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HEAT TRANSFER TO FLOWING GRANULAR MATERIAL

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Abstract—Forced convection heat transfer was investigated for two granular materials flowing along a chute. For each material and for a given depth of flow, the heat transfer coefficient at first increases with velocity, then reaches a maximum and decreases as the velocity increases further. This behavior is believed to be related to changes in the packing density of the material caused by the flow field.

NOMENCLATURE

d,	typical particle diameter;
$\bar{h}$,	average heat-transfer coefficient;
k,	conductivity of bulk material;
k_g,	conductivity of interstitial gas;
L,	length of plate;
Nu_d^*,	Nusselt number, equation (1);
Pe_L^*,	Peclet number, equation (2);
u,	average flow velocity;
α,	thermal diffusivity of bulk material.

1. INTRODUCTION

EACH year large amounts of various materials are handled in granular form, including, for example, grain, coal, ores, plastic pellets, fertilizer and other dry chemicals. In a number of instances these materials are also to be heated prior to processing, or cooled after processing. In these cases the heat is generally transferred by convection between a solid surface and the granules which move relative to that surface. The present work is concerned with this type of heat transfer, that is with forced convection in granular material. The general problem is, of course, extremely complex, as even the flow of a granular material is not yet well understood. The heat transfer process, as usual, requires further insight into the mechanism of energy transport. The purpose of the present work then is to provide some basic experimental data for simple forced convection flows, and it is hoped that these data may contribute to our understanding of this intriguing subject.

2. RELATION TO PREVIOUS WORK

The present investigation concerns the heat transfer to a granular material flowing along an inclined chute. A few of the most pertinent earlier studies on this subject will be reviewed briefly in the following section.

The work most closely related to the present study is probably that by Sullivan and Sabersky [1] who investigated the heat transfer from a flat plate to various granular materials flowing in a hopper, in a direction parallel to the plate. They showed that their experimental results corresponded well to a model in which the granular material was represented by a continuum connected to the heating surface by a special contact resistance. The value of this wall resistance, which was imagined to result from pure conduction through a thin gas layer, was determined empirically from the experimental data. The resistance was found to be approximately equivalent to an air gap of 1/10 of a particle diameter. The correlation derived from this model agreed well with the experimental results. In particular it correctly represented the effect of changes in diameter, in bulk in thermal conductivity, in thermal diffusivity and in the length of the heated plate. The experimental results obtained by Sullivan and Sabersky as well as their predictive curve are shown in Fig. 1. The coordinates are modified Nusselt and Peclet numbers defined as

$$\overline{Nu_d^*} = \bar{h}\frac{d}{k_g} \qquad (1)$$

and

$$Pe_L^* = \left(\frac{k}{k_g}\right)^2\left(\frac{d}{L}\right)^2\frac{uL}{\alpha}. \qquad (2)$$

The results of Sullivan and Sabersky were limited to Peclet numbers (Pe_L^*) of about 5000, and it was the purpose of the present investigation to obtain information for higher Peclet numbers through an increase in velocities.

A number of other investigators have performed research on the same kind of problem. Harakas and

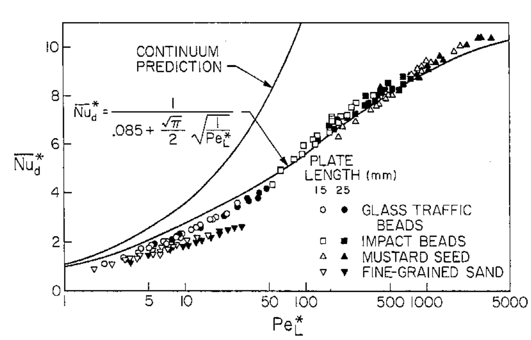

FIG. 1. Data for flow over a flat plate in a hopper as obtained by Sullivan and Sabersky [1].

Beatty [2] as well as Dunsky *et al.* [3] measured the heat transfer from constant temperature plates immersed in rotating packed beds of granular material. Their observations of the effect of particle diameter and residence time at the plate (defined as plate length divided by particle speed) are qualitatively the same as those of Sullivan and Sabersky. That is, they found an increase in the average heat-transfer coefficient with a decrease in the residence time or a decrease in the particle diameter. In addition, Harakas and Beatty [2] varied the interstitial gas within the packed bed and found that the bed may be modelled as a homogeneous continuum provided the residence times are long, the particle diameters small and the bulk thermal diffusivities high.

