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HIGH PRESSURE HEAT TRANSFER INVESTIGATIONS FOR FLUIDIZED BEDS OF LARGE PARTICLES AND IMMERSED VERTICAL TUBE BUNDLES

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Abstract—The overall heat transfer coefficient, h_w, is measured for vertical tube bundles in fluidized beds of glass beads ($\bar{d}_p = 1.25$ and 3.10 mm) and sands ($\bar{d}_p = 0.794$ and 1.225 mm) at pressures of 1.1, 2.6, 4.1 and 8.1 MPa and ambient temperature. Tube bundles of three different pitches (19.5, 29.3 and 39.0 mm) are employed and h_w is reported as a function of fluidizing velocity, G. It is found that h_w increases with pressure, to a lesser extent with tube pitch, and with an increase in particle diameter. The experimental data are compared with the predictions of four theories for h_w and two theories of $h_{w,max}$. It appears that the theory of Ganzha *et al.* is most successful in reproducing the experimental data and it is recognized that the knowledge of reliable bed voidage at the heat transfer surface and in the bulk is crucial for its applicability.

NOMENCLATURE

- a function defined by equation (10a)
- A function defined by equation (10b)
- Ar Archimedes number, $\bar{d}_p^3 g\rho_g(\rho_s-\rho_g)/\mu_g^2$
- C_{pg} heat capacity of gas at constant pressures [J kg^{-1} K^{-1}]
- $\bar{d}_p$ particle diameter [m]
- D_T tube diameter [m]
- g acceleration due to gravity [m s^{-2}]
- G superficial gas mass velocity [kg m^{-2} s^{-1}]
- G_{mf} gas mass velocity at minimum fluidization [kg m^{-2} s^{-1}]
- h_w overall heat transfer coefficient [W m^{-2} K^{-1}]
- $h_{w,max}$ maximum heat transfer coefficient [W m^{-2} K^{-1}]
- k_g thermal conductivity of gas [W m^{-1} K^{-1}]
- Nu particle Nusselt number, $(h_w\bar{d}_p/k_g)$
- Nu_{max} maximum particle Nusselt number, $(h_{w,max}\bar{d}_p/k_g)$
- Pr Prandtl number, $(\mu_g C_{pg}/k_g)$
- Re particle Reynolds number, $(\bar{d}_p G/\mu_g)$
- Re_{mf} particle Reynolds number at minimum fluidization, $(\bar{d}_p G_{mf}/\mu_g)$
- u superficial gas velocity [m s^{-1}]
- u_{mf} gas velocity at minimum fluidization [m s^{-1}]

Greek symbols

- β time fraction that the tube is in contact with bubbles
- $\bar{\varepsilon}$ bulk bed voidage
- $\bar{\varepsilon}_{mf}$ bulk bed voidage at minimum fluidization
- ε_w bed voidage near heat transfer surface
- $\varepsilon_{w,mf}$ bed voidage near heat transfer surface at minimum fluidization
- δ bubble fraction
- μ_g viscosity of gas [kg m^{-1} s^{-1}]
- ρ_g density of gas [kg m^{-3}]
- ρ_s density of solid [kg m^{-3}]

INTRODUCTION

ONE OF the important advantages of fluidized-bed coal combustion is the high heat transfer rates between the bed and the immersed boiler tubes employed to remove the heat of combustion. The industrial combustors with sulphur retention capability are operated with much larger sizes of particles (> 1 mm in diameter) than those widely used in other applications of fluidized beds. Further, the combined cycle electrical power generating units require the operation of fluidized bed combustors at high pressures. Thus, it is of practical importance to know the heat transfer characteristics of large particle fluidized beds at pressures higher than the ambient. The experimental data for such systems of large particles even at atmospheric pressure are scarce and our recent investigations revealed that the existing theories are not adequate for estimation purposes [1, 2]. It will, therefore, be very useful, both from practical and theoretical viewpoints to investigate the heat transfer process for tube bundles immersed in fluidized beds of large particles at high pressures. It is the aim of this paper to report new experimental data for vertical tube bundles immersed in fluidized beds of glass beads ($\bar{d}_p = 1.25$ and 3.1 mm) and sand ($\bar{d}_p = 0.794$ and 1.225 mm) for pressures in the range 1.1–8.1 MPa. The

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bundles are made from 13 mm tubes arranged in an equilateral triangular configuration with pitches (centre to centre spacings) equal to 19.5, 29.3 and 39.0 mm.

