INVESTIGATION OF HEAT AND MASS TRANSFER IN JET DRYING

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The results are given of a combined experimental investigation of the aerodynamics and heat and mass transfer for various nozzle systems. The influence of the system parameters on the drying process is established. Criterial relations are obtained for calculating heat and mass transfer in the jet drying of paper and cardboard.

One means of drying with jet blowing is accomplished by blowing a drying agent with high-performance parameters out of a system of nozzles onto the material to be dried. A number of papers [1–5] have been devoted to this method of drying.

In order to determine the essential mechanism of heat and mass transfer during drying, and to discover the optimum construction parameters and the influence of the operating parameters, a combined study has been carried out of the aerodynamics and mass transfer for various nozzle systems. In addition, heat and mass transfer during combined nozzle and conduction drying have been investigated.

The investigation was carried out in equipment consisting of two high-pressure centrifugal blowers, an electric air heater, a pressure box, a nozzle system, and a screw traverse mechanism. The equipment provided air discharge velocities at the nozzle exits of up to 100 m/sec, and air temperature up to 400° C. The nozzle systems had a nozzle slit width of 0.5–5.0 mm, and an internozzle distance (pitch) of 15–55 mm. Using the screw traverse mechanism, devices mounted on it could be shifted in the vertical and horizontal directions, with a reading accuracy of 0.1 mm.

The device for determining the pressure distribution on the wall due to the jets issuing from the nozzles, consisted of a plate with holes through which were passed two micro-pressure tubes connected to a differential manometer.

The device for determining the local intensity of mass transfer consisted of a plate with a slit 2 mm wide, covered with filter paper, to which water was supplied from a distributing chamber. The chamber was joined to a microburet, which gave a reading of the amount of liquid evaporated. In a test steady mass transfer was realized, during which the filter paper surface was in a saturated condition.

To study nozzle drying combined with conduction drying, a device was used consisting of a heating surface, heated by steam, and a clamp.

During a test, measurements were made of the temperature of the material being dried, and of the drying agent in the pressure box and in the internozzle space, as well as the velocity of the drying agent and the moisture loss in mass transfer and drying. Because of the symmetry between the heat- and mass-transfer processes on the two sides of each nozzle in the nozzle system, the progress of these processes was examined in the region from the axis of the nozzle to the half-pitch along the surface of the material being dried.

It was established that the nature of the pressure distribution over the surface of the material (Fig. 1) is identical in form for all the nozzle systems investigated. The beginning of the minimum pressure section is almost independent of s. Decrease of δ leads to a reduction of the maximum pressure values, while the start of the minimum pressure section approaches the critical point. It was observed that with δ of 5 mm, the pressure at a distance equal to one half-pitch from the critical point (midway between nozzles) was greater for $h = 10$ mm than for $h = 5$ mm, and greater for $h = 5$ mm than for $h = 3$ mm. With $s = 15$ mm for the same nozzle, no pressure maximum between the nozzles was observed.

Measurement of pressure in the expanding jet (at a distance of 0.2 mm from the surface) revealed the existence of a rarefaction region corresponding to the section of constant pressure on the surface.

The aerodynamic investigation made it possible to understand the mechanism of flow of a jet against and in interaction with the other jets, as well as the structure of the resulting jet. The jet issuing from a slit nozzle has an expansion angle of 10°–14° C, depending on the nozzle shape and the treatment of the nozzle rim. When it flows up to the wall at right angles, the jet experiences a compression, in which part of its kinetic energy is transformed into potential energy. After impact with the surface, the potential energy of the jet is transformed into kinetic energy, the jet is reversed, and the velocity of the spreading jet so formed increases sharply. As the experiments showed, a "neck" was formed at the beginning of the spreading jet, this being a section of the jet of constant width, less than the half width of the jet approaching the surface (Fig. 2). As h increases, the width of the neck and its length for constant velocity of discharge from the nozzle increase. As δ decreases, the width and length of the neck are reduced. The parameter s has almost no influence on the neck dimensions. The neck width B may be determined from the empirical formula

$$B = 0.290\,\delta + 0.0812\,h. \qquad (1)$$

At the end of the neck the spreading jet begins to expand. The tests showed that the expansion angle of the jet was the same as for the jet discharging from a nozzle. When the jets meet and merge (at half-pitch), a single jet is formed, whose axis is perpendicular to the surface. With increase of h the width of this jet increases, while the expansion angle of the newly formed jet remains the same as in the approaching and spreading jets.

An experimental determination of the maximum velocity over the section of the spreading jet (Fig. 3) showed that this velocity depends on h, δ, w_0. The qualitative nature of the velocity variation along the coordinate is preserved both for varying h, w_0 and s.

The nature of the variation mentioned for this velocity points to the impossibility of using as characteristic values velocities calculated from formulas for a free turbulent choked jet, as some investigators have done.

