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The effect of initial disturbances in the Hagen-Poiseuille impact jet on the intensification of wall heat transfer

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An experimental study of heat transfer in an impact air jet flowing out of a long round pipe ($l/d > 100$) at low Reynolds numbers of (Re $= 250-12\,000$) was made. Three variants of the pipe inlet geometry were studied: sudden contraction, conical confuser, profiled nozzle. Instantaneous and statistical data on local heat transfer were obtained at large distances to the obstacle ($h/d = 20$). Localization of heat transfer for laminar jets in the critical point region was found for three variants of the pipe inlet. Initial conditions with a lower level of disturbances increase the critical Reynolds number and also promote heat transfer intensification in the critical point region.

Keywords: Hagen-Poiseuille flow, laminar-turbulent transition, initial conditions, velocity pulsations.

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One of the efficient techniques of heat transfer intensification is to use impact jets of gas and liquid. In this case, two applied problems of heat transfer are essential: cooling of localized small areas and sufficiently large areas [1–3]. In practice, the configuration with profiled confusors, high Reynolds numbers (Re $> 10^4$) and small distances to the obstacle $h = (4-6)d$ (where d — nozzle diameter) [1–3] is the most optimal for heat transfer intensification in the near-wall region of impact jets. Given these parameters, there is a small local maximum of heat transfer in the critical point region and a smoothly decreasing distribution of heat flux over the radius of the obstacle. As a result of experiments [4], the heat transfer was greatly increased (by more than 300%) in the critical point region for jet flow from a long tube at low Reynolds numbers. There is a limited number of studies on heat transfer in impact laminar jets under such conditions (flow from a tube, Re < 6000, distance to the obstacle $h/d > 10$) [1–3]. These Reynolds numbers are characterized by the „long-range effect", which means that there is a large distance to the point of transition to turbulence ($x/d = 100-200$, where x — coordinate from the nozzle edge) [5]. When flowing out of the tube, the opening angle in a laminar jet is $3-6^\circ$, while in a turbulent jet this angle is substantially larger ($15-26^\circ$). As a result, hydrodynamic localization of heat transfer in the critical point region [6] is observed in laminar modes. It is known that the „inlet flow is usually more sensitive to perturbations than the fully developed Hagen–Poiseuille flow. Therefore, controlling this aspect may be of practical importance" [7]. Hence, the present paper examines the effect of initial hydrodynamic conditions for a circular long tube on the local heat transfer in the neighborhood of the critical point of impact air macrojets at large obstacle distances ($h/d > 10$). To fulfill this task, the tube inlet geometry (sudden contraction, conical confuser, profiled nozzle) was varied, resulting in a variation of the pulsation level in the initial cross-section of the jet. The applied goal of the research is local intensification of heat transfer at minimum coolant flow rates, i.e. at low Reynolds numbers (Re < 6000).

The experimental setup included a gas line (compressed air source, flexible supply hoses, flow meter, jet source), heat exchange section and measuring equipment. A brass tube with an inner diameter of $d = 3$ mm and a length of $l = 1$ m ($l/d = 333$) was used as the jet source. The supply line had an inner diameter of $D = 15$ mm. Three options of inlet devices were studied: 1) a sudden contraction with an edge of 0.2 mm; 2) a conical confuser with an angle 30° and an edge 1 mm; 3) a profiled nozzle (fourth degree polynomial). In all cases, the flow contraction ratio was $n = (D/d)^2 = 25$. The distance from the nozzle to the obstacle was $h = 60$ mm ($h/d = 20$). The details describing the experiment are given in [4,6]. The heat-exchange section (copper disk $T_w =$ const mode) was heated to $40-50^\circ$C. Film heat flux [8] sensors were located along the radius of the jet spreading. The instantaneous value of heat flux density Q' (time sampling $2 \cdot 10^5$), gas mass flow rate G, wall temperature T_w and jet temperature at the initial cross section T_j were measured in the experiments. The Reynolds number Re $= Ud/\nu$ and Nusselt number at the stagnation point $\mathrm{Nu}_0 = \alpha d/\lambda$ were determined from the mean flow velocity $U = 4G/(\pi\rho d^2)$ and the mean value of heat transfer coefficient $\alpha = Q/(T_w - T_j)$ (Q — mean value of heat flux density). According to [9], the flow in the jet corresponds to the modes of motion in the source (tube): laminar, transient, and turbulent. Diagnostics of the transient flow mode and determination of the critical Reynolds number (Re_{cr}) in the initial cross-section of the jet is based on registering large-scale turbulent structures (puff) using a hot-wire anemometer [7,9]. The basic uncertainty