Canada and McLaughlin [3] have investigated the heat transfer from staggered tube bundles in fluidized beds of sulphated dolomite particles of average diameter 650 and 2600 μm in the pressure range 0.1–1.0 MPa. Xavier et al. [4] measured the heat transfer from an electrically heated copper plate in fluidized beds of glass beads ($\bar{d}_p = 61\,475$ and 615 μm) and polymer beads ($\bar{d}_p = 688$ μm) in the pressure range 0.1–2.5 MPa. The most extensive investigation of heat transfer coefficients was conducted by Borodulya et al. [5] in the pressure range 0.6–8.1 MPa. They measured the heat transfer coefficient between an 18 mm diameter vertical tube immersed in fluidized beds of quartz sand ($\bar{d}_p = 0.126$, 0.25, 0.8 and 1.22 mm) and glass beads ($\bar{d}_p = 0.95$ and 3.1 mm). They could infer several important conclusions both of qualitative and quantitative nature from their experimental data. Some of their results of relevance to the present investigations are reported here. For large particles (1.22 mm sand) the maxima in the heat transfer coefficient, h_w, fluidizing velocity, u, plots at various pressures are less pronounced than for small particles (0.126 mm sand). For the same particle, the heat transfer coefficient increases with pressure. The increase is more for the larger particles than for the small particles. The dependence of $h_{w,max}$ on $\bar{d}_p$ is found to be different at higher pressures (4.1 and 8.1 MPa) than at lower pressures (0.6, 1.1 and 2.5 MPa). For the former, $h_{w,max}$ increases linearly with $\bar{d}_p$, while for the latter the curve has a minimum and this characteristic dependence is similar to that observed at atmospheric pressure [1].

EXPERIMENTAL

The schematic of the fluidized-bed facility consisting of the test bed, particle trap, gas flow and electric resistance measuring devices is shown in Fig. 1. The bed particles are contained in a 105 mm internal diameter stainless steel column with a working height of 600 mm. A Plexiglas port on the column wall is used to illuminate the bed while another on the top cover allows it to be visually examined. The air distributor plate is a perforated disc with 1.5 mm holes drilled in a square pitch arrangement with an open area of about 2%. The downstream side of the plate is provided with a 80 μm mesh steel screen to prevent bed solids raining into the calming section. The latter is a 0.3 m long section below the distributor plate and is provided to stabilize the incoming flow. A pressure gauge is provided at the top end of the bed to measure its pressure. The gas exiting from the bed passes through the particle trap and the orifice meter before exiting into the atmosphere.

The equilateral triangular tube bundles employed in this work are made from 13 mm diameter and 76 mm long wooden cylinders. Three such bundles of 21, 9 and 5 cylinders arranged with 19.5, 29.3, and 39.0 mm centre-to-centre spacings (pitches), respectively, have been investigated. The tubes in a bundle are fixed in a specially designed holder by metallic pins and the bundle is located 30 mm above the distributor plate. The central tube in each case serves the purpose of the heat transfer probe and it is made by winding a 70 μm diameter copper wire. The wire turns are held in position by glue and are machined to a depth of half of the wire diameter to obtain a smooth surface finish. The probe is calibrated at 323.2 K and constitutes one of the arms of a Wheatstone bridge. The heat transfer coefficient is determined by the knowledge of the electrical power required to restore the bridge balance under different fluidizing conditions. Different size glass beads and sands have been used as bed materials and these are charged in the bed to give a height of 1.3–1.5 times the bed diameter. In Table 1 are given the size range, mean particle diameter, and densities of these materials. The precision of these measurements is about $\pm 4\%$.

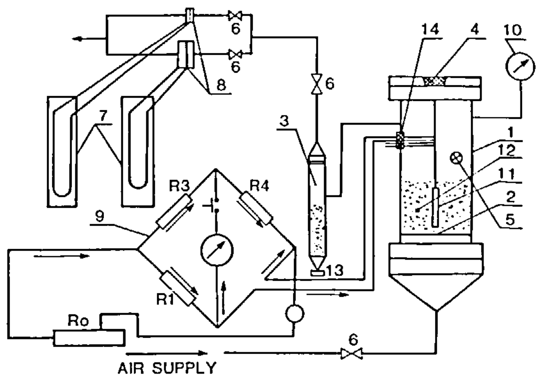

FIG. 1. A schematic of the experimental arrangement: (1) fluidized bed, (2) distributor plate, (3) particle trap, (4) Plexiglas port, (5) light source, (6) control valves, (7) manometers, (8) orifice meter, (9) Wheatstone bridge, (10) pressure gauge, (11) heat transfer probe, (12) thermocouple, (13) solids discharge port, (14) electrical lead manifold.

