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HEAT TRANSFER FROM IN-LAND AND STAGGERED HORIZONTAL SMOOTH TUBE BUNDLES IMMERSED IN A FLUIDIZED BED OF LARGE PARTICLES

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

and

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

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NOMENCLATURE

- Ar, Archimedes number, $d_p^3 g(\rho_s - \rho_g)\rho_g/\mu_g^2$;
- C_{pg}, specific heat of gas [kJ kg^{-1} K^{-1}];
- D_T, tube diameter [m];
- d_p, particle diameter [m];
- g, acceleration due to gravity [m s^{-2}];
- h_w, heat transfer coefficient [W m^{-2} K^{-1}];
- k_g, thermal conductivity of gas [W m^{-1} K^{-1}];
- Nu, Nusselt number, $h_w d_p/k_g$;
- Nu_g, Nusselt number for gas flow without solids, $h_w D_T/k_g$;
- P, tube pitch [m];
- Pr, Prandtl number, $C_{pg}\mu_g/k_g$;
- Re, Reynolds number $U_g d_p \rho_g/\mu_g$;
- S_H, center to center horizontal tube spacing [m];
- S_V, center to center vertical tube spacing [m];
- U_g, superficial gas velocity [m s^{-1}];
- U_s, average solids velocity [m s^{-1}];
- δ, a function of bed voidage, $(\varepsilon_{av} - \varepsilon_{mf})/(1 - \varepsilon_{mf})$;
- ε_{av}, average bed voidage;
- ε_{mf}, bed voidage at minimum fluidization;
- 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}].

THE KNOWLEDGE of the heat transfer coefficient between a fluidized bed and a bundle of immersed tubes is very important for the proper design of fluidized-bed coal combustors for power generation. In such units the bed particle size and the fluidizing gas velocity are much larger than those usually encountered in catalytic reactors and in many of the other applications of fluidized-bed technology. This has led many workers [1–4] in recent years, to examine the heat transfer characteristics of large particle fluidized beds. Here, we report the results of heat transfer coefficient as a function of fluidizing velocity for in-line and staggered tube bundles immersed in a fluidized bed of 2 mm millet particles. The results are also compared with the predictions of three semi-theoretical models [2–4].

The experiments are performed in a rectangular fluidized bed, 60 × 60 cm, and 3-m deep at atmospheric pressure. The bed comprises of spherical millet particles, $d_p = 2$ mm and $\rho_s = 1200$ kg m^{-3}. The settled or static bed height is 60 cm and it is supported on a perforated plate distributor with a free area of 2%. The heat transfer copper tubes are 14 mm in outer diameter and the characteristics of various in-line and staggered tube bundles are given in Table 1. The bottom row in each case is located about 100 mm above the distributor plate. Four electrically heated tubes have been used in each tube bundle. In the in-line tube bundles, the heated tubes are mounted in the middle row and in the rows preceding and following it. In the staggered tube bundle, all the heated tubes are located in the middle row. Temperatures of the bed and probe surface are measured by copper resistance thermometers. A detailed description of the procedure employed in making a run is given elsewhere [5].

The experimentally determined heat transfer coefficients, h_w, for tube bundles of different pitches, P, are given in Figs. 1–3 as a function of fluidizing velocity, U_g. The qualitative variation of these plots is the same as that observed for small particles except the numerical values of h_w are relatively much smaller for large particles. The effect of horizontal pitch, S_H, on h_w is displayed in Fig. 1. The experimental data reveal that for in-line tube bundles the h_w values are almost the same as long as $P > 2D_T$. It may be noted that these in-line tube bundles have a square arrangement of tubes in as much as $S_H = S_V$. In Fig. 2, the influence of vertical pitch, S_V is examined for in-line tube bundles with $S_H = 2D_T$. It may be inferred from Fig. 2 that for $S_H \geq 2D_T$, the effect of vertical pitch on h_w is negligibly small as long as $S_V \geq 2D_T$. On the basis of above conclusions drawn from Figs. 1 and 2, it appears that for any staggered tube arrangement the h_w values will be independent of S_H and S_V, as long as these are greater or equal to $2D_T$. In Fig. 3, a comparison is presented of h_w values for in-line ($S_H = S_V = 2D_T$) and staggered [$S_H = 2D_T$ and $S_V = \sqrt{3}(D_T)$] tube bundles. It is to be noted that the h_w values are almost identical for these two configurations. It would also follow that this result will be valid in general as long as the tube pitches are greater than the above specified values.

