EXPERIMENTS ON HEAT TRANSFER BETWEEN A FLUIDIZED BED AND VERTICAL AND INCLINED SHEETS

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The angle of inclination affects the heat-transfer rate between a sheet and a fluidized bed of corundum particles of sizes 120 and 320μm over a wide range of velocities in the fluidizing agent.

In the design of apparatus with fluidized beds for heating or cooling sheets it is important to know the heat-transfer rate as a function of sheet size and orientation in the bed, not only as a mean for the whole sheet but also for parts varying over the height.

A few experiments have been described [1-3] on the effects of inclination on heat transfer to 100 × 100 mm sheets [3]; the variation in heat transfer with height was not examined, although it is known [4-7] that the maximal heat-transfer coefficient of a vertical wall in a high plant in a fluidized bed is usually lower and is attained at higher speeds than that found when a small component is employed. Heat transfer to a large vertical sheet is analogous to the transfer to the wall at an apparatus, so one expects a substantial effect from sheet size and tilt as regards the heat transfer. Also, the hydrodynamics of the flow around the sheet vary with the inclination to the horizontal, which also affects the heat transfer [8, 9].

We measured the heat-transfer between sheets and a fluidized bed with an apparatus 420 × 170 mm; the fluidized bed was 300 mm deep in the absence of gas flow, and was made of almost monodisperse corundum (particle size distribution defined by state standard 3647-59), the mean grain sizes being $d = 120\mu$m and 320μm, with loose packed densities respectively of 1850 and 2000 kg/mm^3. At low fluidization speeds (with a finer powder) we used a perforated gas distributing grid with an effective cross section of 0.185%, while for the coarser material we used one of 0.75%, which made it possible to obtain uniform fluidization over a wide range of air speeds [10] with reasonable resistances in the grids. The air flow rate was measured with a double stop, the error of measurement in the flow rate not exceeding ± 2.8% [11].

The heat transfer was measured for the calorimeter of Figure 1, which consists of six brass plates 1 (LS59-1), which were insulated one from another by the tufnol 2. One side of the calorimeter was thermally insulated with asbestos 3, while insulation at the side was provided by the tufnol 7. The entire assembly was held in the metal body 9 by the clamping screws 4. In the mid brass plate 1 there was a junction of a Chromel – Alumel thermocouple 12, with a cylinder 11 made of the same material as the plate. The ends of the thermocouple ran via the two-channel porcelain tube 10 and tufnol tube 8 to the six-point potentiometer type KWT with scale of 0-110°C and a recording error of ± 0.5% of full scale. The current junctions of the thermocouples were fitted in metal jackets having d =3 mm and set at the level of the middle of the calorimeter. The holder 5 soldered to the body 6 was used to mount the transducer on the half axles 9, which provided for positive angles of attack (surface of the specimen turned downwards, facing into the air flow) and also negative ones (surface turned upwards). A calorimeter of this design enables one to measure the heat transfer coefficient from the side for each of the six elements, i.e., to follow the variation in heat-transfer rate over the height. Figure 2 and 3 give the mean heat-transfer coefficient taken over the surface of the calorimeter, which has been obtained by averaging the local values for the six elements; the width of the calorimeter was equal to the width of the apparatus, so the gas and material could not move transversely (if we neglect slight influence from the walls of the chamber), which allows us to consider the process as approximately two-dimensional.

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TABLE 1. Heat-Transfer Coefficient in Relation to Sheet Size

Size, mm	100×200	100×400	200×400	400×400	600×400
α, W/m$^2\cdot$°C	610	550	510	480	475

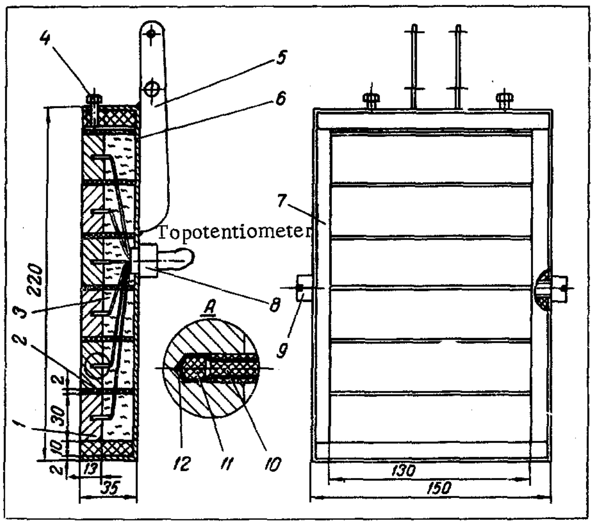

Fig. 1. The calorimeter.

