

and

Variations of j_h factor with H

$$\frac{j_h}{j_{h0}} = 1.1735 \cdot e^{-0.0002 \cdot H} \quad (23)$$

In both correlations H is in A/m. The plots are shown in Fig. 42b.

5.3. Local heat transfer coefficients between a bed and an immersed horizontal probe

The results discussed in the previous points concern the total heat transfer coefficients between a magnetically controlled bed and an immersed surface. The group of Saxena (Saxena *et al*, 1994; Dolidovich *et al*, 1998; Ganzha and Saxena, 1998b) has carried out a research with the aim to determine better the heat transfer probe shape and orientation (with respect to the gas vector). A special modification of the horizontal tube probe has been designed (see insets in Figs. 43, 47 and 48) with narrow heat transfer surfaces (strips) extended along the probe axis. The probe design allows the measurement of the effect of surface element orientation with respect to the gas vector on the heat transfer coefficients. The data obtained in these experiments are shown in Figs. 42 and 43. All of them have been carried out in accordance with the Magnetization FIRST and BATCH solids modes (Hristov, 2002).

Saxena and co-workers (Saxena *et al*, 1994; Dolidovich *et al*, 1998, Ganzha and Saxena, 1998b) have reported that at $H=0$ two phenomena occur:

- i) a cap of defluidized solids at 180° position, and
- ii) an air pocket at 0° position.

Both of them lead to smaller h_w values than those observed at the same gas velocity U and at 90° position where particle convection prevails. The findings are consistent with the experiments with non-magnetic beds with immersed tubes (Botterill, 1975; Saxena *et al*, 1978) and the excellent experiments of Kellogg *et al*. (1983) with a flat surface.

The results obtained under the magnetic field action show different shapes of the $h_w = f(U)$ curves. From a formalistic point of view the plots of Saxena commented here may be separated in three main groups (see Fig. 45) (the separation done by the present author) :

- **Group A.** Curves with an initial section of small variations of h_w followed by a almost sharp increase up to a plateau. Such curves are shown in Figs. 43-a, 44-1-4 and 45- A). They slightly resemble those in

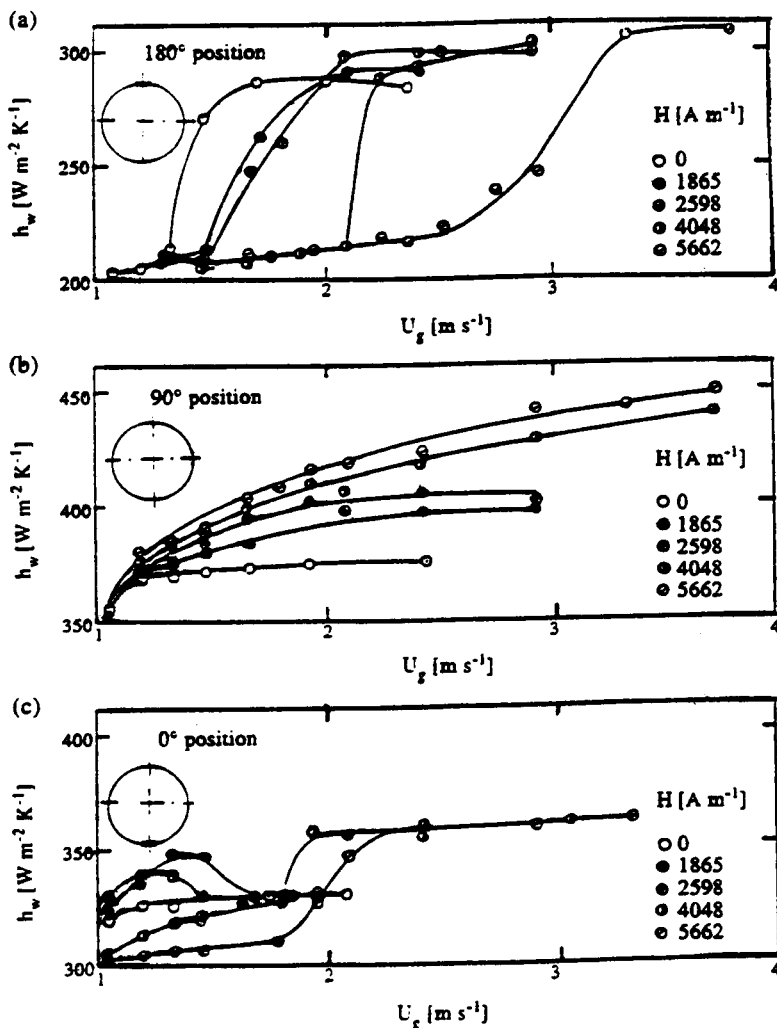


Fig. 43: Variations of h_w with U and H . Results of Ganzha and Saxena (1998b) System: Iron shot ($1086 \mu\text{m}$)- air. The other conditions - see Table 7. Original Fig.3 of Ganzha and Saxena (1998b).

non-magnetic fluidized bed despite the fact that a maximum is slightly observable. All of them have been obtained in the field intensity range 0-5500 A/m.

