Pergamon

Int. J. Heat Mass Transfer. Vol. 41, No. 1, pp. 203–208, 1998

Printed in Great Britain
0017–9310/98 $19.00+0.00

PII: S0017–9310(97)00109–9

Heat-transfer rate variations from the surface of a heater probe in a magnetofluidized bed

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(*Received* 30 *September* 1996)

Abstract—A cylindrical strip heater heat-transfer probe is designed and employed to measure heat-transfer coefficients in the horizontal configuration at three angular positions (0, 90 and 180°) relative to gas flow while submerged in a magnetically stabilized fluidized bed of 1086 μm iron shots. The superficial air velocity is varied up to about 3.8 m s^{-1}, and measurements have been conducted for five values of magnetic-field intensity up to 5662 A m^{-1}. In each case, pressure drops across the bed and a section of it are determined to obtain values of superficial minimum fluidization and minimum bubbling velocities, and gross bed voidage. The heat-transfer coefficient is found to be dependent on the angular position at the horizontal cylindrical probe immersed in the bed. The magnetic field destabilizes the gas pocket at the upstream side of the probe and this characteristically influences the h_w values. The magnetic interparticle forces augment the gas flow in the equatorial lateral zones by the formation of a channel at the probe surface leading to gas bypassing. At the downstream side, the variation is somewhat similar to the variation observed for the total heat-transfer coefficient. Experimental minimum bubbling velocities are well corrected by a semitheoretical expression proposed by the authors. © 1997 Elsevier Science Ltd.

INTRODUCTION

The gross behavior of magnetofluidized beds in relation to their hydrodynamic and heat-transfer characteristics have been investigated by many workers, as is evident from the two recent reviews of Liu *et al.* [1] and Saxena *et al.* [2]. Many applications of catalytic gas synthesis and conversion reactions are exothermic in character and can be preferentially conducted in magnetically stabilized beds. The bed charge can be either pure or composite magnetic material particles or an admixture of magnetic and non-magnetic material particles. However, to remove the heat of reaction, heat exchanger surfaces must be provided in the reactor and, hence, surface to bed heat-transfer rates are important design information. Such limited studies have been conducted in magnetically stabilized beds involving measurements of total heat-transfer coefficient (h_w) as a function of superficial gas velocity (U_g) and magnetic-field intensity (H). These investigations have been referred to and discussed by Saxena *et al.* [2], and Ganzha and Saxena [3]. The latter workers [3] report h_w values for an iron bed of average diameter (d_p) 1086 μm and for H values up to 5662 A m^{-1}. However, such measurements cannot provide any information concerning the variation of heat-transfer rates at different angular positions of the cylindrical surface as has been widely observed for bubbling fluidized beds [4, 5]. Further, local heat-transfer rates knowledge is a potential source for probing the structure of the stabilized beds in the vicinity of the surface.

Saxena and Dewan [6], and Saxena *et al.* [2] made measurements of heat-transfer rates from the surface of a cylindrical heat-transfer probe employing 5 mm square brass–foil pieces cemented on the surface of an electrically heated Nylon rod at five angular positions separated by 36° and at different axial distances from the probe end. These measurements did not give absolute values of h_w because independent heat sources were not provided at each position, and further varying heat losses occurred at different axial positions as shown by the two-dimensional numerical heat-transfer calculations of Brich *et al.* [7]. The present work is intended to eliminate this deficiency. A cylindrical strip heater heat-transfer probe has been designed and employed to measure representative values of heat-transfer coefficients at three angular positions relative to the gas flow. These are 0, 90 and 180°. Measurements cover wide ranges of U_g and H values up to 3.8 m s^{-1} and 5662 A m^{-1}, respectively.

EXPERIMENTAL

The experimental facility employed in this work is similar to that employed in our earlier measurements [3], and is described in detail by Wu *et al.* [8, 9]. The compressed, dried and filtered air enters the 12.5 mm thick transparent Plexiglas fluidization column, with an internal diameter of 0.102 m, through a 38.1 mm

