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Prediction of maximum heat transfer coefficient in gas fluidized bed

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Abstract—Heat transfer from a 26 mm i.d. smooth tube, horizontally immersed in a gas fluidized bed, is studied using particulate solids in the size range 70–161 μm and multiorifice distributors of different free area. Internal wall heat transfer coefficients are determined for operating velocities ranging from U_{mf} to $5U_{mf}$ for bed temperatures of 40–70°C. Heat transfer results are analysed and a correlation to predict the maximum heat transfer coefficient is proposed. An analytical method to determine the Nusselt number corresponding to the maximum heat transfer coefficient is also proposed.

INTRODUCTION

THE MECHANISM of heat transfer from an immersed surface in gas fluidized beds has been analysed by various workers and this topic has been reviewed in detail by Gutfinger and Abuaf [1], Saxena *et al.* [2] and Saxena and Gabor [3]. Among the models available in the literature, the more common are due to Mickley and Fairbanks [4] and Botterill and Williams [5]. The Mickley and Fairbanks type of model assumes transient conduction of heat to a two-phase homogeneous mixture of gas and solid, having the properties corresponding to the incipient state of fluidization.

The model of Botterill and Williams [5] considered the individual properties of gas and solid as against assigning arbitrary properties to the emulsion packet. This model suffered the limitation of short contact time during which period heat cannot penetrate the second particle layer. Hence, this single particle model was later improved for two particle layers by Botterill and Butt [6] and further, to any chain of unlimited length, by Gabor [7].

Selzer and Thomson [8] rightly remarked that, for any of these models to apply, it is necessary to have a clear interpretation of heat penetration depth and the short contact time criterion. They stressed the need to test the applicability of the models for distributors of different type. Heat transfer in a gas fluidized bed in general is affected by bubbles which, in turn, are affected by distributors apart from other operating parameters. A heat transfer model which accounts for the hydrodynamics of the bed is considered to be more realistic [8]. It is a well proven fact that the heat transfer rate in a gas fluidized bed increases up to an optimum value and then decreases with increasing flow rate of the gas. Though the particle movement, and its concentration near the surface, are responsible for effective heat transfer, these two factors have an opposing nature with increased intensity at higher gas flow rates. Hence, it has been a difficult task over many years to explain the optimum heat transfer rate.

Most of the models cannot explain the optimum condition satisfactorily. More recently Chen and Pei [9] developed a new model to express the maximum heat transfer coefficient, however, it does not consider the effect of distributors. The validity of the proposed correlation was not tested for a gas flow rate below the optimum condition. Their rigorous mathematical model was later simplified to a simple correlation by suitable assumptions. The model of Chen and Pei lacks the definition of a fully developed bed and also the corresponding range of operating velocities. Furthermore, it seems that the model is applicable only for particulate fluidization, which is affected to a very high degree by the gas distributor. Hence, in our present work, a new model analogous to that of Chen and Pei, but with an entirely different approach, has been developed incorporating the effect of the distributor and defining a fully developed bed.

THEORETICAL TREATMENT

Though fluidization starts from the incipient flow rate, U_{mf}, a fully developed fluidized bed, that is to say stable fluidization, occurs depending on the minimum operating velocity as influenced by distributors [10, 11]. It can be assumed that from the gas velocity U_{mf} to the minimum operating velocity U_m, required for stable fluidization, the bed is in an emulsion state. Hence the heat transfer from an immersed surface in such a situation is analogous to transfer of heat to a moving bed of solids past an immersed surface. For

