Int. J. Heat Mass Transfer. Vol. 27, No. 8, pp. 1219–1225, 1984
Printed in Great Britain

0017 9310/84 $3.00 + 0.00
Pergamon Press Ltd.

HEAT TRANSFER BETWEEN FLUIDIZED BEDS OF LARGE PARTICLES AND HORIZONTAL TUBE BUNDLES AT HIGH PRESSURES

V. A. BORODULYA, V. L. GANZHA and A. I. PODBEREZSKY
Luikov Heat and Mass Transfer Institute, B.S.S.R. Academy of Sciences, Minsk, B.S.S.R., U.S.S.R.

and

S. N. UPADHYAY* and S. C. SAXENA
Department of Chemical Engineering, University of Illinois at Chicago, Box 4348, Chicago, IL 60680, U.S.A.

(*Received* 21 *March* 1983)

Abstract—The experimental heat transfer data for horizontal square inline tube bundles (D_T = 13.0 mm and pitch values are 19.5, 29.3 and 39.0 mm) immersed in fluidized beds of glass beads ($\bar{d}_p$ = 1.25 and 3.1 mm) and sands ($\bar{d}_p$ = 0.794 and 1.225 mm) are measured as a function of fluidizing velocity and system pressure (1.1, 2.6, 4.1 and 8.1 MPa). The heat transfer coefficient values are found to increase with particle diameter, system pressure but are almost independent of tube pitch in the range investigated here. The h_w values are compared with the predictions of five different theories available in the literature. The two correlations for Nu_{max} are also considered and evaluated. Significant conclusions are drawn on the basis of reported h_w data for large particles at high pressures.

NOMENCLATURE

a	function defined by equation (5)
A	function defined by equation (4)
Ar	Archimedes number, $g\bar{d}_p^3\rho_g(\rho_s-\rho_g)/\mu_g^2$
C_{pg}	heat capacity of gas at constant pressure [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 flow velocity [kg m^{-2} s^{-1}]
G_{mf}	superficial gas mass flow velocity at minimum fluidization [kg m^{-2} s^{-1}]
h_w	overall heat transfer coefficient [W m^{-2} K^{-1}]
h_{wf}	overall heat transfer coefficient for solids free gas flow [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}]
L_{mf}	bed height at minimum fluidization [m]
Nu	particle Nusselt number, $h_w\bar{d}_p/k_g$ [W m^{-2} K^{-1}]
Nu_{max}	maximum particle Nusselt number, $h_{w,max}\bar{d}_p/k_g$
Nu_T	tube diameter based Nusselt number, h_wD_T/k_g
Nu_f	tube diameter based Nusselt number for solids free gas flow, $h_{wf}D_T/k_g$
ΔP_t	pressure drop in the top part of the bed above L_{mf} [N m^{-2}]
Pr	Prandtl number, μ_gC_{pg}/k_g
Re	particle Reynolds number, $\bar{d}_pG/\mu_g$
Re_{mf}	particle Reynolds number at minimum fluidization, $\bar{d}_pG_{mf}/\mu_g$
S_H	horizontal tube pitch [m]
u	superficial gas velocity [m s^{-1}]
u_{mf}	superficial gas velocity at minimum fluidization [m s^{-1}]
u_s	superficial solids velocity [m s^{-1}].

Greek symbols

β	time fraction that the tube is in contact with bubbles
ε	bulk bed voidage
ε_{mf}	bulk bed voidage at minimum fluidization
ε_w	bed voidage near tube surface
$\varepsilon_{w,mf}$	bed voidage near the tube 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 solids [kg m^{-3}].