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NOMENCLATURE

A	bed cross-sectional area [m^2]
Ar	Archimedes number
d_p	average particle diameter [m]
E_R	potential energy density ratio
g	acceleration due to gravity [$m\ s^{-2}$]
H	magnetic-field intensity [$A\ m^{-1}$]
h_w	heat-transfer coefficient [$W\ m^{-2}\ K^{-1}$]
I	electrical current [A]
L	length of either a bed section or total bed [m]
M	mass of bed particles [kg]
Sa	characteristic number
T_b	bed temperature [K]
U_g	superficial gas velocity [$m\ s^{-1}$]
U_{mb}	superficial minimum bubbling gas velocity [$m\ s^{-1}$]
U_{mf}	superficial minimum fluidization gas velocity [$m\ s^{-1}$]
V_p	probe volume [m^3].
Greek symbols	
ΔP_b	bed pressure drop [kPa]
ΔP_L	pressure drop across a bed section of length L [kPa]
ε_b	bed voidage
μ_b	bed permeability [$H\ m^{-1}$]
μ_M	permeability of magnetic particle material [$H\ m^{-1}$]
μ_0	permeability of free space [$H\ m^{-1}$]
ν	kinetic gas viscosity [$m^2\ s^{-1}$]
ρ_g	gas density [$kg\ m^{-3}$]
ρ_s	density of solid particle material [$kg\ m^{-3}$].

diameter pipe and a conical expander. It has a 0.21 m long calming section, and a 3.5 m tall combined bed and freeboard section. Four pressure probes, located at 6, 66.1, 142.3 and 332.8 mm above a combination gas distributor plate having 61 holes of 2.0 mm diameter, connected to DP cells, measure the pressure drops across the distributor, across the bed, and across a bed section of known length. A Helmholtz electromagnet comprising of two coils having an inner diameter of 0.358 m and separated by a gap of 0.171 m produce an uniform and time-invariant magnetic field up to a maximum value of 27, 137 A m^{-1}.

To investigate the angular dependence of heat-transfer coefficient (h_w) on the surface of a cylindrical probe immersed in a bed of particles, a heater heat-transfer probe has been designed. Its schematic and dimensions are shown in Fig. 1. The probe consists of a cylindrical Bakelite rod of 24.9 mm outer diameter and is 96.9 mm long. A slot, 5.7 mm wide and 1.5 mm deep, is machined on its surface along the length. A strip heater, prepared by winding 80 μm insulated copper wire on a Bakelite strip, is installed in the surface slot of the Bakelite rod. The tightly wound copper wire is held in position on the strip by glue, and is finished with a coat of an electric resistant varnish. The heater copper wires are brought out through a central axial cylindrical channel. This probe constitutes an arm of a bridge as described in an earlier work [3]. The probe resistance at 323.2 K is 22.0 Ohm, and it is calibrated by adjusting an arm resistance to secure the bridge balance for a low value of the current. The probe is installed at 47 mm above the distributor plate in the fluidization column. Unlike the earlier work [3], a digital ammeter is used to establish directly the current through the probe at bridge balance, which facilitates the computation of electrical power fed to the strip heater. The strip heater surface area is 510.15 mm^2. The final expression for the computation of experimental h_w is

$$h_w = [43124.4 I^2/(323.2 - T_b)] \qquad (1)$$

where I is the current through the probe at bridge balance, and T_0 is the bed temperature.

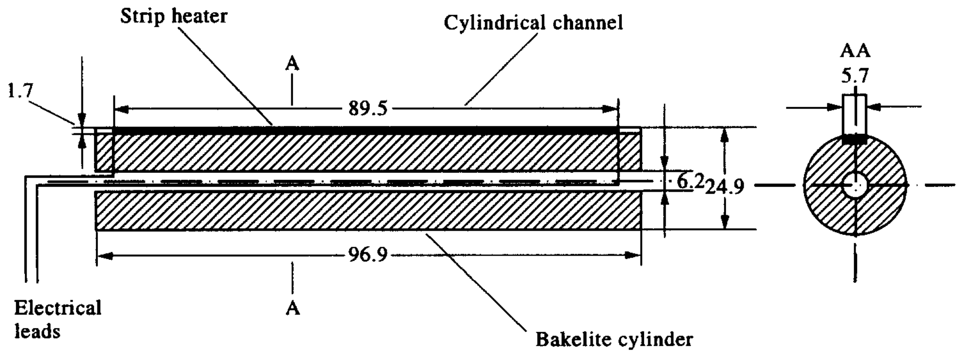

Fig. 1. A schematic of the heater heat-transfer probe (all dimensions are in mm).