For comparison we examined the heat transfer to a copper sphere 15 mm in diameter, and a brass plate (L S59-1) of size equal to one element in the calorimeter (Fig. 1) with thermally insulated end surfaces. The plate could be set only in the vertical position. The heat-transfer coefficient was measured in every case by means of regular conditions of the first kind [12]. The cooling rate was measured in the range from 120 to 40°C at a layer temperature of 20°C; the coefficient of variation in the result for the heat-transfer coefficient did not exceed ± 6%.

We examined the effects of sheet size by using a small heating system fuelled by natural gas with a hooded gas distributor designed for treating metal sheets; the apparatus was 250 × 800 mm, and the height of the layer of corundum at rest was 800 mm above the level of the hoods, the mean grain size of the monodisperse corundum being $d = 400 \mu m$ in accordance with state standard 3647-59. The fluidized bed was heated to 100°C, and in it we inserted vertically steel sheets (30 KhGSA steel), which were at room temperature, 14.6 mm thick, and size (see Table 1) from 100 × 200 mm to 400 × 600 mm (the smaller dimension was the vertical one). The temperatures of the sheets were recorded with Chromel–Alumel thermocouples mounted in the middle of the sheet, which were connected to an ÉPP-0.9 potentiometer with a scale of 0–1100°C.

With the sheet vertical, the general trend in heat-transfer coefficients with gas speed did not differ essentially from that of bodies of other shapes, although the maximal transfer coefficient decreased as the sheet became larger (Fig. 2); the same was observed in the small heating plant, and small plates gave more size effect than large ones. An analogous result has been obtained [13] for small transducers.

Deviation from a vertical position in either direction reduced the heat transfer coefficient (Fig. 3a). The heat transfer is reduced on deviation from the vertical because of the formation of a cap of immobile material above the inclined surface, while under it there is an air bubble, which prevents heat transfer between the plate and the layer [8, 9]. The heat transfer to the upward facing surface increased with the velocity of the gas on account of the more vigorous sliding of the material, but at the same time it was reduced at the surface facing downwards on account of closer packing of the layer under the plate.

The highest heat-transfer coefficient was obtained for the vertical plate with air speeds less than those found with a sphere (Fig. 2), while in using an apparatus with a fluidized bed and examining the transfer to the walls [4, 7], the maximum value was obtained at speeds higher than those for a small body. The heat-transfer rate of the calorimeter fell from the bottom upwards (Fig. 3a), although it has been observed [5, 7] that the wall has a boundary layer of sinking dense material, whose heating tends to reduce the heat transfer towards the bottom of the plate. We examined the reasons for this disagreement and concluded that the heat transfer was influenced by the air emerging from under the lower end part of the calorimeter and rising along the heat-transfer surface. This was verified by fitting underneath the calorimeter a big piece of tin plate, which enabled us to deflect the air from under the calorimeter either to the insulated surface or to the transfer surface (Fig. 3b). We found that bringing up air to the insulated surface in this way resulted in a much reduced transfer coefficient, the value being lower than that on bringing air to the transfer surface, particularly when the air speeds were close to those for the onset of fluidization. The distribution of the heat-transfer rate over the height of the calorimeter was also affected (Fig. 3b). Here also, the maximum heat-transfer coefficient was attained not with the sheet vertical but with the apparatus set with a small positive angle of attack.

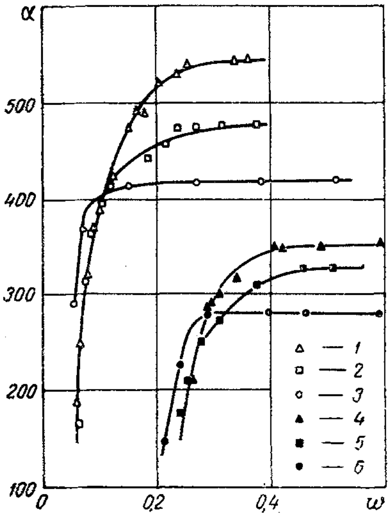

Fig. 2. Heat transfer coefficient α, W/m²·°C as a function of the speed of fluidizing agent (air w, m/sec: 1, 2, 3) corundum 120 μm; 4, 5, 6) corundum 320 μm; 1, 4) sphere, 15 mm in diam; 2, 5) plate 30 × 130 × 13 mm; 3, 6) plate 200 × 130 × 35 mm.