NOMENCLATURE

- A_b cross-sectional area of bed [m^2]
- A_s surface area of heater [m^2]
- Ar Archimedes number, $d_p^3\rho_g(\rho_s-\rho_g)g/\mu_g^2$ [—]
- C_{pg}, C_{ps} specific heat of gas and particle [$J\,kg^{-1}\,K^{-1}$]
- C_{vg}, C_{vs} volumetric specific heat of gas and particle [$J\,m^{-3}\,K^{-1}$]
- d_p particle diameter [μm]
- d_T immersed tube diameter [m]
- F factor in equation (17)
- Fr Froude number based on particle diameter, U_{mf}^2/d_pg [—]
- Fr' Froude number based on immersed tube diameter, U_{mf}^2/d_Tg [—]
- g gravitation constant [$m\,s^{-2}$]
- h_{mf}, h_{max} heat transfer coefficient at minimum fluidization velocity and maximum heat transfer coefficient [$W\,m^{-2}\,K^{-1}$]
- k_e, k_g thermal conductivity of emulsion phase and gas [$W\,m^{-1}\,K^{-1}$]
- n frequency of packet renewal [s^{-1}]
- Nu, Nu_{max} Nusselt number, hd_p/k_g, and its maximum, $h_{max}d_p/k_g$ [—]
- Pr Prandtl number, $C_{pg}\mu_g/k_g$ [—]
- q heat flux [$W\,m^{-2}$]
- Re_{mf}, Re_{opt} Reynolds number, $Ud_p\rho_g/\mu_g$ at minimum fluidization velocity, U_{mf}, and at optimum velocity, U_{opt} [—]
- T_b, T_0, T_w temperature of bed, inlet gas and immersed surface [K]
- U, U_{mf}, U_{opt}, U_s superficial, minimum fluidization, optimum and solid particle velocity [$m\,s^{-1}$].

Greek symbols

- α factor in equation (9) [—]
- β factor in equation (9) [—]
- ε, ε_{mf} bed voidage and its value at minimum fluidization [—]
- μ_g viscosity of gas [$kg\,m^{-1}\,s^{-1}$]
- ρ_e, ρ_g, ρ_s density of emulsion, gas and solid [$kg\,m^{-3}$]
- τ packet contact time [s].

fine solids ($d_p < 0.3$ mm) when contact time is small ($\tau < 1$ s), the contact resistance due to the thin film of gas adjacent to the surface is not significant [12]. Hence, in such a case, emulsion resistance alone can be treated for predictive purposes, and the uniform surface renewal of packets [4] may be used to calculate the average heat transfer coefficient. This is also similar to the model of Wunder [13] wherein heat transfer from a wall to a well mixed gas layer is considered.

Under steady-state operation at minimum fluidization velocity U_{mf} for a heater of surface area A_s at temperature T_w and the bed at T_b fluidized by a gas entering at T_0, the heat balance equation is

$$A_sh_{mf}(T_w-T_b) = A_bU_{mf}\rho_gC_{pg}(T_b-T_0). \quad (1)$$

For the gas velocity, U (i.e. $U_{mf} \leqslant U \leqslant U_m$), h_{mf} will increase to h such that

$$h = (U/U_{mf})h_{mf}. \quad (2)$$

Equation (2) can be obtained from equation (1) assuming negligible change of the ratio $(T_w-T_b)/(T_b-T_0)$ over the range of velocities U_{mf} to U_m. Substituting h_{mf} as obtained by uniform surface renewal theory [4]

$$h = 2(U/U_{mf})(C_{pe}K_e\rho_e/\pi\tau)^{0.5} \quad (3)$$

where $C_{pe} = C_{ps}(1-\varepsilon_{mf})$, $\rho_e \simeq \rho_s$, k_e = const. [kg], and τ is the contact time to be evaluated. Since at U_{mf}, bubbles are assumed to be absent

$$\tau = (1/n). \quad (4)$$

The renewal frequency rate n can be taken as [21]

$$n = \text{const.}\cdot(U_s/d_p)Pr^{-1/3} \quad (5)$$

where the mean particle rising velocity U_s at U_{mf}, is

$$U_s = U_{mf}/\varepsilon_{mf}. \quad (6)$$

Using equations (4)–(6) in equation (3) and rewriting

$$h = \text{const.}\cdot(U/U_{mf})[C_{ps}k_g(1-\varepsilon_{mf})U_{mf}/\varepsilon_{mf}d_p]^{0.5}Pr^{-1/6} \quad (7)$$

$$\frac{hd_p}{k_g} = \text{const.}\cdot(U/U_{mf})\left[\left(\frac{C_{ps}\rho_s}{C_{pg}\rho_g}\,\frac{C_{pg}\rho_g}{k_g}\,\frac{U_{mf}d_p\rho_g}{\mu_g}\right)\right]^{0.5}Pr^{-1/6} \quad (8)$$

equation (8) may be rewritten as

$$Nu = \text{const.}\cdot(U/U_{mf})Re_{mf}^{0.5}(\alpha\beta)^{0.5}Pr^{0.3} \quad (9)$$

where $\alpha = (1-\varepsilon_{mf})/\varepsilon_{mf}$ and $\beta = C_{vs}/C_{vg}$. When $Nu = Nu_{max}$, the corresponding optimum velocity U_{opt} may be substituted into equation (9). For this optimum condition, Todes [14] proposed a correlation for Re_{opt}