Ernst [4] examined the heat transfer to a confined flow of granular material while varying the velocity of a superimposed counterflow of the interstitial gas. His observations of the effect of particle diameter and residence time are in agreement with those made later by Harakas and Beatty [2]. Ernst noted only a small decrease in the heat-transfer coefficient for a given residence time as the velocity of the interstitial gas was increased in the direction opposite to that of the bulk flow.

Perhaps the most interesting studies, relating to the present work, have been performed by Botterill and his associates. Boterrill *et al.* [5] studied the heat-transfer characteristics of a flowing granular media as a means of gaining a better understanding of the limiting factors in fluidized bed heat transfer. These results, obtained in an apparatus similar to that of Sullivan and Sabersky qualitatively confirm the dependence of the heat-transfer coefficient on residence time and on particle diameter. In addition however, Botterill [5] briefly mentions that the heat-transfer coefficient reached a maximum and then decreased as the velocity of the flow was increased. As a possible explanation he suggests that this may have been due to "wall effects and/or looser particle packing at the higher solids flowrates". This seems to have been the first time such a maximum was observed.

Botterill *et al.* [5] attempted to use a discrete particle model to explain his results but found it necessary (as did Sullivan and Sabersky) to introduce at the wall a hypothetical gas film of thickness equal to about 10% of the particle diameter. This provided a good fit of the data for intermediate ranges of particle velocity but did not adequately model the observed behavior at very low or very high velocities (beyond the observed maxima). They concluded that it would be necessary to allow for an effective gas film of varying thickness in order to fit the data over the entire range of velocities.

On the question of the physical reality of the gas gap at the wall, Botterill and Desai [6] propose that it is probably represented by an "effective gap" resulting from packing defects and particle interactions near the wall. They also describe experiments in which a surface-mounted thermistor detector was used to record the minute transient temperature fluctuations produced by passing particles. This work suggested that "considerably less than half" of the particles at the wall moving past the detector actually touched the surface. It also seemed to confirm the expectation that the particle packing near the wall was a function of the shape of the particles.

In addition to working with flowing packed beds, Desai did experiments with freely fluidized beds [7]. He found that for comparable particle residence times the heat-transfer coefficients for the flowing packed beds were generally higher than those for the fluidized beds. This was explained in terms of the denser particle packing which was believed to exist near the wall of the flowing packed bed.

Botterill and Desai conclude [6] that the particle packing density and the freedom of the particles near the wall are important factors governing the heat transfer to a fluidized or flowing packed bed. Not until these parameters are included, according to Botterill, will any model of the heat-transfer process be complete. This observation has special relevance to the present work.

Of the many attempts that have been made to model the heat transfer to gas fluidized beds, one of the most successful is the one by Kubie and Broughton [8]. In their model, packets of material from the bed are swept to the heat-transfer surface where transient conduction occurs for the time of packet residence. Allowance is made for the variation of the void fraction within a distance of one particle diameter from the surface. This is an important feature of the model as it permits the bulk density and thermal conductivity to vary according to some specified voidage distribution function in the vicinity of the wall. The effective conductivity of a packet of given voidage was computed using the method of Kunii and Smith [9]. It was found that for the voidage distribution assumed to exist in a bed of uniform spherical particles, the thermophysical properties of the bulk changed very rapidly with distance from the surface.

3. EXPERIMENTAL INSTALLATION

As stated earlier the present experiments were designed to extend the heat transfer data obtained by Sullivan and Sabersky to higher flow velocities and correspondingly higher Peclet numbers; their work was performed by measuring the heat transfer from a flat plate which was placed in a relatively small hopper (80×80 mm cross-section). Much larger hoppers are required to obtain significant increases in velocity and high velocities are obtained much more easily for flows along an inclined chute (open channel). A chute was therefore selected for the present test installation.

A schematic drawing of the chute is shown in Fig. 2. The chute is 25 mm wide and 1.2 m long, which was sufficient to establish a flow of essentially constant depth along most of the chute. The floor of the chute was constructed of aluminum and provisions were made so that a heated section could be inserted into the floor. Care was taken so that the heated insert would fit

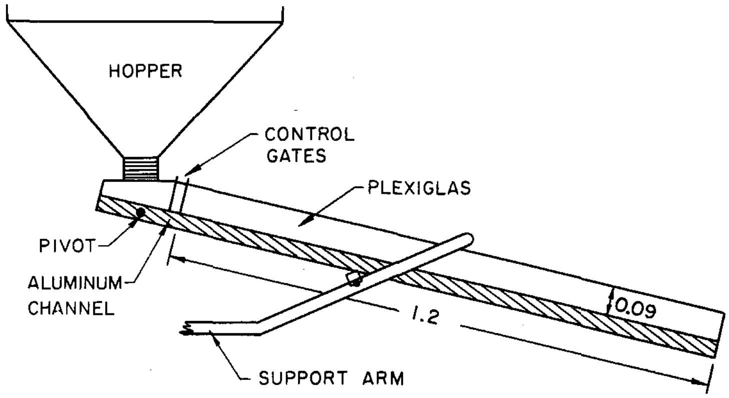

FIG. 2. Diagram of chute used in present experiments. Heated test section was inserted into bottom of chute (dimensions in m).

