signals, which were converted from voltage-time signals, were sampled at a rate of 500 Hz in a sampling period of 60 s and stored. The sample length comprised 30000 data points, which were enough to detect the full spectrum of signals in the system [14–16].

The mean value of temperature difference (ΔT) between the heater surface and the riser content was determined after the fluctuations of temperature difference was stabilized. The measurements were repeated in the stabilized steady state condition until the mean value of ΔT deviation was less than 5% [17]. The heat transfer coefficients (h) were determined by

$$h = \frac{Q}{A(T_h - T_b)} \quad (3)$$

from the known heat supply, Q , and mean temperature

difference between the heater surface and the riser content. The heat flux from the heater to the riser column content was evaluated by the energy balance in the riser column. The physical properties of liquid phase were measured at the room temperature ($T = 298$ K) at which the experiments were carried out.

3 RESULTS AND DISCUSSION

The heat transfer characteristics can be described more conveniently by analyzing the temperature difference fluctuations between the heating source and the riser content of the liquid-solid circulating fluidized beds. A typical example of temperature difference fluctuations in the riser can be seen in Fig. 3, which indicates that the fluctuations increase but the mean value of temperature difference decreases, with increasing surface tension of liquid phase. These imply that the heat transfer from the heater to the bed content of the riser becomes more favorable with higher surface tension.

Figure 4 shows that the holdup of solid particles increases gradually with increasing liquid surface tension. This can be the reason why the temperature fluctuations increase but the mean value of ΔT decreases. That is, the turbulence generated by the fluidized particles in the riser increases with increasing holdup of particles, because the particles flow as a dispersed phase in the riser.

Figure 5 shows the effects of liquid velocity on the heat transfer coefficient in the riser of liquid-solid

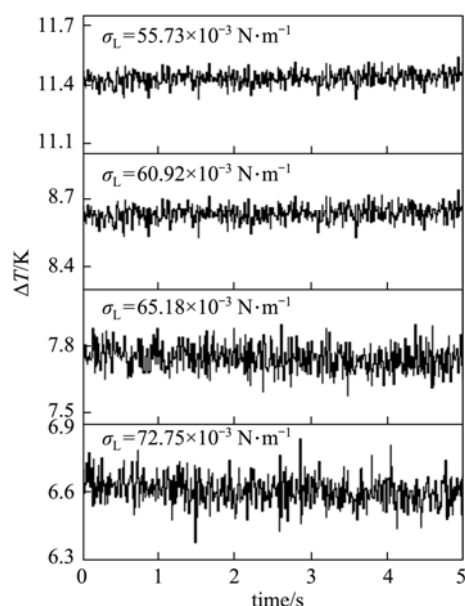


Figure 3 Typical example of ΔT fluctuations in the riser of liquid-solid circulating fluidized beds ($d_p = 1.0$ mm, $U_L = 23.5 \times 10^{-2} \text{ m} \cdot \text{s}^{-1}$, $G_s = 2.5 \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$)

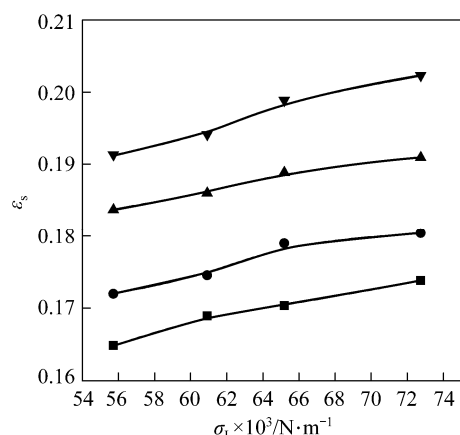


Figure 4 Effects of surface tension of liquid phase on the ε_s in the riser of liquid-solid circulating fluidized beds ($U_L = 23.5 \times 10^{-2} \text{ m} \cdot \text{s}^{-1}$, $d_p = 1.0$ mm) $G_s/\text{kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$: ■ 2.5; ● 4.0; ▲ 6.0; ▼ 8.0