$$Re_{opt} = Ar/(18+5.2Ar^{0.5}). \quad (10)$$

From this correlation, it can be noted that $Re_{opt} \propto Ar$ for low values of Ar and $Re_{opt} \propto Ar^{0.5}$ for high values of Ar. Sathiyamoorthy [11] obtained empirical relations for Re_{opt} and showed that $Re_{opt} \propto Ar$ for $Ar \leqslant 1000$, and $Re_{opt} \propto Ar^{0.5}$ for $3000 \leqslant Ar \leqslant 10^7$. Hence using these criteria, and also the established facts [15] that $Re_{mf} \propto Ar$, for $Re \leqslant 20$ and again proportional to $Ar^{0.5}$ for $Re \geqslant 1000$, equation (9) may be transformed for the optimum flow condition, as

$$Nu_{\max} = \text{const.} \cdot Ar^{0.5}[(C_{vs}/C_{vg})((\overline{1-\varepsilon_{mf}})/\varepsilon_{mf})]^{0.5}Pr^{0.3} \quad \text{for } Ar \leqslant 1000 \qquad (11)$$

$$Nu_{\max} = \text{const.} \cdot Ar^{0.25}[(C_{vs}/C_{vg})((\overline{1-\varepsilon_{mf}})/\varepsilon_{mf})]^{0.5}Pr^{0.3} \quad \text{for } 10^3 \leqslant Ar \leqslant 10^7. \qquad (12)$$

Correlations (11) and (12) are similar to those proposed by Chen and Pei [9], except for a slight variation in the values of exponents determined from the published data.

EXPERIMENTAL WORK

A 200 mm i.d., 1000 mm long fluidizing column, provided with four side ports at 200 mm intervals so as to insert, horizontally, a 26 mm o.d. smooth surface silica heater of 200 mm effective heating length, was used. A schematic of the experimental set-up is shown in Fig. 1. The heater element was nichrome wire coiled to house tightly inside a silica sheath. The wall temperature of the heater was taken as the mean of three temperatures measured using 30 SWG copper–constantan thermocouples, which were positioned at equal intervals and imbedded on the sheath of the heater. Four multiorifice distributors, the details of which are given in Table 1, and particulate solids such as zircon, rutile, sand and alumina in the overall size range of 70–161 μm, were used for fluidizing with air up to the operating velocity $U = 5U_{mf}$. The physical and thermal properties of bed material are given in Table 2. The free area of distributors was fixed to achieve smooth fluidization for the respective bed materials. The criteria adopted for the design of the distributors are similar to those considered by Fakhimi and Harrison [10], and analysed later by Sathiyamoorthy [11] for choosing the operating velocity corresponding to active functioning of all the orifices. Experiments have been carried out immersing the heater within the bed at 200 mm above the distributor and for a static bed height of 800 mm. The wall heat transfer coefficient at steady-state condition has been calculated by the equation

$$h = q/(T_w - T_b)_{\text{mean}}. \qquad (13)$$

RESULTS AND DISCUSSION

Figure 2 shows the variation of the parameter $Nu/(\alpha\beta\, Re_{mf})^{0.5}Pr^{0.3}$ with (Re/Re_{mf}) and it is found