INTRODUCTION

THE PROJECTED scarcity of petroleum fuels has necessitated the development of pressurized fluidized-bed coal combustors. The proper design and efficient operation of these units require the knowledge of heat transfer coefficients between immersed boiler tubes and fluidized beds of large particles (> 1 mm). There are many investigations of this nature for small particles (< 1 mm) at ambient conditions and most of these are summarized by Botterill [1], and Saxena *et al.* [2]. For large particles and particularly at high pressures the investigations are scarce [3–6]. The measurements at

* Permanent address: Department of Chemical Engineering, Institute of Technology, Banaras Hindu University, Varanasi 221005, India.

high pressures with small particles have been conducted by Altshuler and Sechenov [7], Borodulya *et al.* [3, 4], Botterill and Desai [8], Denloye and Botterill [6], Rabinovich and Sechenov [9], Traber *et al.* [10], and Xavier *et al.* [11]. In addition, several workers such as Borodulya *et al.* [3, 4], Catipovic *et al.* [12], Golan *et al.* [13, 14] and Zabrodsky *et al.* [15], have investigated large particles at ambient pressures.

In most of the above works, the system pressure is up to 1 MPa except Xavier *et al.* [11] and Borodulya *et al.* [3, 4] who have operated up to 2.5 and 8.1 MPa, respectively. Out of all these studies only Canada and McLaughlin [5] have examined horizontal tube bundles for large particles and for pressures up to 1 MPa. Here we report measurements of heat transfer conducted on square inline tube bundles of three different pitches (19.5, 29.3 and 39.0 mm) 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) at pressures of 1.1, 2.6, 4.1 and 8.1 MPa. These experimental results are analyzed to examine the dependence of the heat transfer coefficient, h_w, on such parameters as fluidizing velocity, pressure, particle diameter and tube pitch. These data are also used to establish the reliability of available theories of heat transfer for large particles. All the theories except one are developed primarily on the basis of information generated around 1 atm. The present data will thus provide a rationale to assess these theories for their adequacy at high pressures. In the next section, we describe our experimental facility and the results of the heat transfer coefficient obtained under different conditions.

EXPERIMENTAL

The experimental arrangement consists of the cylindrical fluidized bed, off-gas cleaning system, tube bundle with heat transfer probe, gas flow and electrical measuring devices. The bed is contained within a 600 mm long and 105 mm diameter cylindrical stainless steel column and is supported on a perforated plate distributor with an open area of about 2%. The static bed height is maintained at about 100 mm. The bundles are made in an inline square arrangement from 13 mm diameter wood cylinders. Three such bundles of 25, 9 and 5 cylinders with 19.5, 29.3 and 39.0 mm center-to-center spacing (pitch), respectively, have been investigated. The central tube in each case serves as the heat transfer probe and is made by a single winding of a 70 μm copper wire around the cylinder and held in position by an adhesive glue. The surface of the probe is then smoothed by machining it to a depth of half the wire diameter. The probe is calibrated at 323.2 K by treating it as a resistance thermometer in the arm of a Wheatstone bridge. The heat transfer coefficient is determined from the knowledge of the power required to restore the bridge balance under different fluidizing conditions. The measurements are made at pressures of 1.1, 2.6, 4.1 and 8.1 MPa with air as the fluidizing medium. Glass beads and sands of two different

Table 1. Properties of solids

Material	Size range (mm)	$\bar{d}_p$ (mm)	ρ_s (kg m^{-3})
Glass bead	3.0–3.2	3.1	2830
Glass bead	1.2–1.3	1.25	2630
Sand	1.0–1.5	1.225	2580
Sand	0.63–1.0	0.794	2700

diameters are used as bed material and their relevant properties are listed in Table 1.

The experimental heat transfer coefficient, h_w, for narrow cut glass beads of average diameter 1.25 and 3.1 mm and horizontal tube bundles of pitch 19.5, 29.3 and 39.0 mm are shown in Fig. 1 as a function of fluidizing velocity and four system pressures. Similar plots for 0.794 and 1.225 mm sands are displayed in Fig. 2. It is clear from these plots that h_w follows in all cases the same qualitative variation with respect to fluidizing velocity, system pressure, change in particle diameter and pitch. In all cases, for a given particle and tube bundle at a fixed pressure, the h_w values increase with an increase in the mass fluidizing velocity, G. The increase is rapid at low values and becomes relatively slower at higher values of G. Thus, h_w vs G plots exhibit a flat maximum for these large particles at these high operating pressures. It is also to be noted that h_w is consistently larger at higher pressures over the entire fluidization velocity range investigated here. The