The approximately constant values of h_w for $S_H > 2D_T$ and $S_V \geq 2D_T$ are to be interpreted as leading to definite conclusions concerning the solids mixing and bubble growth phenomena in baffled beds. The results do lend support to the qualitative picture that as long as the tube spacing is wide enough both of these processes are uninfluenced by tube pitch and therefore the heat transfer characteristics remain unchanged due to variation in P. The present results quantify this conclusion and suggest the critical values of $S_H > 2D_T$

*On leave from Department of Chemical Engineering, Institute of Technology, Banaras Hindu University, Varanasi—221005, U.P., India.

Table 1. Tube bundle characteristics

Tube arrangement	In-line				Staggered (equilateral triangular)
Horizontal pitch (mm)	28	42	84	28	28
Vertical pitch (mm)	28	42	84	56	$14\sqrt{3}$
Number of tubes in the bundle	130	70	20	70	112
Number of tubes in a vertical column	13	10	4	7	
Number of tubes in a horizontal row	10	7	5	10	16

and that of $S_V \geq 2D_T$. The relative sensitivity of S_H in comparison to S_V in controlling h_w as revealed by present measurements is to be recognized [6]. The observed decrease in the values of h_w when S_H is decreased to $2D_T$ for in-line tube bundle, Fig. 1, and for staggered tube bundle, Fig. 3, is to be taken as a limit for the congestion of tubes in a bundle. It would suggest that for $S_H \leq 2D_T$ the solids movement in the bed is seriously hampered and this causes the heat transfer coefficient to drop. A similar conclusion follows from a different set of experiments performed in 0.3048 m^2 fluidized bed with silica sand (d_p = 167 and 504 μm) by Saxena [7] and Grewal and Saxena [8].

We will now examine the abilities of recent semi-analytical theories which have attempted to mechanistically model the heat transfer process from immersed surfaces in fluidized beds of large particles. Glicksman and Decker [2] argue that large particles, because of their large thermal time constant, do not suffer any appreciable temperature change during their contact with the heat transfer surface. The particles therefore maintain an essentially constant temperature of the bed. The transfer of heat takes place mainly by particle convection and eddy-induced lateral mixing of the gas during its flow past the particles. According to them [2],

$$Nu = (1 - \delta)(9.42 + 0.042\, Re\, Pr) \qquad (1)$$

where

$$\delta = 1 - [(1 - \varepsilon_{av})/(1 - \varepsilon_{mf})], \qquad (2)$$

for a horizontal tube immersed in a fluidized bed of large particles. The h_w values obtained from equations (1) and (2) are given in Figs. 1–3 for the corresponding experimental conditions. The theoretical values are considerably larger than the experimental values for smaller values of U_g. Furthermore, the theoretical values decrease rather slowly with increasing U_g and for the large U_g values the agreement between theory and experiment is much better than for the small U_g values. Some of the disagreement between the theory and experiment probably creeps in because of the approximate procedures employed for estimating ε_{av}, ε_{mf} and U_{mf} according to the correlations given by Staub and Canada [9], Geldart and Cranfield [10], and Aerov and Todes [11] respectively.

Staub [3] contends that the gas flow in a fluidized bed of large particles is in the turbulent regime and finally he shows that

$$Nu = \left[1 + \left(\frac{150}{d_p}\right)^{0.73} \left(\frac{\rho_s U_s}{U_g \rho_s}\right)\right]^{0.45} Nu_g, \qquad (3)$$

for 20 μm < d_p < 1000 μm and for d_p > 1000 μm, it is taken as 1000 μm. Also,

$$U_s = 0.42(1 - \varepsilon_{av}) S_H^{0.4}. \qquad (4)$$

Staub [3] recommends the use of equations given by Colburn for estimating Nu_g for flow across tube banks [12], and the h_w values so obtained are also shown in Figs. 1–3. The Staub model predictions are not regarded as satisfactory.

Zabrodsky *et al.* [4] have modified the Zabrodsky's steady state conduction model [13] and proposed that

$$h_w = \frac{7.2\, k_g(1 - \varepsilon_{av})^{2/3}}{d_p} + 26.6\, U_g^{0.2} C_{pg} \rho_g d_p. \qquad (5)$$

The calculated h_w values from equation (5) are also shown in Figs. 1–3. The predictions of this model are satisfactory in the high velocity range to the extent that the computed values are in fair agreement with the experimental values. Like the work of Glicksman and Decker, this effort [4] also does not take into account the presence of other tubes in the bed.

