STUDY OF MASS TRANSFER BETWEEN A SPHERICAL BODY AND A TURBULENT GAS STREAM

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The results are presented of an investigation of mass transfer for a single sphere and for a sphere in a packed bed with different kinds of packing.

The great majority of driers operate in conditions where a stream of the drying agent passes through a bed of the material being dried making it possible for a vigorous process to occur.

It is thus of interest to determine for these conditions the dependence of the mass transfer coefficient on the hydrodynamic regime and the physical properties of the drying agent in order to allow calculation of the first-stage drying time from the well-known mass balance equation.

By way of example the authors have studied mass transfer for a single sphere of d = 60 mm moistened with water, and for spheres arranged in a monodisperse layer of a bed, the diameter of the bed spheres corresponding to that of the solitary sphere.

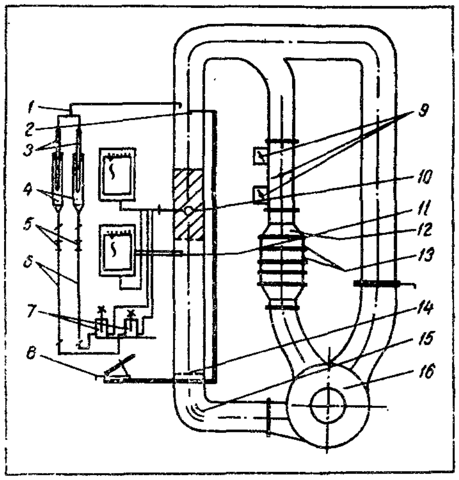

Fig. 1. The experimental layout: 1—connecting tube; 2—pitot tube; 3—internal tube; 4—reservoir volume; 5—supply tube; 6—capillaries; 7—intermediate reservoir volumes; 8—micromanometer; 9—gate-valves; 10—test sphere; 11—thermocouples; 12—electric air heater; 13—control sections; 14—grids; 15—guide vanes; 16—blower.

The tests were carried out in a closed-circuit wind tunnel (Fig. 1) with an air circuit length of 15 m and diameter 0.3 m in the range $7.55 \cdot 10^3 - 87 \cdot 10^3$ of Reynolds number and 50°–90° C. of temperature of the water vapor-air mixture.

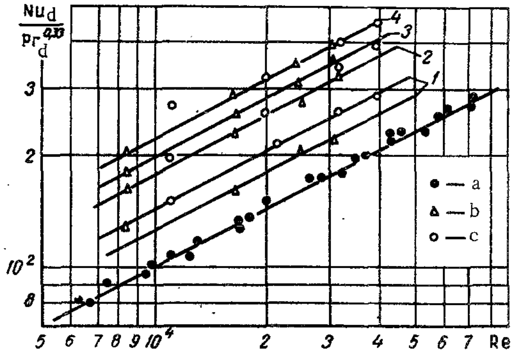

Fig. 2. Dependence of $Nu_d/Pr_d^{0.33}$ on Re for the single sphere (a), and for different kinds of packing (b—cubic; c—square pyramid): 1–4 refer to rows 1–4, respectively.

Air was supplied by the centrifugal blower 16. To avoid displacement of the air to the periphery of the bed, special guide vanes 15 were used.

Stabilization of the stream in the working section of the tunnel was accomplished by means of the grids 14.

The velocity non-uniformity in the core of the stream, this constituting 75–80% of the section, did not exceed 2% of the stream velocity on the axis of the working section. Downstream of the working section a part of the air was blown out to atmosphere, the remainder being returned to the blower through the bypass duct. Upstream of the blower, in one of the bypass ducts, there was an electric heater 12. The power to its elements was under automatic control allowing the temperature in the bed to be maintained to within ±0.3%.

Two copper-constantan thermocouples 11 were mounted upstream of the tunnel working section. One measured the temperature of the heated air-water vapor mixture, and the other the wet bulb temperature.

The air velocity was controlled by means of a system of gate-valves 9 and was measured with a pitot tube 2 connected to a MMN-8 type micromanometer. The special construction of the tube increased its sensitivity by a factor of 2, to allow greater accuracy in stream velocity measurement.

