Int. J. Multiphase Flow Vol. 19, No. 3, pp. 535–538, 1993
Printed in Great Britain.
0301-9322/93 $6.00 + 0.00

LETTER TO THE EDITOR

THE LOCATION OF PEAK HEAT TRANSFER ENHANCEMENT IN SUSPENSION FLOWS

1. INTRODUCTION

The relationship between the heat transfer enhancement due to the presence of solid particles and the fluid–solid interactions in flowing suspensions has been studied by several researchers. Relatively recent investigations have been made by Brandon & Thomas (1970), Plass & Molerus (1974) and Zisselmar & Molerus (1979). In all these studies, it has been proved that, in the viscous sublayer, the strong mutual interaction between the fluid and solid phases increases the turbulent intensity, thus the solid particles enhance the wall-to-suspension heat transfer by thinning the viscous sublayer.

Brandon & Thomas (1970) have obtained a nondimensional grouping, $d_p^* = (d_p/D)(\mathrm{Re})^{11/16}$, as a result of their theoretical analysis and have reported the occurrence of a peak heat transfer enhancement at a constant value of d_p^*, which has been found to be approx. 4.4 for water–glass powder suspension flows (figure 1). In this grouping, d_p and D are the particle and pipe diameters, respectively. The flow Reynolds number can be defined by $\mathrm{Re} = (Du_s\rho_{ave})/\mu$, where u_s is the average suspension velocity, ρ_{ave} is the volume-averaged density of the suspension and μ is the fluid viscosity.

Zisselmar & Molerus (1979) have reported that the increase of the solids concentration up to a critical value ($\sim 3\%$ by vol) causes more encounters between particles and eddies, which lead to a further increase of turbulence and, in turn, to a higher heat transfer rate (Plass & Molerus 1974).

The objective of this letter is to investigate the applicability and usefulness of the interaction model using the experimental heat transfer data of Özbelge & Somer (1988), Plass & Molerus (1974) and Brandon & Thomas (1970).

2. INTERACTION MODEL

In dilute fluid–solid suspensions, the particle–particle interactions can be neglected; but, fluid–solid particle interactions are important. The relative motion of a particle in a turbulent fluid has been expressed by Hinze (1959) as follows:

$$\frac{\mathrm{d}v_p}{\mathrm{d}t} + av_p = av_f + b\frac{\mathrm{d}v_f}{\mathrm{d}t} + c\int_{t_0}^{t}\frac{\left(\dfrac{\mathrm{d}v_f}{\mathrm{d}t'}\right) - \left(\dfrac{\mathrm{d}v_p}{\mathrm{d}t'}\right)}{\sqrt{t-t'}}\,\mathrm{d}t', \qquad [1]$$

where a, b and c are coefficients; v_p and v_f are the particle and fluid velocities, respectively: and t and t' are time. The coefficient "a" is called the "characteristic frequency" which determines the motion of the particles and is equal to the reciprocal of the time required for the fluid to change the flow state of a particle; "a" is defined by

$$a = \frac{36\mu}{(2\rho_p + \rho_f)d_p^2}; \qquad [2]$$

ρ_p and ρ_f are the particle and fluid densities. Kuchanov & Levich (1967) have shown that as the turbulent motion frequency or the reciprocal of the Kolmogoroff time scale (w_η) gets closer to the characteristic frequency, turbulent energy dissipation will increase as a result of increasing fluid–solid interactions. The experimental work by Townsend (1951) has indicated that the maximum energy dissipation occurs at a wavenumber which is given by

$$\tfrac{1}{5}w_\eta = \frac{1}{5}\left(\frac{\epsilon}{\nu}\right)^{1/2}, \qquad [3]$$

where ϵ is the local rate of energy dissipation per unit mass and ν is the kinematic viscosity. Laufer (1954) has determined the wall region as the region where the maximum rate of local energy dissipation occurs in pipe flow and the average rate of energy dissipation may be estimated by

$$\epsilon_{\text{ave}} = \frac{2fV^3}{D}. \qquad [4]$$

In [4] f, V and D represent the Fanning friction factor, the average velocity and the diameter, respectively. Brandon & Thomas (1970) have obtained the criterion for the maximum fluid–solid interactions by assuming that these interactions occur at a maximum rate in the viscous sublayer, where the rate of turbulent energy dissipation is a maximum. Considering the previous works by Townsend (1951) and Laufer (1954), they have started their derivation with the following equation:

$$a = \tfrac{1}{5} w_\eta. \qquad [5]$$

From [2] and [5], it follows that

$$\frac{36\mu}{(2\rho_p + \rho_f)d_p^2} = \frac{1}{5} w_\eta. \qquad [6]$$

They have derived the nondimensional grouping d_p^* by using [3], [4] and [6] and the Blasius equation to relate the friction factor and Re. The d_p^* value, which will determine the location of the peak heat transfer enhancement, has been expressed by

$$d_p^* = \frac{d_p}{D}(\text{Re})^{11/16} = 11.9\left(\frac{\rho_f}{2\rho_p + \rho_f}\right)^{1/2}. \qquad [7]$$