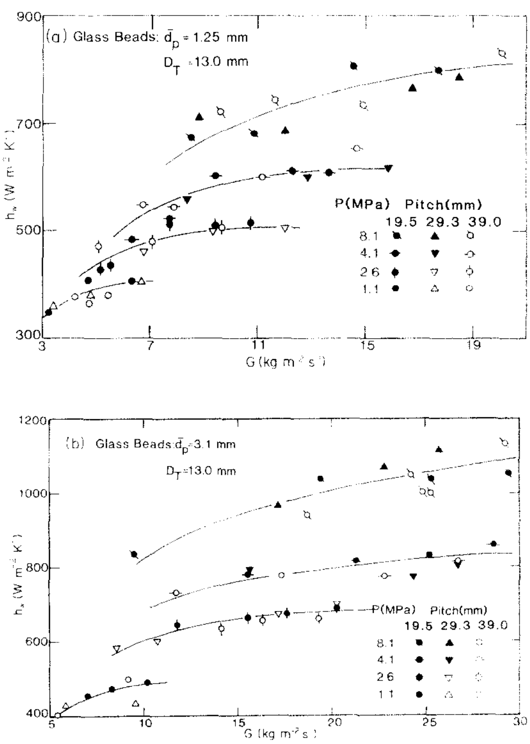

FIG. 1. Variation of h_w with G for a horizontal tube bundle in a fluidized bed of glass beads ($\bar{d}_p$ = 1.25 and 3.1 mm) at various pressures and tube pitches.

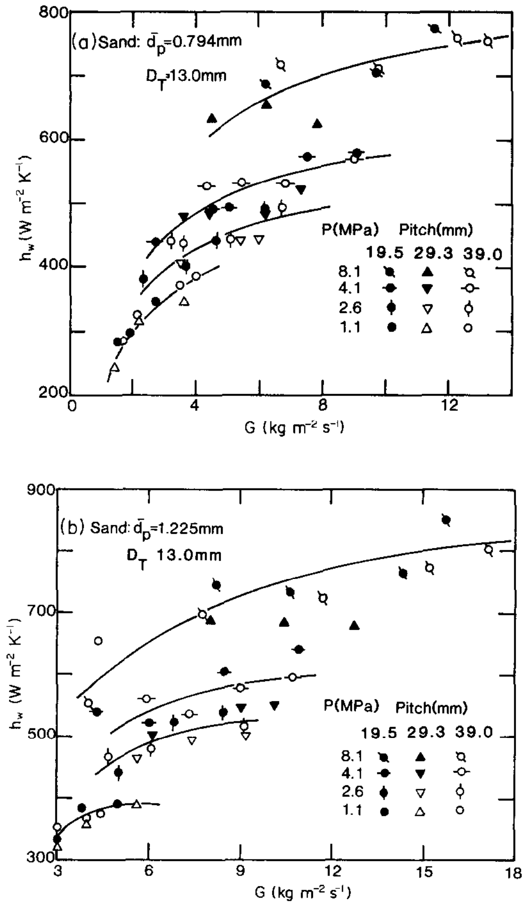

FIG. 2. Variation of h_w with G for a horizontal tube bundle in a fluidized bed of sand particles ($\bar{d}_p$ = 0.794 and 1.225 mm) at various pressures and tube pitches.

values increase by a factor of 2.0–2.5 for the present case. Further, for the conditions of the present experiments no systematic effect of tube pitch is found on h_w for these inline tube bundles. For otherwise identical conditions, the h_w values for larger particles are greater than for smaller particles. This difference for glass beads is about 15–25% and up to 10% for sand particles. The qualitative variations in h_w with system and operating parameters can be explained on the basis of the hydrodynamics of fluidized beds and the heat transfer process involving particle convection and gas convection [16].