- **Group B.** Smooth curves without sharp changes with the variations of U despite the field intensities. They are demonstrated in Figs. 43-b, 44- 5-6, 45-a and 45-b. The field intensity range is approximately 5000 - 9000 A/m.

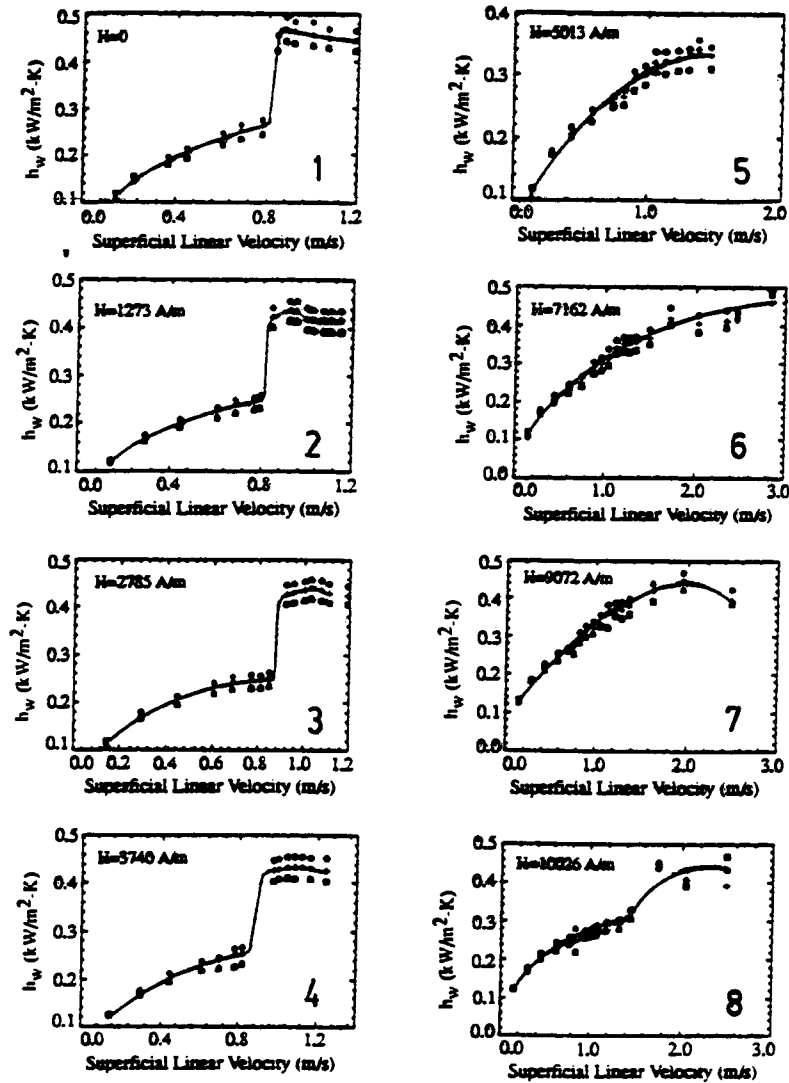


Fig. 44: Dependence of h_w on increasing U for different field intensities H . Iron-shot ($733 \mu\text{m}$)- air and three angular positions relative to gas-flow vector. $\bullet$ - 45° , $\triangle$ - $+90^\circ$ and $\blacksquare$ - -180° . Continuous curves represent the mean values. Original Fig.13 of Saxena *et al.* (1994). The present author adds the numbers in the pictures.

