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The influence of condensation on the supersonic flow sizes

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The role of condensation on the shape and size of a supersonic argon stream flowing from a nozzle into a rarefied space is considered. It is shown that with the growth of cluster sizes, both the primary „traditional" supersonic jet and the external cluster flow formed when heavy clusters penetrate through the lateral compressed layers of the primary flow into the surrounding background gas increase. The type of the correction factor in the well-known empirical formula proposed by Ashkenas and Sherman is found, in view of which this formula can be used under the conditions of clustered flows. The reasons for the impact of clusters on the gas dynamics of supersonic flow, as well as conditions and limitations of such an effect, are discussed.

Keywords: gas dynamics, supersonic nozzle, condensation, clusters, argon jet, photometry.

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The literature presents many experimental studies, as well as theoretical and empirical models, describing the processes of supersonic gas jets formation in flowing from different-configuration nozzles into a rarefied flooded space [1–3]. For instance, the classical paper by Ashkenas and Sherman [1] proposes a reliable description of the supersonic jet longitudinal size (from the nozzle edge to Mach disk) for various gases, which is widely used over the world. However, beginning from the last midcentury, studies of formation of van der Waals clusters arising during adiabatic gas outflowing from the nozzle [4,5], as well as active practical application of these clusters in various technologies, necessitated defining the clusters effect on the shape and geometric dimensions of supersonic jets. As our studies showed, changes depending on the cluster mean size are observed in longitudinal dimensions of the so-called „barrels" in the form of which supersonic jets expand during outflowing from both sonic and supersonic nozzles into a flooded rarefied space [6]. At the same time, it was found out that under certain conditions a new-type flow coflowing with conventional barrels [7] arise around clustered supersonic jets, i. e., „primary" barrels; the shape of this flow is similar to that of the primary one, but dimensions are significantly larger. The authors named it as „wake". As shown by the analysis of formation conditions and properties of this flow, it stemmed from formation of clusters in the primary jet.

The goal of this study was to reveal the effect of clusters on the geometry of both the primary and coflowing jets, and also to obtain corrections making it possible to use the model given in [1] in the case of the clustered supersonic jet.

The studies were performed at the pilot laboratory gas-dynamic bench LEMPUS-2 whose detailed description is given in [8]. In this work, an argon supersonic flow in the continuous-outflow mode was used. The jet gas luminosity was excited with a focused 10 keV electron beam. Luminosity of the gaseous objects under study was registered by the Nikon D7200 camera through a quartz optical window. The gas flow, electron beam and optical device axes formed an orthogonal vector triplet. In view of the focused electron beam scattering from phonon particles, secondary electron drift towards the earthed nozzle, and also of the existence of long-living excited particle levels, the emission was observed in both the upstream and downstream directions. Fig. 1, *a* presents an example of the argon flow photo. The brighter is the image area, the higher is the respective local density of gas. One can clearly see the conventional spindle structure of the primary supersonic jet with brighter edges that are the region of lateral compression shocks and with the zone of mixing. Expectedly, in the case of outflowing from the supersonic nozzle, the so-called X-like configuration is formed instead of the conventional Mach disk; in this configuration, lateral compression shocks join together, and a second lower-intense barrel is formed downstream. The coflowing jet („wake") glows much less brightly (and is slightly visible in the photo). However, proper secondary processing of the image (subdividing the image converted to the „shades of gray" format into separate areas with relatively low difference in the emission intensities, as well as regulation of their brightness, contrast, white-balance, and depth of dark and light areas) finally provides significantly more informative image of the same jet (Fig. 1, *b*) which enables the analysis of the flow geometrical dimensions, shape and specific structural features. In this work, data on the cross dimensions of the primary jet and „wake" in the region of maximum cross section were analyzed.