From the experimental data we may find the value of the ratio h/δ at which the velocity on the jet axis is still equal to that at the nozzle exit. This ratio proved to lie in the range 3–4.5. While it is natural to seek to reduce h/δ, this is possible only up to a known limit, since when $h \leq \delta$, a decrease of the velocity of the agent is observed owing to the occurrence of resistance due to compression of the jet.

The local intensity of mass transfer varies continuously along the surface of the material (Fig. 3). The maxima and minima of mass transfer intensity shift as h increases, moving away from the critical point. The form shown for variation of local mass transfer is characteristic of cases where values of the ratio h/δ are small (up to 8.0, approximately) and the velocities of the drying agent are large. In the rest of the cases the local mass transfer intensity decreases continuously along the surface being dried, and no clear intensity maxima and minima are observed. It should be noted that for narrow nozzles (δ up to 1 mm) at large values of s (55 mm) and with h up to 15 mm, some increase of local mass transfer intensity is observed, beginning at a distance equal to approximately a quarter pitch and beyond.

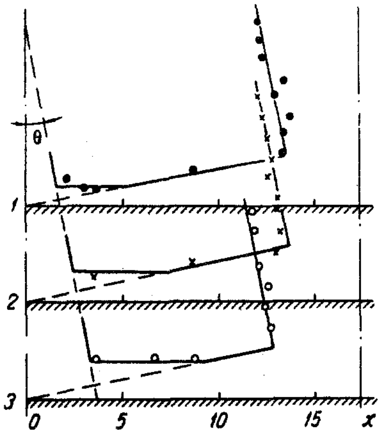

Fig. 2. Jet contours with s = 35 mm and δ = 2 mm: 1) h = 5 mm; 2) h = 10 mm; 3) h = 15 mm.

The combined aerodynamic and mass-transfer investigations allow us to identify four characteristic sections, apparent from an examination of Figs. 1–3.

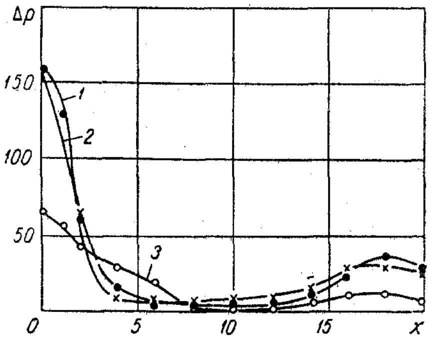

Fig. 1. Pressure distribution on the surface of the material with s = 35 mm and δ = 2mm: 1) h = 5 mm; 2) h = 10 mm; 3) h = 15 mm.

The first section corresponds to the impinging action of the jet, which promotes a decrease of the hydrodynamic boundary layer thickness. It extends from the critical point to a distance $r \approx \delta/2 + h \operatorname{tg} \vartheta$, corresponding roughly to the beginning of formation of the "neck" in the spreading jet. The local mass-transfer intensity in this section is reduced, although the velocity in the spreading jet increases from zero to a maximum value.

The second section is characterized by the presence of the "neck" in which the velocity of the drying agent scarcely decreases and its flow is laminar. A further drop of local intensity occurs here due to the increase of the hydrodynamic boundary layer thickness and decrease of the pressure on the surface of the material. The end of the second section corresponds to the beginning of the fall in jet velocity, and coincides with the end of the neck.

The third section is characterized by an increase in local mass-transfer intensity due to the creation of a turbulent boundary layer and a decrease in thickness of the laminar sublayer. The surface pressure remains practically constant throughout this section, while the velocity of the agent decreases somewhat owing to the onset of turbulence and to the inflow of air. The transition from laminar to turbulent flow, as calculation shows, took place at a Reynolds number of $1.7 \cdot 10^4$–$2.2 \cdot 10^4$. The boundary layer thickness at the end of the neck (transition from laminar to turbulent conditions), calculated from the formulas given by Eckert [5], was 0.18, 0.22, and 0.30 mm, which agreed with the neck thickness obtained experimentally. It turned out that the boundary layer thickness is proportional to h, a relationship which remains valid in the range of the spreading jet.

The fourth and last section begins from the pressure increase on the material surface and the sharp decrease of velocity in the spreading jet, due to direct interaction of the merging jets, flowing together into a single jet directed normally to the surface of the material. The mass transfer intensity then decreases somewhat, but for appreciable values of h/δ and s in the region of jet interaction, an increase in the intensity is observed, due to the relative increase in the part played by turbulence at the comparatively small velocities in this section. The size of this section increases with increase of h.

