PERGAMON International Journal of Heat and Mass Transfer 44 (2001) 3373–3379

International Journal of HEAT and MASS TRANSFER

www.elsevier.com/locate/ijhmt

Technical Note

Heat transfer enhancement in turbulent upward flows of liquid–solid suspensions through vertical annuli

Tülay A. Özbelge *

Department of Chemical Engineering, Middle East Technical University, Ankara 06531, Turkey

Received 14 March 2000; received in revised form 12 December 2000

Abstract

This paper aims to explain the effects of radial solid concentration distributions (RSCDs) [T.A. Özbelge, A. Beyaz, Dilute solid–liquid upward flows through a vertical annulus in a closed-loop system, Int. J. Multiphase Flow (in press); T.A. Özbelge, A. Beyaz, Seyreltik Sıvı-Katı Karışımlarının Akış Özellikleri, TÜBİTAK Project İNTAG-822, Report No: 196 I 010, Ankara, 1999] on the mechanism of heat transfer enhancement achieved in water–feldspar upward flows [T.A. Özbelge, S.H. Köker, Int. J. Heat Mass Transfer 39 (1) (1996) 135] through vertical annuli having different aspect ratios ($\kappa = 0.31$, 0.42 and 0.54) at different operating conditions. The increasing trend of local solid concentrations from the inner wall to the outer wall of the annulus [Özbelge and Beyaz (loc. cit.), Özbelge et al. (loc. cit.)] is found to be favorable for the enhancement of heat transfer, since the heat transfer between the hot and the cold streams occurs across the inner wall [Özbelge and Köker (loc. cit.)]. Also, the applicability of the fluid–particle interaction model [C.A. Brandon, D.G. Thomas, in: Proceedings of the Fourth International Heat Transfer Conference, Paris, Paper CT-2.1, 1970] to turbulent liquid–solid flows in the vertical annuli [Özbelge and Köker (loc. cit.)] is checked here. The location of peak heat transfer enhancement is determined at the dimensionless grouping of $d_p^* = (d_p/D_h)(Re_s)^{11/16} = 4.2$ for water–feldspar slurries flowing turbulently upward in the vertical annuli which is the same value as that obtained in horizontal pipes [T.A. Özbelge, Int. J. Multiphase Flow 19 (3) (1993) 535], regardless of the geometry. This is in accordance with the interaction model [Brandon and Thomas (loc. cit.); Özbelge (loc. cit.)]. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

The subject of heat transfer in particulate flows became popular during the 1950s, when seeding the flow with micron-sized solid particles was considered as a 'heat transfer augmentation technique'. The understanding of heat transfer to liquid–solid suspensions is important in science and technology. Some of the applications of heat transfer to liquid–solid flows are in power plants using slurries as fuels or as heat transfer media [6,7] and in fluidized beds [8].

Several studies on flow and heat transfer characteristics of two-phase flows have been conducted in the past. Toda et al. [9] and Furuta et al. [10] measured the radial concentration distributions of particles in vertical pipes. They reported that the distributions were related to the size and the density of particles as well as to the liquid velocity. Moreover, Furuta et al. [10] classified the patterns of radial solid distributions by means of the particle Reynolds number and the flow Reynolds number, in vertical upward and downward fully developed turbulent flows. Brandon and Thomas [4] measured the heat transfer rates to water suspensions of glass microspheres with mean diameters from 0.020 to 0.86 mm which were used in concentrations of less than 0.02 volume fraction of solids in both vertical upward and also horizontal transport. The Reynolds number was varied from 20 000 to 90 000. Brandon and Thomas [4], Plass and Molerus [11], and Zisselmar and Molerus [12] explained that the strong mutual interaction between the

---

* Tel.: +90-312-210-2621; fax: +90-312-210-1264.
E-mail address: tozbelge@metu.edu.tr (T.A. Özbelge).