An iron-shot powder of a narrow size range with an average diameter of 1086 μm is used as a bed material. The slumped unaerated bed height is 78 mm. Pressure drop measured across probes located at 6 and 66.1 mm above the distributor plate are used to compute the average bed voidage, ε_b, from the following relation:

$$\varepsilon_b = 1-(A\Delta P_L)[(AL-V_p)g(\rho_s-\rho_g)]^{-1}. \quad (2)$$

The bed height measurements are also taken at each U_g value and employed to compute ε_b from the following relation:

$$M = AL(1-\varepsilon_b)\rho_s. \quad (3)$$

Here, A is the bed cross-sectional area, ΔP_L is the pressure drop across a bed section of length L, V_p is the probe volume, g is the acceleration of gravity, ρ_s and ρ_g are the solid particle and gas densities, respectively, and M is the mass of bed particles.

RESULTS AND DISCUSSION

The bed pressure drop (ΔP_b) values as a function of increasing and decreasing U_g values for five H values are graphed in Fig. 2. The experimentally determined U_{mf} and U_{mb} values are indicated on the graph in each case. At $H = 0$, $U_{mf} = U_{mb}$. U_{mf} is exper-

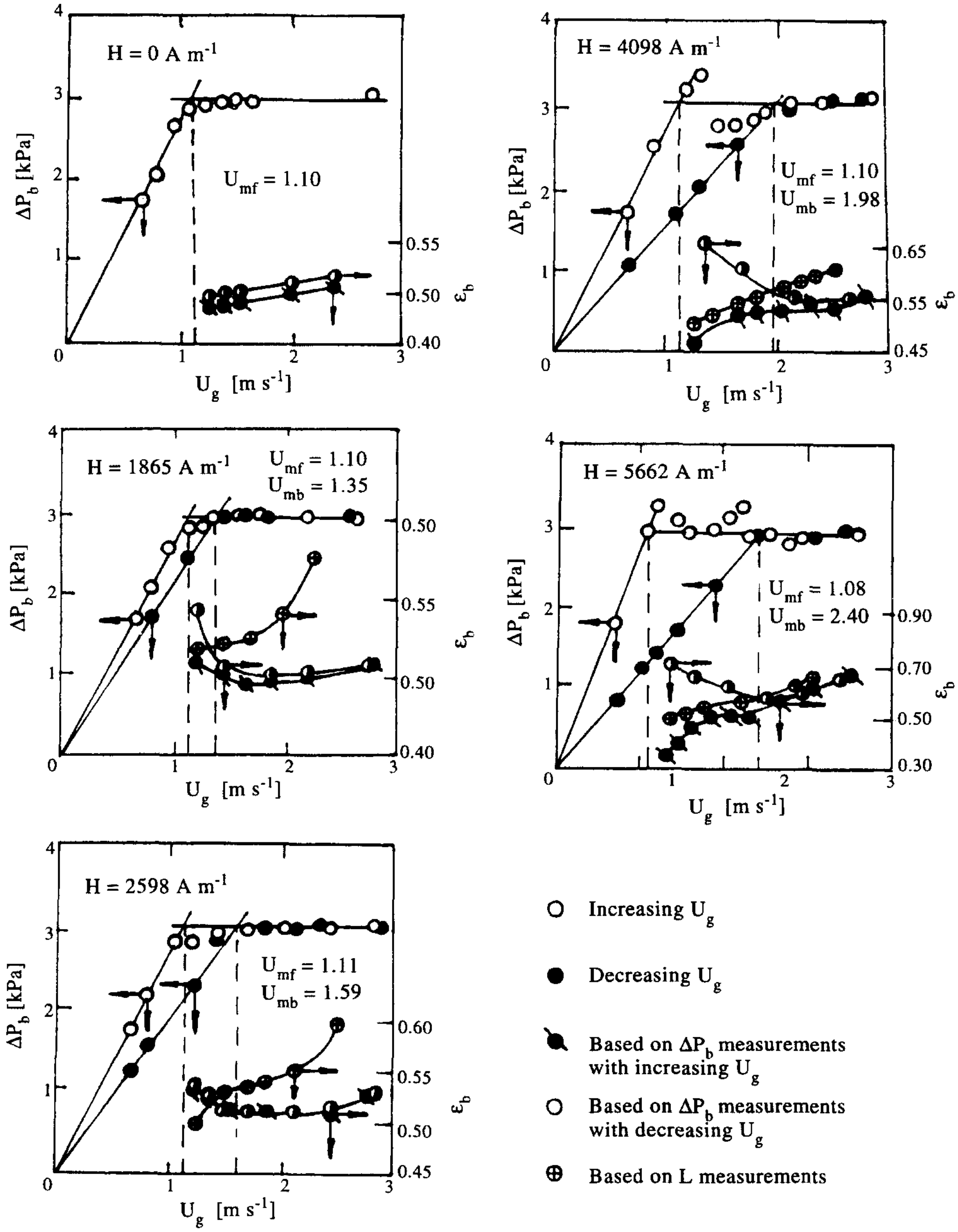

Fig. 2. Variation of ΔP_b and ε_b with U_g and H.