smoothly into the floor without leaving any ridges that might obstruct the flow. The chute could be positioned at various angles of inclination by a simple clamping arrangement. The depth of flow could be measured by a pointed probe similar to those common in experiments for the flow of water in open channels.

A diagram showing an exploded view of the heat transfer section is shown in Fig. 3. The actual test section consists of a copper plate 0.8 mm thick, 12 mm wide and 64 mm long. This test section is surrounded by a large plate as shown, and is separated from it by a small air gap to reduce heat conduction to the sides. The gap in turn was covered with tightly fitting tape, again to prevent any obstructions to the flow. The

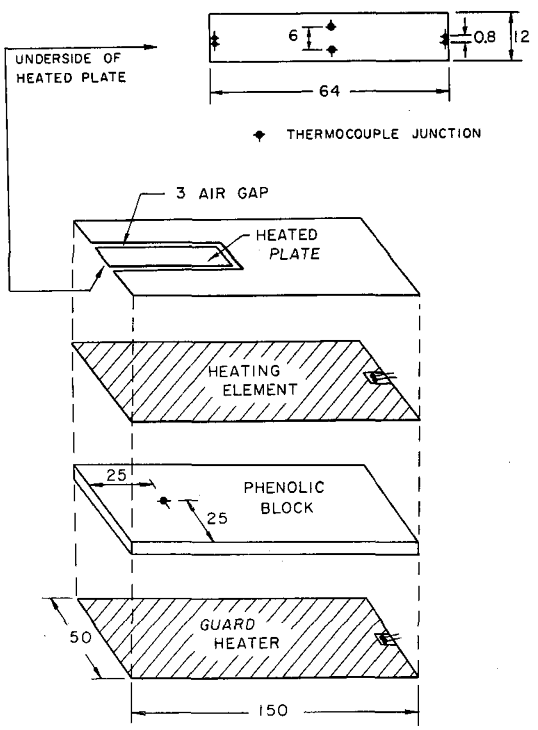

FIG. 3. Exploded view of heated test section (dimensions in mm).

heating element, a commercially obtained component, was mounted directly underneath. An insulating material (a thin phenolic block) and a guard heater mounted below the heating element completed this subassembly. Thermocouples were placed in the locations indicated on the diagram as well as on both sides of the phenolic block. During an experiment the power to the guard heater could be adjusted so that the temperatures on the two sides of the block were equal. This then insured that all of the heat generated in the main heating element would flow toward the bottom of the chute. This in turn made it possible to calculate the heat transfer rate to the test section from the power supplied to the main heating element.

The bulk temperature was measured by a thermocouple which was placed into the flowing material, and the temperature was, of course, essentially equal to the temperature of the material in the hopper reservoir, prior to entering the chute. The surface temperature was determined from the thermocouples on the plate. These measurements were then sufficient to determine the heat-transfer coefficient, h, for the flow along the heated surface. In order to determine the average flow velocity, the mass flow rate was first determined by weighing. The mass flow rate was then divided by the cross-sectional area of the stream and by the density. This density of the flowing stream was taken to be equal to the bulk density of the stationary material, which may differ from the density of the flowing material. The difference, however, is estimated to be less than 10%.

In the experiments two different materials were used, glass beads and mustard seeds. They were selected because each consisted of particles which were essentially spherical and uniform in size, and the thermal properties of the two materials were quite different. The pertinent quantities were measured in our laboratory and they are listed in Table 1.

4. EXPERIMENTAL RESULTS AND DISCUSSION

A series of experiments were conducted with glass beads and mustard seeds flowing along the inclined

Table 1.

	Mean particle size (mm)	Bulk specific gravity	Thermal conductivity ($W\,m^{-1}\,°C^{-1}$)	Thermal diffusivity ($m^2\,s^{-1}$)
Glass traffic beads	0.33	1.46	0.21	0.17
Mustard seed	2.1	0.72	0.14	0.08

chute. By adjusting the inclination of the chute and the position of an inlet gate, the desired combinations of velocity and depth of flow could be obtained. In this manner several sets of data were taken, each for a given depth of flow and a range of velocities. Heat transfer rates were selected so as to provide temperature differences of 10–20°C which may be measured easily and accurately. After the desired flow conditions had been established, power was supplied to the heating element and all temperatures were allowed to reach steady state values before measurements were taken.