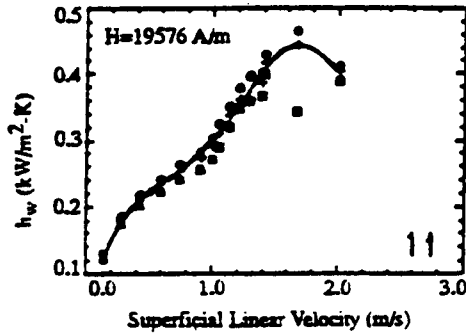
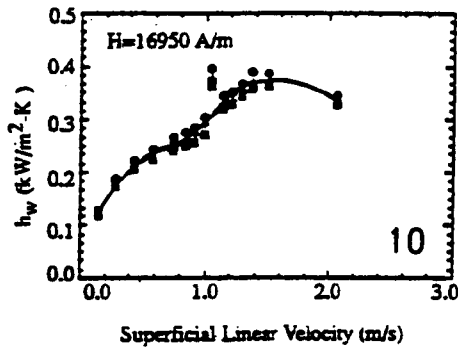
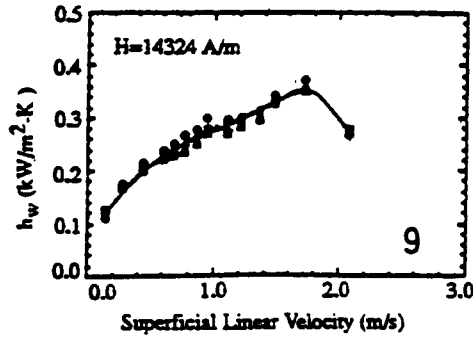


Fig. 44: cont.

- **Group C.** Smooth curves with clearly defined maxima of h_w . No sharp changes exist and the curves are similar to those observed in non-magnetic beds of fine particles (Botterill, 1975) (see Fig. 5.8 in Botterill, 1975). The average values of all the local measurements exhibit a smooth variation with the gas velocity.

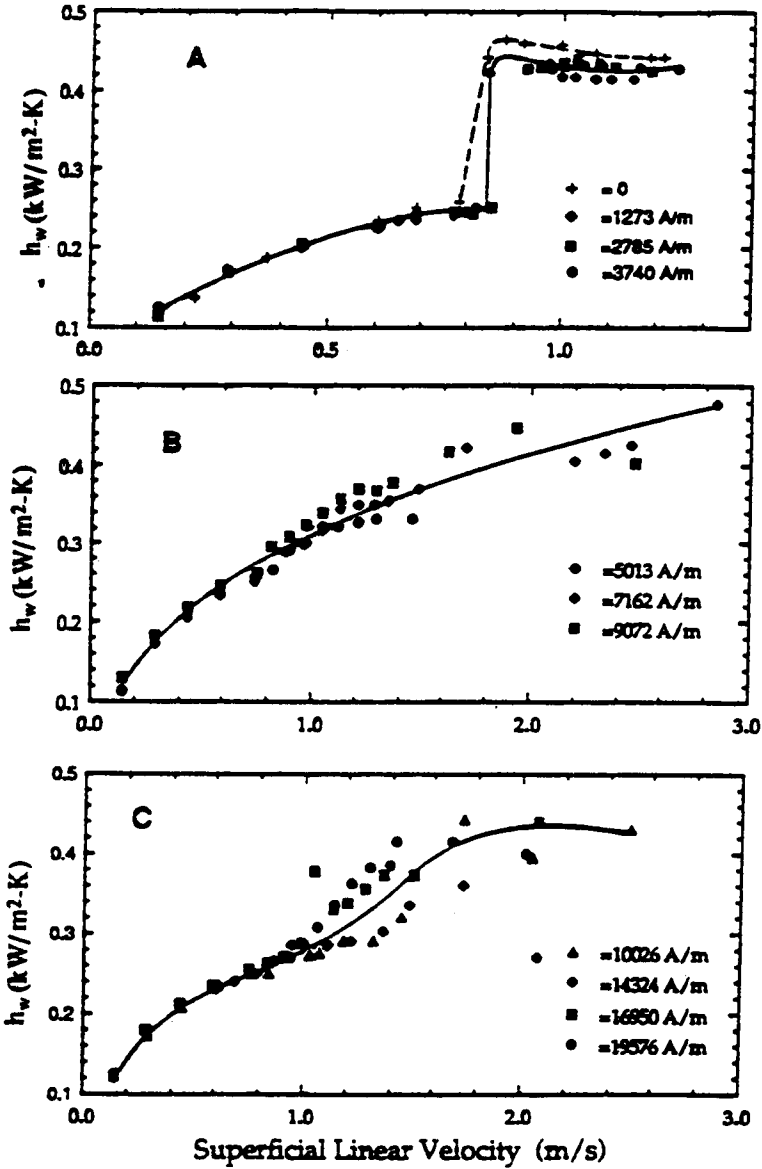


Fig. 45: Variations of average values of h_w (by averaging the three angular position data shown in Fig. 44). Original Fig.18 of Saxena *et al.* (1994)