For a given pressure and tube bundle, h_w increases with G due to enhanced particle convection but at higher velocities this rate of increase reduces due to a decrease in the solids concentration in the region close to the heat transfer surface. The contribution to h_w due to gas convection on the other hand continuously increases with gas velocity. These two facts together yield the characteristic dependence of h_w on G mentioned above and displayed in Figs. 1 and 2. As the gas pressure is increased the gas convection contribution to h_w increases rapidly and consequently the heat transfer coefficient increases with pressure. It is somewhat surprising that the effect of horizontal tube pitch is not found even when its value is as low as 19.5 mm or $1.5D_T$. This is not in agreement with the observations made at ambient pressures by Zabrodsky *et al.* [15], Borodulya *et al.* [3, 4], Grewal and Saxena [17], and Saxena [18]. The present results suggest that at high pressures due to the increased value of gas density the formation of particle bridging between the adjacent tubes, 'lee' stacks on the down stream side of the tube or in general stagnant solids in the region around a tube is prevented. As a result smooth fluidization occurs even for a relatively tight bundle.

The effect of particle diameter is particularly important to note, because h_w for larger particles is larger than for smaller particles and this trend becomes more pronounced with increasing pressure. For smaller particles at ambient pressure, the dependence of h_w on d_p decreases. The reason for the difference in this characteristic dependence of h_w on d_p lies in the mechanism of heat transfer. While for small particles, particle convection plays a dominant role, for large particles the gas convection is more important and its contribution to h_w enhances as the pressure increases. In the present case for glass beads when the particle diameter increases from 1.25 to 3.10 mm, h_w increases by 15% at the lowest pressure and by 25% at the highest pressure. For sand particles where the size is somewhat smaller and its increase also is moderate (0.794–1.225 mm), h_w increases only by about 10% at the highest pressure and is about the same at the lowest pressure.

COMPARISON WITH HEAT TRANSFER THEORIES

In the previous section we discussed the qualitative dependence of h_w on system and operating parameters on the basis of the generally advocated and accepted mechanism of heat transfer. Now we will examine the success of the available theories to quantitatively predict the observed h_w data. However, all the theories except one [16] are developed and examined on the basis of data mostly at ambient or in a few cases at pressures up to 1.0 MPa. The theory of Ganzha *et al.* [16] gives particular attention to the formulation of the gas convection contribution to h_w which becomes very important at pressures above ambient. We briefly review these heat transfer theories in the following.

Ganzha *et al.* [16] expressed the overall heat transfer coefficient as the additive contribution of gas film conduction and gas convection. They finally express the particle Nusselt number as

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

where

$$\varepsilon_w = \varepsilon_{w,mf} + 1.65A(1-\varepsilon_{mf})\{1-\exp(-a/A^2)\}, \quad (2)$$

$$\varepsilon_{w,mf} = 1 - \frac{(1-\varepsilon_{mf})[0.7293+0.5139(\bar{d}_p/D_T)]}{[1+(\bar{d}_p/D_T)]}, \quad (3)$$

$$A = (Re - Re_{mf})/\sqrt{Ar}, \quad (4)$$

and

$$a = 0.367 \ln \{(\varepsilon_{w,mf} - \varepsilon_{mf})/(1 - \varepsilon_{mf})\}. \quad (5)$$

Staub [19] developed a model for horizontal tube bundles in which he accounted for the restrictions caused to the motion of large particles in the bed by the tubes. Considering a turbulent flow regime in the bed he derives

$$\frac{Nu_T}{Nu_f} = \left[1 + \left(\frac{150}{\bar{d}_p(\mu m)}\right)^{0.73} \left(\frac{\rho_s u_s}{\rho_g u}\right)\right]^{0.45}, \quad (6)$$

for 20 μm $< \bar{d}_p <$ 1000 μm, and $\bar{d}_p$ is taken as 1000 μm for 1000 μm $< \bar{d}_p <$ 3000 μm in equation (6). The solids circulation velocity, u_s, is expressed in the following form by employing the concept of mixing length

$$U_s = 0.42(1 - \varepsilon) S_H^{0.4}. \quad (7)$$

Nu_f is calculated from the Colburn equation for heat transfer from tube banks [20].