Table 1. Comparison of experimental and calculated U_{mb} values

H [A m^{-1}]	0	1865	2598	4048	5662
U_{mb} (exp.) [m s^{-1}]	1.10	1.35	1.59	1.98	2.40
U_{mb} (cal.) [m s^{-1}]	—	1.33	1.44	1.70	2.20

imentally found to be independent of H and its value is equal to 1.10 ± 0.01 m s^{-1}. U_{mb} increases with an increase of H. In Table 1 is shown a comparison of experimental U_{mb} values with those calculated from the following correlation proposed by Ganzha and Saxena [10]:

$$U_{mb} = U_{mf} + 0.0015(\nu/d_p)Ar^{0.81}E_R{}^{0.59} \quad (4)$$

where

$$Ar = gd_p^3(\rho_s - \rho_g)/\rho_g\nu^2$$

$$E_R = 3\mu_b H^2/2gd_p\rho_s \quad (5)$$

and

$$\mu_b = \varepsilon_b\mu_0 + (1-\varepsilon_b)\mu_0 \exp(0.03\mu_M H). \quad (6)$$

Here, Ar is the Archimedes number, E_R is the ratio of the magnetic potential energy density to the gravitational potential energy density, ν is the kinetic gas viscosity, μ_0 is the permeability of free space, μ_b is the bed permeablity, and μ_M is the magnetic permeability of iron shots. These experimental U_{mb} values are systematically greater than the computed values. The magnitude of disagreement is not of serious concern, because the systematic trend may be attributed to the difficulty in completely demagnetizing the bed particles simply by fluidization at $H = 0$. Weakly magnetized bed particles are known to lead to higher U_{mb} values [11].

In Fig. 2, are also shown the ε_b values as a function of U_g computed from equations (2) and (3). The agreements between ε_b values computed from ΔP_b values for increasing and decreasing U_g values are in reasonable agreement with each other at low H values where the interparticle forces are relatively weak to the extent that bed particle arrangement responds to the changing drag force on them. When H is large, the agreement between the two sets of ε_b values worsens and particularly in the magnetically stabilized-bed regime. The reason for this lied in the inability of the bed structure to return from the configuration it has acquired during increasing U_g values to what it should be when U_g is being decreased under the influence of drag forces. The strong interparticle forces hold the bed structure at a higher degree of ordered bed alignment and increased bed voidage acquired during increasing values of U_g. As a result when U_g is decreased, the bed configuration controlled by strong magnetic interparticle forces do not change and do not adjust to the reduced drag forces, consequently the measured ΔP_b values are smaller, and hence ε_b values are larger as computed from equation (2). These calculated ε_b values shown in Fig. 2 are much larger than the real values which are controlled by magnetic forces. ε_b values based on bed height measurements increase with increase in U_g, and are somewhat greater than those obtained from ΔP_b data. The bed particle creep along the column wall during the particle arrangement process and may be also partly due to the magnetic-field enhanced nonuniformity. This phenomenon is responsible for making ε_b values determined from L measurements to be greater than those determined from ΔP_b data.

The measured h_w values for the three angular positions of the strip heater on the heat-transfer probe surface are presented in Fig. 3 as a function of U_g at five H values. In Fig. 3(a), the strip heater is located at downstream side of the probe (180° position) and Fig. 3(b, c) corresponds to equatorial (90° position) and upstream (0° position) sides of the probe, respectively. At $H = 0$, a cap of defluidized solids at 180° position, and an air pocket at 0° position lead to smaller h_w values than the values for the same U_g at 90° position where particle convection prevails. These findings of the present work are in complete conformity with the measurements of other workers [5]. The variations of h_w in the magnetically stabilized and the partially stabilized regimes are better understood for the three positions individually as H is increased. This discussion is presented below.