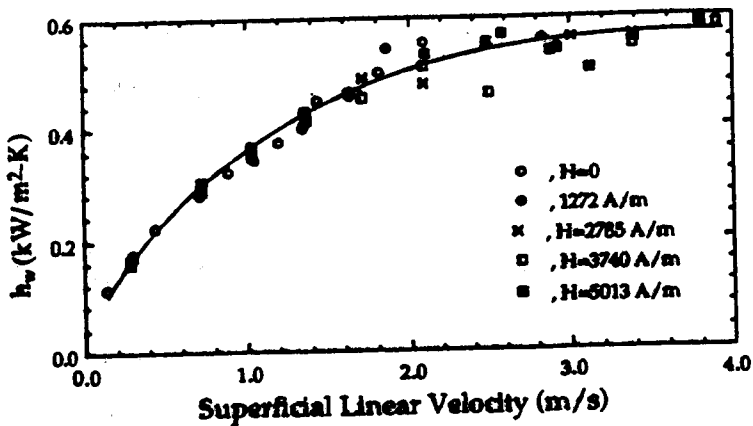


Fig. 46: Variations of average values of h_w (by averaging the data from five angular positions (0° , 45° , 90° , 135° and 180°) shown on Fig.14 of Saxena *et al* (1994). Iron-shot ($1511 \mu\text{m}$)- air. Original Fig.19 of Saxena *et al.* (1994).

The formalism applied here is due to the fact that all the curves of Saxena shown in Figs. 43 and 44 need a more detailed analysis. The plots may be assumed as raw data for further data treatment and interpretations. The reconstruction of the experimental conditions done here gives more information on reasons leading to that formal separation of the curves.

5.3.1 Re-construction of the experimental conditions

Two experimental situations were reconstructed on the basis of data available from various sources (see the figure captions). Figures 47 and 48 show two combined plots of $\max h_w$ variations with H (Fig. 47) and with U (Fig. 48).

The data presented in Fig. 47 show two main effects, discussed below.

5.3.1.1. The effect of the angular position on the value of $\max h_w$.

Better results (i.e higher values of h_w) are observed at 90° position, thus confirming the results of Saxena *et al.* (1978) and Kellogg *et al.* (1983). The monotonic increase of h_w with U shown in Fig. 43-b does not indicate changes of the regimes (fixed bed- MSB- fluidized bed). The comments of Ganzha and Saxena (1998b) attribute that behaviour to the particle arrangement near the probe surface. The particle alignment in a vertical