0017-9310/01/$ - see front matter © 2001 Elsevier Science Ltd. All rights reserved.
PII: S 0 0 1 7 - 9 3 1 0 (0 0) 0 0 3 6 6 - 5

Nomenclature

C_f	solid concentration in the feed slurry, wt%
C_s	local solid concentration in radial direction, wt%
D	pipe diameter, mm
D_i	inner pipe diameter, mm
D_h	hydraulic diameter of annulus, $D_o - D_i$, mm
D_o	outer pipe diameter, mm
d_p^*	dimensionless grouping
d_p	particle diameter, mm
h_s	heat transfer coefficient for slurry in the annulus, W/m^2 K
h_{sw}	heat transfer coefficient for single-phase (water) flow in the annulus, W/m^2 K
r	radial distance measured from the center of the concentric pipes, mm
Re_s	slurry Reynolds number, $Re_s = D_h U_m \bar{\rho}_m / \bar{\mu}_m$
Re_{sw}	Reynolds number for single-phase (water) flow in the annulus, $Re_{sw} = D_h U_m \rho_w / \mu_w$
U_m	slurry or mixture velocity in the annulus, m/s or cm/s

Greek symbols

κ	aspect ratio D_i/D_o
$\bar{\mu}_m$	average mixture or slurry viscosity, $\bar{\mu}_m = \mu_w(1 + 2.5\bar{\phi}_s)$, kg/m s
μ_w	water viscosity, kg/m s
ρ_f	solid density in the feed slurry, kg/m^3 or g/cm^3
$\bar{\rho}_m$	average transport mixture density in the test section $= \bar{\phi}_s\rho_p + (1 - \bar{\phi}_s)\rho_w$, kg/m^3 or g/cm^3
ρ_p	particle density, kg/m^3 or g/cm^3
ρ_s	radial local solid density, kg/m^3 or g/cm^3
$\bar{\rho}_s$	average solid transport density in the test section, kg/m^3 or g/cm^3
ρ_w	water density, kg/m^3 or g/cm^3
ϕ_s	radial local transport volume fraction of solids in the test section $= \rho_s/\rho_p$

fluid and the solid phases increased the turbulent intensity; thus the solid particles enhanced the wall-to-suspension heat transfer by thinning the viscous sublayer. A dimensionless grouping $d_p^* = (d_p/D)(Re)^{11/16}$ was reported for the occurrence of a peak heat transfer enhancement at a constant value of $d_p^* = 4.4$ for water–glass powder suspension flows [4]. Özbelge [5] investigated the applicability of the previously proposed model [4] to the water–feldspar flows in a horizontal pipe and concluded that a particular combination of particle size (0.161 mm), pipe diameter (41 mm), flow Reynolds number (26 500) and feed solid concentration (1% v/v) would determine the magnitude of the peak heat transfer enhancement, while its location was set by d_p^* in accordance with the interaction model [4]. She further reported the value of d_p^* as 4.2 for water–feldspar slurries flowing turbulently in horizontal pipes [5]. This model needs to be checked for the liquid–solid flows in the other geometries, especially in the annular geometry which has many applications in food and chemical industries, mining operations and wastewater treatment processes.

A relatively recent study by Özbelge and Köker [3] investigated the effects of the experimental parameters on the enhancement of heat transfer from hot water–feldspar slurries flowing turbulently upward in vertical annuli and reported that the combined effects of particle size, width of annular gap, ratio of hydraulic diameter to mean particle diameter, solid content of slurry, Prandtl and the flow Reynolds numbers would determine the percentage of heat transfer enhancement to or from turbulent water–feldspar upflows through the vertical annuli. It was concluded that at relatively low Reynolds numbers (around 16 000) the particle–wall, particle–eddy interactions represented roughly by the ratio of particle size to hydraulic diameter (d_p/D_h) and the average transport solid density ($\bar{\rho}_s$) in the test section were the most effective factors in determining the heat transfer enhancement.