The experimental values of heat transfer coefficient, h_w, as a function of gas mass fluidizing velocity, G, for the four particles are shown in Figs. 2 and 3. In each case results include data for four pressures (1.1, 2.6, 4.1 and 8.1 MPa) and three tube bundles differing in pitch (19.5, 29.3 and 39.0 mm). For particles of a given size, the h_w values depend upon pressure and increase monotonically with it. For a given particle size and pressure, the h_w values also depend upon the tube pitch. This dependence is sensitive to pressure and at higher pressures the difference in h_w values is larger for the same difference in pitch than that at a lower pressure. The h_w values for widely spaced tubes are greater than for closely packed tubes in a bundle under otherwise identical conditions. In general, h_w values exhibit the conventional dependence on G, i.e. the values increase with increasing G in the beginning, attain a maximum value and then decrease with further increase in G. However, the sharpness of maximum seems to depend

Table 1. Properties of solids

Material	Size range (mm)	$\bar{d}_p$ (mm)	ρ_s (kg m^{-3})
Glass beads	3.0–3.2	3.10	2630
Glass beads	1.2–1.3	1.25	2630
Sand	1.0–1.5	1.225	2580
Sand	0.63–1.0	0.794	2700

upon the system pressure and this decreases as the pressure increases. To infer about the influence of particle diameter on h_w, we examine the first and the last two plots of Fig. 2 collectively. The first set reveals that for spherical glass beads as the mean particle diameter is increased from 1.25 to 3.1 mm, the heat transfer coefficient increases. The second set also exhibits the same trend though the magnitude of the difference appears to be smaller than in the previous case. Also the difference is relatively pronounced at the highest

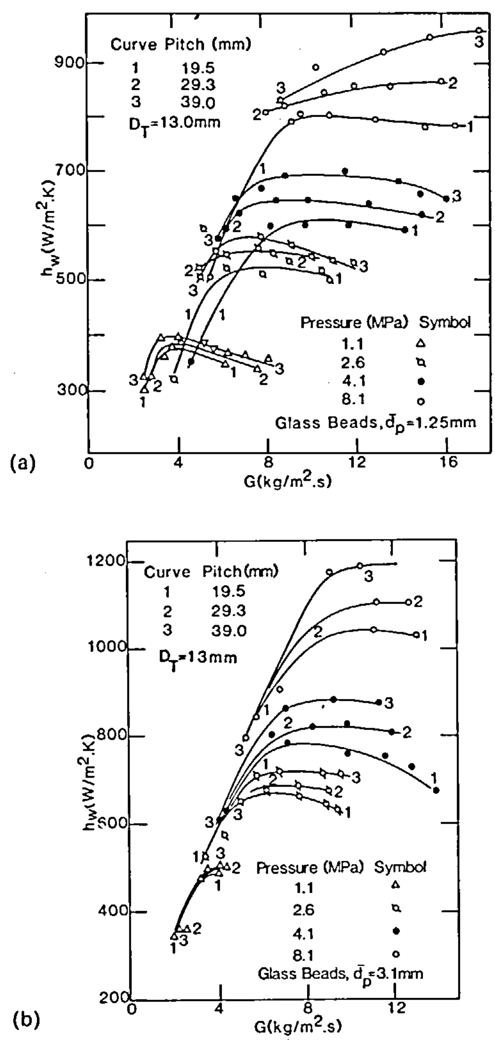

FIG. 2. Dependence of h_w on G at various pressures for vertical tube bundles immersed in fluidized beds of glass beads.

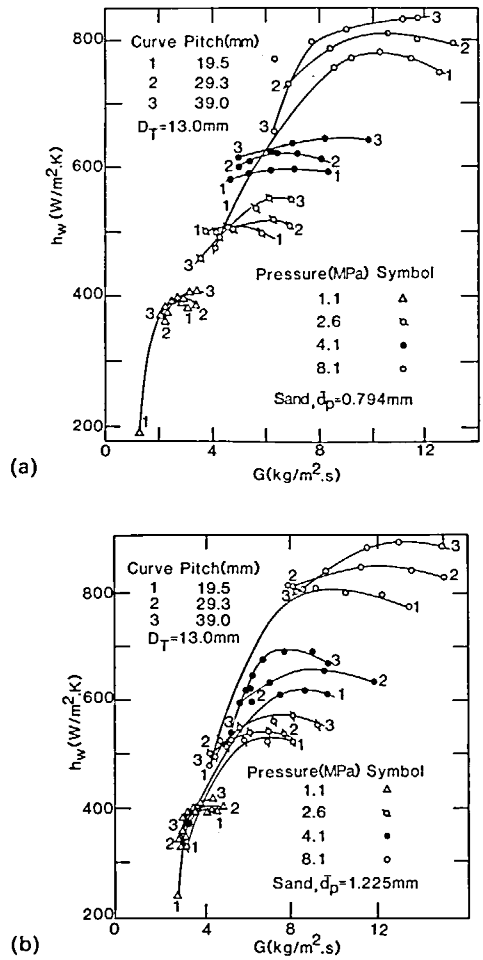

FIG. 3. Dependence of h_w on G at various pressures for vertical tube bundles immersed in fluidized beds of sand particles.

