Journal of Engineering Physics and Thermophysics, Vol. 74, No. 4, 2001

INVESTIGATION OF THE HYDRODYNAMICS OF VORTEX PNEUMATIC SPRAYERS

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UDC 533.6:069.83:66.047

Results of experimental investigations of the hydrodynamics of vortex pneumatic sprayers are discussed.

Spray drying is a commonly recognized highly efficient method of dehydration of liquid materials in different branches of industry; therefore, its intensification, contributing to an increase in the moisture density of the volume of the drying chamber, especially in drying thermosensitive materials, is of great practical importance and is quite a topical problem. One way of intensifying the process of spray drying is to increase the surface of heat and mass exchange by increasing the dispersity of the spray and its homogeneity. This problem is related to the development and investigation of new dispersing devices that ensure a better interaction of the phases owing to the improvement of the quality of spraying and the rational distribution of liquid droplets in the working volume of the apparatuses. Our investigation in [1] showed that out of the entire range of dispersing devices, this problem could most completely be addressed by swirl pneumatic sprayers. They are simple in design and reliable in operation; they do not require substantial expenditures for their realization and can easily be realized in the designs of not only apparatuses being created but in operating drying units as well. Their application is most expedient in production processes where great amounts of compressed air with a pressure of $(3–4)\cdot 10^5$ Pa are used. The quality of spraying in pneumatic sprayers is determined to a significant degree by the conditions of the interaction of the phases. It is known [2] that in the outflow of the solution from the liquid nozzle in the form of a film the utilization factor of the air-flow energy is an order of magnitude higher than in its outflow in the form of a jet. Therefore, the aim of the present work is to investigate the influence of the hydrodynamics of a liquid channel on the efficiency of spraying of the liquid by swirl pneumatic sprayers; the scheme of one of them is presented in Fig. 1.

The liquid system of the sprayer consists of the pipeline for feeding a liquid 5, the liquid nozzle 6, and the swirler (vortex generator) of a liquid 7. A distinctive feature of the design in question is that it enables one to produce a strongly swirled air jet that forms the attached structure of flow of a gas-liquid mixture at the outlet from the nozzle 4 [3]. The gas-liquid flow at the outlet from the mouth of the nozzle changes the direction of its motion and is pressed against its external end portion with an annular channel (groove) 9, moving to the edge of the head 8, and is dispersed from it, forming the cone of a sprayed liquid with a root angle of 180°. In movement of the head 8 relative to the end surface of the air-blast nozzle, the root angle of the cone of the sprayed liquid decreases smoothly and its diameter becomes contracted. The annular groove 9 decreases the friction surface of the gas-liquid flow and contributes to an increase in the dispersity of the spray. The design in question enables one to realize all possible forms of outflow of a liquid from the nozzle 6: as a jet, a film, and a system of polydisperse droplets. The first form is attained by re-

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Academic Scientific Complex "A. V. Luikov Heat and Mass Transfer Institute," National Academy of Sciences of Belarus, Minsk, Belarus. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 74, No. 4, pp. 102–104, July–August, 2001. Original article submitted January 18, 2001.

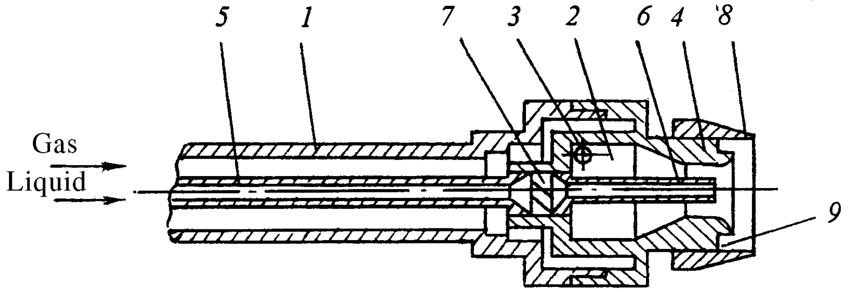

Fig. 1. Scheme of a vortex pneumatic sprayer: 1) casing; 2) vortex chamber; 3) tangential air channels; 4) air-blast nozzle; 5) pipeline for feeding a liquid; 6) liquid nozzle; 7) swirler of a liquid; 8) head; 9) annular groove.