From these studies, it has been obviously clear that the radial solid concentration profiles will provide the most valuable information to explain the heat transfer mechanism and the heat transfer enhancement. Therefore most recently, Özbelge and Beyaz [1,2] have obtained the radial solid concentration profiles in the vertical upward flows of water–feldspar slurries through an annulus to clarify the relationship between the latter profiles [1,2] and the heat transfer enhancement determined previously [3] in a similar system. One of the objectives of this paper is to discuss the effects of the radial solid distributions on the heat transfer enhancement in water–feldspar upflows through the vertical annuli, after summarizing the author's previous two studies [1–3] and the other objective is to check the applicability of the interaction model [4] to the slurry flows in the annular geometry in order to obtain the location of peak heat transfer enhancement for water–feldspar upflows through the vertical annuli.

2. Experimental

A schematic diagram of the experimental apparatus is given in Fig. 1. It consists of two-main lines, a hot slurry upward-flow in the annulus and a cold water downward-flow in the inner pipe. Shielded iron–con-

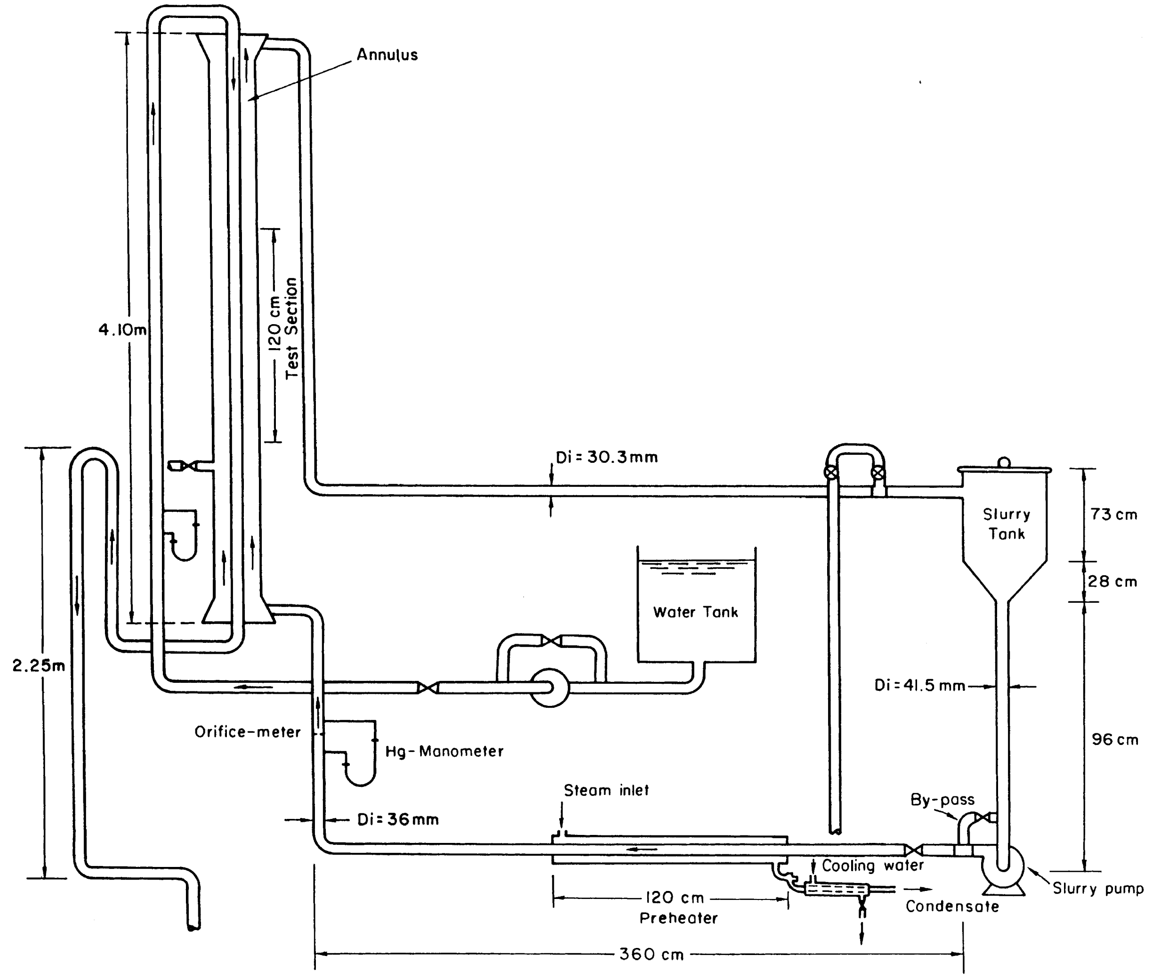


Fig. 1. Schematics of experimental set-up in the heat transfer study [3].