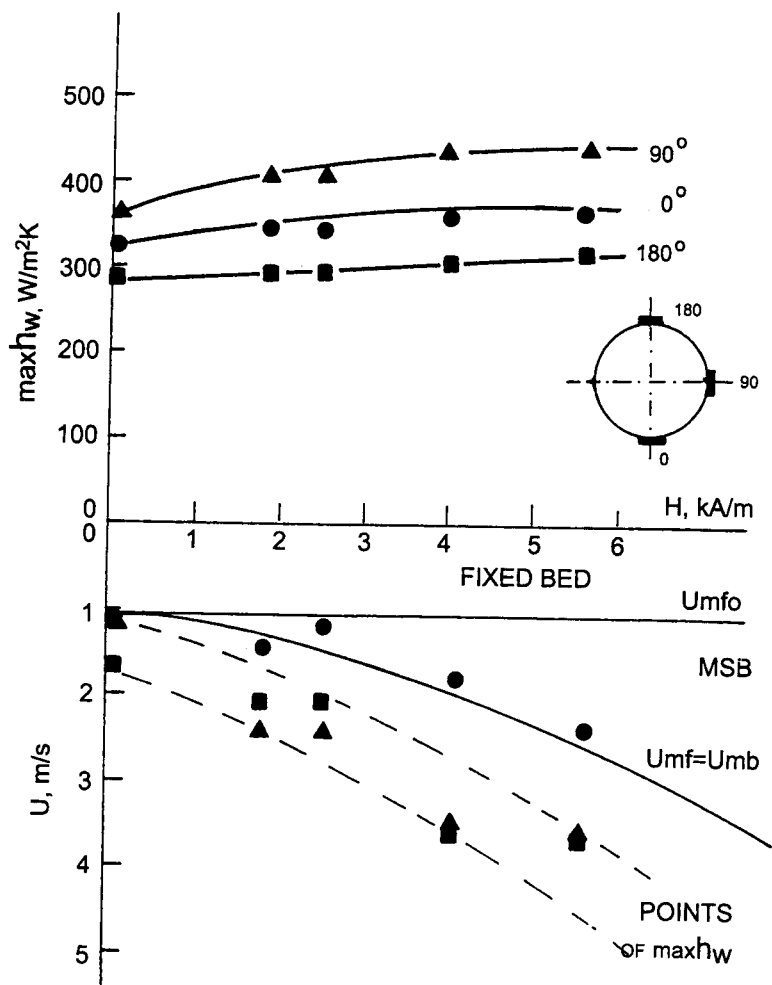


Fig. 47: A reconstruction of the experimental conditions corresponding to the maximum heat transfer coefficients at three angular positions shown on Fig. 43. Iron-shot ($733\ \mu\text{m}$)- air. Present author data treatment.

The upper part represents the variations of h_w with H . The lower part of the phase diagram is designed by means of the data summarized in Table I Ganzha and Saxena (1998b).

direction as a result of the simultaneous action of both the field and gas flow results in the formation of a gas channel between the probe surface and the first layer of particles. This leads to a preferential gas flow (gas bypass) near the probe and dominating gas convection effects on the heat transfer.

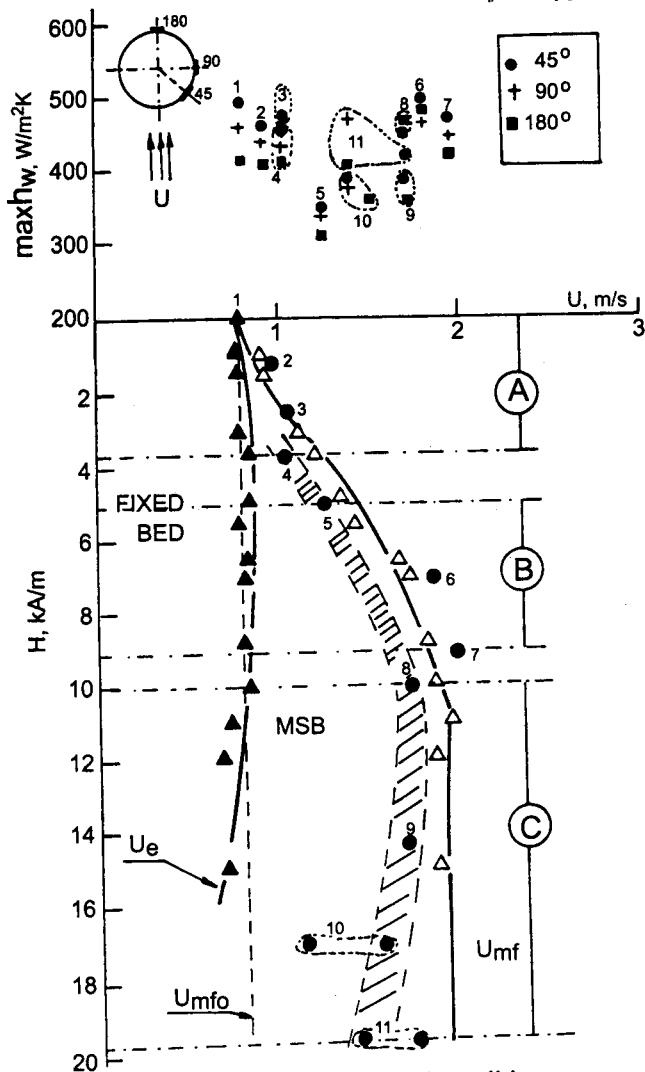


Fig. 48: A reconstruction of the experimental conditions corresponding to the maximum heat transfer coefficients at three angular positions shown on Fig. 44. Iron-shots (733 μm)- air. Present author data treatment.

The upper part represents the variations of h_w with U . The lower part is the phase diagram designed by means of the data shown on original Fig.12 of Saxena *et al.* (1994).

Note 1: The numbers of the points corresponds to the numbers of the graphs on Fig. 44.

Note 2: The sections A, B and C correspond to the three pictures shown on Fig. 45.

The position of 0° gives lower results that may be attributed to the complicated behaviour of the gas bubbles in magnetically controlled beds and the formation of gas pocket at the upstream side of the probe. According to Ganzha and Saxena (1998b) the gas pocket formation is impeded to the extent that no decrease in h_w is observed (Fig. 43-c) with increase of U . On the other hand, they comment that instead a monotonic increase in h_w occurs until the fluidization onset is reached (velocity U_{mf} - Fig. 47, or U_{mb} in accordance with Ganzha and Saxena, 1998b).

