The Structure of Supersonic Underexpanded Nitrogen Microjets

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Abstract This article contains the results of investigating the gas-dynamic structure of supersonic underexpanded axisymmetric microjets of nitrogen flowing from sound nozzles with a diameter of 10 ÷ 340 μm. The length of the supersonic part of the jet significantly increases together with a decrease in nozzle diameter starting from the size 23 μm. Measurement results are compared with known data obtained for macro- and microjets.

Keywords: Micro Flow, Supersonic Microjets, Micro Pitot Tube

1. Introduction

Recently, supersonic microjets have found a use in controlling gas-dynamic flows (Kumar and Alvi 2006, Zhuang et al. 2006, Lou et al. 2006). The main advantage of microjets is their local impact and the possibility of creating arrays of high density microjets without increasing gas consumption. The effectiveness of using supersonic microjets depends on the length of their supersonic core length (range capability) which, in turn, is determined by the diameter and the Mach number at the nozzle exit, the degree of off-design of the jet, and the adiabatic exponent of gas. On the basis of experimental data for macrojets in a wide range of sizes of nozzles, Mach numbers, and the degree of off-design and temperature of the gas, the studies Shirie and Seubold (1967), Pogorelov (1977) present universal relations between the off-design of the jet and the length of its supersonic part. These relations show that under otherwise equal conditions the length of the supersonic part is proportional to the exit diameter of the nozzle. The impact of the nozzle scale factor in micron sizes on the length of the supersonic core length of the jet has not been previously investigated. The aim of this work is to study experimentally the impact of the diameter of a sonic nozzle on the length of the supersonic core length of a nitrogen jet flowing out into the atmosphere.

2. The Experiment

In the experiments, the gas-dynamic structure of supersonic jets of nitrogen flowing out from round sonic nozzles with a sharp edge of diameter D = 10.4, 23, 65.3 and 340 μm was investigated (Fig.1). The subsonic part of the nozzles was a conic narrowing with an initial diameter of 4 mm at an angle of 47°. The roughness of the nozzle edge was ≅ 1 μm. The experiments were carried out with the gas at room temperature in the range of the jet's off-design values of N = 1.38 ÷ 4.2, which corresponds to a range of Mach numbers of the calculated jet M_j = 1.25 ÷ 2.06.

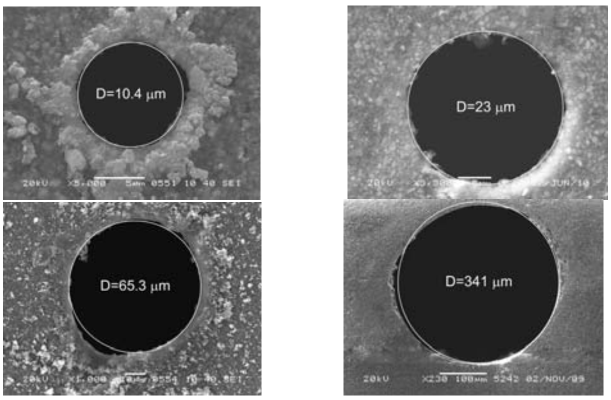

Fig. 1. SEM images of the nozzles

Measurements in the jet were made using an impact tube (Pitot tube) with diameter of 12 μm and a wall thickness of 1 μm. We measured the distribution of total pressure along the axis of the jet. Simultaneously we recorded the pressure of nitrogen in the chamber before the nozzle.

3. Results

As an example, Figure 2 shows the distribution of total pressure on the jets axis, normalized to the total pressure at the nozzle exit for the degree of off-design $N = 3$ and for three sizes of nozzle diameter. It can be seen that the relative length of the section with a periodic change in total pressure, which corresponds to the presence of the wave structure in the jet, increases with a decrease in the diameter of the nozzle. Moreover, the relative length of the section of the jet where the total pressure exceeds the level corresponding to the transition to subsonic flow also increases.

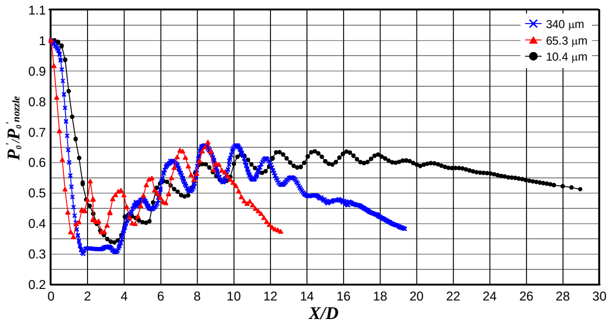

Fig. 2. Distribution of total pressure on the jets axis

Figure 3 shows the integrated data of measuring the relative supersonic core length X_s/D against the degree of the jet's off-design N. Figure 3 also shows the universal relations obtained by Shirie and Seubold (1967), Pogorelov (1977) and experimental data for micronozzles obtained by Phalnikar et al. (2008). It can be seen that the lengths of supersonic sections in the jets flowing out from the nozzles with a diameter of 65 µm and more are in good agreement with universal relations. For smaller diameters, the relative length of the supersonic section is significantly increased. However, no significant changes in the value of the average shock cell length of the wave structure in the jets were found (see Fig. 4) except for the nozzle with the diameter of 10.4 µm.