At 180° position for $H = 1865$ A m^{-1}, the solids movement in the upstream gas flow occurs at a slightly greater value of U_g than U_{mb} and this causes a sudden steep increase in h_w value. At around $U_g = 2$ m s^{-1}, the h_w approaches its maximum value which is even slightly greater than that at $H = 0$. This is due to the partial stabilization of the bed which is characterized by the existence of smaller bubbles in comparison to an unstabilized bed. This results in a smaller value of bed voidage and, hence, a larger value of the interstitial gas velocity for the same U_g. The same qualitative variations of h_w are observed at the three other larger H values. Larger stabilized-bed regions are clearly displayed in h_w variation with U_g as H is increased. The low h_w values in the stabilized-bed region are particularly noticeable. The overall quantitative variation of h_w at this position is characteristically similar to that observed for the total heat-transfer coefficient for a cylindrical heat-transfer probe [2, 3].

At 90° position for $H = 1865$ A m^{-1}, h_w exhibits a monotonic increase in h_w with U_g over the entire velocity range, and the variation is qualitatively similar to that at $H = 0$. These values, however, are greater than those for $H = 0$, and cover all the three regimes, namely, fixed-, stabilized-, and partially stabilized-bed regimes. It is interesting to note that the same qualitative behavior is observed also at the three greater H values, and further h_w is greater as H is increased at the same U_g. This trend is attributed to increasing magnetic stabilization or partial stabilization of the bed with increasing H. A more interesting attribute in

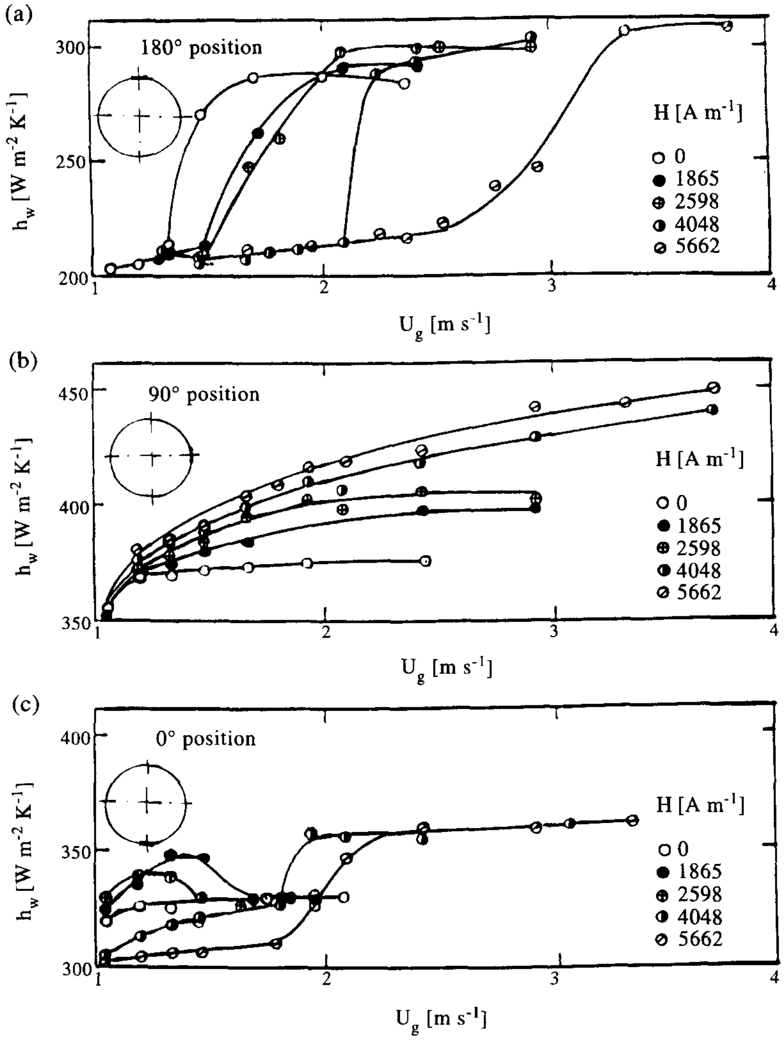

Fig. 3. Variation of h_w with U_g and H.

this variation of h_w is the smoothness and lack of abrupt changes in h_w values as U_g is increased and different fluidization regimes are encountered. The reason for this is in the structural arrangement of the bed particles in the region close to the probe surface. The magnetic interparticle force between the magnetized particles results in the formation of a larger channel between the probe surface and the first row of particles than between the consecutive rows or neighboring particles. This leads to a preferential gas flow or gas bypassing at the probe surface. The predominant mode of heat transfer is by gas convection, which increases with increase in U_g. As H increases, the interparticle force increases, resulting in a bigger channel formation and greater gas flow at the probe surface. This causes h_w to increase due to increase in gas convection component, which is the predominant mode of heat transfer.