At the position of 180° the movements of solids occur (Ganzha and Saxena, 1998b) at velocities slightly greater than U_{mf} . In accordance with the authors the value of h_w ($H=1865$ A/m) is greater than that observed at $H=0$ due to the small gas bubbles (smaller than in the non-magnetic bed).

Ganzha and Saxena (1998b) have commented that it is understandable that the $max h_w$ values at 0° are smaller than the corresponding values of 90° position, but are greater than those at 180° position. The present author's viewpoint is that the differences are due to different intensities of the gas convection at the three positions discussed. As it is well established (on the results already commented), the gas convection dominates as heat transfer mechanism in magnetically controlled fluidized beds. The gas convection at 90° position is greater (due to the axial orientation of the channel) than that observed inside the gas pocket at 0° position. On the other hand, the gas convection effect at 180° is minimal due to the domination gas flow orientation along the channels (between the particle aggregates). The heat transfer coefficient at 180° position should be greater if the gas flow should streamline the probe in a direction along the tangent at that point of the surface. Such a situation exists at 90° . However, the particle arrangement in magnetically controlled beds (axial fields) and the use of horizontal tube probes (or other types of heat transfer surfaces) lead to these results. A possible increase of the heat transfer coefficients at 0° and 180° positions may be obtained in a transverse field forming channels transverse to the gas flow (i.e. along the tangents at these points). Unfortunately, such experiments do not exist, so the idea awaits experimental verifications.

5.3.1.2. The effect of the regime on the value of $max h_w$

Further analysis indicates that the increase of the field intensity leads to higher local heat transfer coefficients. However, these results should be accepted with caution due the implicit effect of the gas velocity U . The reconstructed phase diagram in Fig. 47 clearly demonstrates that the higher

values of h_w correspond to higher gas velocities. Therefore, it resembles the case of the total heat transfer coefficients discussed above. As mentioned by Ganzha and Saxena (1998b) the higher values of h_w are possible due to higher interstitial gas velocity as a result of lower bed voidage in MSB regime. However, this explanation does not confirm the fact that in the regime of MB the particle arrangement is anisotropic, as noted above.

The complete data available about the experiments with 733 μm iron shot were employed to reconstruct the experimental situations shown in Fig. 48. Before further analysis, it should be noted that the values of h_w obtained at 45° position are higher than those observed at 90° position. The data at 180° confirm the results discussed in the previous point. The possible explanation is the fact that no gas pockets exist at that position like at 0°. Furthermore, at 45° position, no formation of a large channel is possible between the probe surface and the first particle layer due to the particle arrangement along the vertical axis (fluid flow or the field lines).

The phase diagram in Fig. 48 strongly indicates that the groups of the $h_w = f(U)$ curves defined above correspond to different field intensities and regimes. The curves of Group A correspond to situations of low field intensity effects. The points 1-3 belong to the fluidized bed regime. The velocity is slightly higher than U_{mf} (the partially stabilized regime in accordance with Saxena) and small bubbles exist that enhance the heat transfer due to the gas convection. Point 4 also belongs to the same group and its location on the phase diagram is in a narrow marginal zone just before the fluidization onset. From a qualitative point of view the gas convection effects on h_w are like those mentioned for points 1-3.

The group B curves correspond to the points 5 and 6 and partially to the marginal point 7. It is clear that the lower values of h_w are exhibited by the stabilized bed (point 5). The points 6 and 7 confirm again the fact that higher gas velocities may compensate the negative effect of the field intensity (deceleration of the particle motions and channel formation).

The curves from Group C with clearly defined maxima of h_w definitively demonstrate the effect of the increasing field intensity. All the points correspond to the marginal zone just before the fluidization onset and exhibit the lowest heat transfer coefficients. Thus, this is a strong indicator of the bed structure effect on the heat transfer characteristics. The channel formation along the gas-flow vector decreases the local (as well as the total) heat transfer coefficients. The situation could be changed by the formation of a

different particle arrangement, by a transverse field for example. However, such experimental data do not exist in the literature.

The results were discussed above as a function of two macroscopic parameters – the gas superficial velocity and the field intensity. The intimate side of the heat transfer analysis needs information about the bed expansion and porosity. Unfortunately, the plots in Fig. 12 in Saxena *et al.* (1994) do not allow a clear reading of the gas voidage values for 1511 μm particles. Despite this, Fig. 49 (Saxena *et al.*, 1994) shows a part of the experimental situations investigated by Saxena's group. The detection of the points corresponding to the maxima of h_w lead to the information plotted in Fig.50.