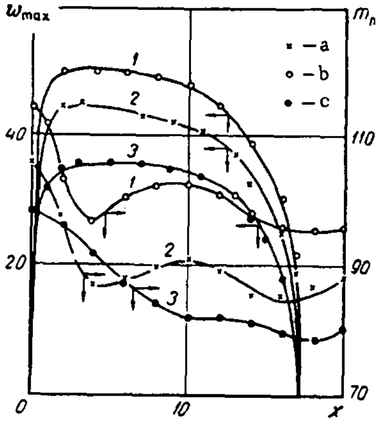

Fig. 3. Maximum velocities in the spreading jet, and local intensities of mass transfer as functions of the coordinate, with s = 35 mm and δ = 2 mm: 1) h = 5 mm; 2) h = 10 mm; 3) h = 15 mm.

The dependence of δ, s, h of heat and mass transfer intensity during the first and second stages of drying enables us to determine the influence of these constructional parameters on the drying process and on the energy expended in achieving it.

The drying rate is reduced with increase of s and h, while increase of δ leads to an enhanced rate of drying. The power required of the blowers and computed for 1 m^2 of material being dried (specific power) may be calculated from the formula

$$N_{sp} = \frac{\delta}{s} w_0 \frac{H}{\eta_K}. \qquad (2)$$

This formula shows the need to determine an efficient ratio δ/s for which a high intensity of the process will be obtained with a comparatively small flow rate of the drying agent per 1 kg of evaporated moisture.

We shall designate an effective velocity equal to the flow rate of drying agent in unit time per unit area of surface being dried. It is determined from the expression

$$w_e = \frac{\delta}{s} w_0. \qquad (3)$$

This velocity, as the experimental data show (Fig. 4), is uniquely determined by m_I for a given h and various values of s and δ. The experimental points for m_I, obtained at various values of w_0 and constant δ and s, lie on the curves shown in Fig. 4, which also implies the uniqueness of the dependence of m_I on w_e. The sharp rise of the curves becomes smoother with w_e of 1 m/sec, which may be assumed to be an efficient value of velocity. Hence an efficient ratio between the nozzle slit width and pitch is taken to be 0.020. We note that the region of favorable δ/s may be chosen in the range 0.015–0.030.

A study of the influence of the regime parameters on the drying process was carried out with a nozzle system satisfying the efficient ratio of δ/s. A nozzle system with a pitch of 25 mm and a slit width of 0.5 mm was investigated.

With increase of w_0 at constant t_0, the temperature of the surface of the material near the nozzle increases somewhat, and a particularly noticeable increase is observed when w_0 is varied from 10 to 60 m/sec. Increase of w_0 from 25 to 90 m/sec with $t_0 = 150°$ C for h of 5 mm causes an increase in temperature from 73° to 85° C.

With increase of t_0 at constant w_0, the temperature of the material also increases. With t_0 at 80° C, w_0 of 50 m/sec, and h of 5 mm, the surface temperature of the material was 46° C; with 200° C it was 90° C; and with 350° C the material temperature was 96° C. At high t_0, the material temperature exceeded the wet-bulb temperature. For nozzle drying, however, the temperature of the material is lower than for conduction drying.

Increase of w_0 and t_0 leads to increased intensity of drying, both in the first and second drying stages. The intensity of first-stage drying is several times greater than in other drying methods for corresponding conditions, and the intensity in the second stage is also greater.

The very large heat transfer and high rates of mass transfer and of drying are explained, in particular, also by the fact that in nozzle drying volume evaporation occurs above the surface of the material in the stream of drying agent. The specific mechanism of combined action of volume evaporation and molar

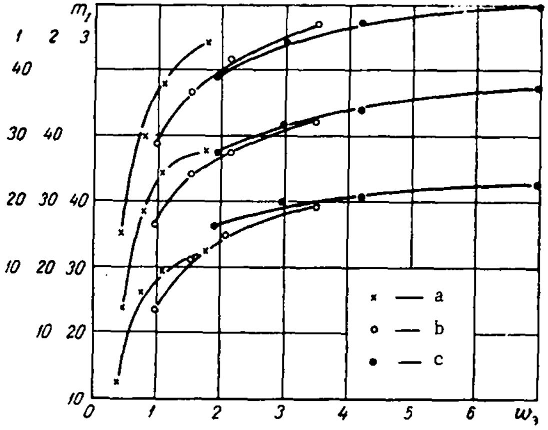

Fig. 4. Intensity of first-stage drying as a function of effective velocity: a) δ = 0.5 mm; b) 1 mm; c) 2 mm; 1) h = 5 mm; 2) h = 10 mm; 3) h = 15 mm.

mass transfer are evidenced by the fact that the intensity of steady mass transfer was higher than that of drying.

In the range of variation of specific mass of material from 75 to 1100 g/m², as the investigation showed, the intensity of drying during the first stage remained constant, all other conditions being equal. The experimental data on heat and mass transfer were reduced in the form of dimensionless generalized variables, from which functional relationships were constructed.