stantan thermocouples were used to measure the slurry temperatures extended into annulus horizontally with their tips in-between the inner and outer pipes, while the thermocouples measuring water temperatures extended into the center of the inner pipe. Shielded iron–constantan thermocouples of surface type were used to measure the wall temperatures on the outside surface of the inner pipe. The measuring and the calculation procedures for the temperatures and the heat transfer coefficients respectively, are given elsewhere [3].

The experimental set-up used for the hydrodynamic study [1,2] was a modification of the previous one [3], since a larger annular gap was necessary to determine the local solid concentrations at the several points along the radial distance. This necessitated a larger capacity head tank and the other adjustments in the system to work at the proper conditions, such as raising the head tank to a level above the exit of the annulus to avoid the leakage of air into the system and using a slurry pump with higher power and capacity. Both ends of the inner pipe were closed to avoid the leakage of the slurry into the inner pipe. The ranges of the parameters in the hydrodynamic and the heat transfer studies are given in (Tables 1 and 2).

A sampling probe designed previously by Özbelge and Somer [13] was used to measure the local radial solid concentrations at a cross-section of the annulus perpendicular to the flow. Further details are given elsewhere [1–3,13].

3. Results and discussion

Several experiments were performed with hot-water flow without solids in the annulus cooled by the cold-water flow in the tube-side to check the accuracy of the experiments in each concentric pipe-set [3]. The individual heat transfer coefficients for single-phase water

Table 1
The ranges of parameters in the flow experiments [1,2]

Solid concentration in feed slurry, C_f (% v/v)	0.3–2.3
Feldspar particle size, d_p (mm)	0.064–0.230
Reynolds number of the slurry, $Re_s = D_h U_m \bar{\rho}_m / \bar{\mu}_m$	800–20 000
Mixture velocity in the annulus, U_m (m/s)	0.008–0.193
Particle density, ρ_p (kg/m^3)	2400
Vertical length of annulus (m)	5
Hydraulic diameter, D_h (m)	0.1
Annular gap, $D_h/2$ (m)	0.05
Aspect ratio, D_i/D_o	0.2

Table 2
The ranges of parameters in the heat transfer experiments [3]

Solid concentration in feed slurry, C_f	0.75–2.5 (wt%) or 0.3–1 (% v/v)
Feldspar particle size, d_p (mm)	0.072–0.191
Reynolds number of the slurry, $Re_s = D_h U_m \bar{\rho}_m / \bar{\mu}_m$	15 500–55 500
Mixture velocity in the annulus, U_m(m/s)	0.248–1.25
Particle density, ρ_p (kg/m^3)	2500
Vertical length of annulus (m)	4.1
Hydraulic diameters, $D_h = D_o - D_i$ (m)	0.036, 0.030, 0.024
Annular gaps, $D_h/2$ (m)	0.018, 0.015, 0.012
Aspect ratios, D_i/D_o	0.308, 0.423, 0.538
Solid heat capacity C_p (J/kg K)	836.8
Solid thermal conductivity, k_s (W/m K)	1.09