Let us use the formula proposed in [1] to generalize the data on the maximal cross size of the jets (notice that the correctness of applying to the jet cross sizes the Ashkenas–Sherman dependence in the case of outflowing

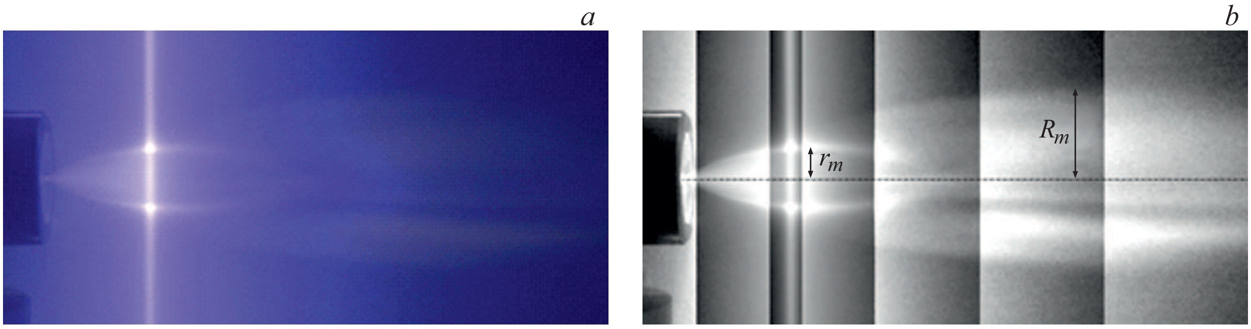

Figure 1. The image of the supersonic flow under the conditions of cluster formation and in the presence of a coflowing cluster jet. a — the initial photo, b — the image after processing.

from supersonic nozzles and formation of the X-like structure is an assumption that is also going to be verified in this study):

$$r_m/d_* = k\sqrt{N}, \tag{1}$$

where r_m is the jet radius in the maximal cross section, d_* is the nozzle diameter in the critical cross section, $N = P_0/P_\infty$ is the ratio between the stagnation pressure and background-space pressure, k is the constant numerical coefficient. This empirical formula was obtained for the modes when formation of gas clusters in jets was negligible. To verify relation (1) under the conditions of developed condensation, let us analyze the recorded measurements of radii of the conventional primary jet (r_m) and clustered „wake" (R_m). The LEMPUS-2 bench equipment ensured controlling not only initial flow parameters (P_0, P_∞, T_0) but also their variations within the required range. This allowed performing independent series of measurements by changing one of the main variable parameters of the flow with keeping constant two others.

Fig. 2, a presents the measurements of r_m (circles) and R_m (squares) versus $N^{0.5}$ at fixed P_0 and T_0 and P_∞ variation (series 1). This figure also demonstrates dependence (1) calculated for r_m and R_m with constant coefficients (the lower and upper curves, respectively). Since variation in the background pressure does not affect formation of clusters in the jet, formula (1) with the fixed coefficient describes experimental data with a high accuracy.

Fig. 2, b presents the measurements in the same coordinates depending on the P_0 variation at fixed T_0 and P_∞ (series 2). As expected based on the results of previous studies, the experimental data do not obey a linear dependence and tend to increase with increasing P_0.

A similar result is observed also in plotting the dependence of cross sizes of the primary and coflowing jets on T_0 at fixed P_0 and P_∞ (series 3). When temperature increases, intensity of the cluster formation process decreases, and cross sizes of the primary and coflowing jets also decrease. Thus, coefficient k in relation (1) remains constant in the absence of condensation or in the absence of its variation, increases with increasing stagnation pressure and decreasing stagnation temperature, and, hence, with increasing cluster size and condensate fraction for both the primary jet and clustered „wake". Thereat, as in the previously described case [6], the increase in coefficient k tends to a certain limit.

Using experimental dependences demonstrated in Fig. 2, it is possible to determine coefficients k and K of the conventional and clustered jets, respectively, for each measurement result depending on the mean cluster size $\langle S\rangle$ calculated according to [4]. The obtained dependences determined based on the measurements of both the primary jet (circles) and „wake" (squares) are presented in Fig. 3. Experimental data obtained by varying either stagnation pressure (dark symbols) or stagnation temperature (empty symbols) form unified dependences having similar shapes. The curves in the main panel are plotted in the logarithmic abscissa scale (to make visible the point where the dependence approaches the lower limit). The Fig. 3 inset presents the same curves but in the linear scale of the $\langle S\rangle$ axis (thus illustrating the tend to the upper limit). Evidently, the dependences tend to constant limits both with decreasing cluster size and significantly increasing cluster size. The lower limit is caused by the constancy of the coefficients in the absence of condensation, while the upper limit arises due to the restriction of the condensate fraction in the jet and also to the restriction of the efficiency of the monomer background scattering (m is the monomer mass) from the jet cluster particles (M is the cluster mass) when their ratio tends to infinity ($M/m \to \infty$). The k and K variation ranges for both jets are restricted by the cluster size range $10 < \langle S\rangle < 10^4$.