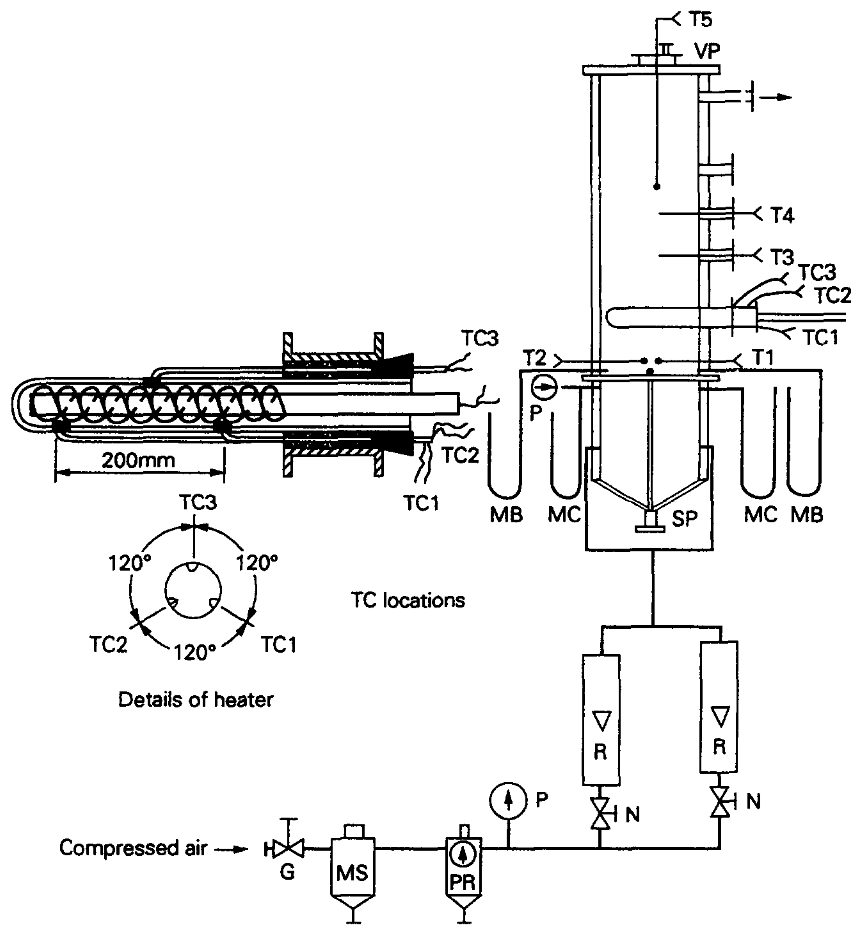

FIG. 1. Schematic diagram of 20 cm i.d. fluidized bed assembly.

Table 1. Details of the multiorifice distributors' plates

Distributor type	Fraction free area, $\phi \times 10^4$	Number of orifices, N	Orifice diameter, d_o [mm]	Orifice spacing, P [mm]	Thickness of the distributor plate, t [mm]	Materials of construction
A	27.3	121	0.95	16.6	6.1	Aluminium
B	52.0	325	0.80	10.0	5.0	Mild steel
C	9.15	121	0.55	16.6	6.1	Mild steel
S	8.8	55	0.80	8.0	5.0	Mild steel

Table 2. Properties of particulate solids

Bed material	Density, ρ [kg m^{-3}]	Average particle size, d_p [μm]	Minimum fluidization velocity, U_{mf} [m s^{-1}]	Bed voidage at U_{mf}, ε_{mf}	Specific heat of solid, C_p [J kg^{-1} K^{-1}]
Zircon	4550	140, 161	4.61, 4.986	0.45, 0.44	$262.2+0.3294T-4010\times10^3$, $297 < T < 372$
Rutile	4500	114, 150	2.75, 4.77	0.40, 0.38	$321.3+0.0205T-1139\times10^3$, $273 < T < 713$
Alumina	4000	70	0.95	0.45	$894.0+0.3631T-2115\times10^4$, $273 < T < 1973$
Sand	2250	114	1.40	0.45	$748.2+0.6002T-1660\times10^4$, $273 < T < 848$
Calcium fluoride	3180	161	3.92	0.42	$778.34+0.201T$, $273 < T < 1651$

that the ordinate varies almost linearly with (Re/Re_{mf}) for all bed materials and distributors. This result agrees well with equation (9). However, equation (9) does not account for the change in the intercepts as observed from Fig. 2. Hence the constant in equation (9) has to be suitably modified to take into consideration the different particulate solids used. From Fig. 2 it may be noted that, for the case of alumina with distributors of various free area, a common slope close to unity and a single intercept are obtained. However, intercept values are different with rutile and zircon and these may be the function of U_{mf}, or d_p.

