Determination of the heat transfer coefficient during the leakage of a subsonic axisymmetric air mini jet onto a plate

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Abstract. In the present article, the heat transfer coefficient was determined experimentally when a subsonic jet flows onto a plate. The jet escaped from axisymmetric nozzles with a diameter of \(d = 290\), \(540\), and \(980\) μm. The experiments were carried out at the speeds of \(V = 5\), \(20\), \(40\), \(60\), \(80\) and \(100\) m/s in the Reynolds numbers range of \(100\) – \(7000\). The Nusselt number distribution was obtained for different distances between the nozzle and cooled surface.

1. Introduction
There are a lot of papers the heat transfer coefficient determining when a subsonic jet flows onto a heated surface [1, 2]. However, the number of papers where mini- and microjets were used, are extremely small. In [3], the authors used a jet escaping from the stainless tube with an external diameter of \(D = 1.6\) mm and an internal \(d = 125\) μm. The channel length was 25 mm; the Reynolds numbers range varied from 690 to 1770. The authors used a stainless plate 50 μm thick coated with a black paint from below. A thermal imaging microscope was used to record the surface temperature.

The Nusselt number is the main characteristic of the heat transfer process when the jet flows onto a plate. The paper [4] describes several general approaches for the Nusselt number determination. A metal foil heated by the electric current is exposed to a gas jet. The heat flux is set by the electric current, the surface temperature is measured by glued thermocouples, thermal imagers or liquid crystals. In every case, the foil thickness becomes a decisive factor for microscales due to the lateral heat flux in the foil with the high thermal conductivity. The manufacture of thin foils means great technical difficulties for the thermocouple method. Thermal imaging is also possible only if the foil is coated with the quite thick layer of a thermally emitting paint.

The plate surface is underestimated by the thermal imager when using plastics. The reason is the plastic transparency for infrared radiation, due to which the measured temperature is averaged in the layer with a thickness equal to the depth of infrared radiation penetration into the plastic. The scale of the problems considered requires the temperature averaging in the layer of max 10 microns thickness.

The method of surface temperature distribution measuring based on a thermosensitive fluorescent coating was developed for this purpose.

The authors compared two panoramic methods to study the heat transfer process between a jet and a plate. The first method suggests that the cooled surface was made of polyether ether ketone (commercial name is PEEK) with the relatively low thermal conductivity in order to avoid the lateral heat transfer inside the material. This plastic has the high heat dissipation and is suitable for direct
thermal imaging measurements. The second approach involves the thermosensitive fluorescent coating based on rhodamine B, applied to a stainless plate. Data obtained by these methods are compared with the results of numerical simulation.

The surface of the stainless plate of 15 μm thick was coated with a thin layer of the fluorescent paint; its fluorescence intensity depends on its temperature. Rhodamine B is a convenient fluorophore that is already used in aerodynamic measurements. The coating included rhodamine B and an optically transparent polymer – the polyurethane varnish. Under the influence of the exciting radiation, the resulting coating fluoresced with a maximum intensity at a wavelength of 600 nm. To measure the temperature distribution on the surface of the plate, a polyurethane varnish coating with a rhodamine concentration of 30 mg/ml was used. In this case, the penetration depth of the exciting radiation was about 2 μm, and the layer thickness (about 50 μm) did not matter.

The experiments to study the heat transfer of a microjet plate involving the fluorescent coatings based on rhodamine B, enabled to measure the surface temperature distributions with much simpler technical means with the higher spatial resolution. Therefore, we have chosen this very method of heat transfer coefficient determining. It is necessary to know the surface temperature $T_w$ and the adiabatic temperature of the surface $T_{wa}$, as well as the heat flux $q$, which was determined by the input electric power to determine the heat transfer coefficient:

$$q = UI \quad \alpha = \frac{q}{T_w-T_{wa}}.$$

The Nusselt number was defined in the standard way as $Nu = \frac{\alpha d}{\lambda}$ where $\alpha$ is the heat transfer coefficient, $d$ is the diameter of the nozzle, and $\lambda$ is the air thermal conductivity coefficient.

2. Experiments

Figure 1 shows the nozzle diagram, their internal geometry and photos of the nozzle exit. Table 1 presents the parameters at which the experiments were performed.