At 0° position, the h_w variation is a more complicated and is a reflection of the instability of a gas bubble in a magnetic field. Initially, as U_g is increased for $H = 1865$ A m^{-1}, h_w increases primarily because of gas convection as in a fixed bed corresponding to the stabilized regime. These h_w values are greater than for $H = 0$ at the same U_g due to larger interstitial gas velocity in the stabilized regime. As U_g is increased, bed is fluidized, the degree of stabilization decreases and formation of gas pocket at the upstream side of the probe occurs. This lowers the value of h_w, and finally h_w acquires the value close to that of a bubbling fluidized bed at $H = 0$. At $H = 2598$ A m^{-1}, the same qualitative variation of h_w with U_g is observed, and its numerical magnitude in relation to $H = 1865$ A m^{-1} is not emphasized here pending more detailed measurements. At greater H values of 4048 and 5662 A m^{-1}, the gas pocket formation is impeded to the extent that no decrease in h_w is observed with increase in U_g, but instead a monotonic increase in h_w occurs until U_{mb} is reached. For U_g greater than U_{mb}, h_w increases to acquire its constant maximum value which is greater than that at $H = 0$. The reason for this is the same as at two other positions. Also, it is understandable that the maximum h_w value at 0° position is smaller than the corresponding value at

90° position, but is larger than that at 180° position at the probe surface.

The observed gross hydrodynamic behavior of the bed in different regimes is well in accord with that expected on the basis of different regimes proposed by Saxena *et al.* [2]. For 1086 μm iron shot bed fluidized by air, the Archimedes number is 361 965, and for H values in the range 1018–10 320 A m^{-1}, corresponding to Sa values in the range 2.0–14, the moderate magnetic-field characteristics will be encountered, Saxena *et al.* [2]. In this work, the H values are well within this range as H is varied only from 1865 to 5662 A m^{-1}. In the fixed-bed regime ($U_g < U_{mf}$), ΔP_b is found to be independent of H, the bed surface is flat and no particle motion is observed. One of the consequences of this behavior is, as seen above, that U_{mf} is independent of H. In the stabilized-bed regime ($U_{mf} \leqslant U_g < U_{mb}$), ΔP_b exhibits fluctuations and these increase with increase in H. A similar dependence is evident for the magnitude of the velocity range, ($U_{mb} - U_{mf}$), only small ΔP_b fluctuations are observed and these are attributed to smaller size of bubbles in the presence of an external magnetic filed. h_w values are on average greater than those for $H = 0$, and, hence, operation in this regime for certain applications may be preferable and advantageous.

CONCLUSIONS

On the basis of h_w measurements with a specially designed probe immersed in a magnetofluidized bed reported here, the following major conclusions may be drawn.

(a) The heat-transfer coefficient varies with the angular position at the probe surface for the same values of U_g and H.

(b) The observed variations at $H = 0$ for the three positions at the cylindrical heat-transfer probe surface are in conformity with the trends reported by other workers. The h_w values are largest in the equatorial lateral zones and smallest at the downstream side of the probe where a cap of defluidized solids resides at low U_g values. As U_g is increased beyond U_{mf}, the cap of solids destabilizes and h_w increases with increase in U_g to achieve its maximum value. At the upstream side, the h_w values are of intermediate magnitude and exhibit very weak dependence on U_g in conformity to that at 90° position.

(c) The observed relative trends in the variation of h_w values at the three positions are maintained for all H values investigated in this work. At the 90° position, h_w exhibits a monotonic increase in its value as U_g is increased. This is the consequence of increased voidage at the probe surface resulting in the formation of a channel. This channel provides an easy bypass path for the fluidizing gas and the gas convective heat-transfer component controls the magnitude of the total heat-transfer coefficient. The variation of h_w at the 180° position is qualitatively similar to that for the total heat-transfer coefficient. The variation of h_w at the 0° position is related to the stability of the gas pocket at the upstream side of the cylindrical probe.

(d) The presence of probe in the bed did not alter the values of U_{mf} or U_{mb} based on limited measurements being reported here and in an earlier work [3].

(e) The measured U_{mb} values are adequately predicted by a correlation developed by Ganzha and Saxena [10].

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