circulating fluidized bed. In this figure, h increases with increasing liquid velocity, way into the high U_L range. This is ascribed to that the holdup of solid particles does not decrease significantly in the higher range of U_L . This is an advantage of liquid-solid circulating fluidized bed, as compared with the conventional liquid-solid fluidized bed in which the h value increases with U_L but decreases with a further increase in U_L [5, 6]. It is noted that the thermal boundary layer around the heater immersed in the riser constitutes the resistance for heat transfer from the heater surface to the riser content [9]. The thermal boundary layer could be eroded and thus be thinner by means of effective contacting with fluidized solid particles in the riser. In general, the momentum of fluidized solid particles

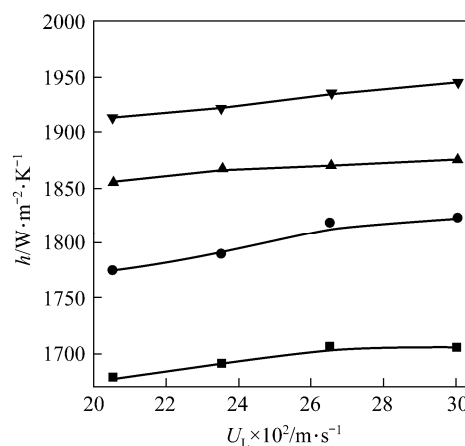


Figure 5 Effects of liquid velocity on the heat transfer coefficient in the riser of liquid-solid circulating fluidized beds ($\sigma_L = 65.18 \times 10^{-3} \text{ N} \cdot \text{m}^{-1}$) $G_s/\text{kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ ($d_p \times 10^3/\text{m}$): ■ 2.5 (0.5); ● 4.0 (0.5); ▲ 4.0 (1.0); ▼ 6.0 (1.0)

could increase with increasing liquid velocity, which could become more effective for the particles to attack the thermal boundary layer. However, in the relatively higher range of U_L , the holdup of fluidized particles decreases considerably with a further increase in the liquid velocity in conventional liquid-solid fluidized beds. These are the reason why the heat transfer coefficient decreases with a further increase in the liquid velocity. This weakness of conventional liquid-solid fluidized beds could be circumvented by employing the circulation of solid particles.

Figure 6 shows that the h value increases with an increase in the particle size in all the cases studied in the riser of liquid-solid circulating fluidized beds. It seems that the larger particles with more inertia force are more effective to promote turbulence in the riser and to attack the boundary layer at the heater surface.

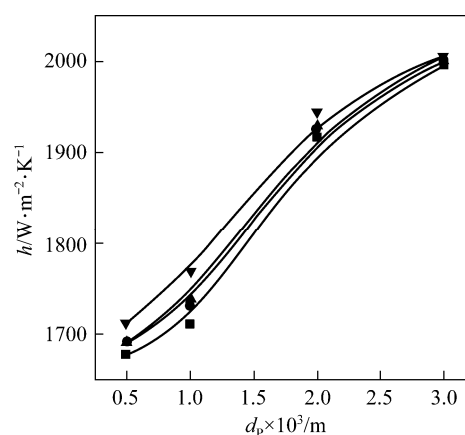


Figure 6 Effects of particle size on the heat transfer coefficient in the riser of liquid-solid circulating fluidized beds ($G_s = 2.5 \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$) $U_L \times 10^2/\text{m} \cdot \text{s}^{-1}$ ($\sigma_L \times 10^3/\text{N} \cdot \text{m}^{-1}$): ■ 20.5 (65.18); ● 23.5 (65.18); ▲ 23.5 (72.75); ▼ 26.5 (72.75)

The turbulence is enhanced from the hindrance effects of fluidized particles by disturbing the continuous upward flow of liquid phase.