As our analysis showed, the obtained experimental data may be described by the following relation:

$$r_m/d_* = \Big(k_{\min} + \Delta k\big(1 - \exp(-\langle S\rangle/q)\big)\sqrt{N}\Big), \tag{2}$$

where $\Delta k = k_{\max} - k_{\min}$; $k_{\max} = 0.134$ is the maximal $k(\langle S\rangle)$ value in the clustered jet at $\langle S\rangle \to \infty$; $q = 1650$ is the constant coefficient (the same for both jets) obtained in optimizing the dependence, which appeared to be equal to the constant included in the Γ^* dependence [4]. Evidently, in the absence of condensation, i.e. at $\langle S\rangle = 1$, factor $\exp(-\langle S\rangle/q)$ tends to unity and k tends to $k_{\min} = 0.113$, while with increasing cluster size the exponent tends to zero

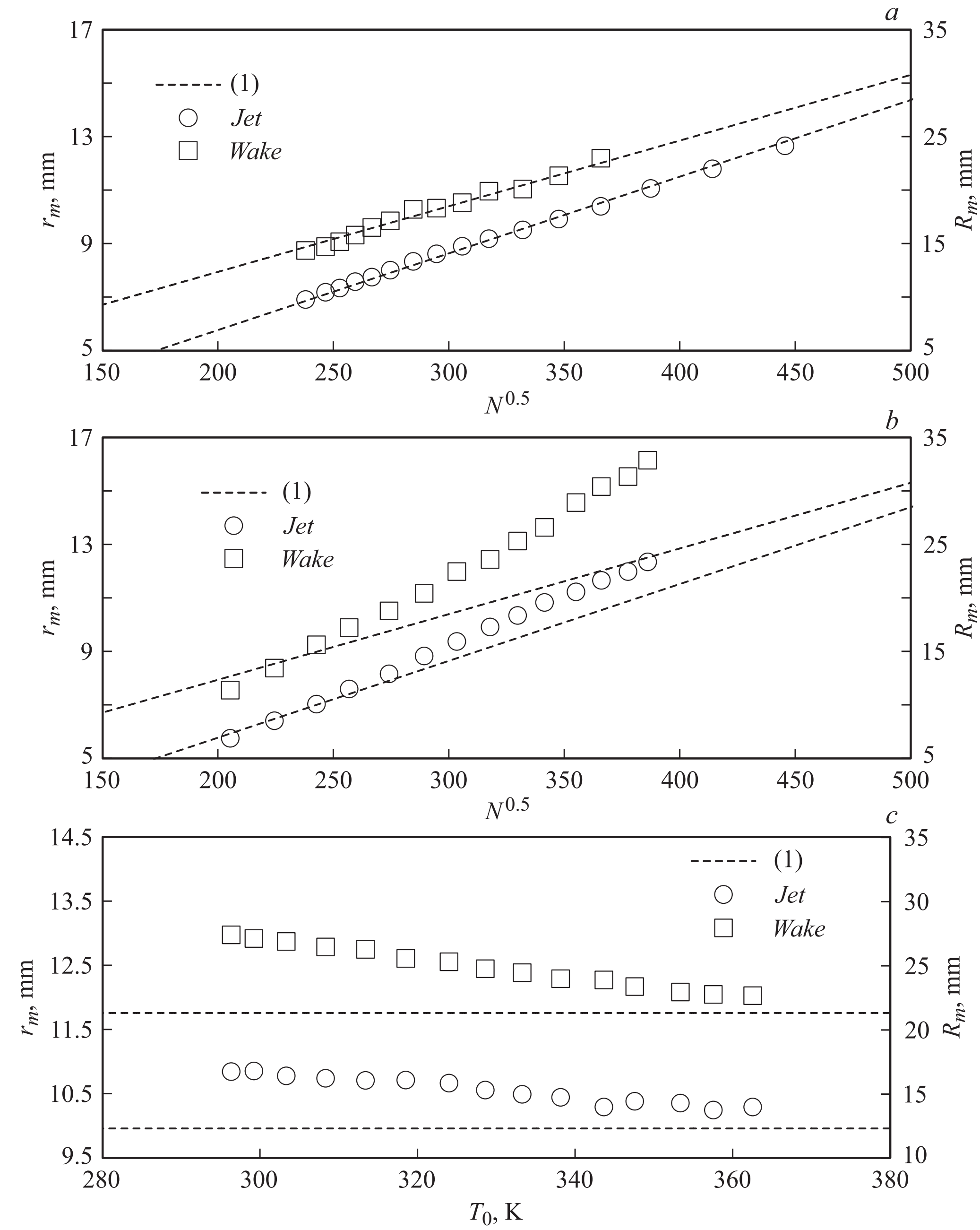

Figure 2. Variations in r_m and R_m in the maximal cross section occurring in expanding from the supersonic nozzle ($d_* = 0.24$ mm, outlet cross section diameter $d_a = 1.55$ mm, diffusor length $L = 3$ mm, Mach number $M_a = 8.6$). a — P_∞ variation at fixed $P_0 = 0.4$ MPa, $T_0 = 42°$C, b — P_0 variation at fixed $P_\infty = 6$ Pa, $T_0 = 32°$C, c — T_0 variation at fixed $P_0 = 0.6$ MPa and $P_\infty = 5$ Pa. Values of coefficients are: $k = 0.12$, $K = 0.256$.

and coefficient k tends to $k_{\max}$. The obtained coefficient k dependence in the primary flow is represented in Fig. 3 by the lower curve (the left-axis scale); that in the „wake" is represented by the upper curve (right−axis scale). It is worth emphasizing that the paper presents the results for only one of the used nozzles whose parameters are shown in Fig. 2. However, the data the authors possess at present on several supersonic nozzles also fall on the proposed generalizing dependence.