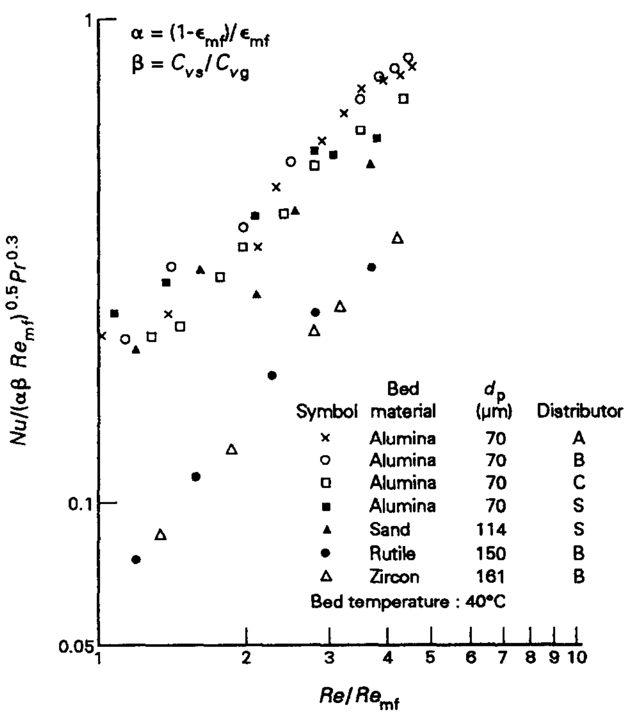

FIG. 2. Effect of Re/Re_{mf} and distributor on Nu.

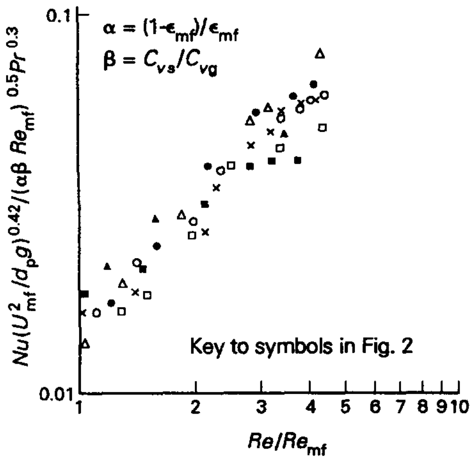

FIG. 3. Effect of Re/Re_{mf} on Nusselt number incorporating Froude group based on particle diameter, d_p.

The Froude group is selected to effectively incorporate those parameters. A least square fit of the data of intercept values with the Froude group (Fr), whether based on particle diameter d_p or d_T, gave an exponent of -0.42 to Fr. Hence, the generalized correlation for Nu is

$$Nu = \text{const.} \cdot Fr^{-0.42}(\alpha\beta\, Re_{mf})^{0.5}(Re/Re_{mf})Pr^{0.3}. \quad (14)$$

Figures 3 and 4 show the plot of experimental data conforming to the correlation type (14) for the Froude group based on d_p and d_T respectively. The constant in correlation (14) is 0.0755, for Fr based on d_p, and 0.0144, for Fr' based on d_T. The correlation of Leva and Wen [16] for Nu in the case of an external wall is proportional to $Fr^{-0.2}$, whereas in our case the exponent is two fold higher for heat transfer from immersed surfaces.

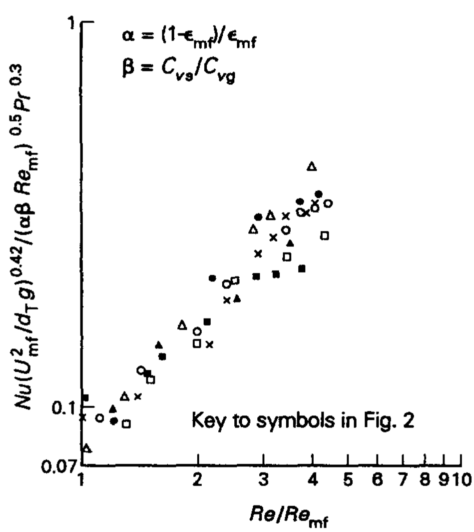

FIG. 4. Effect of Re/Re_{mf} on Nusselt number incorporating Froude number based on tube diameter, d_T.

It should be noted that equation (14) is valid up to $Re \leqslant Re_{opt}$, that is for the ascending branch of the conventional Nu vs Re plot. Hence, for the optimum conditions corresponding to the maximum heat transfer rate in a gas fluidized bed, the variation of the parameter, $Nu_{max}\ Fr^{0.42}/(C_{vs}/C_{vg})^{0.5}Pr^{0.3}$, with Archimedes number, Ar, is shown in Fig. 5. The data collected from the literature [8, 17–35], along with the results of our present studies, have been analysed and are shown in Fig. 5. The complete heat transfer data of our studies, as obtained for various gas–solid systems and distributors, have been presented in tabular form in our earlier publication [36]. The correlation obtained from a least square fit of our data is