Figure 7 shows that the heat transfer coefficient increases gradually with increasing the solid circulation rate in the riser. This can be due to the increase of solid holdup in the riser with an increase in the solid circulation rate. As can be expected, the turbulence in the riser could be increased by increasing the hindrance effects of particles on the liquid flow and by increasing the contacting frequency among fluidized solid particles, with an increase in the solid holdup in the riser. In addition, the increase of solid holdup leads to the enhancement of contacting frequency of particles with the heater surface, resulted in the decrease in the thickness of thermal boundary layer around the surface of heating source.

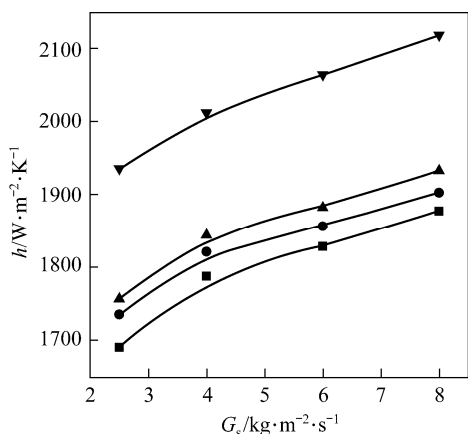


Figure 7 Effects of solid circulation rate on the heat transfer coefficient in the riser of liquid-solid circulating fluidized beds ($\sigma_L = 65.18 \times 10^{-3} \text{ N} \cdot \text{m}^{-1}$)
 $d_p \times 10^3/\mu\text{m}$ ($U_L \times 10^2/\text{m} \cdot \text{s}^{-1}$): ■ 0.5 (23.5); ● 1 (26.5); ▲ 1 (26.5); ▼ 2 (26.5)

Figure 8 shows that the heat transfer coefficient increases slightly with an increase in the surface tension of liquid phase. It is understood that the thermal conductivity of liquid phase decreases slightly with increasing content of ethanol in the continuous liquid phase. In addition, the turbulence in the riser of the liquid-solid circulating fluidized bed could increase with increasing surface tension of liquid phase. This can be inferred from that the fluctuations of temperature differences in the riser increases and the mean value of temperature difference between the heater surface and the riser content decreases, with an increase in the surface tension of liquid phase, as depicted in Fig. 3. The increase of liquid surface tension leads to the increase of cohesive force between liquid and particles at the interface [18], which promotes the drag force acting on the particles fluidized in the continuous liquid medium. This results in the slight increase of solid holdup (Fig. 4) and thus in the increase of turbulence in the riser. Therefore, the value of heat transfer coefficient increases with an increase in the surface tension of liquid phase.

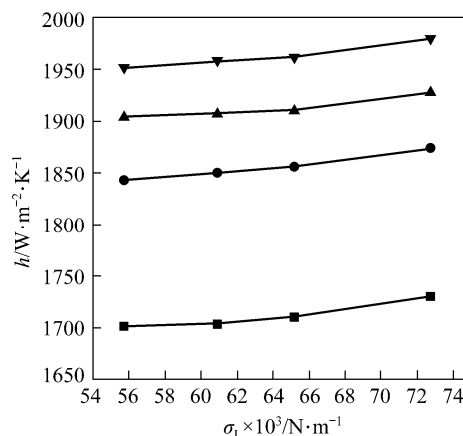


Figure 8 Effects of surface tension of liquid phase on the heat transfer coefficient in the riser of liquid-solid circulating fluidized beds ($U_L = 20.5 \times 10^{-2} \text{ m} \cdot \text{s}^{-1}$)
 $G_s/\text{kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ ($d_p \times 10^3/\mu\text{m}$): ■ 2.5 (1); ● 4.0 (1); ▲ 4.0 (2); ▼ 6.0 (2)