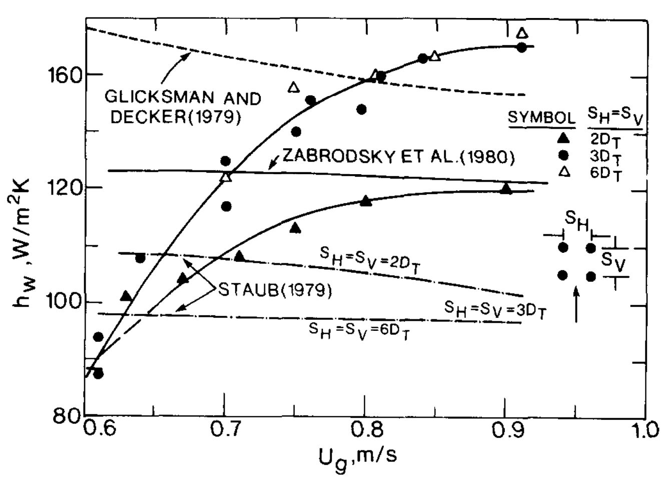

FIG. 1. Variation of h_w with U_g for in-line tube bundles (D_T = 14 mm) of different pitches immersed in a fluidized bed of millet particles (d_p = 2 mm): comparison of experiment and theory.

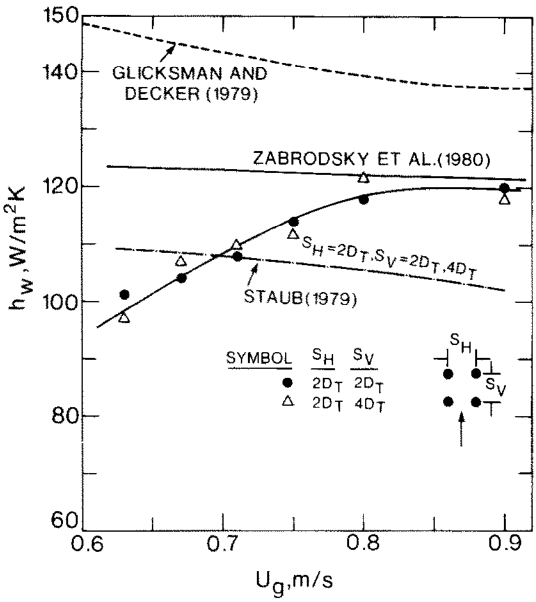

FIG. 2. Variation of h_w with U_g for in-line tube bundles of $S_H = 2D_T$ and different S_V ($2D_T$ and $4D_T$) immersed in a fluidized bed of millet particles ($d_p = 2$ mm): comparison of experiment and theory.

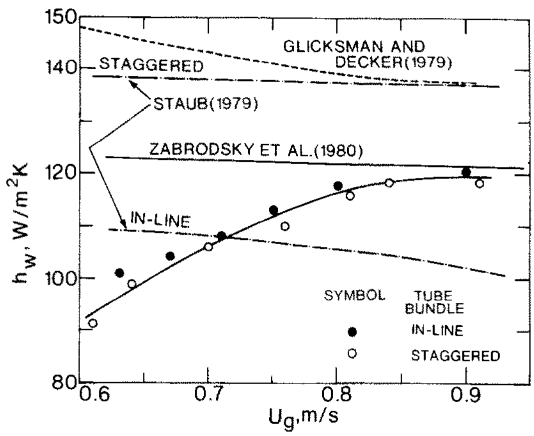

FIG. 3. Variation of h_w with U_g for in-line and staggered tube bundles ($D_T = 14$ mm, $P = 2D_T$) immersed in a fluidized bed of millet particles ($d_p = 2$ mm): comparison of experiment and theory.

The above analysis clearly brings out the inability of the current theories to predict the surface-to-bed heat transfer in fluidized beds of large particles. The experimental data for such systems are also somewhat limited. It is, therefore, concluded that coupled theoretical and experimental investigations of heat transfer in large particle fluidized beds are urgently needed in view of their important bearing on energy generation from coal.

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