flow in the annulus, h_{sw}, were calculated and plotted with respect to flow Reynolds numbers, Re_{sw}, and a straight line of 'h_{sw} vs Re_{sw}' for each annulus (or for each aspect ratio) was obtained to be used as a reference for the determination of the percent enhancement in the convective heat transfer coefficient of the slurry, h_s, if any, by the addition of solids to water. The reference line of 'h_{sw} vs Re_{sw}' was also calculated from a generalized correlation for heat transfer in turbulent flow of a single-phase in an annulus [14]. For each aspect ratio, h_{sw} vs Re_{sw} and h_s vs Re_s were plotted on the same graph. The vertical distance between the curve and the reference line at each slurry Reynolds number (Re_s) yielded the ratio of (h_s/h_{sw}) at that Re_s. A representative figure from [3] is given here (Fig. 2) where it can be observed that h_s vs Re_s curve gives a minimal vertical distance to the corresponding reference line (a minimum enhancement ratio (ER), h_s/h_{sw} or 0 ER) at an intermediate Re_s. This behavior can be explained with the radial solid concentration profiles [1,2] and the average transport solid densities ($\bar{\rho}_s$) evaluated from these profiles. Keeping the feed solid concentration (FSC) constant, the amount of solids carried to the annulus increases with the increasing Re_s due to the decrease in the amount of settled solids in the horizontal pipe section. As a result, $\bar{\rho}_s$ in the test section increases until there is no solids settled in the horizontal pipe section and all the solids are fully suspended with the increasing Re_s; then the $\bar{\rho}_s$ in the test section decreases at the higher values of the Re_s due to the more homogeneous distribution of the whole solids, added to the head tank in the preparation of the feed slurry, within the closed-loop system. This means that at an intermediate Re_s, a peak value of the $\bar{\rho}_s$ (thus of the transport mixture density, $\bar{\rho}_m$) is reached in the test section, where the effect of the radial solid concentration distribution (RSCD) on the heat transfer mechanism becomes less significant, especially in a narrow annular

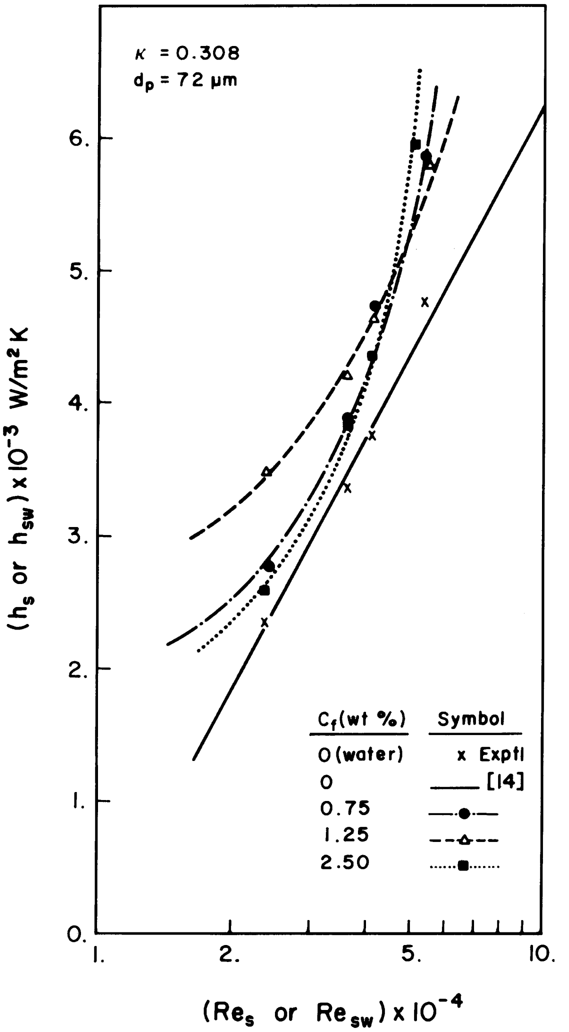


Fig. 2. h_s vs Re_s, with C_f as a parameter for $\kappa = 0.308$ and $d_p = 0.072$ mm [3].