pressure and is practically negligible at the lowest pressure. It is well known that for small particles, h_w decreases with an increase in $\bar{d}_p$, while for large particles it increases with $\bar{d}_p$. The above qualitative trends are interesting to know for fluidized bed systems of large particles at high pressures but the ultimate goal is to have a reliable theory which could explain all these observed variations of h_w on operating and system variables. Therefore, in the next section we compare all these data with the available theories with a view to provide an insight into the mechanisms of heat transfer and to develop an assessment of these theories.

COMPARISON WITH THEORY

The experimental data reported in the previous section on four particles, three tube bundles having different pitches, four different pressure levels, and comprising of 235 data points, will be now compared with the predictions of various theories of heat transfer [1, 6–8]. The theories of Maskaev and Baskakov [9], and Denloye and Botterill [10] for the maximum heat transfer coefficient are also considered. A critical assessment of some of these theories [6, 10] is given by Zabrodsky *et al.* [1] and here only the relations employed for computation will be reproduced though some discussion is given in the next section. According to Glicksman and Decker [6]

$$Nu = (1-\delta)(9.3+0.042\ Re\ Pr), \qquad (1)$$

where

$$\delta = (\bar{\varepsilon}-\bar{\varepsilon}_{mf})/(1-\bar{\varepsilon}_{mf}). \qquad (2)$$

$\bar{\varepsilon}$ is computed as a function of the fluidizing velocity, u, from a relation given by Staub and Canada [11] i.e.

$$\bar{\varepsilon} = \frac{u}{1.05\ u+\{(1-\varepsilon_{mf})/\bar{\varepsilon}_{mf}\}u_{mf}}. \qquad (3)$$

Catipovic *et al.* [7] proposed that

$$Nu = 6(1-\beta)+0.0175(1-\beta)\ Ar^{0.46}\ Pr^{0.33} + (\beta\bar{d}_p/D_T)(0.88\ Re_{mf}^{0.5}+0.0042\ Re_{mf})\ Pr^{0.33}, \qquad (4)$$

where

$$(1-\beta) = 0.45+0.061(u-u_{mf}+0.125)^{-1}. \qquad (5)$$

The theory of Zabrodsky *et al.* [1] yields

$$h_w = 7.2k_g(1-\bar{\varepsilon})^{2/3}(\bar{d}_p)^{-1}+26.6u^{0.2}C_{pg}\rho_g\bar{d}_p. \qquad (6)$$

The turbulent boundary layer theory of Ganzha *et al.* [8] gives:

$$Nu = 8.95\ (1-\varepsilon_w)^{2/3} + 0.12\ Re^{0.8}\ Pr^{0.43}\ (1-\varepsilon_w)^{0.133}\ (\varepsilon_w)^{-0.8}, \qquad (7)$$

where

$$\varepsilon_w = \varepsilon_{w,mf}+{}^{1.65}A(1-\bar{\varepsilon}_{mf})\{1-\exp(-a/A^2)\}, \qquad (8)$$

$$\varepsilon_{w,mf} = 1-\frac{(1-\bar{\varepsilon}_{mf})[0.7293+0.5139(\bar{d}_p/D_T)]}{[1+(\bar{d}_p/D_T)]}, \qquad (9)$$

$$a = 0.367\ \ln\{(\varepsilon_{w,mf}-\bar{\varepsilon}_{mf})/(1-\bar{\varepsilon}_{mf})\}. \qquad (10a)$$

and

$$A = (Re-Re_{mf})/\sqrt{Ar}. \qquad (10b)$$

The maximum heat transfer coefficient, $h_{w,max}$, is given by Maskaev and Baskakov [9] and Denloye and Botterill [10] as follows:

$$Nu_{max} = 0.21Ar^{0.32}, \quad \text{for}\quad 1.4\times10^5 < Ar < 3.0\times10^8, \qquad (11)$$

and

$$Nu_{max} = 0.843\ Ar^{0.15}+0.86\bar{d}_p^{1/2}\ Ar^{0.39}, \quad \text{for}\quad 10^3 < Ar < 2\times10^6. \qquad (12)$$

In Fig. 4, all the presently generated 235 data points are shown plotted and compared with the predictions of equation (7). The continuous line in this graph with a slope of 0.8 implies a complete agreement between theory and experiment. The majority of the data points agree with the model predictions based on the theory of Ganzha *et al.* [8] within an uncertainty of $\pm 15\%$. Only about 15 data points lie beyond this uncertainty band and all of these refer to the largest particle of glass bead, 3.1 mm in diameter. We do not consider that this disagreement is a symptom of any systematic experimental error or any basic deficiency in theory. Most probably, it creeps into the calculations because of our inability to establish the bed voidage in the bulk or at the surface either in general or at the minimum fluidization condition. Direct measurement of these voidage values will be of great help in assessing this theory of heat transfer for large particle systems.