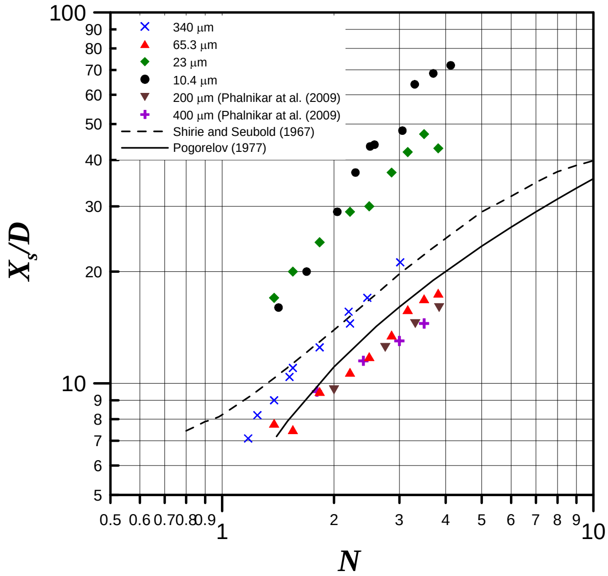

Fig. 3. Supersonic core length

The most significant changes in the dimensionless parameters of the jet with different nozzle diameters are related to the Reynolds number Re and the Knudsen number Kn, calculated on the basis of flow parameters at the nozzle exit and its diameter. For the nozzles with a diameter of 200 µm or more, the Reynolds numbers exceed the value of 10^4 ($Kn < 10^{-4}$). For the nozzles with diameter 10.4 µm and 23 µm, the Reynolds numbers lie in the range of $\sim 10^3$, and Kn numbers lie in the range of $\sim 10^{-3}$. According to the study Avduevskij et al. (1971), the range of Reynolds numbers $10^3 - 10^4$ separates the regimes of laminar and turbulent outflow of underexpanded macrojets at their initial part. Accordingly, the microjets of small diameter may have a more extended section of laminar flow, which reduces the intensity of mixing processes and increases the length of the supersonic section. However, this does not explain the reasons for the further growth of the relative range capability of microjets with decrease in the nozzle diameter.

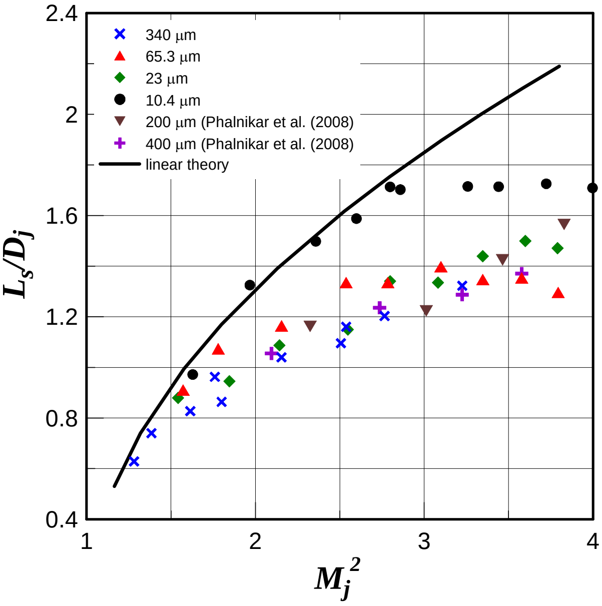

Fig.4. A comparison of shock cell length

On the other hand, at relatively large Knudsen numbers, the effects of rarefaction can occur in microjets of small diameter, for example, slipping of the flow in the nozzle, which also leads to increased length of the supersonic part of the jet. Yet, the same effects lead to increased role of viscosity in the flow. Therefore, identifying the causes of the increase in the range capability of supersonic microjets requires further experimental and theoretical studies.

3. Conclusion

Thus, for the first time we discovered a significant increase in the relative supersonic core length of axisymmetric underexpanded nitrogen jets flowing out into the atmosphere from sonic nozzles with a diameter of 10–20 μm.

It is shown that the relative supersonic core length in underexpanded microjets flowing out from the nozzles with a diameter larger than 65 μm is well described by the universal relations obtained for jets of macroscopic sizes. Little impact of the nozzle size on the average length of wave structure cells in the initial part of an underexpanded microjet is demonstrated.

This work was supported by the Russian Foundation for Fundamental Research (Grant 11-08-00205-a), the Interdisciplinary Integration Project of the Presidium of SB RAS no. 110, and the Program of the Presidium of SB RAS no. 11/10.

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