gap. This may cause a minimum heat transfer enhancement due to the suppression of turbulence by solids at that operating condition. Increasing $\bar{\rho}_s$, in the test section, may favor the heat transfer to some extent by thinning the viscous sublayer due to the increasing particle–wall interactions; on the other hand, the freedom of solid particles in the radial direction will be limited depending on the width of the annular gap, particle size and the FSC at that Re_s. Also, the relative heat capacity of the liquid and the solid phases is an important factor to be considered. As the average transport concentration of the solids increases in the test section, the heat capacity of the mixture becomes even lower than that of water since the heat capacity of feldspar is only about one-fifth that of water. At relatively lower Re_s, yielding lower $\bar{\rho}_s$ in the test section, the RSCD should become more effective on the heat transfer enhancement. This was supported by the results of the previous studies [1–3] where the measured local solid concentrations near the inner wall were smaller than those around the outer wall of the annulus in the water–feldspar upward flows (Fig. 3). The solid particles, having greater freedom in bombarding the inner wall to thin the viscous boundary layer, would enhance the heat transfer since the latter occurred between the hot and the cold streams across the inner wall of the annulus. As a result of these two competing effects (i.e., the particle–wall interactions and the relative heat capacities of the phases), the ER changes with the average $\bar{\rho}_m$ and the radial distribution of the solids in the test section, depending on the particle size, FSC, width of the annular gap, physical properties of the phases and the Reynolds number.

From the experimental results [3], it was observed that an intermediate FSC of 1.25 wt% (or 0.5% v/v) was favorable for relatively high enhancement ratios (ERs) in using feldspar particles of 0.072 or 0.127 mm in average diameter, at relatively low Re_s of around 18 000 in the annular gap of 18 mm [3]; a higher FSC 2.5 wt% (1% v/v) was required for 0.191 mm particles to obtain almost the same ERs. This shows that a high number density of particles is obviously important for the significant particle–wall collision rates [3]. As the width of the annular gap was decreased to the values of 12–15 mm, a smaller FSC of 0.75 wt% (0.3% v/v) would be enough in favoring the high heat transfer ERs for all the particle sizes in the range of 0.072–0.191 mm [3]. After the occurrence of the minimum or 0 ERs at the intermediate Reynolds numbers (22 000 to 34 000) depending on the operating conditions, the ER started to increase again with Re_s (40 000–50 000), but not as high as those at the lower slurry Reynolds numbers around 18 000 in the heat transfer study. This was in accordance with the decreasing $\bar{\rho}_m$ in the test section with the increasing Re_s in the closed-loop system at a constant FSC. Therefore, the effect of the RSCD on the ER became important again, because of the increasing freedom of solid particles next to the inner wall. This behavior of solids was observed at relatively low Re_s of around 20 000 in the hydrodynamic study without heat transfer [1–3], which corresponded to the higher values of Re_s (around 40 000) in the heat transfer study because of the change in mixture viscosity with the steady-state temperature of the system.

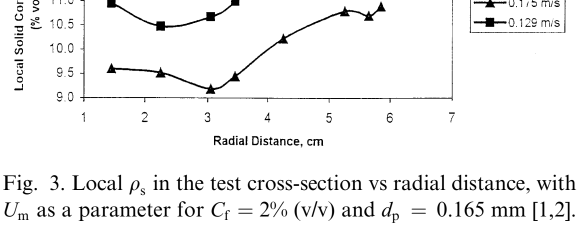


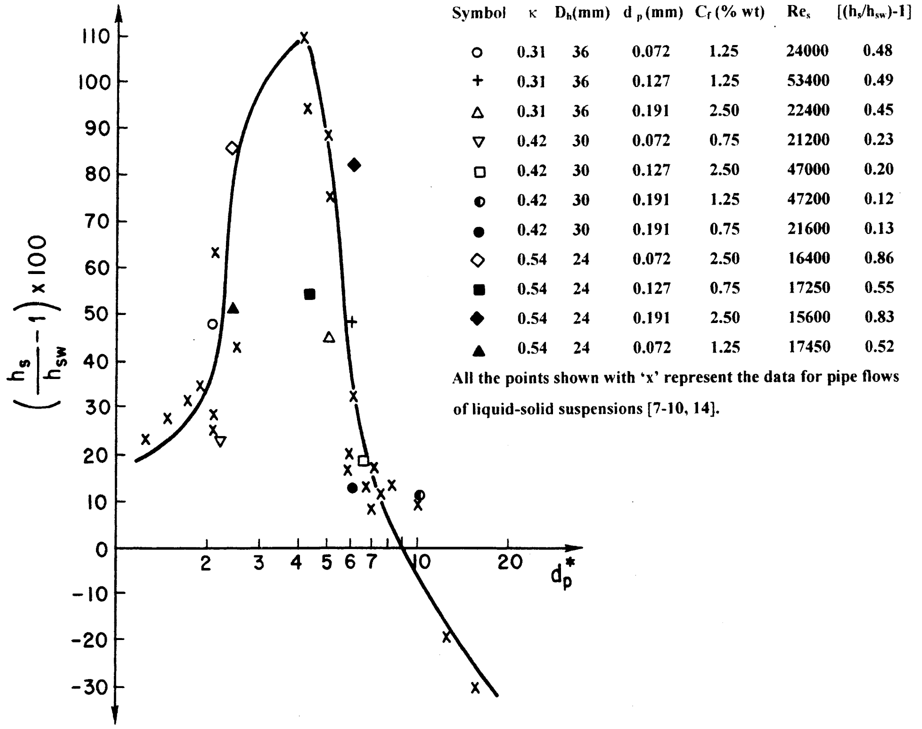
Fig. 3. Local ρ_s in the test cross-section vs radial distance, with U_m as a parameter for $C_f = 2\%$ (v/v) and $d_p = 0.165$ mm [1,2].