$$Nu_{max} = 0.0046 Fr^{-0.42} Ar^{0.63}(C_{vs}/C_{vg})^{0.5} Pr^{0.3} \quad (15)$$

where Fr is based on particle diameter. The above correlation closely fits with the proposed equation (11). However, the exponent to Ar is 0.63 as against 0.5. In our present analysis of the data, we could not incorporate the factor, $(1-\varepsilon_{mf})/\varepsilon_{mf}$, as most reports lack this information. Hence, the constant in equation (15) is again dependent on the voidage factor, especially at U_{mf}. Our present analysis of the data, and the proposed model, finally results in an almost similar expression to the one proposed by Chen and Pei [9]. It may be seen from Fig. 5 that for $Ar \leqslant 1000$, the data are scattered even beyond 20% of the least square line. However, it may be noted that the correlation of Chen and Pei [9] for $Ar < 1000$ fitted well with a standard deviation of 18%. They did not consider the data of refs. [8, 19–25, 27–31] in their analysis. They also proposed the classification of fine powders up to $Ar = 2 \times 10^4$ and large particles above this limit. It may only be taken as a qualitative estimate because, for $Ar = 10^4$, for an air–sand system, a particle size as large as 494 μm is obtained. As most of our data is for $Ar \leqslant 1000$, we have not attempted to propose a correlation for $Ar \geqslant 1000$. Chen and Pei proposed the following correlation for large particles:

$$Nu_{max} = 0.013 Ar^{0.37} Pr^{1/3}(C_{vs}/C_{vg})^{1/3}$$
$$(2 \times 10^4 \leqslant Ar \leqslant 10^7). \quad (16)$$

Our proposed correlation (12) also closely fits with the above equation except for the voidage parameter and the constant, which is to be evaluated and examined for its dependency on the Fr group. All the proposed correlations are valid only when the heat transfer due to radiation is insignificant. A generalized prediction of maximum heat transfer coefficient to immersed surfaces, like a single cylinder and sphere in gas fluidized beds, has been suggested by Shah [37] and his prediction is based purely on the analysis of published data. The correlation of Shah [37] for heat transfer due to conduction and convection is

$$Nu_{max} = 7.6 F Re_{opt}^{0.158}(C_{ps}/C_{pg})^{0.18}(d_T/d_p)^{0.805}$$
$$\text{for } Re_{opt} \leqslant 170 \quad (17)$$

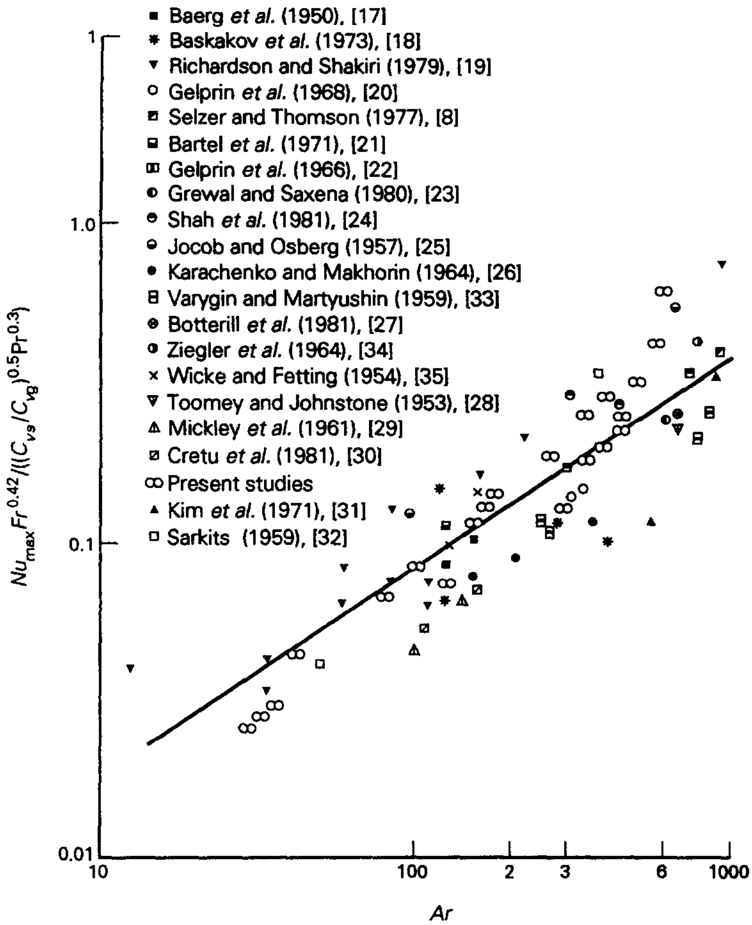

FIG. 5. Nu_{max} as a function of Ar, Fr, Pr and C_{rs}/C_{rg}.