The results of the experiments are represented in terms of a Nusselt number and a Peclet number defined by Sullivan and Sabersky [equations (1) and (2)]. These parameters were developed on the basis of a model consisting of a continuum flowing along a wall, but separated from the wall through a contact resistance.

Let us examine first the data obtained for the flow of the glass beads. In Fig. 4 these data are plotted together with those obtained earlier by Sullivan and Sabersky. The dotted line represents the semi-empirical relation just mentioned. For Peclet numbers below about 120, the new data closely follow the trend set by the ones obtained earlier and match the values indicated by the empirical curve. As the flow velocity, and with it the Peclet number, increases however, the data deviate greatly from the trend established by the previous work and from the semi-empirical curve. The data may be grouped according to the depth of the flowing stream of granules. For each depth, a curve is defined which reaches a maximum and then decreases with further increases in velocity. The curves for lower depths fall below those for the deeper flows. This behavior was certainly unexpected and gives an important indication of the complexity of the flow of a granular material. One may, however, offer at least a qualitative explanation for the observed results which seems quite plausible.

To follow this explanation consider first a set of data for a given depth of flow. Starting at the lowest Peclet number, it is seen that, as the flow velocity increases the heat transfer coefficient tends to increase, as it would in a continuum. The velocity increase, however, also brings about a higher mobility of the individual particles of the granular material, which leads to a decrease in the packing density, particularly near the heating surface. This decrease in density impedes the heat-transfer process. Beyond a certain velocity the density effect becomes the dominant one and it leads to the decrease in the Nusselt number. It is also pertinent to note that for the experiments with the glass beads

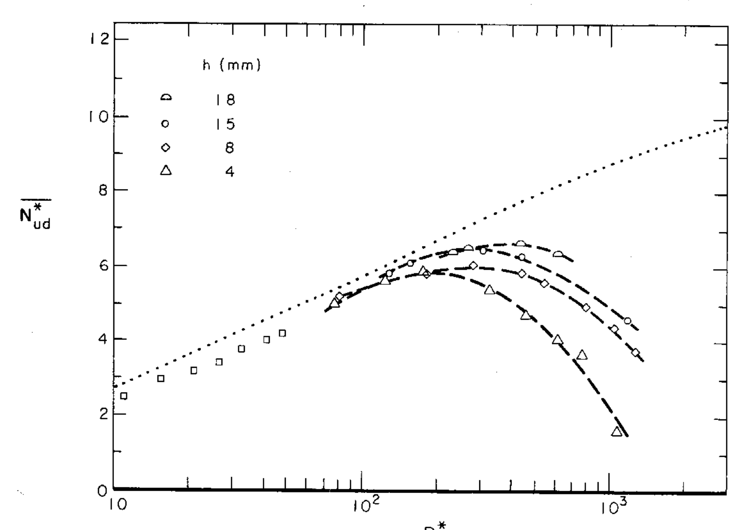

FIG. 4. Data for glass beads. Each curve corresponds to a given depth of flow indicated by the various symbols. Points marked by squares are data obtained by Sullivan and Sabersky [1] and the dotted curve is their empirical relation.

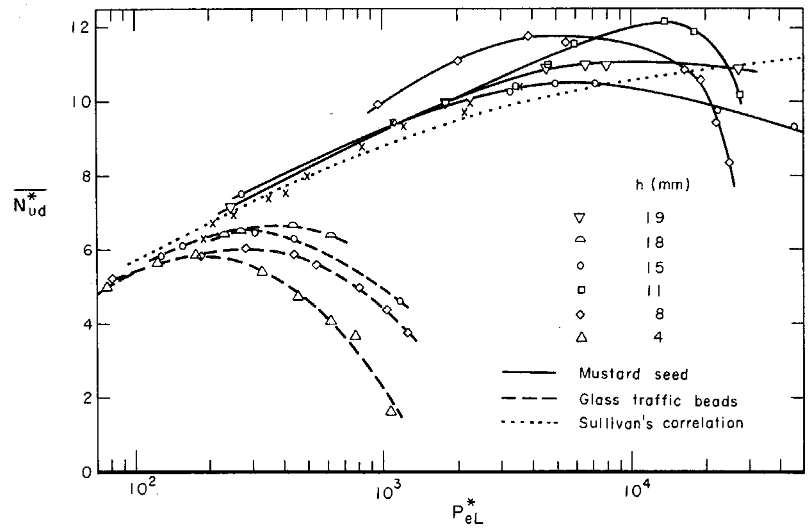

FIG. 5. Combined data for glass beads and mustard seed. Each curve corresponds to a given depth of flow as indicated by symbols. Crosses represent data obtained by Sullivan and Sabersky for mustard seed.

