Experimental study of shock-wave structure of supersonic underexpanded microjets

I Timofeev¹, V Aniskin² and A Maslov²
¹Novosibirsk State University, 630090, Novosibirsk, Russian Federation
²Khristianovich institute of theoretical and applied mechanics, 630090, Novosibirsk, Russian Federation

e-mail: ivan.timofeev.koi@gmail.com

Abstract. The structure of supersonic underexpanded room temperature air microjets is experimentally studied. Microjets escaping from the nozzles with characteristic heights of 22.3 and 83.3 μm and widths of 2410 and 3900 μm respectively with the Reynolds numbers of 640 and 2390. At these Reynolds numbers hot-wire anemometer measurements of mass flow pulsations are performed. It is shown that low value of the mass flow pulsations are corresponding with the high supersonic core length.

1. Introduction

In view of the broad possibilities of application of microscopic gas and liquid devices (microfluidics), considerable research interest is presently devoted to studying fluid flows on the microscopic scale, including both the fluid flow in channels and jet emission from micron-sized orifices. Depending on the output pressure, a jet can be either subsonic or supersonic. Both subsonic and supersonic microjets used in macroscopic flow control, noise reduction, and jet cooling systems.

The number of reported experimental investigations devoted to supersonic microjets is not large [1–7]. Previously, we have studied in detail the structure of axisymmetric supersonic microjets [3, 4]. It was found that the relative shock cell size in micro and macrojets have no significant differences. However, at some values of the jet pressure ratio, the supersonic core length of microjets exhibits a significant increase as compared to that of macrojets. Here, the jet supersonic core length defined as the distance from the nozzle exit to a point on the jet axis where the flow velocity attains the local sound velocity value. A transition from the regime of a large supersonic core length to that characteristic of macrojets takes place at Reynolds numbers between 1100 and 2100 and related to the transition from laminar to turbulent flow.

There are numerous experimental and theoretical works devoted to studying the structure, noise, and interaction with obstacles for supersonic rectangular macrojets [8–10]. However, to the best of our knowledge, no published data are available on the supersonic core length of two-dimensional supersonic macrojets. Experimental investigations of the structure of supersonic microjets have not been reported except for our recent work [5], in which data were presented for the only one Reynolds number.

The goal of the present research was in getting deeper knowledge of the structure of the supersonic jet core. In this investigation hot-wire anemometer measurements were used to show the average signal and mass flow rate pulsations in the supersonic microjet.
Used nozzles were produced by the technology from [4]. Each nozzle had a cylindrical prechamber with a diameter of 4 mm and a wedge shaped narrowing taper part. In the present work, data are presented for jets escaping from nozzles with height of 83.3 μm and 22.3 μm.

2. Experiments

The nozzle dimensions and experimental parameters listed in the table 1. Here AR is the aspect ratio - ratio of width and height of the nozzle, JPR is the jet pressure ratio (defined as the ratio of static pressure at the nozzle exit to pressure in the surrounding space), Re is the Reynolds number calculated for the given nozzle height and gas parameters at the nozzle exit.

| Height (μm) | Width, (μm) | AR   | JPR | Re |
|------------|-------------|------|-----|----|
| 83.3       | 3823        | 45.9 | 1.06| 2390|
| 22.3       | 2593        | 116  | 1.06| 640 |

Previously supersonic flat underexpanded microjets studied using the method of flow visualization [7] and measuring the total pressure distribution along the jet axis [6]. Pitot tube measurements shows that for micronozzles with height below 50 μm realized a high supersonic core length effect.

Hot-wire anemometer experiment’s scheme presented in figure 1. The working fluid was room temperature air, and the supersonic air microjet was escaping into atmosphere. The wire sensor, which had the wire diameter of 5 μm and the length of 200 μm, mounted in a holder that could be moved in three mutually perpendicular directions with the Narishige NT 88E micromanipulator and positioned in space to within an accuracy of ±1 μm. The sensor position monitored using the Nikon SMZ 1500 stereoscopic microscope.