The plots in Fig.50 demonstrate two contradictory situations. First of all, the decreased bed voidage leads to higher interstitial gas velocity and higher heat transfer coefficients in a fluidized bed regime. The control of the bed porosity may be obtained by two possible mechanisms:

- The increased field intensity increases the bed porosity above a certain field intensity that reduces the interstitial gas velocity and gas convection effect (due to repulsing forces between the aggregates)
- The increased field intensity decreases the particle mobility that leads to larger particle aggregates and larger particle residence time near the surface. Both phenomena reduce the heat transfer rate.

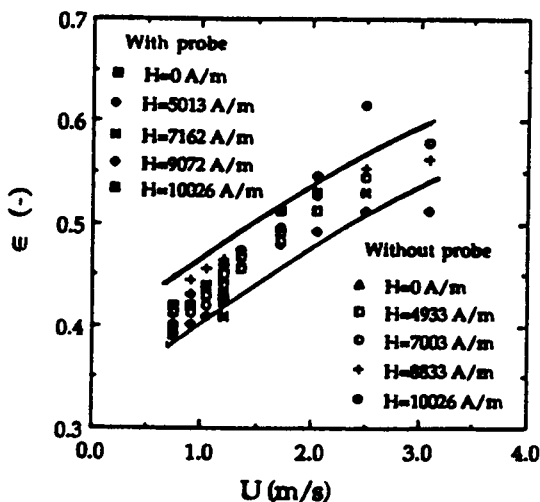


Fig. 49: Variations of bed porosity with U and H for a bed of iron shot (733 μm average diameter). Original Fig. 17 of Saxena *et al.* (1994).

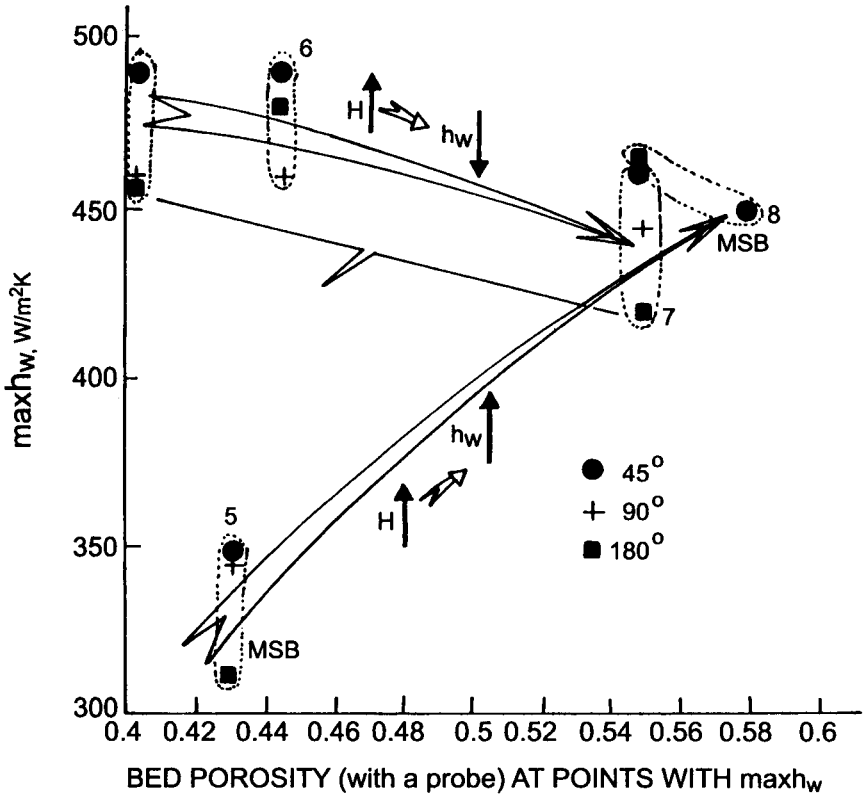


Fig. 50: Maximum h_w as a function of the bed porosity (detected by Fig. 43) at the points defined on Fig. 48. Present author data explanation of the data.

Second, in a stabilized bed the increased porosity (i.e. the extended range for bed expansion) is available under higher field intensities and gas velocities. In the absence of particle motions the increased contribution of the gas convection is the only possible mechanism.

5.3.2 Data correlations for local values of $max h_w$

The data recovered from various sources published by Saxena's group were correlated by Eq. (17). The plots are shown in Fig. 51, while the coefficients are summarized in Table 10.