the flows at a larger depth also lead to larger heat-transfer coefficients. Presumably, the larger depths produce a larger pressure at the bottom of the chute which will tend to delay the decrease in density caused by the velocity. This qualitative description is, of course, incomplete. The actual mechanism concerning the density decrease is likely to be more complex involving other interactions between the particles.

The relation between velocity and density for the flow of a granular material in a chute has also been noted in a parallel study which is to be published in the near future [10]. In this study, which is an analytical one, the motion of an assembly of particles is computed directly from the basic laws of mechanics. As the assembly moves along the inclined chute definite velocity and density profiles develop and the density near the bottom is definitely lower than the average density. The effect of shear stress on density has also been noted experimentally by Savage and Sayed [11] in their study of a Couette-type flow.

The data corresponding to the flow of mustard seed are shown in Fig. 5, in which the previous data are also shown for reference. The data for the mustard seed show good agreement with the results by Sullivan and Sabersky for the lower Peclet numbers, say $Pe_L^* < 1000$. Each curve again corresponds to a constant depth of flow and as before each shows a maximum and a subsequent decrease as the velocity is increased further. The curve corresponding to a depth of 19 mm lies above that for a depth of 15 mm which follows the trend observed for the heat transfer to the glass beads. The two curves for the lower depths (8 mm and 11 mm) do not follow this pattern and even intersect the other curves. As mentioned earlier, this again indicates that the effects determining the density and heat-transfer mechanism near the heated wall are not likely to be simple functions of velocity and depths alone, even though these two quantities are certainly of major importance.

5. SUMMARY AND CONCLUSIONS

Heat-transfer characteristics of granular material flowing along a chute were investigated. For each material the heat-transfer coefficient at first increased with velocity as had been observed in earlier experiments. As the velocity was increased further, however, a maximum value was reached beyond which a decrease in the heat-transfer coefficient was observed. It is believed that this observed phenomenon is related to the changes in density near the heating surface. This density apparently is strongly dependent on the flow velocity, but is expected to also depend on other factors such as the pressure and the general flow field. The results are of practical interest in that they show that, contrary to the usual experience in convective heat-transfer, increasing the flow velocity may not necessarily lead to an increase in the heat-transfer coefficient. In addition the results shed some further light on the flow mechanics of granular materials. They show that the flow may produce density changes, and these density changes can have a significant effect on the heat transfer mechanism and probably also on the surface shear.

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TRANSFERT THERMIQUE A UN MATERIAU GRANULAIRE EN ECOULEMENT

Résumé—On étudie la convection forcée pour deux matériaux granulaires en écoulement dans une chute. Pour chaque matériau et pour une hauteur de chute donnée, le coefficient de transfert thermique croît d'abord avec la vitesse, puis atteint un maximum et décroît quand la vitesse continue d'augmenter. On suppose que ce comportement est relié au changement de densité du lit de matériau, provoqué par le champ d'écoulement.

WÄRMEÜBERGANG AN FLIESSENDES GRANULAT

Zusammenfassung—Der Wärmeübergang bei erzwungener Konvektion wurde für zwei Granulate, die eine Rutsche hinunterfließen, untersucht. Für jedes Material und eine gegebene Tiefe der Strömung nimmt der Wärmeübergang zunächst mit der Geschwindigkeit zu, erreicht ein Maximum und nimmt dann bei weiter zunehmender Geschwindigkeit wieder ab. Es wird angenommen, daß dieses Verhalten auf Änderungen der Packungsdichte des Materials als Folge des Geschwindigkeitsfeldes zurückzuführen ist.

ТЕПЛОПЕРЕНОС ПРИ ТЕЧЕНИИ ГРАНУЛИРОВАННОГО МАТЕРИАЛА

Аннотация — Исследовалась вынужденная конвекция при течении по лотку дисперсного материала двух видов. Для каждого материала при заданной толщине зернистого слоя коэффициент теплообмена сначала увеличивается с ростом скорости, достигает максимума, а затем уменьшается. Предполагается, что такая зависимость обусловлена изменением порозности зернистого слоя при течении.