A typical comparison of the above mentioned four theories [1, 6–8] with our data for glass beads of 3.1 mm in diameter is displayed in Fig. 5 for two pressure levels namely, 1.1 and 4.1 MPa. The trends observed here for departure between theory and experiment are quite noteworthy and many points are to be emphasized. The still higher pressure (8.1 MPa) data exhibit departure from various theories which are similar to those

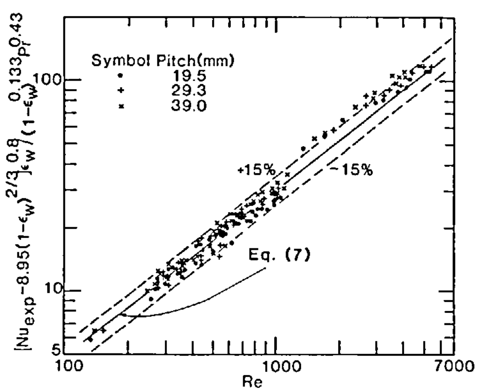

Fig. 4. Comparison of the present experimental data with theory. Data refer to particles of sand ($\bar{d}_p$ = 0.794 and 1.225 mm) and glass beads ($\bar{d}_p$ = 1.25 and 3.1 mm) at pressures of 1.1, 2.6, 4.1 and 8.1 MPa.

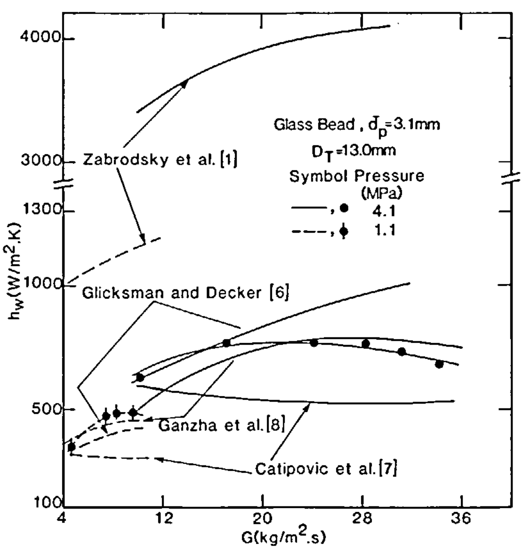

Fig. 5. Comparison of present experimental data for glass beads at two pressures with the predictions of different theories.

observed for data at 4.1 MPa. The general remarks which follow from this comparison of Fig. 5 are: (a) the theory of Ganzha *et al.* [8] is considered appropriate both from qualitative and quantitative viewpoints, (b) the theory of Glicksman and Decker [6] reproduces the experimental h_w values at lower values of G and the disagreement between the theory and experiment increases with increasing G. Of greater importance is the fact that theory predicts a monotonic increase in h_w with G in the present range of investigation where the experiments exhibit a maximum, (c) the theory of Catipovic *et al* [7] leads to h_w values which are consistently and appreciably smaller than the experimental values. Furthermore, with increasing G, the computed values decrease while the experimental values first increase with the increase in G, acquire a maximum and then decrease with a further increase in G, (d) Zabrodsky *et al.*'s [1] theory was found to be fairly successful in correlating the heat transfer data for large particles at ambient pressure [1, 2]. However, here it is found to be inadequate to reproduce the present experimental data at higher pressures. As seen from Fig. 5 the calculated values are appreciably larger than the experimental values.