Glicksman and Decker [21] emphasize the concept of steady-state conduction from the heat transfer surface to the first row of particles and lateral mixing of the gas, and express the overall heat transfer coefficient as

$$Nu = (1 - \delta)(9.3 + 0.042 Re\, Pr), \quad (8)$$

where

$$\delta = (\varepsilon - \varepsilon_{mf})/(1 - \varepsilon_{mf}), \quad (9)$$

and

$$\varepsilon = u/[1.05u + (1 - \varepsilon_{mf}) u_{mf}/\varepsilon_{mf}]. \quad (10)$$

Catipovic *et al.* [12] express the heat transfer coefficient as composed of contributions due to emulsion and bubble phases and finally show that

$$Nu = [6 + 0.0175 Ar^{0.46}\, Pr^{0.33}](1 - \beta) + \beta(\bar{d}_p/D_T) \times [0.88 Re_{mf}^{0.5} + 0.0042 Re_{mf}]\, Pr^{0.33}, \quad (11)$$

where

$$(1 - \beta) = 0.45 + \frac{0.061}{(u - u_{mf}) + 0.125}. \quad (12)$$

Zabrodsky *et al.* [15] also assumed like many previous workers that h_w comprises of heat conduction from the surface to the particles through the gas film, and gas convective contribution which is evaluated semi-empirically in terms of the 'filtrational' part of the effective thermal conductivity. Their final result is

$$h_w = 7.2 k_g (1 - \varepsilon)/\bar{d}_p + 26.6 u^{0.2} C_{pg} \rho_g \bar{d}_p, \quad (13)$$

where

$$\varepsilon = \varepsilon_{mf} + \frac{\Delta P_t}{g \rho_s L_{mf}}. \quad (14)$$

Here ΔP_t is the experimental pressure drop measured across the top part of the fluidized bed above the L_{mf} level at different u values.

Maskaev and Baskakov [22], and Denloye and Botterill [6] have given relations for evaluating the maximum heat transfer coefficient for a bed of coarse particles. Their expressions are respectively

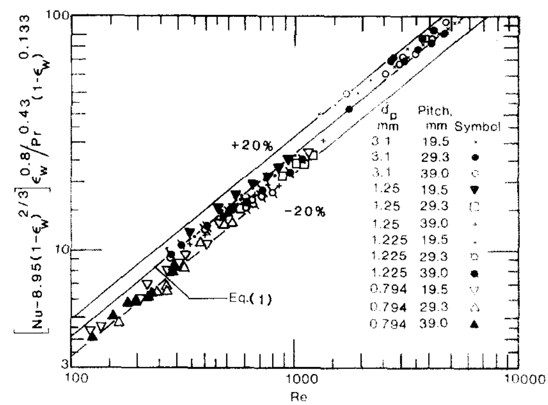

FIG. 3. Comparison of the present experimental data of h_w for glass beads and sands at pressures and tube pitches with the theory of Ganzha *et al.* [16].

$$Nu_{max} = 0.21 Ar^{0.32} \text{ for } 1.4 \times 10^5 < Ar < 3.0 \times 10^8, \quad (15)$$

and

$$Nu_{max} = 0.843 Ar^{0.15} + 0.86 \bar{d}_p^{0.5}\, Ar^{0.39} \quad \text{for } 10^3 < Ar < 2 \times 10^6. \quad (16)$$

The experimental data points presented in Figs. 1 and 2 are compared with the predictions of Ganzha *et al.*'s [16] theory, equations (1)–(5), in Fig. 3 where

$$[Nu - 8.95(1 - \varepsilon_w)^{2/3}]\varepsilon_w^{0.8}(1 - \varepsilon_w)^{-0.133}\, Pr^{-0.43}$$

is plotted against Re on a log–log scale. The continuous line with a slope of 0.8 represents equation (1). The graph represents around 170 data points and all except about 15 points agree with the predictions of theory within a deviation of $\pm 20\%$. The reproducibility of our data is about $\pm 4\%$ but their accuracy is judged only as $\pm 10\%$. In view of the appreciable uncertainty in establishing bed voidage at the heat transfer surface, i.e. ε_w and $\varepsilon_{w,mf}$, we regard this comparison between theory and experiment as quite good and conclude that the theory of Ganzha *et al.* [16] appears completely reliable in predicting heat transfer coefficients from immersed surfaces for large particles and pressures. The accuracy of prediction is coupled with our ability to establish voidage in the bulk of the bed and at the heat transfer surface.