A vertical surface resembled the upper part of the surface of an inclined sheet in receiving less fluidizing agent, there being a layer of fine-grained material having the porosity close to that of the unfluidized layer and its loosest packing. This layer was seen on visual observation, and it hinders heat transfer at the surface. This layer moves downwards in response to the density difference between the sheet and the body of the apparatus, and this steady motion has superimposed on it pulsations that move the material along the heat-transfer surface, and also displace the material from the surface into the fluidized bed (the latter occurs mainly from bubbles traveling along the surface). The longitudinal displacements of constant amplitude have an effect that increases as the plate becomes smaller in the sense that the surface of a small plate receives at the ends more cold material, so the heat-transfer coefficient increases. The thickness of this boundary layer is reduced on raising the air speed, while the rate of motion of the material and the pulsations increase, which increases the heat-transfer coefficient (Fig. 3b). Air deflected to the heat-transfer surface by the piece of bent tin disrupts the descending layer of material; but the rising air bubbles from under the edge of the calorimeter become larger and become detached from the side surface and pass into the layer, i.e., the boundary layer is completely disrupted only in the lower part, so the heat-transfer coefficient in the upper part of the calorimeter is less than that in the lower one (Fig. 3b). The devised set of the small positive angle of attack (5-10°) causes the boundary layer to be disrupted also in the upper part of the sheet, on account of the air accumulating underneath, so the heat-transfer coefficient is the same over the entire height of the sheet. At large angles of attack, a gas cushion is formed under the plate, which reduces the heat-transfer coefficient. If the surface is small, while the

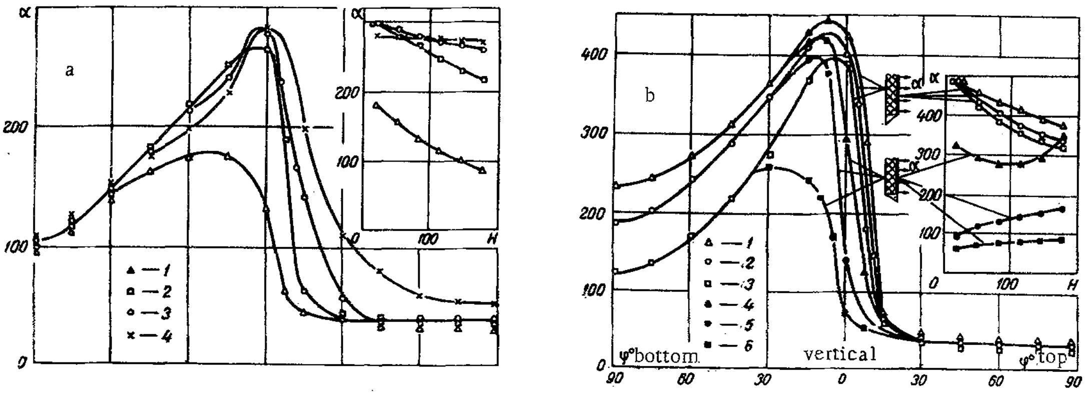

Fig. 3. Heat transfer coefficient α W/m²·°C (mean along height) as a function in angle of plate inclination relative to vertical line φ^0 and distribution of local heat transfer coefficients along height (H, distance from lower edge of plate, mm) when plate is vertical: a) corundum 320 μm; b) corundum 120 μm; air from above the end face is removed to heat transfer (1, 2, 3) or heat-insulated (4, 5, 6) surface of calorimeter.

air speed is sufficiently large, this gas cushion is disrupted by turbulent pulsations, and the heat-transfer coefficient remains at the value for the vertical position with any positive angle of attack [1]. At negative angles of attack, the heat transfer is much reduced, because the thickness of the boundary layer is increased by deposition of fine-grained material above the surface. This material slides slowly downwards and becomes very hot, which substantially reduces the heat-transfer coefficient in the lower part relative to the upper one.

Our results indicate that the best position for the sheet in the fluidized bed to give uniform heating or cooling on both sides is vertical. If larger transfer is to be produced on one side, the sheet should be set at a small angle to the vertical, 5-10°. The exact angle is dependent on the size and on the gas speed.

If larger items are to be treated in a fluidized bed, account must be taken of the thickness, since this increases the flux of air emerging from under the bottom edge along the side surfaces, which tends to intensify the heat transfer, especially at low speeds. In this case, one needs to take into account also the shape of the lower part of the item, since this can deflect the air to one side or uniformly over both sides.

One can intensify the heat transfer to large sheets at gas speeds close to the onset of fluidization by providing the lower part of the sheet with an additional flow of fluidizing agent either from under a gas distributing grid or by means of special inlets set in the layer. Conditions with fluidization speeds close to the critical ones are very promising for treating sheets of brittle or weak materials, which might be damaged in a well fluidized bed. Under such conditions there is also practically no loss of material.

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