As a representative study for sand, experimental data for 1.225 mm diameter particles are shown plotted in Fig. 6 at pressures of 1.1 and 8.1 MPa along with the predictions of all four theories. Most of the comments made above in relation to Fig. 5 are valid here also. However, while comparing various theories with experiment, a fact that needs to be kept in perspective is that the various theoretical predictions come closer to each other for small particles and their agreement with the experimental values will improve particularly around atmospheric pressure. Thus, the predictions of Glicksman and Decker [6] while generally smaller than the observed values do exhibit a fair agreement with the latter. A similar remark is applicable for the theory of Catipovic *et al.* [7]. Further, both of these theories [6, 7] are capable of reproducing the experimental data at lower pressures ($\lesssim 1.1$ MPa) though the variation of h_w with G is not appropriate as noted before. The proposed theory of Ganzha *et al.* [8] reproduces the experimental

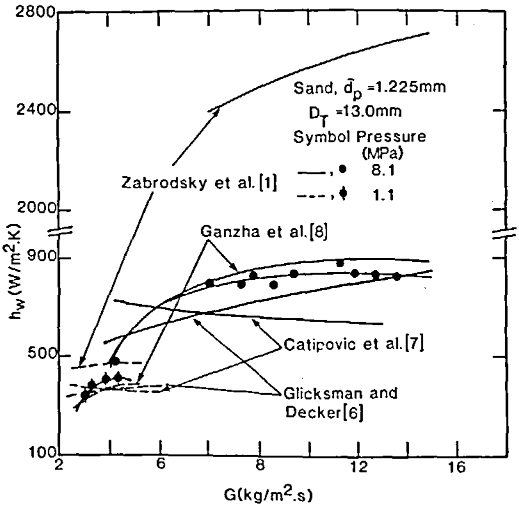

FIG. 6. Comparison of present experimental data for sand particles at two pressures with the predictions of different theories.

data at the two pressures both in absolute magnitude as well as in the variation of h_w with G. The predictions based on the theory of Zabrodsky *et al.* [1] are gross overestimates of the observed data and the magnitude of disagreement is larger at higher pressure (8.1 MPa) than at the lower pressure (1.1 MPa).

The theories of Maskaev and Baskakov [9], and Denloye and Botterill [10] for the maximum heat transfer coefficient are also examined on the basis of the present data with some of the representative data reported in Table 2. Denloye and Botterill [10] derived the expression for Nu_{max}, equation (12), which is valid only for the range $10^3 < Ar < 2 \times 10^6$. We have, therefore, found it essential to include the data for sand of diameter 0.794 mm. The computed values based on equation (11) for both the particles are in qualitative agreement with the experimental values in as much as the Nu_{max} values decrease with decreasing system pressure. The quantitative agreement between the theory [9] and experiment is also considered adequate

Table 2. Comparison of experimental and predicted Nu_{max}

Pressure (MPa)	Archimedes number	Experimental	Nu_{max} Maskaev and Baskakov [9]	Denloye and Botterill [10]
		Glass beads: $\bar{d}_p = 3.1$ mm		
8.1	2.15×10^8	108.7	97.3	—
4.1	1.35×10^8	89.2	83.9	—
2.6	8.74×10^7	79.5	73.1	—
1.1	4.01×10^7	59.7	56.9	—
		Sand: $\bar{d}_p = 0.794$ mm		
8.1	3.28×10^6	20.5	25.5	—
4.1	2.00×10^6	18.9	21.8	14.4
2.6	1.35×10^6	17.0	19.5	13.1
1.1	6.02×10^5	13.1	15.0	10.7

as the two generally agree within an average departure of about 15%. The present work, therefore, adds credence to the theory of Maskaev and Baskakov [9]. On the other hand, equation (12), which could be tested only to a limited extent is found to reproduce the experimental data points within an average deviation of about 21%. On the basis of this comparison, it would appear that the theory of Denloye and Botterill [10] is reasonable though the extent of comparison being limited warrants to draw any general conclusion.

DISCUSSION

In the present effort are reported the experimental data of heat transfer coefficients as a function of fluidizing velocity for vertical tube bundles of three different pitches at several pressures in the range 1.1–8.1 MPa. These data for large particles are compared with a theory recently developed by the authors and also with the predictions of available theories in the literature. A detailed and critical examination of these investigations enable us to conclude about certain general trends in variation of h_w with G, and their appropriateness in reproducing h_w. These will be discussed in the following with an appraisal of the theories particularly in relation to their suitability at high pressures.

First, the nature of variation of h_w with G as observed around 1 atm is preserved in the experimental data up to the highest pressure investigated here. This characteristic dependence involves an increase in the value of h_w with increasing G till a maximum value for h_w is reached and thereafter it decreases with an increase in G. In beds of small particles, this initial increase in h_w is explained on the basis of enhanced solids movement resulting from increased bubbling as G increases. At higher pressures, the bed structure improves [4, 5] and the bubbling becomes more uniform but still h_w increases with G, but relatively less rapid. At relatively higher values of G, the voidage increase is such that the net result is a decrease in the value of h_w. With increasing pressure, the effective decrement in h_w with increasing G is less so that the maxima are less pronounced at higher pressures than at lower pressures. Similar results are encountered for large particles except now the major contribution to h_w is due to the large gas flow through the bed resulting in large values of the convective component.