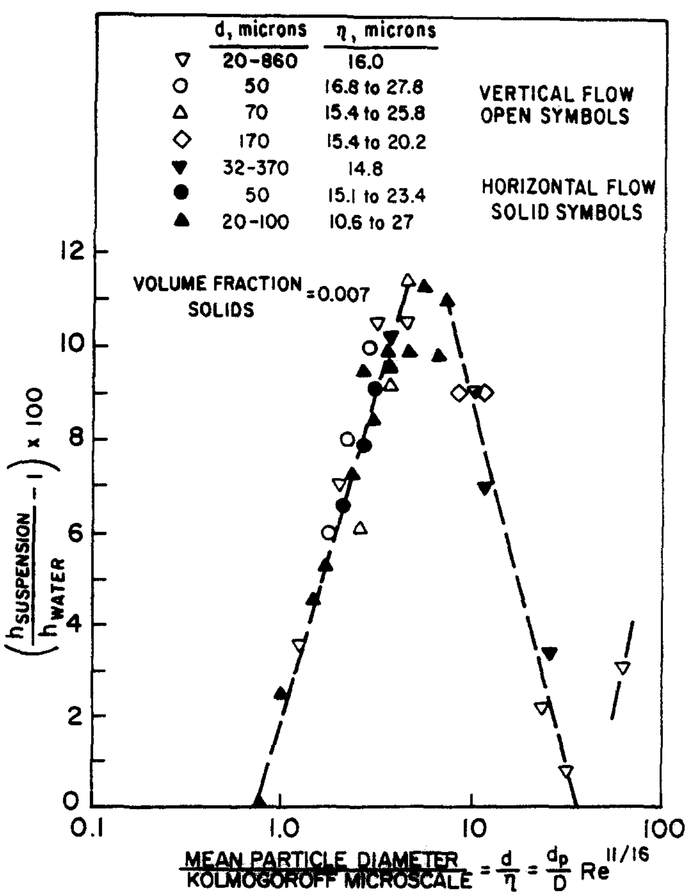
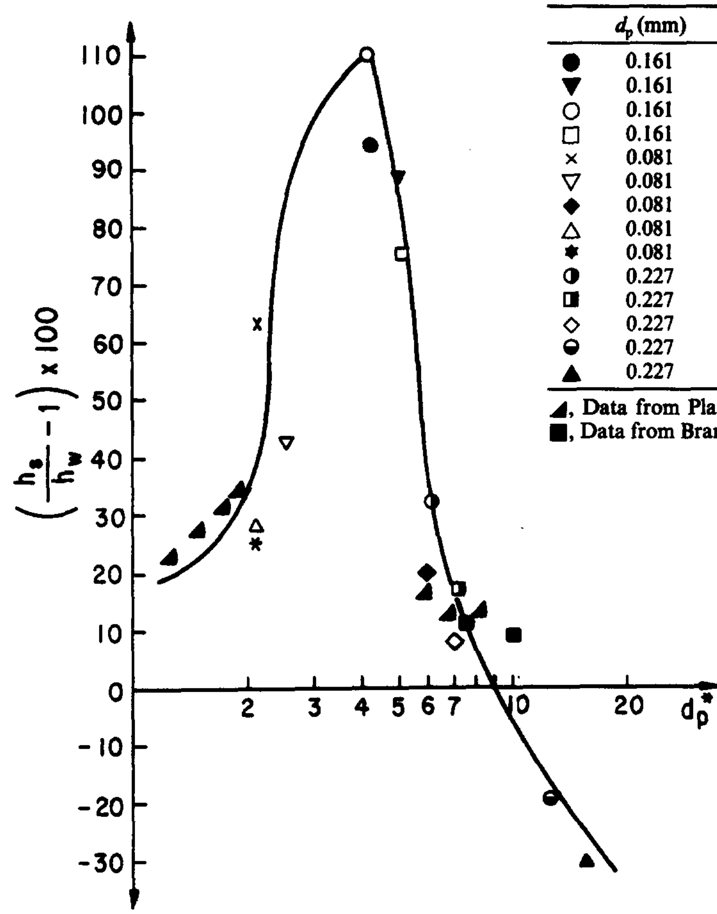


Figure 1. Effect of particle size and system characteristics on the convective heat transfer to dilute water suspensions (Brandon & Thomas 1970).



	d_p (mm)	C_{feed} (% vol)	Re
●	0.161	0.5	27,000
▼	0.161	0.5	34,000
○	0.161	1.0	26,000
□	0.161	3.0	34,000
×	0.081	0.5	27,000
▽	0.081	0.5	34,000
◆	0.081	0.5	115,000
△	0.081	1.0	26,000
*	0.081	3.0	27,000
◑	0.227	0.5	27,000
◨	0.227	0.5	34,000
◇	0.227	3.0	34,000
⊖	0.227	0.5	78,000
▲	0.227	0.5	107,000

◢, Data from Plass & Molerus (1974).
■, Data from Brandon & Thomas (1970).