where $F = 1.24$ for spherical particles and unity for non-spherical particles. Shah recommends using Todes' correlation [14] for $Re_{opt} < 170$ and also for horizontal cylinders and spheres of $d_T = 12$ mm and larger. For higher Re_{opt} (i.e. > 170), he noted up to 38% deviation. Precise evaluation of Re_{opt} imposes the restriction of Shah's correlation. However, his correlation incorporates the ratio d_T/d_p, which does not appear in our proposed correlation, and also that of Chen and Pei [9]. Although at this stage it could not be incorporated by our analytical approach, it would be possible to express the constant of correlation (15) in terms of this parameter. Hence most of the data on immersed objects such as a sphere, plate or cylinder are to be grouped, and analysed, taking into consideration the location of these surfaces inside the bed. Such kind of work, especially for the optimum heat transfer condition, is scant and has to be explored.

CONCLUSION

A new analytical approach has been developed to derive an expression for predicting the heat transfer coefficient in a gas fluidized bed and has been verified by experiments for a fine particle system, i.e. for $Ar < 1000$, using multiorifice distributors of a free area fraction of 8.8×10^{-4}–52×10^{-4}.

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PREDICTION DU COEFFICIENT DE TRANSFERT THERMIQUE MAXIMALE DANS UN LIT FLUIDISE GAZEUX

Résumé—Le transfert thermique à partir d'un tube lisse de 26 mm de diamètre, immergé dans un lit fluidisé gazeux est étudié en utilisant des particules solides de taille variant entre 70 μm et 161 μm, et des distributeurs multi-orifices ayant des aires libres différentes. Les coefficients de transfert thermique aux parois internes sont déterminés pour des vitesses opératoires allant de U_{mf} à $5U_{mf}$, pour des températures de lit variant de 40 à 70°C. Les résultats de transfert thermique sont analysés et une formule est proposée pour prédire le coefficient maximal de transfert thermique. On propose aussi une méthode analytique pour déterminer le nombre de Nusselt correspondant à ce maximum.

BERECHNUNG DES MAXIMALEN WÄRMEÜBERGANGSKOEFFIZIENTEN IN EINEM GAS-FLIESSBETT

Zusammenfassung—Der Wärmeübergang an einem Glattrohr mit 26 mm Durchmesser, das waagerecht in ein Fließbett mit Gas als Trägerfluid eingebaut ist, wird mit Partikeln zwischen 70 und 161 μm und Lochplatten unterschiedlicher freier Fläche untersucht. Der Wärmeübergangskoeffizient an der Innenwand wurde im Bereich einer um den Faktor 5 unterschiedlichen Strömungsgeschwindigkeit und für Temperaturen des Fließbetts zwischen 40 und 70°C bestimmt. Die Ergebnisse der Wärmeübergangsuntersuchungen werden analysiert und es wird eine Gleichung zur Berechnung der maximalen Wärmeübergangskoeffizienten vorgeschlagen. Außerdem wird eine Gleichung für die Nusselt-Zahl empfohlen, die für den maximalen Wärmeübergangskoeffizienten gilt.

ОПРЕДЕЛЕНИЕ МАКСИМАЛЬНОГО КОЭФФИЦИЕНТА ТЕПЛОПЕРЕНОСА В ПСЕВДООЖИЖЕННОМ СЛОЕ

Аннотация—С использованием твердых макрочастиц с размерами 70–161 мкм и распределительных устройств различной свободной площади с множественными отверстиями исследуется теплоперенос от гладкой трубы диаметром 26 мм, помещенной горизонтально в псевдоожиженный слой. Определяются коэффициенты теплообмена на внутренней стенке для рабочих скоростей, изменяющихся от U_{mf} до $5U_{mf}$, в диапазоне температур слоя, составляющем 40–70°C. Анализируются результаты по теплопереносу и предлагается соотношение для расчета максимального коэффициента теплопереноса. Предлагается также аналитический метод определения числа Нуссельта, соответствующего максимальному коэффициенту теплопереноса.