![Figure 1](image)

**Figure 1.** The hot wire measurements experiments scheme.

Figure 2(a) and figure 2(b) shows the typical microphotographs along the greater axis of the jets escaping from the nozzles with height of 83.3 μm and 22.3 μm consequently. Pressure in the prechamber equal to 2 atm.
Figure 2. Photographs of air microjets escaping from the micronozzles at pressure in the prechamber equal 2 atm. Height of the micronozzle: (a) 83.3 μm, (b) 22.3 μm.

Figure 3 presents the longitudinal profile of the pressure measured by the Pitot tube in the jet escaping from the nozzle with height of 83.3 μm. The measurements performed along the line of intersection of the nozzle symmetry planes.

Figure 3. Longitudinal distribution of pressure along a jet escaping from the nozzle with h = 83.3 μm for various off-design parameters.

As can be seen, the $P_0'$ value exhibits a smooth change of pressure along the microjet. The pressure value in the prechamber is not high enough that a shock-wave structure is realized in the jet.

The supersonic core length of the flat underexpanded microjets was determined from $P_0'$ distributions along the line of intersection of the nozzle symmetry planes. The results presented in figure 4. However, the supersonic core length of the jet escaping from nozzle with $h = 22.3$ μm at JPR < 1.5 is greater than the values for other microjet, i.e. long supersonic core length regime. Analogous increase in the jet range observed for supersonic axisymmetric microjets [4]. Indeed, it was found in [4] that the supersonic core
length of axisymmetric microjets escaping from nozzles with diameters above 60 μm corresponds to that of axisymmetric macrojets, while the microjets escaping from nozzles with diameters below 60 μm exhibit long supersonic core length.

![Graph showing supersonic core length vs JPR](image)

**Figure 4.** Supersonic core length vs JPR.

Figures 5 and 6 show contours of the average signal (a) and the RMS mass-flow pulsations (b) for the supersonic jets escaping from micronozzles with the height of 83.3 μm and 22.3 μm reference. Pressure in the prechamber in both cases were 2 atm. As can be seen for the contours of microjet escaping from the nozzle with height of 22.3 μm (figure 6) at the distance of 10 nozzle sizes from nozzle plane, microjet starts to expand. It depends on the laminar-turbulent transition in the jet-mixing layer. Also we could notice that in the case of the jet escaping from the nozzle with height of 83.3 μm jet starts to expand closely to the nozzle exit.

Recently, we have demonstrated [11] that the long supersonic core length regime of supersonic axisymmetric microjets related to a laminar flow in the jet-mixing layer. It suggested that an increase in the supersonic core length of supersonic flat underexpanded microjets also related to a laminar flow in the mixing layer.
Figure 5. The contours for microjet escaping from the nozzle with height of 83.3 μm: (a) average signal and (b) RMS signal.

Figure 6. The contours for microjet escaping from the nozzle with height of 22.3 μm: (a) average signal contour and (b) RMS signal.

As for the axisymmetric microjets, high supersonic core length effect is realized for the two-dimensional microjets. The growths of the supersonic core length are associated with the laminar flow in the jet-mixing layer. Supersonic core length of the jet escaping from the nozzle with height of 22.3 μm is equal to the $L_c/h = 10$. 
In the jet’s downstream the flow starts to expand. This effect could be seen in the plot of average and RMS signals. For the jet escaping from the nozzle with height of 83.3 μm, length of laminar mixing layer is commensurate with nozzle height. The turbulence of the jet-mixing layer occurs starts closer to the nozzle exit. Due to this effect jet starts to expand on the distance of \( X/h = 2.5 \) and supersonic core length is equal to \( L_c/h = 5.5 \).

3. Conclusion
Hot-wire anemometer measurements shows that flow regime of jet-mixing layer are affect to the supersonic core length. It is shown that laminar flow regime in the jet-mixing layer contribute to the length of the supersonic section increases.

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