Figure 2. Location of peak heat transfer enhancement [experimental heat transfer data from Özbelge & Somer (1988)].

3. EXPERIMENTAL WORK

The heat transfer data tested here have been obtained in a closed-loop system circulating water–feldspar slurries at different operating conditions. The test section is a horizontal copper pipe of 41.5 mm dia. The slurry flowing through the pipe is heated by steam condensing in the shell around the test section. The details of the experimental work, the calculational technique for the suspension heat transfer coefficient and the heat transfer data have been presented elsewhere (Özbelge & Somer 1988). Using the abovementioned data, the nondimensional grouping d_p^* values at various flow conditions have been calculated and the "percentage enhancement" vs d_p^* plot has been prepared, as shown in figure 2. The percentage enhancement is defined as follows:

$$\% \text{ enhancement} = \left(\frac{h_s}{h_w} - 1\right) \times 100, \qquad [8]$$

where h_s is the wall-to-suspension heat transfer coefficient and h_w is the wall-to-water heat transfer coefficient if it was pure water flowing at the same operating conditions instead of suspension. The h_w values have been calculated by the well-known Sieder & Tate (1936) equation.

4. RESULTS AND DISCUSSION

As suggested by Brandon & Thomas (1970), two independent experimental approaches have been used by Özbelge & Somer (1988) to obtain the heat transfer data: one is variation of the flow

Re at a fixed particle size and a fixed inlet solid concentration (concentration of the slurry prepared in the feed tank = C_{feed}); the other is variation of the particle size at an approximately constant Re and a fixed inlet solid concentration. The maximum error in the experiments is around $\pm 7\%$. These experimental data points can be observed to outline the entire enhancement curve in figure 2.

For the purpose of comparison, some of the heat transfer data of Plass & Molerus (1974) and by Brandon & Thomas (1970) are also shown in figure 2; they almost follow the same enhancement curve. Since, in this study and in the other two abovementioned experimental studies, the densities of the solid phases are close and the liquid phase is water in all of them, the location of the peak heat transfer enhancement seem to be in good agreement with the proposed interaction model of Brandon & Thomas (1970). The location of peak heat transfer enhancement found in figure 2 is at around $d_p^* = 4.2$, while the one determined by Brandon & Thomas (1970) is at around $d_p^* = 4.4$ (figure 1). These two d_p^* values are almost the same, but the magnitudes of the percentage enhancement values are different. Therefore, it can be concluded that there exists a particular combination of particle size, pipe diameter, flow Re and solids concentration which will determine the magnitude of the peak heat transfer enhancement in suspension flows, while its location is determined by d_p^* in accordance with the interaction model and [7].

REFERENCES

BRANDON, C. A. & THOMAS, D. G. 1970 Transport characteristics of suspensions. *Proc. 4th Int. Heat Transfer Conf.*, Paris, Paper No. CT-2.1.

HINZE, J. O. 1959 *Turbulence*. McGraw Hill, New York.

KUCHANOV, S. & LEVICH, V. 1967 Energy dissipation in a turbulent gas containing suspended particles. *Soviet Phys. Dokl.* **12,** 549–551.

LAUFER, J. 1954 The structure of turbulence in fully developed pipe flow. Report NACA-TR-1174, National Bureau of Standards, Washington, DC.

ÖZBELGE, T. A. & SOMER, T. G. 1988 Hydrodynamic and heat transfer characteristics of liquid–solid suspensions in horizontal turbulent pipe flow. *Chem. Engng J.* **38,** 111–122.

PLASS, L. & MOLERUS, O. 1974 *Chem. Ing. Tech.* **8,** 355.

SIEDER, E. N. & TATE, C. E. 1936 *Ind. Engng Chem.* **28,** 1429.

TOWNSEND, A. A. 1951 On the fine scale structure of turbulence. *Proc. R. Soc. Lond.* **208A,** 534–542.

ZISSELMAR, R. & MOLERUS, O. 1979 Investigation of solid–liquid pipe flow with regard to turbulent modification. *Chem. Engng J.* **18,** 233–239.

T. A. ÖZBELGE

Department of Chemical Engineering

Middle East Technical University

Ankara 06531, Turkey