The prechamber was a cylinder with a conical narrowing to the nozzle exit. There was a hole for measuring pressure in the prechamber.

![Nozzle Diagram and Photos](image)

**Figure 1.** The scheme of the nozzles, its internal geometry and SEM images of the nozzle exit.

| d (µm) | Re     | h/d   | V (m/s) |
|--------|--------|-------|---------|
| 980    | 340-7000 | 0.5-10 | 5-100   |
| 540    | 187-3700 | 1-18  | 5-100   |
| 290    | 100-2000 | 1.7-30 | 5-100   |
The prechamber was a cylinder with a conical narrowing to the nozzle exit. There was a hole for measuring pressure in the prechamber.

Figure 2 shows the experimental scheme and a photo of the test bench.

![Experimental Scheme and Test Bench Photo](image)

**Figure 2.** The experimental scheme and a test bench photo.

![Thermal Test Bench Scheme](image)

**Figure 3.** The thermal test bench scheme.

Nitrogen was used as the working gas. The gas flow rate was set with a flow controller. The nozzle was mounted on a coordinate rack which permitted the nozzle to be moved in the vertical direction. This enabled to change the distance between the nozzle and the plate. Two cameras were used in the
experiments: one recorded the fluorescence intensity of the coating of the heat stand, the second recorded the distance between the nozzle and the surface of the heat stand. To excite the heat stand surface fluorescence, a blue LED located next to the first camera was used.

The heat stand (figure 3) was a textolite parallelepiped with a rectangular hole in the center. The stainless steel foil with a thickness of 15 μm was fixed with copper bars in the grooves of the textolite. An electric current was supplied to the copper busbars. A layer of varnish with rhodamine was applied on a stainless foil, the layer thickness of about 90 μm. The bottom plate was insulated with an airgel. The airgel was chosen as a heat insulator, for the material has a very low thermal conductivity coefficient $\lambda = 0.016$ W/(mK).

As an example, figure 4 shows the distribution patterns of the adiabatic temperature, the temperature of the heated plate, and the Nusselt number for the nozzles of 540 and 290 μm. The good axisymmetric distribution of the adiabatic temperature, the heated plate temperature, and the Nusselt number are clearly seen at a small distance from the heated surface. Then, as the distance increases, the distribution becomes not axisymmetric.

Figure 4. The distribution of adiabatic temperature, the heated plate temperature, and the Nusselt number for the nozzles with a diameter $d = 540$ μm, Re = 2220 (a) and $d = 540$ μm, Re = 1200 (b)

Figure 5 shows the Nusselt number distribution at different distances between the cooled surface and nozzle with a diameter of 980 μm at $V = 60$ m/s.

Figure 5. The Nusselt number distribution for the 980 μm nozzle.
The Nusselt number at the frontal point ranges from 37 to 46 and reaches its maximum value at a height of \( h/d = 4.1 \).

The Nusselt number distribution at the frontal point when the jet escapes from the 540 µm nozzle is almost the same and equals to 17-19 (see figure 6).

![Figure 6. The Nusselt number distribution for the 540 µm nozzle.](image)

The Nusselt number distribution at the frontal point in the case of the smallest nozzle (290 µm in diameter) is of the similar nature (figure 7). Here, the Nusselt number reaches 8 – 8.5.

![Figure 7. The Nusselt number distribution over the plate for the 290 µm nozzle.](image)

3. Conclusion
The Nusselt numbers decrease significantly as the nozzle diameter decreases.

For the nozzles with a diameter of 540 and 290 µm, the Nusselt number distribution is practically independent of the location of the nozzle above the heated surface in the range of distances \( x/d \) from 0.9 to 10.

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References
[1] Dyban E P and Mazur A I 1982 Convective heat transfer during jet flow around bodies (Kiev: Naukova Dumka)
[2] Colucci D W and Viskanta R 1996 Exp. Therm. and Fluid Science 13 71-80
[3] Patil V A and Narayanan V 2005 Microscale Thermophysical Engineering 9 183-97
[4] Maslov N A, Aniskin V M, Korotaeva T A and Tsibulskaya E O 2019 AIP Conference Proceedings 2125 030002