We will now consider specific data sets and examine the abilities of different theories to reproduce h_w as a function of G. Thus, in Figs. 4 and 5, h_w data for glass beads of mean diameter 3.1 mm at pressures of 8.1 and 4.1 MPa are considered, respectively. In each case, data for all the three pitches are shown and no systematic effect of tube pitch on h_w is evident. This justifies the comparison of these data with the theories developed for heat transfer from single tubes. The trends of agreement and departure of experimental data points from different theories in the two figures are remarkably

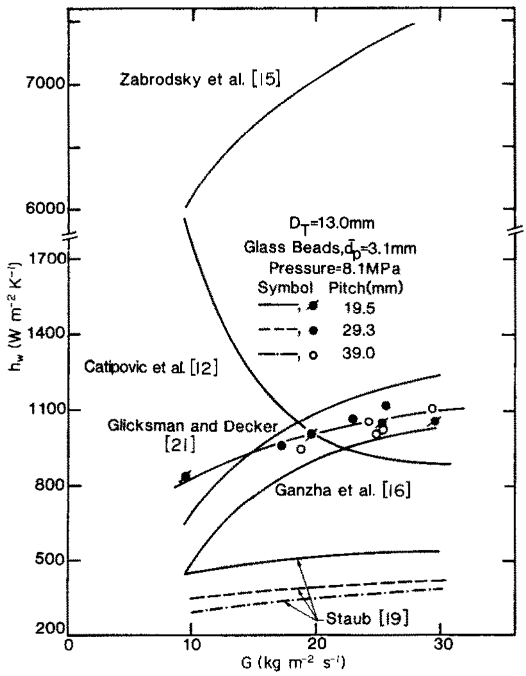

FIG. 4. Comparison of experimental and calculated heat transfer coefficients for horizontal tube bundles and a fluidized bed of glass beads ($\bar{d}_p$ = 3.1 mm) at 8.1 MPa pressure.

similar. Thus, the theories of Ganzha *et al.* [16], and Glicksman and Decker [21] are considered adequate in reproducing the observed dependence of h_w on G. Predictions of Staub's [19] theory are considerably smaller than the experimental results though its applicability to particles of 3.1 mm diameter can be questioned. We wanted to explore its appropriateness specially because it is formulated for horizontal tube bundles. This point will be clarified further in the following while discussing results of sand particles. Zabrodsky *et al.*'s [15] theory leads to values which are much greater than the experimental values. Our preliminary calculations suggest that this discrepancy creeps in h_w probably due to an approximate calculation of the gas convection contribution. With some justification, the exponent of ρ_g (13) can be changed from 1 to 0.5 [6, 11]. With this modification the agreement between the calculated and experimental values gets considerably improved. The calculated values from Catipovic *et al.*'s [12] theory are in complete disagreement with the experimental values. The theory fails to reproduce both the observed magnitude and the qualitative trend of variation of h_w with G.

Experimental data of sands of average diameter 1.225 mm are shown in Fig. 6 along with the calculated values on different models mentioned above. The conclusions that can be drawn from a comparison of theory and experiment as given in this figure are in complete accord with those mentioned above and based on Figs. 4 and 5. As mentioned above in connection with the dependence of h_w on G, the increase of h_w with G for the larger values of the latter is very slow and thereafter it decreases slowly with further increases in G, Figs. 1 and 2, and consequently determination of Nu_{max} is not very precise. We have compared the estimated experimental Nu_{max} values for glass beads ($\bar{d}_p$ = 3.1 mm) and sand ($\bar{d}_p$ = 0.794 mm) in Table 2. The latter choice is dictated by the desire to obtain a value of Ar so that the correlation of Denloye and Botterill [6] could be examined. It is clear from Table 2 that in all cases there is a satisfactory qualitative agreement between theory and experiment, i.e. the Nu_{max} values