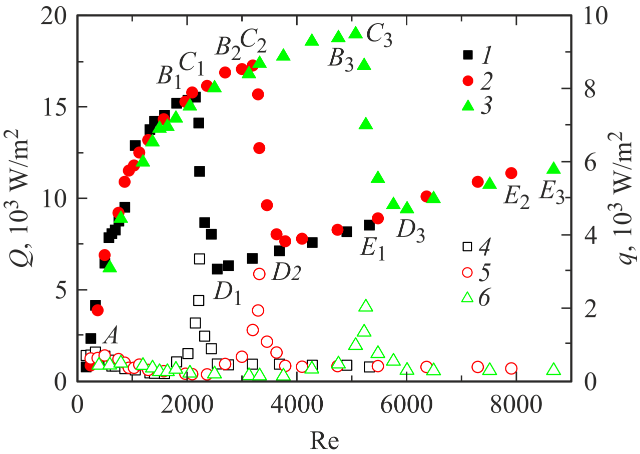

Figure 1. The mean value of heat flux density Q (*1–3*) and RMS value of heat flux density fluctuations q (*4–6*) in the impact jet. *1, 4* — sudden contraction; *2, 5* — conical confuser; *3, 6* — profiled nozzle.

of the instantaneous heat flux density measurement was 2–4% [8], Nusselt number — 4–6%, Reynolds number — 1–5%.

The results of the impact jet study for the three tube inlet options are shown in Fig. 1. Here, the parameters Q (mean value of heat flux density) and q (RMS value of heat flux density fluctuations) at the stagnation point are plotted as the Reynolds number varies. The data for option 2 (inlet — conical confuser) are consistent with the experiments [6]. For all three inlet options, the following regions at Re variation can be distinguished (similar to [6]). The laminar region ($A{-}B_1$, $A{-}B_2$, $A{-}B_3$) is characterized by a monotonic growth of Q and a low level of q. The flow in such a jet is characterized by instability in the mixing layer [10,11]. Preliminary experiments for options 1, 3 showed that the velocity profile at the beginning of the jet is close to the Poiseuille distribution, as for option 2 (conical confuser) [6], and the area of transition to turbulence is located at $h/d > 20$. The section with laminar-turbulent transition in the tube ($B_1{-}C_1{-}D_1$, $B_2{-}C_2{-}D_2$, $B_3{-}C_3{-}D_3$) is characterized by a high decrease Q and high pulsations level q and high pulsations. The flow motion in the transition jet corresponds to a mode with statistical time intermittency: at some time intervals the flow is laminar, at others — turbulent [9]. The following values are obtained for the critical Reynolds number: option 1 — $\mathrm{Re}_{cr1} = 2023$, option 2 — $\mathrm{Re}_{cr2} = 3004$, option 3 — $\mathrm{Re}_{cr3} = 4759$. Thus extrema Q at points C_1, C_2, C_3 correspond to transition numbers Re: option 1 — Re = 2156, option 2 — Re = 3202, option 3 — Re = 5072. The turbulent region ($D_1{-}E_1$, $D_2{-}E_2$, $D_3{-}E_3$) is characterized by a slight monotonic increase Q and a low level of q. Variation of the initial conditions leads not only to an increase in Re_{cr}, but also to a change in the maximum fluctuation level q. Initial conditions with lower level of perturbations increase the critical Reynolds number and also promote heat transfer intensification in the critical point region. The maximum level of fluctuations q for options 1 and 3 is consistent with the maximum degree of turbulence (Tu = 13.6 and 11.3%, respectively) in the initial cross section of the jet; for case 2, these data (Tu = 12.5%) are presented in [6].

Experiments on the distribution of the mean value of the heat flux density over the the cooper disk radius showed results similar to those obtained in [6]. For the laminar jet, localization of the heat flux density near the stagnation point in contrast to the turbulent jet was obtained for three options of input devices. It was found that the opening angle in the laminar jet is 3–6°, while in the turbulent jet it is equal to 20–26°.