The experimentally obtained values of heat transfer coefficient were correlated in term of operating variables such as liquid velocity, solid circulation rate, particle size and surface tension of liquid phase by means of non-linear regression method. The correlation is

$$h = 4147 U_L^{0.07} G_s^{0.10} d_p^{0.09} \sigma_L^{0.08} \quad (4)$$

which is fitted with the experimental h with a correlation coefficient of 0.954. Eq. (4) is valid in the following ranges of operating variables: $0.205 \leq U_L \leq 0.300 \text{ m} \cdot \text{s}^{-1}$, $2.5 \leq G_s \leq 8.0 \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, $0.5 \leq d_p \leq 3.0 \times 10^{-3} \text{ m}$ and $55.73 \leq \sigma_L \leq 72.75 \times 10^{-3} \text{ N} \cdot \text{m}^{-1}$.

In terms of dimensionless numbers, Eq. (5) reads

$$Nu = 1.58 Pr^{-0.15} Re^{0.02} We^{-2.99} \quad (5)$$

The parity plot is shown in Fig. 9.

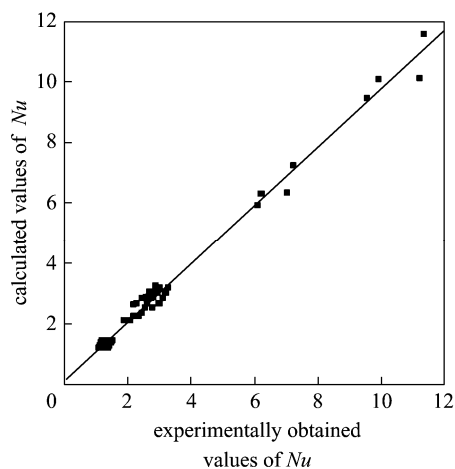


Figure 9 Comparison between the calculated and experimentally obtained values of Nu in liquid-solid circulating fluidized beds with low surface tension media

4 CONCLUSIONS

The heat transfer characteristics in the riser of liquid-solid circulating fluidized bed were successfully analyzed by employing the immersed heater-to-riser heat transfer system with relatively low surface tension liquid media. The value of heat transfer coefficient increased with an increase in the liquid velocity, even in the higher range. The heat transfer coefficient increased with increasing solid circulation rate and particle size, which can be due to the higher turbulent movement of particles and the increase of solid holdup in the riser. The value of heat transfer coefficient increased with increasing liquid surface tension, which can be due to the increase of the thermal conductivity of liquid phase as well as turbulence arising from the increase of solid holdup in the riser.

NOMENCLATURE

A	surface area of heater, m^2
d_p	particle diameter, m
G_s	solid circulation rate, $\text{kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$
g	gravitational acceleration, $\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-2}$
h	overall heat transfer coefficient, $\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$
k_L	thermal conductivity of liquid phase, $\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$
L	test section in the riser, m
Nu	Nusselt number ($= hd_p/k_L$)
ΔP	pressure drop, $\text{N} \cdot \text{m}^{-2}$
Pr	Prandtl number ($= c_p \mu_L / k_L$)
Q	amount of heat supply, W
Re	Reynolds number ($= d_p \rho_L U_L / \mu_L$)
T	temperature, K
ΔT	temperature difference between T_h and T_b , K
t	time, s
U	fluid superficial velocity, $\text{m} \cdot \text{s}^{-1}$
We	Weber number [$= d_p \rho_L (U_L)^2 / \sigma_L$]
ε	phase holdup
$\mu_{L,app}$	apparent liquid viscosity, $\text{Pa} \cdot \text{s}$
ρ	density, $\text{kg} \cdot \text{m}^{-3}$
σ_L	surface tension, $\text{N} \cdot \text{m}^{-1}$