The test model was made of porous ceramic, the choice being based on the following requirements: the dimensions should be stable during the moistening process; the pore structure should be uniform; and the mechanical strength should be sufficient.

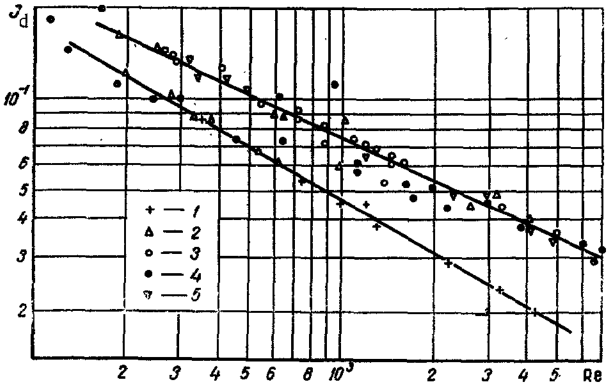

Fig. 3. Dependence of J_d on Re: 1 is our test data; 2 is the data of [6]; 3—[7]; 4—[4, 5]; 5—[8].

The wall thickness of the sphere (d = 60mm) was 5 mm, the porosity 35–38%, and the pore diameter 2–10 μ. The sphere diameter was chosen such that the cross-sectional area of its mid-section did not exceed 5% of the area of the tunnel working section.

The sphere was mounted at the center of the air stream on a special tubular holder of 8-mm diameter, also used to supply water to the interior of the sphere via a plastic tube and to take out the thermocouple leads. The seven copper-constantan thermocouples mounted in the sphere were connected to two multipoint type KVT potentiometers. One thermocouple measured the temperature of the water inside the sphere, and the other six were used to control the temperature of the evaporation surface.

The supply of water to the sphere was accomplished via the special volumes 4 with their inner tubes 3.

The inner tube connected the working section channel with the water in the reservoir volume. Decrease of the water in the annular gap was accomplished by leakage of air along the inner tube leading to a reduced pressure above the water surface. Vertical displacement of the inner tube allowed the required constant pressure to be maintained in the sphere water supply system. The capillary 6 of 2-mm diameter and 1000-mm length was used to measure the amount of water being evaporated. An air bubble was injected into supply tube 5 ahead of the capillary, was displaced into the capillary as the water evaporated, taking the form of a cylinder with $H/d_0 = 5 - 10$. Tests showed that there was no displacement of the air bubble with the supply system disconnected.

To avoid air passing into the sphere interior, an intermediate volume 7 was included in the supply system, in series behind the capillary. The capillary was calibrated by weighing with the aid of a Class 1 analytical balance.

Alignment tests were carried out with an excess pressure of p = 1470 N/m^2. The measurements showed (for the single sphere) that with temperature t = 70° C of the heated water vapor-air mixture and velocity in the working section of 15 m/sec and above, the wall temperature of the rearward part of the sphere was 2°–3° C below the wet bulb temperature. To eliminate increase of temperature in the rearward part of the sphere, the pressure in the supply system had to be increased to 3430 N/m^2.

The experimental data obtained were correlated on a logarithmic scale in the form of the correlation (Fig. 2),

$$\mathrm{Nu_d} = A\,\mathrm{Re}^n\,\mathrm{Pr}^{0.33}, \qquad (1)$$

and the mass transfer coefficients were determined from the relation

$$\beta = i/(p_w - p_s). \qquad (2)$$

The test data obtained for different temperatures (t = 50, 70, 90° C), did not show any significant differentiation with temperature level, such as was noted in references [2, 3]. The parameter Gu to the power 0.13, introduced by the above authors in order to generalize the parametric equations obtained for each temperature level to a single equation, can be omitted in our case, since for the single sphere the location of all the experimental points on the graph (Fig. 2) is in good agreement with the relation

$$\mathrm{Nu}_d^* = 0.9\,\mathrm{Re}^{0.5}\mathrm{Pr}_d^{0.33}. \qquad (3)$$

In the study of mass transfer from spheres (d = 60 mm) in the layer of a bed in a turbulent gas stream, two types of packing were used, cubic and square pyramid. The location of the spheres in the bed changed both along the radius of the tunnel section and over its height (the sphere was placed in rows 1 to 5 along the direction of the air stream).