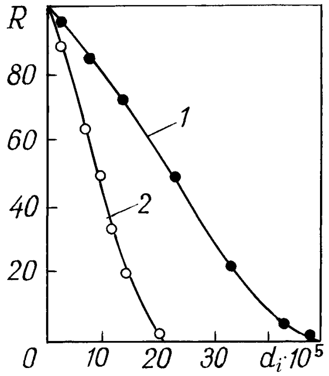

Fig. 2. Influence of the form of feed of a liquid on the size distribution of droplets in the cone of a vortex sprayer ($C_{\text{ch}} = 0.625$, $G_{\text{liq}}/G_{\text{g}} = 1$, $\Delta P = 98.1$ kPa, $\text{Re}_{\text{liq}} = 3.5 \cdot 10^3$, and $F_0 = 38.5 \cdot 10^{-6}$ m^2): 1) $X = F_{\text{sw}}/F_{\text{liq}} = 0$; 2) 0.285. R, %: $d_i \cdot 10^5$, m.

moval of the swirler 7 from the design, whereas the second and third forms are organized by the swirler for a certain velocity of outflow of the liquid. The change in the velocity of outflow of the liquid was ensured by variation of both the cross sections of the nozzle 6 and the swirler 7 and the flow rate of the liquid.

In the given design of a sprayer, the form of outflow of a liquid is of great importance, since the liquid is fed to the rarefaction zone and is slightly affected just by the air flow drawn in to the nozzle's mouth from the ambient medium. Figure 2 shows plots of the size distribution of the droplets of a sprayed liquid in the cone of a vortex sprayer versus the form of outflow of the liquid from the nozzle. As the working fluid we used ordinary tap water. In order to determine the dispersity of the spray, we employed the catching method [4] as the most simple and universal. Analysis of the obtained dependences shows that for the same geometric dimensions of the sprayer and technological parameters of the process of spraying (the liquid velocity in both cases was equal to 0.7 m/sec) organization of the film form of outflow owing to the swirl of the liquid enables us to significantly reduce the polydispersity of the spray cone and to decrease the average droplet diameter. This is due to the fact that when the swirler is absent and the velocity is low the liquid ($V_{\text{liq}} < 0.5$) flowing out in the form of a jet is fully drawn in to the outlet edge of the nozzle 4 by an air flow of velocity 140–200 m/sec and is sprayed. However, already for $0.5 < V_{\text{liq}} < 1.0$, it is only part of the jet that is drawn in to the edge of the air-blast nozzle and its other part begins to disintegrate into large agglomerates at a certain distance from the mouth of the liquid nozzle 6 along the sprayer axis. As V_{liq} increases above 1.0, the amount of the liquid drawn in to the edge of the air-blast nozzle decreases progressively and the quality of its dispersion is accordingly degraded.

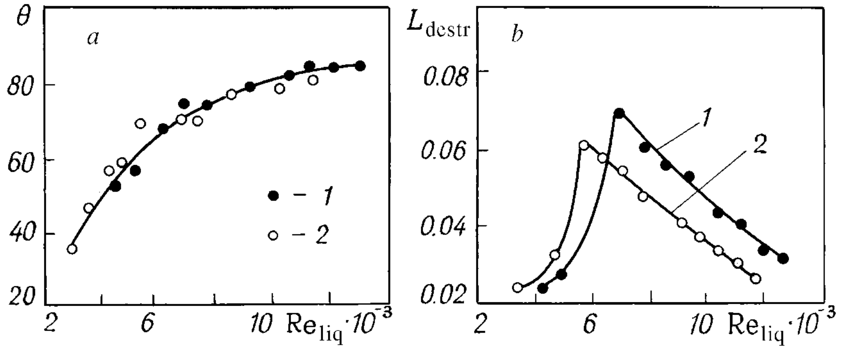

Fig. 3. Root angle of outflow of the solution film from the liquid nozzle (a) and distance "mouth of the nozzle–destruction zone of the film" (b) as functions of Reynolds number (C_{ch} = 0.625, l_{liq}/d_{liq} = 9.0, d_{liq}/d_n = 0.5, and F_{liq} = 15.9·10^{-6} m^2): a: 1) X = 0.19; 2) 0.38; b: 1) 0.19; 2) 0.285. θ, deg; L_{destr}, m.