The plots and the trendlines in Fig. 51 show the two opposite tendencies to those shown in Fig. 50. Fortunately, they clearly illustrate the particle size

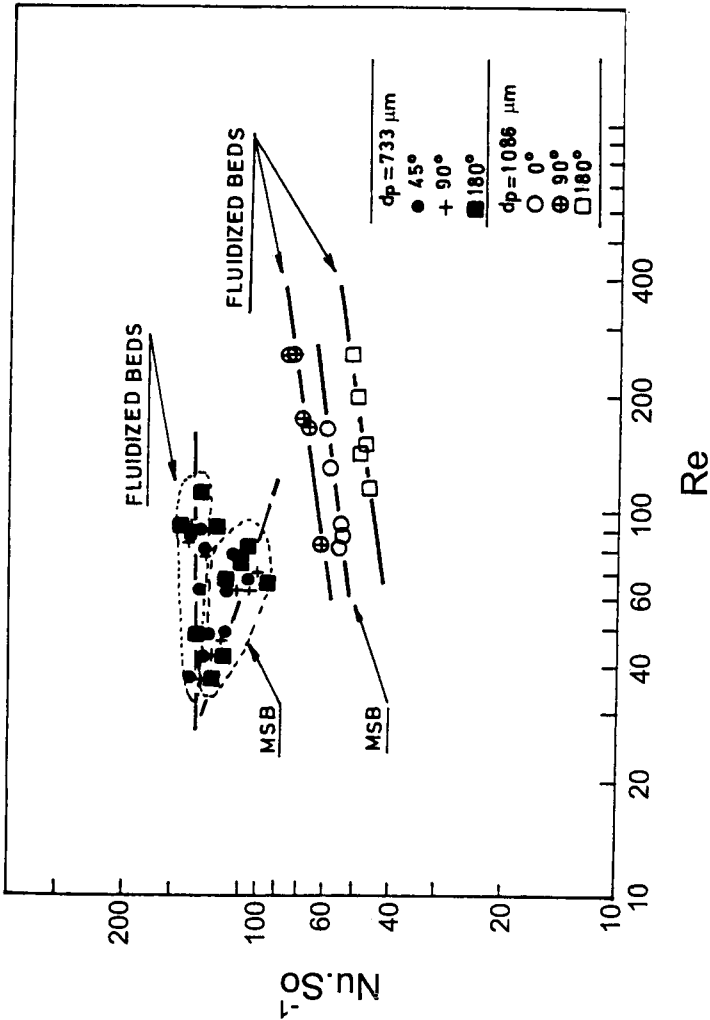


Fig. 51: Data correlations by Eq. (17).

effect. Upon equal field intensities the smaller particles form finer aggregates than the coarser ones, so the former allow the achievement of higher heat transfer coefficients. Therefore, there is no contradiction with the results from non-magnetic beds.

The different trends exhibited by the plots in Fig. 51 may be attributed to the fact that in the group of 1086 μm particles dominate the points corresponding to a fluidized bed regime, while in the group of 733 μm particles dominate the point obtained in MSB. The different heat transfer mechanisms in both regimes discussed above explain the different trends of the lines. For example, such problems were commented upon in the case of total heat transfer coefficients (see Fig. 40 for example).

5.3.3 Short comments on the local heat transfer coefficients.

The results summarized here indicate that the experimental data concerning the local heat transfer coefficients between a bed and an immersed horizontal tube are not sufficient for better elucidation of the phenomena under the action of an external magnetic field. The investigations of Saxena's group are a strong basis for further investigations, but need a deep analysis of the relationships between the bed hydrodynamics and the heat transfer. The attempt to correlate the data available meets troubles due to the dispersed results and insufficient number of data points. The analysis done here gives a fruitful trend for better elucidation of the phenomena.

5.4. Admixture Beds - Major Experimental Findings

The heat transfer in magnetically controlled beds of admixtures of magnetic and nonmagnetic particles has been investigated, but not as intensively as the cases of pure magnetic solids. The application of the Magnetization LAST mode has not been reported in the literature and the data available cover the Magnetization FIRST and the On-Off modes. Table 11 summarizes data of these experiments.

5.4.1. Magnetization FIRST mode - total heat transfer coefficients

The first reports belong to Arnaldos (1986) and Arnaldos *et al.* (1986,1987) with beds of nickel-silica sand and iron-shot silica sand admixtures (in the experimental set-up shown in Fig. 4a) in a wide range of variations of the admixture content. Later experiments with a horizontal tube