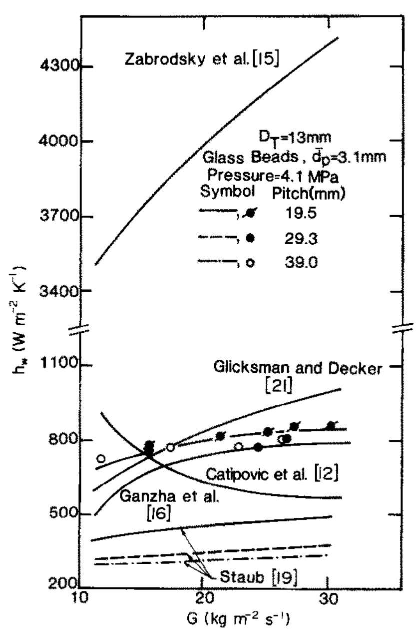

FIG. 5. Comparison of measured and calculated heat transfer coefficients for horizontal tube bundles and a fluidized bed of glass beads ($\bar{d}_p$ = 3.1 mm) at 4.1 MPa pressure.

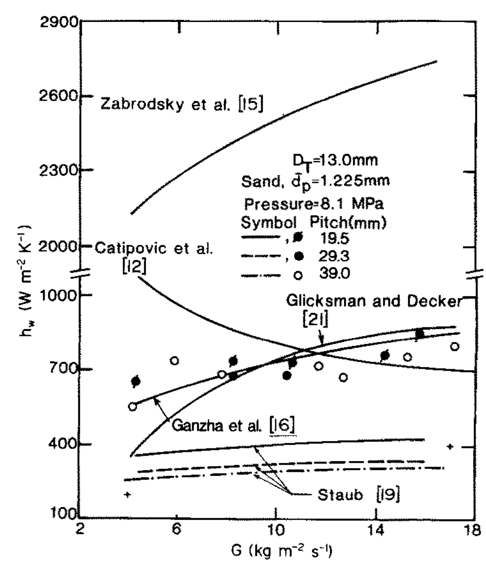

FIG. 6. Comparison of measured and calculated heat transfer coefficients for horizontal tube bundles and a fluidized bed of sand ($\bar{d}_p$ = 1.225 mm) at 8.1 MPa pressure.

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

Pressure (MPa)	Archimedes number	Nu_{max} Experimental	Maskaev and Baskakov [22]	Denloye and Botterill [6]
		Glass beads: $\bar{d}_p = 3.1$ mm		
8.1	2.29×10^8	110.3	99.4	—
4.1	1.49×10^8	97.1	86.7	—
2.6	1.02×10^8	83.3	76.7	—
1.1	4.59×10^7	61.6	59.4	—
		Sand: $\bar{d}_p = 0.794$ mm		
8.1	3.2×10^6	19.8	25.4	—
4.1	1.89×10^6	15.23	21.4	14.2
2.6	1.29×10^6	13.4	19.0	12.81
1.1	5.78×10^5	11.6	14.7	10.4

decrease as the Archimedes number or pressure decreases. However, for glass beads the experimental Nu_{max} values are consistently larger, while for sand these are consistently smaller than those predicted on the basis of Maskaev and Baskakov's [22] relation. Denloye and Botterill's [6] relation gives Nu_{max} values consistently smaller than the experimental values for sand. The disagreement between calculated and experimental values ranges between 8.0–22.0% and in view of the uncertainties in our data we do not attach much significance to it except for its systematic nature, which is somewhat intriguing.

CONCLUSIONS

Based on the analysis of the present experimental heat transfer data from horizontal tube bundles in beds of large particles at high pressures in terms of the available theories some general conclusions can be drawn.

The heat transfer coefficient increases as the particle size is increased for large particles. This result is in sharp contrast with the findings in the literature for small particles at ambient pressure.

For square inline horizontal tube bundles (D_T = 13 mm), it is found that the heat transfer coefficient is insensitive to the variation in the horizontal and vertical pitch in the range $1.5D_T$–$3.0D_T$.

Three of the five available heat transfer theories for h_w are found to be unsuccessful in reproducing the experimental data. These are due to Zabrodsky *et al.* [15], Catipovic *et al.* [12], and Staub [19]. The theories due to Glicksman and Decker [21], and Ganzha *et al.* [16] can successfully correlate the experimental data.