Secondly, the measurements suggest that under otherwise identical conditions, the h_w values are larger for a tube bundle with a larger value of pitch than for a bundle with a smaller value of pitch. Thus, in all cases, the h_w is largest for the bundle with a pitch of 39.0 mm and is smallest for a tube bundle with a pitch of 19.5 mm. This pitch variation when interpreted in terms of the tube diameter corresponds to a variation of $0.5D_T$–$2D_T$. For the present experiments, the ratio of tube gap : particle diameter varies between the limits of 1.95–32.7. The magnitude of the differences in h_w values as the pitch is varied is, however, not very pronounced in relation to the uncertainty associated with the experimental values. The dependence of h_w on tube pitch is a maximum at the highest pressure and for the largest particle (glass beads, $\bar{d}_p = 3.1$ mm) where it is about 13%. As this magnitude is somewhat comparable to the absolute error in the measured h_w values, we have compared these data for tube bundle with the predictions of theories developed for single tubes.

Thirdly, it appears reasonable to conclude that the present theory of Ganzha et al. [8] is appropriate in reproducing the experimental data. Most significantly, this theory is capable of reproducing the observed dependence of h_w on G, as seen from Figs. 5 and 6. It follows from equation (7) that the heat transfer is controlled by two terms. The first term which accounts for the gas film conduction depends only on ε_w and its contribution decreases with an increase in ε_w resulting from increasing G. On the other hand the gas convection contribution controlled by the second term depends on G (through Re), and on ε_w. The net contribution of this term is involved and its magnitude depends on the value of G. For smaller values of G, the voidage function does not change much with G and the net increase in the value of this term comes through the occurrence of $Re^{0.8}$ and hence increases with G. For larger values of G, the voidage function decreases rapidly with G and consequently the entire second term decreases, but slowly with increasing G. As a result, equation (7) has the virtue of simulating the observed dependence of h_w (or Nu) on G. It must be emphasized, therefore, that the appropriate value of the voidage at the heat transfer surface and its dependence on various system and operating parameters must be accurately known. So far very little emphasis has been paid to this aspect. Kimura et al. [12] from their measurements on packed granular beds in cylindrical containers concluded that voidage variations exist around the wall in a region of width $\bar{d}_p/2$. Botterill and Denloye [13] extended this concept and proposed the relation of equation (9) between the voidages in the region close to the wall and in the bulk of the bed at the minimum fluidization condition. Based on some of our yet unpublished results dealing with the hydrodynamic investigations of fluidized beds under pressure and on semi-empirical arguments, we developed the relation of equation (8). For a proper appraisal of the theory [8], it is essential that a reliable relation of the type of equation (8) be known. Fitzgerald et al. [14] reported the design of an instrumented cylinder which is claimed to be capable of measurement of voidage around its circumference. It is also stated in a subsequent publication [7] that the voidage at the surface of a tube varies much less with gas velocity than the overall bed voidage. Our current experience is not in accord with this statement and we hope to see this aspect resolved with much more detailed measurements.

The comparison of the proposed theory [8] with present data as displayed in Fig. 4, is made on the basis of effective gas velocity through the bed. In computing it due account is given to the bed area which is occupied by the heat transfer tubes. This mode of calculation improves the agreement between theory and experiment. For all the 235 data points, the root-mean-square deviation is 12%.

The theories of Glicksman and Decker [6], and Zabrodsky *et al.* [1], in general, overestimate h_w for large particles, at high fluidizing velocities and at high pressures. Under such conditions, the contribution of gas convection to h_w is large and both these theories fail to account this properly. As pointed out before, voidage plays an important role here and discrimination between the values at the heat transfer surface and in the bulk of the bed is essential. Glicksman and Decker [6] consider only bulk voidage, and Zabrodsky *et al.* [1] do not consider voidage at all while formulating the convection contribution to h_w. Further, in the latter work [1], the convection component of h_w is taken as proportional to ρ_g which turns out to be a gross overestimate for high pressure operation. The bulk of the disagreement between theory and experiment can be reconciled, if following Xavier *et al.* [4], we take the convection contribution to be proportional to $\sqrt{\rho_g}$.

Catipovic *et al.* [7] formulate a heat transfer coefficient as composed of convection contributions from particles, gas and bubbles. For a given gas–solid fluidized-bed system, h_w is only a function of β. β increases with $G-G_{mf}$, and computed h_w is found to decrease monotonically with increasing G. Thus, this theory, equation (4), fails to reproduce the correct dependence of h_w on G. This calculation like the other two [6, 1] needs a basic improvement in the formulation of the convective component of the heat transfer coefficient which was assumed to be that given by Baskakov and Suprun [15].