Thus, based on the measurements performed, corrections for the known Ashkenas−Sherman model [1] were obtained, which account for the influence of condensation on the geometry of both the conventional supersonic jet and revealed coflowing clustered jet. It was established that the shape of the dependence for the clustered „wake" appeared to be similar, which evidences for the similarity of the gas-dynamic processes defining the shape and geometric parameters of the conventional supersonic flows and coflowing clustered jet arising only under certain conditions during

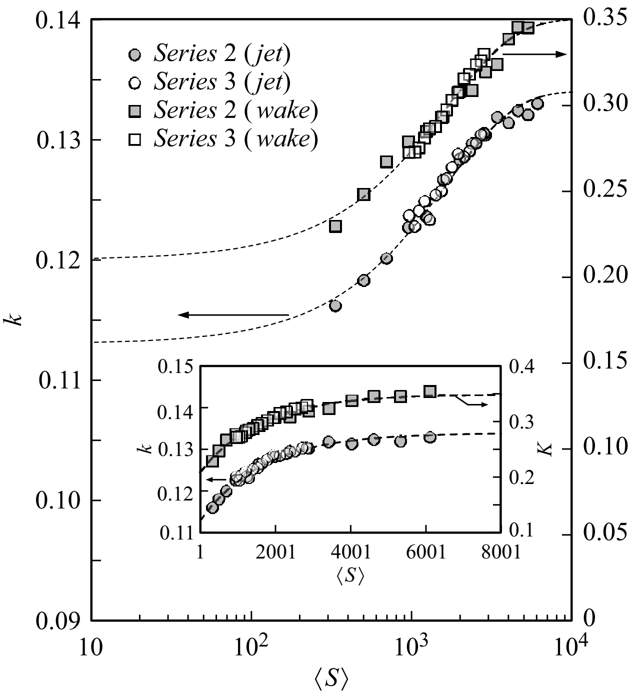

Figure 3. Coefficients k and K for the conventional jet and clustered „wake" respectively, with varying P_0 (series 2) and T_0 (series 3) versus the mean size $\langle S \rangle$ of the jet clusters (in the logarithmic and linear coordinates).

the conventional jet outflow with condensation. Some features distinguishing the conventional and clustered jets from each other were also revealed. Empirical dependences obtained for argon made it possible to estimate the effect of condensation on the supersonic jet gas dynamics during outflowing into a rarefied medium.

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Conflict of interests

The authors declare that they have no conflict of interests.

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