Subscripts

b	bed content
h	heater surface
L	liquid phase

REFERENCES

- Atta, A., Razzak, S.A., Nigam, K.D.P., Zhu, J.X., "Gas-liquid-solid circulating fluidized bed reactors: Characteristics and applications", *Ind. Eng. Chem. Res.*, **48**, 7876–7892 (2009).
- Liang, W.G., Yu, Z.Q., Jin, Y., Wang, Z., Yang, Y., He, M.Y., Min, E.Z., "Synthesis of linear alkyl benzene in a liquid-solid circulating fluidized bed reactor", *J. Chem. Tech. Biotechnol.*, **62**, 98–102 (1995).
- Lan, Q., Bassi, A., Zhu, J.X., Margaritis, A., "Continuous protein recovery from whey using liquid-solid circulating fluidized bed ion-exchange extraction", *Biotechnol. Bioeng.*, **78**, 157–163 (2002).
- Zhu, J., Zheng, Y., Karmanev, D., Bassi, A., "Gas-liquid-solid circulating fluidized beds and their potential applications to bioreactor engineering", *Can. J. Chem. Eng.*, **78**, 82–94 (2000).
- Fan, L.S., *Gas-Liquid-Solid Fluidization Engineering*, Butterworths, Boston, U. S. A (1989).
- Kim, S.D., Kang, Y., "Heat and mass transfer in three-phase fluidized-bed reactors—An overview", *Chem. Eng. Sci.*, **52**, 3639–3660 (1997).
- Kim, S.D., Kang, Y., "Hydrodynamics, heat and mass transfer in inverse and circulating three-phase fluidized-bed reactors for wastewater treatment", *Stud. Surf. Sci. Catal.*, **159**, 103–108 (2006).
- Kuramoto, K., Tsutsumi, A., Chiba, T., "High-velocity fluidization of solid particles in a liquid-solid circulating fluidized bed system", *Can. J. Chem. Eng.*, **77**, 291–298 (1999).
- Shin, K.S., Song, P.S., Lee, C.G., Kang, S.H., Kang, Y., Kim, S.D., "Heat transfer coefficient in viscous liquid-solid circulating fluidized beds", *AIChE J.*, **51**, 671–677 (2005).
- Hashizume, K., Kimura, Y., "Heat transfer characteristics of liquid-solid circulating fluidized beds", *Heat Transfer-Asian Res.*, **37**, 127–137 (2008).
- Kim, S.H., Cho, Y.J., Song, P.S., Kang, Y., Kim, S.D., "Phase holdup characteristics in three-phase circulating fluidized beds", *Korean Chem. Eng. Res.*, **37**, 916–920 (1999). (in Korean)
- Kang, T.G., Song, P.S., Choi, G.S., Cho, Y.J., Kim, S.D., "Heat transfer coefficient in a three-phase circulating fluidized-bed bioreactor", *Korean Chem. Eng. Res.*, **40**, 640–645 (2002). (in Korean)
- Assael, M.J., Charitidou, E., Wakeham, W.A., "Absolute measurements of the thermal conductivity of the mixtures of alcohols with water", *Int. J. Therm. Phys.*, **10**, 793–803 (1989).
- Fan, L.T., Kang, Y., Yashima, M., Neogi, D., "Stochastic behavior of fluidized particles in a liquid-solid fluidized bed", *Chem. Eng. Commun.*, **135**, 146–160 (1995).
- Woo, K.J., Kim, J.S., Kang, Y., Kim, S.D., "Effects of chaotic temperature fluctuations on the heat transfer coefficient in liquid-liquid-solid fluidized beds", *Chem. Eng. Technol.*, **24**, 829–834 (2001).
- Kim, J.S., Woo, K.J., Kang, Y., Nam, C.H., Kim, S.D., "Temperature fluctuations and heat transfer in liquid drop columns", *J. Chem. Eng. Japan*, **34**, 185–192 (2001).
- Lim, D.H., Jang, J.H., Jin, H.R., Kang, Y., Jung, H., Kim, S.D., "Heat transfer in three-phase(G/L/S) circulating fluidized beds with low surface tension media", *Chem. Eng. Sci.*, **66**, 3145–3151 (2011).
- Atkins, P., Paula, J., *Physical Chemistry*, 7th edition, Oxford University Press, UK, 150–154 (2002).