At high slurry Reynolds numbers around 45 000, the ER might decrease due to the gain of high momentum by particles in the direction of flow, and prevention of their lateral motion which contributed to the thinning of the viscous boundary layer; but this effect was compensated by the increasing number density of the solid particles at the higher FSCs. Therefore, the ER increased again with the slurry Reynolds numbers, especially at moderately high FSCs, due to the interaction between the particles and high-intensity eddies which created favorable patterns for better heat transfer [3,15].

In this paper, the location of peak heat transfer enhancement for turbulent water–feldspar upflows in the vertical annuli is determined by plotting the percent enhancement $[(h_s - h_{sw}) \times 100/h_{sw}]$ vs dimensionless grouping of $d_p^* = (d_p/D_h)Re_s^{11/16}$ at different operating conditions which are most favorable for the higher heat transfer rates (Fig. 4). From Fig. 4, d_p^* is obtained to be 4.2 for water–feldspar slurries flowing turbulently upward in the vertical annuli which is the same value of d_p^* as in the water–feldspar flows in horizontal pipes [5], regardless of the geometry. This is in accordance with the interaction model [4] where it is found that d_p^* is a function of the material densities of the fluid and solid phases in the suspension, as a result of a detailed theoretical derivation given in [4,5].

4. Conclusions

The average transport solid density ($\bar{\rho}_s$) resulting in the test section as a function of the particle size, particle density, feed solid concentration, slurry Reynolds number and the hydraulic diameter of the annulus determines the magnitude of the peak heat transfer



Symbol	κ	D_h(mm)	d_p(mm)	C_f(% wt)	Re_s	$[(h_s/h_{sw})-1]$
○	0.31	36	0.072	1.25	24000	0.48
+	0.31	36	0.127	1.25	53400	0.49
△	0.31	36	0.191	2.50	22400	0.45
▽	0.42	30	0.072	0.75	21200	0.23
□	0.42	30	0.127	2.50	47000	0.20
◐	0.42	30	0.191	1.25	47200	0.12
●	0.42	30	0.191	0.75	21600	0.13
◇	0.54	24	0.072	2.50	16400	0.86
■	0.54	24	0.127	0.75	17250	0.55
◆	0.54	24	0.191	2.50	15600	0.83
▲	0.54	24	0.072	1.25	17450	0.52

All the points shown with 'x' represent the data for pipe flows of liquid-solid suspensions [7-10, 14].

Fig. 4. Location of peak heat transfer enhancement for water–feldspar upward flows through vertical annuli.

enhancement in the turbulent slurry flows through the vertical annuli, while its location is set by the dimensionless grouping of $d_p^* = (d_p/D_h)Re_s^{11/16}$ in accordance with the interaction model [4]. The value of d_p^* is determined as 4.2 for water–feldspar upward flows through the vertical annuli.