Quite a different picture is observed in organization of the other two forms of outflow. As has already been noted, in this case the system for feeding a liquid in the vortex sprayer incorporates the swirler. When the air flow arrives the entire liquid is drawn in to the edge of the air-blast nozzle and is sprayed from it, forming a cone in which no large agglomerates are observed. Investigations of the operation of the liquid system of the vortex sprayer without feed of an air flow showed that the formation of the film or droplet form of outflow of a liquid from the nozzle 6 depends on its velocity. For low velocities, $V_{liq} < 0.2$ m/sec, the liquid flows out from the nozzle in the form of a cord whose number of filaments is determined by the number of channels in the swirler. With increase in the velocity, $V_{liq} > 0.2$ m/sec, the outflow acquires the film form since the liquid forms a "bubble" in the shape of an ellipsoid of revolution at the outlet from the nozzle; large droplets and agglomerates are separated from the external vertex of this ellipsoid. Such a form of film outflow is caused by the fact that the film is contracted at a certain distance from the nozzle's mouth under the action of surface tension forces. With increase in the outflow velocity the size of the "bubble" grows, and for a certain value of V_{liq} the surface tension forces turn out to be insufficient for the film to collapse. As a result, the film outflow acquires the shape of a "tulip" from whose edges large droplets are separated. The root angle formed by the film at exit from the nozzle's mouth can be used as the quantity which characterizes a change in the size in film outflow of the liquid. Figure 3a gives the root angle of the film versus the Reynolds number for a vortex sprayer with different values of $X = F_{sw}/F_{liq}$. The number Re_{liq} was changed by variation of the swirler cross section and by controlling the liquid flow rate, which was varied within 40–160 kg/h. It is seen from the dependences that the experimental points fall satisfactorily on the single curve for different X. As Re_{liq} increases, the value of the root angle of the film θ increases but the rate of change in θ decreases. The initial portion of the curve characterized by the most rapid growth in the angle θ corresponds to the form of outflow of the liquid in the shape of a "bubble" and a "tulip." The portion of the curve that corresponds to small changes in θ is due to the formation of film outflow in the shape of a cone. This is confirmed by the dependence of the distance "mouth of the nozzle – destruction zone of the film" on the Reynolds number (Fig. 3b). The character of the dependence $L_{destr} = f(Re_{liq})$ for sprayers with dissimilar cross sections of the swirlers of the liquid is identical. As Re_{liq} grows we observe first the departure of the destruction zone from the nozzle and then its approach. Such behavior of the dependence is explained by the fact that for small values of the Reynolds number the film outflow has the shape of an ellipsoid of revolution of a bubble whose size increases with Re_{liq} and the formation of droplets occurs on the external vertex of the ellipsoid. With a certain value of the Reynolds number, the destruction zone shifts to the ellipsoid, owing to which it acquires the shape of a "tulip" and then of a cone and, with increase in Re_{liq}, begins to approach the nozzle practically linearly until the film begins to fail immediately at the nozzle, i.e., the outflow becomes a dropletform. Thus, the passage from the film form of outflow to a droplet form and conversely in the case of the swirl of a liquid is determined by the velocity of its outflow.

The droplet form of outflow is attained for large values of the Reynolds number and hence rather high velocities of outflow of the liquid, which can be obtained when the values of the excess pressure of the solution are large. For example, in a vortex sprayer with $C_{\text{ch}} = 0.625$, $d_{\text{liq}}/d_{\text{ch}} = 0.5$, $l_{\text{liq}}/d_{\text{liq}} = 9.0$, and $F_{\text{sw}}/F_{\text{liq}} = 0.285$ the droplet form of outflow occurred for $V_{\text{liq}} = 12.1$ m/sec, which was attained when $\Delta P_{\text{liq}} = 520$ kPa.

It follows from the analysis of Fig. 3b that the film form of outflow depends on the value of the ratio $F_{\text{sw}}/F_{\text{liq}}$. For example, for $\text{Re}_{\text{liq}} = 6.0 \cdot 10^3$ in the sprayer with $X = 0.19$ the film has the shape of a "bubble," whereas in the sprayer with $X = 0.285$ it has the shape of a "tulip," i.e., it is as if the liquid flow in dispersers with a smaller value of X lags behind in its development. Apparently, this is related to the change in the kinetic energy of a liquid flow determined by both its velocity and mass flow rate.

The performed analysis shows that out of the three forms of outflow of the liquid from the nozzle it is the film form that is the most acceptable for operation of vortex sprayers. With the given form of outflow, even for air-flow velocities of 5–10 m/sec, the film of the solution shifts to the air-blast nozzle directly from the liquid nozzle and is sprayed from the edges of the head 8. The optimum values of the velocity of flow of the liquid through the swirler are in the range 1.5–5.0 m/sec, and they are attained for values of the excess pressure of 40–100 kPa. No influence of the change in the flow velocity of the liquid on the dispersity of the spray is detected in the indicated range.

NOTATION

R, mass fraction of droplets (whose diameter is larger than d_i) in the cone; d_i, running diameter of the droplets; F_0, cross-sectional area of tangential channels; $C_{\text{ch}} = d_{\text{n}}/d_{\text{ch}}$, degree of contraction of the vortex chamber; d_{n} and d_{ch}, diameters of the air-blast nozzle and the vortex chamber; ΔP and ΔP_{liq}, excess pressure of the air and the liquid; G_{liq} and G_{g}, flow rate of the liquid and the gas; $\text{Re}_{\text{liq}} = V_{\text{liq}} d_{\text{liq}}/\nu_{\text{liq}}$, Reynolds number of the liquid flow; V_{liq}, axial velocity of flow of the liquid; d_{liq}, diameter of the liquid nozzle; ν_{liq}, kinematic viscosity of the liquid; X, degree of contraction of the liquid system of the sprayer; F_{sw} and F_{liq}, cross-sectional areas of the channels of the swirler and the liquid nozzle; l_{liq}, length of the liquid nozzle; L_{destr}, distance "mouth of the nozzle–destruction zone of the film"; θ, root angle of outflow of the solution film.

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