Acknowledgements—We are grateful to the U.S. National Science Foundation for partly supporting this work under a U.S.A.-U.S.S.R. cooperative research program.

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TRANSFERT THERMIQUE ENTRE DES LITS FLUIDISES DE GRANDES PARTICULES ET DES FAISCEAUX DE TUBES HORIZONTAUX POUR DES GRANDES PRESSIONS

Résumé—Des expériences sur des faisceaux de tubes horizontaux en ligne à pas carré (D_T = 13 mm et valeur du pas : 19,5 ; 29,3 et 39,0 mm) immergés dans lits fluidisés de billes de verre ($\bar{d}_p$ = 1,25 et 3,1 mm) et de sable ($\bar{d}_p$ = 0,794 et 1,225 mm) permettent la mesure du transfert thermique en fonction de la vitesse de fluidisation et de la pression (1,1 ; 2,6 ; 4,1 ; et 8,1 MPa). Les valeurs du coefficient de transfert thermique augmentent avec le diamètre des particules, la pression du système, mais sont plutôt indépendantes du pas des tubes dans le domaine étudié ici. Les valeurs de h_w sont comparées aux prédictions de cinq théories différentes disponibles dans les textes. Les deux relations pour Nu_{max} sont considérées. Des conclusions sont tirées sur la base des données de h_w pour des grosses particules aux pressions élevées.

WÄRMEÜBERGANG ZWISCHEN EINEM FLIESSBETT MIT GROSSEN PARTIKELN UND EINEM WAAGERECHTEN ROHRBÜNDEL BEI HOHEM DRUCK

Zusammenfassung—An einem waagerechten Rohrbündel, das sich in fluchtender Anordnung (D_T = 13,0 mm ; Teilung 19,5 ; 29,3 und 39,0 mm) in einem Fließbett aus Glasperlen ($\bar{d}_p$ = 1,25 und 3,1 mm) und Sanden ($\bar{d}_p$ = 0,794 und 1,225 mm) befindet, wird der Wärmeübergang in Abhängigkeit von der Fluidisationsgeschwindigkeit und vom Systemdruck (1,1 ; 2,6 ; 4,1 und 8,1 MPa) experimentell untersucht. Es zeigt sich, daß der Wärmeübergangskoeffizient mit dem Partikeldurchmesser und dem Systemdruck ansteigt, im untersuchten Bereich jedoch fast unabhängig von der Rohrteilung ist. Die Werte für h_w werden mit Berechnungen nach fünf unterschiedlichen Theorien aus der Literatur verglichen. Die beiden Korrelationen für Nu_{max} werden ebenfalls berücksichtigt und ausgewertet. Aufgrund der mitgeteilten h_w-Daten werden für große Partikel bei hohen Drücken wesentliche Schlußfolgerungen gezogen.

ТЕПЛООБМЕН МЕЖДУ ПСЕВДООЖИЖЕННЫМ СЛОЕМ КРУПНЫХ ЧАСТИЦ И ГОРИЗОНТАЛЬНЫМИ ПУЧКАМИ ТРУБ ПРИ ПОВЫШЕННОМ ДАВЛЕНИИ

Аннотация—Получены экспериментальные значения коэффициентов теплообмена между коридорно расположенными пучками труб (D_T = 13,0 мм с шагами 19,5; 29,3 и 39,0 мм) и псевдоожиженными слоями стеклянных шариков ($\bar{d}_p$ = 1,25 и 3,1 мм) и песка ($\bar{d}_p$ = 0,794 и 1,225 мм) в виде функций скорости псевдоожижающего газа и давления (1,1; 2,6; 4,1 и 8,1 МПа). Найдено, что с ростом диаметра частиц и давления коэффициенты теплообмена увеличиваются, в то же время слабо завися от шага труб в исследованном диапазоне их значений. Экспериментальные значения коэффициентов теплообмена сопоставляются с расчетными, полученными с помощью пяти различных корреляций, имеющихся в литературе. Для сопоставлений использованы также две известные корреляции для расчета Nu_{max}. Проведенная работа позволила сделать некоторые выводы о теплообмене псевдоожиженных слоев крупных частиц.