It is concluded, therefore, that the three theories [1, 6, 7] need improvement in the calculation of the contribution arising from gas convection to total heat transfer coefficient for large particles fluidized by high pressure gas. In this calculation, it appears that the surface voidage and its variation with the fluidizing gas plays a very important role which is currently very poorly understood. The theory of Ganzha *et al.* [8] is found to correlate all of the present experimental data.

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ETUDE DU TRANSFERT THERMIQUE AUX PRESSIONS ELEVEES ENTRE DES LITS FLUIDÍSES A GROSSES PARTICULES ET DES GRAPPES DE TUBES VERTICAUX

Résumé—Le coefficient global de transfert thermique h_w est mesuré pour des grappes de tubes verticaux dans des lits fluidisés de billes de verre ($\bar{d}_p$ = 1,25 et 3,10 mm) et du sable ($\bar{d}_p$ = 0,794 et 1,225 mm) à des pressions de 1,1, 2,6, 4,1 et 8,1 MPa et à la température ambiante. On emploie des tubes avec trois pas différents (19,5, 29,3 et 39,0 mm) et h_w est fonction de la vitesse de fluidisation G. On trouve que h_w augmente avec la pression, à un degré moindre avec le pas entre tubes avec l'accroissement du diamètre de particule. Les résultats expérimentaux sont comparés avec les prédictions de quatre théories pour h_w et deux pour $h_{w,max}$. On constate que la théorie de Ganzha et alii est la meilleure pour reproduire les résultats et que la connaissance de la fraction de vide à la surface de transfert et dans le coeur est cruciale pour son applicabilité.

UNTERSUCHUNG DES WÄRMEÜBERGANGS BEI HOHEM DRUCK IN FLIESSBETTEN MIT GROSSEN PARTIKELN UND SENKRECHTEN ROHRBÜNDELN

Zusammenfassung—Es wird der Gesamtwärmedurchgangskoeffizient h_w an senkrechten Rohrbündeln in Fliessbetten aus Glasperlen ($\bar{d}_p = 1{,}25$ und 3,10 mm) und Sandkörnern ($\bar{d}_p = 0{,}794$ und 1,225 mm) bei Drücken von 1,1; 2,6; 4,1 und 8,1 MPa und bei Umgebungstemperatur gemessen. Es wurden drei verschiedene Rohrbündeltypen eingesetzt (19,5; 29,3 und 39,0 mm) Teilung. Der Wärmedurchgangskoeffizient h_w wird in Abhängigkeit von der Fluidisierungsgeschwindigkeit G dargestellt. Es zeigt sich, daß h_w mit zunehmendem Druck ansteigt, in geringerem Maße mit der Rohrverteilung und zunehmendem Partikeldurchmesser. Die Versuchsdaten werden mit den Aussagen von vier Theorien für h_w und zwei Theorien für $h_{w,max}$ verglichen. Die Theorie von Ganzha *et al.* gibt die Versuchsdaten am besten wieder und es stellt sich heraus, daß die genaue Kenntnis von Hohlräumen in der Schüttung an der Wärmeübergangsfläche und am Umfang für die Anwendbarkeit wesentlich ist.

ИССЛЕДОВАНИЕ ТЕПЛООБМЕНА МЕЖДУ ПСЕВДООЖИЖЕННЫМИ СЛОЯМИ КРУПНЫХ ЧАСТИЦ И ПОГРУЖЕННЫМИ В НИХ ПУЧКАМИ ВЕРТИКАЛЬНЫХ ТРУБ ПРИ ВЫСОКИХ ДАВЛЕНИЯХ

Аннотация—Излагаются результаты исследований теплообмена между вертикальным пучком и псевдоожиженным слоем стеклянных шариков ($\bar{d}_p = 1{,}25$ и 3,1 мм) и песка ($\bar{d}_p = 0{,}794$ и 1,225 мм) при давлениях 1,1; 2,6; 4,1 и 8,1 МПа и комнатной температуре. Опыты проводились с пучками, имеющими шаг 19,5; 29,3 и 39 мм. Общие коэффициенты теплообмена, h_w, представлены в виде функции массовой скорости псевдоожижающего газа. Найдено, что h_w увеличивается с ростом давления, в меньшей мере – с увеличением шага труб и с ростом диаметра частиц. Экспериментальные данные сопоставлены с расчетными, полученными с помощью четырех известных корреляций для h_w и двух для $h_{w,max}$. Оказалось, что наилучшее совпадение с экспериментальными данными дает соотношение, полученное в работе Ганжи с соавторами, при этом отмечена важная роль, которую играет порозность слоя у теплообменной поверхности.