At an intermediate slurry Reynolds number (22 000 to 34 000) depending on the operating conditions, a minimum or 0 heat transfer ER may occur. This is caused most probably by the suppression of the turbulence due to a high average transport concentration of solids in the test section of the annulus, since the latter increases up to a certain value (a peak value of $\bar{\rho}_s$) with the slurry Reynolds number and then decreases as determined by the flow characteristics of the system [1–3]. The radial solid concentration distribution becomes more effective on the heat transfer enhancement at the slurry Reynolds numbers below and above that yielding the minimum ER. The increasing trend of the radial local solid concentrations from the inner wall to the outer wall of the annulus [1,2] seems to favor the heat transfer across the inner wall, due to the greater freedom of the particles in bombarding the inner wall so as to thin the viscous boundary layer. Also, the relative heat capacity of the liquid and the solid phases is an important factor to be considered for the heat transfer enhancement [3].

Acknowledgements

The work [1,2] was financed by the Scientific and Technical Research Council of Turkey (TÜBİTAK). The author expresses her appreciation for this support.

References

[1] T.A. Özbelge, A. Beyaz, Dilute solid–liquid upward flows through a vertical annulus in a closed-loop system. Int. J. Multiphase Flow 27 (4) (2001) 737–752.

[2] T.A. Özbelge, A. Beyaz, Seyreltik Sıvı-Katı Karışımlarının Akış Özellikleri. TÜBİTAK Project İNTAG-822, Report No: 196 I 010, Ankara, 1999.

[3] T.A. Özbelge, S.H. Köker, Heat transfer enhancement in water–feldspar upflows through vertical annuli, Int. J. Heat Mass Transfer 39 (1) (1996) 135–147.

[4] C.A. Brandon, D.G. Thomas, Transport characteristics of suspensions, in: Proceedings of the Fourth International Heat Transfer Conference, Paris, Paper CT-2.1, 1970.

[5] T.A. Özbelge, Location of peak heat transfer enhancement, Int . J. Multiphase Flow 19 (3) (1993) 535–538.

[6] C.J. Park, K.O. Choj, D.S. Doh, An experimental and theoretical study on the augmentation of heat transfer by suspended solid particles in the flowing fluid in a vertical tube, Hwahak Konghak 27 (1989) 682–688.

[7] R.G. Boothroyd, Flowing Gas–Solids Suspensions, first ed., Chapman & Hall, London, 1971, pp. 167–190.

[8] G.W. Govier, K. Aziz, Flow of Complex Mixtures in Pipe, Van Nostrand Reinhold, New York, 1972 (Chapters 7–9).
[9] M. Toda, T. Shimizu, S. Saito, S. Maeda, Preprint for 37th Annual Meeting of Society of Chemical Engineers, Japan, 1972, B-310.
[10] T. Furuta, S. Tsujimoto, M. Okazaki, R. Toei, Concentration distribution of particles in solid–liquid two-phase flow through vertical pipe, Kagaku Kogaku Ronbunshu 4 (1978) 105.
[11] L. Plass, O. Molerus, Simultane warmeübergangs und druck verlustmessungen an feststoff/flüssigkeits-suspensionen im übergangsbereich vom homogenen zum heterogenen suspensions-transport, Chem.-Ing.-Tech. 46 (1974) 355–356.
[12] R. Zisselmar, O. Molerus, Investigation of solid–liquid pipe flow with regard to turbulence modification, Chem. Eng. J. 18 (1979) 233–239.
[13] T.A. Özbelge, T.G. Somer, Hydrodynamic and heat transfer characteristics of liquid–solid suspensions in horizontal turbulent pipe flow, Chem. Eng. J. 38 (1988) 111–122.
[14] B.S. Petukhov, L.I. Roizen, Generalized relationship for heat transfer in a turbulent flow of gas in tubes of annular section, High Temp. 2 (1964) 65–68.
[15] A. Alajbegovic, A. Assad, F. Bonetto Jr., R.T. Lahey, Phase distribution and turbulence structure for solid–liquid upflow in a pipe, Int. J. Multiphase Flow 20 (1994) 453–479.