It was established from reduction of the test data that the values of the mean mass transfer coefficients, when the sphere was moved in a row along the tunnel radius, did not vary from row to row by more than 5%; the values of the mean coefficients for a sphere located at the center of a row of each of the beds may be obtained from a correlation equation of the form

$$\mathrm{Nu}_d = A\,\mathrm{Re}^{0.5}\mathrm{Pr}_d^{0.33}, \qquad (4)$$

where the value of A for rows 1–4 is, respectively: 1.35, 1.8, 2, 2.2.

It may be seen from the last equations that the values of the mean mass transfer coefficients are constant for the fourth and subsequent rows, for equal Re.

In order to compare our results with those of [4, 5], where heat and mass transfer were studied during drying of Zeolite spheres (d = 16 mm) in an air stream, we reprocessed our data by the method adopted in these references. The mass transfer factor

$$J_d = \frac{\beta p_f}{G/M}\left(\frac{\mu}{\rho D}\right)^{2/3}$$

was introduced in [4, 5] as a determining parameter.

Allowing for the effect of the free volume the Re number is expressed as

$$\mathrm{Re} = Gd/\mu(1-\varepsilon).$$

The tests in [4, 5] were made with three bed variants ($\varepsilon = 0.444$, 0.576, and 0.778). In logarithmic coordinates processing of the test data gave the following relations, respectively:

$$J_d = 1.127/(\mathrm{Re}^{0.41} - 1.5),$$
$$\varepsilon J_d = 2.06/\mathrm{Re}^{0.575}.$$

Presentation of our data in the same coordinates (Fig. 3) shows that the points, both for the cubic($\varepsilon = 0.475$) and the square ($\varepsilon = 0.35$) packing, fall very well along the straight line

$$J_d = 2.1/\mathrm{Re}^{0.55}.$$

As is seen from the graph, the divergence of our test data from that of [4–8] increases with increasing Re. This may be explained by the different hydrodynamic conditions of the stream entrance to and exit from the bed layer, and by the level of stream turbulence at the entrance to the working section being different. Tests that we conducted specially to determine the effect of turbulence level at the entrance on the mass transfer coefficients showed that the latter may be increased by 15–20% by introducing additional metal screens ahead of the bed layer. Since the turbulence level was not quoted in the references cited, it was not possible to create even approximately similar hydrodynamical conditions in the equipment, which considerably hampered comparison of the results obtained.

As a result of the investigation conducted it has been established that the mass transfer on a single sphere and on a sphere in a bed exposed to a turbulent gas stream may be described by a single relation, and that, independently of the kind of packing, in a stabilized turbulent flow region (after 3–4 rows), the mass transfer coefficients may be determined from the single correlation equation

$$\mathrm{Nu}_d = 2.2\,\mathrm{Re}^{0.5}\,\mathrm{Pr}_d^{0.33}.$$

NOTATION

d is the sphere diameter, m; d_0 is the capillary diameter, m; β is the mass transfer coefficient, $(\mathrm{kg/m^2 \cdot sec})/\mathrm{N/m^2}$; Nu_d is the Nusselt diffusion number; p_w is the partial pressure of water vapor, corresponding to saturation pressure at the wall temperature, $\mathrm{N/m^2}$; p_s is the partial pressure at the temperature of the gas stream, $\mathrm{N/m^2}$; J_d is the mass transfer factor; p_f is the partial pressure of air in the boundary layer, $\mathrm{N/m_2}$; G is the mass velocity of the gas, $\mathrm{kg/m^2 \cdot hr}$; M is the molecular weight; μ is the absolute viscosity, $\mathrm{N/m^2 \cdot sec}$; ρ is the density, $\mathrm{kg/m^3}$; D is the diffusion coefficient for water vapor passing through the gas film, $\mathrm{m^2/sec}$; ε is the voidage.

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