The investigation resulted in the following criterial equation for determining the intensity of drying of various types of paper and cardboard during first-stage drying:

$$\mathrm{Re}^* = 0.332\,\mathrm{Re}^{0.812}\,\mathrm{Gu}^{1.03}\,(s/\delta)^{0.590}. \qquad (4)$$

Eliminating from Re the quantity δ/s appearing in it, we may write (4) in the form

$$\mathrm{Re}^* = 0.332\,\mathrm{Re}_1^{0.812}\,\mathrm{Gu}\,(\delta/s)^{0.222}. \qquad (5)$$

With the assumed efficient ratio of δ/s, (5) takes the form

$$\mathrm{Re}^* = 0.140\,\mathrm{Re}_1^{0.812}\mathrm{Gu}^{1.03}. \qquad (6)$$

The experimental points are described very well by the proposed relationships for the drying process; these criterial relations were obtained with variation of Re_1 from $15 \cdot 10^2$ to $16 \cdot 10^4$.

To calculate the mean heat transfer coefficient in the period of constant drying rate, the following criterial relation is suggested:

$$\mathrm{Nu} = 5.76 \cdot 10^{-3}\,\mathrm{Re}^{0.779}\,(s/\delta)^{0.604}. \qquad (7)$$

The influence of temperature is taken into account by the quantities characterizing the physical properties of the medium. With an efficient ratio of δ/s, the expression takes the form

$$\mathrm{Nu} = 2.91 \cdot 10^{-3} \cdot \mathrm{Re}_1^{0.779}. \qquad (8)$$

The experimental points are brought together satisfactorily by the relationships obtained, the deviation of the points not exceeding ±6–8%.

The form of the relationships differs from those usually assumed, in that Re* is used as the unknown relative variable, and not the Nusselt diffusion parameter. The advantage of the dependence assumed is that it yields directly the value of mass transfer intensity required in engineering design.

It is usual to take the quantity s as a characteristic length. Reduction of the experimental heat and mass transfer data showed that s cannot be a characteristic length when there is variation of pitch and height, as occurred in our investigation. The thickness of the hydrodynamic boundary layer, on which the intensity of the heat and mass transfer processes depends, could serve as a characteristic length. Because of the fact that the boundary layer thickness proved to be proportional to the height of elevation of the nozzles above the material, it is convenient to take h as the characteristic length.

As a characteristic velocity we use the root mean square velocity at the surface of the material, or the root mean square mean integral velocity at half-pitch, or indeed the mean arithmetic or root mean square velocities at the sections corresponding to the critical point and half-pitch.

The investigation has shown that the intensity of heat and mass transfer is not a single-valued function of these velocities, but depends on h, δ, and s. Therefore, the effective velocity w_e was taken as the characteristic velocity. The physical constants entering into the parameters were evaluated at the mean temperature in the boundary layer.

The nozzle method of drying may be used alone or in combination with other methods. Its combination with the conduction method intensifies the process considerably (by a factor of 2–5 and more, depending on the conditions, compared with ordinary strong conduction-convection drying), ensures controlled drying, uniform over the thickness of the material, yields material of good quality, and makes possible complete automation of the drying process.

The aerodynamic and mass-transfer investigations carried out have explained the mechanism of spreading and interaction of jets from various nozzle systems, as well as the influence of the regime parameters on heat and mass transfer, and they enable optimum drying conditions to be chosen on a scientific basis.

The results of this investigation allow a method linked to the kinetics of drying to be devised for the design of drying equipment which enables high-performance drying with recirculation of the drying agent.

NOTATION

x) coordinate; w_0) velocity of drying agent at the nozzle exit; w_{max}) maximum velocity in the spreading jet; Δp) pressure at the surface of the material; δ) width of the nozzle slit; s) distance between the nozzles (pitch); h) distance from the rim of nozzle to material (elevation of nozzle); ϑ) lateral expansion angle of the jet; H) total head created by the blower; η_K) total efficiency of the blower and its drive; m_l) local intensity of mass transfer; m_I) intensity of drying during the first stage; T_0, t_0) temperature of the drying agent at the nozzle exit; $\mathrm{Re}^* = m_I h/\eta$) Reynolds number for mass flow of the substance; η) dynamic viscosity of the water vapor-air mixture; $\mathrm{Gu} = (T_0 - T_M)/T_M$) modified Gukhman parameter; T_M) wet-bulb temperature; $\mathrm{Re} = w_e h/\nu$) Reynolds number; w_e) effective velocity; ν) kinematic viscosity; $\mathrm{Re}_1 = w_0 h/\nu$; $\mathrm{Nu} = \alpha_M h/\lambda$) Nusselt number; α_M) heat transfer coefficient, calculated at the wet-bulb temperature; λ) thermal conductivity of the water vapor-air mixture.

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