Comparison of heat transfer at the critical point of the impact jet in the form of the $\mathrm{Nu}_0 = f\,(\mathrm{Re})$ dependence is shown in Fig. 2 for three options of the tube entrance at the same parameters ($d = 3$ mm, $h/d = 20$). For comparison in this figure, the correlation dependence $\mathrm{Nu}_0 = 5.25\mathrm{Re}^{0.5}\mathrm{Pr}^{0.33}(h/d)^{-0.77}$ [1] is shown as a solid line, with which the results of our experiments in the case of jet expiration from the nozzle agree well ($d = 3$ mm, $h/d = 20$. The experiments are described in [6]). At the same time, for an impact jet flowing from a long tube (for three inlet variations), nonmonotonic heat transfer behavior is observed in the $\mathrm{Re} < 6000$ region. The Nusselt number maxima for the jet from the tube (points C_1, C_2, C_3 in Fig. 2) are reached at Re = 2156 (option 1), 3202 (option 2), Re = 5072 (option 3) and correspond to the extremes of the mean heat flux density Q (points C_1, C_2, C_3 in Fig. 1). A significant increase in Nusselt number (up to 300%) in the range of Re = 500–6000 is observed for the jet flowing out of the tube compared to the case where the jet flows out of the nozzle. At $\mathrm{Re} > 6000$ the difference in heat transfer for the two options of jet formation (from the tube and from the nozzle) virtually disappears. At low Reynolds numbers ($\mathrm{Re} < 500$) our data are in satisfactory agreement with the results of experiments for laminar microjets [12].

The influence of initial conditions on the critical Reynolds number in long tubes and channels has been studied in detail [6,13]. At the same time, the initial flow varied from hydraulically smooth (profiled confusors) to flows with a local detached region [14,15]. As Re_{cr} increases, a decrease in the friction coefficient is observed, while no significant effect of the initial conditions on the heat transfer level was found [15]. In this paper, using an impact jet as an example, it is found that there is a correlation between the inlet geometry, the critical Reynolds number in the long tube, and the level of the average heat transfer in the critical point region. This significant difference between the impact jet problem and the flow in a channel is as follows. In the first case, the laminar jet has a small opening angle, and the cooling area at $h = \mathrm{const}$ is nearly conserved. An increase in Re_{cr} leads to an increase in the coolant flow rate and hence to a larger value of the heat flux density. However, the maximum average value of the heat flux density (points C_1, C_2, C_3in Fig. 1) or Nusselt number (points C_1, C_2, C_3 in Fig. 2) for the flow from the long

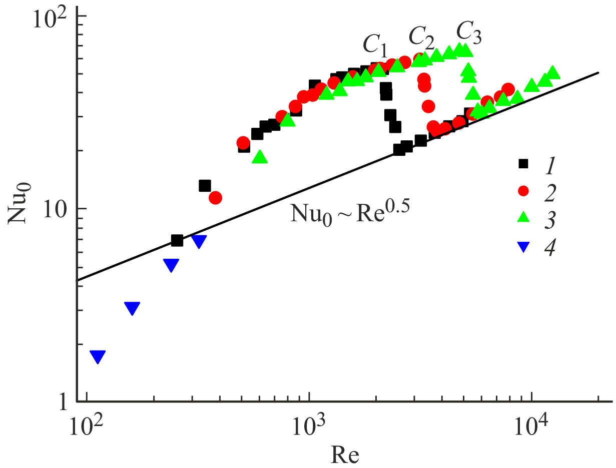

Figure 2. Heat transfer at the critical point of an impact jet. *1* — sudden contraction, *2* — conical confuser, *3* — profiled nozzle, *4* — impact microjet [12]. The line represents the correlation dependence [1].

tube corresponds to the laminar-turbulent transition region (Re = 3202, option 2). Thus, the heat transfer maximum does not correspond to the initial Poiseuille profile. It is known that the laminar-turbulent transition in tubes occurs according to the intermittency mechanism, when large-scale vortex structures (puff) [7] alternately form and disappear. For this experiment (points C_1, C_2, C_3 in Fig. 1), the fraction of turbulent structures (intermittency coefficient) is approximately 8–10%. The influence of such large-scale structures on heat transfer requires a more detailed study.

Thus, this paper shows that changing the hydrodynamic conditions at the inlet of a long tube ($l/d > 100$) in the form of sudden contraction, conical confuser and profiled nozzle greatly affects the critical Reynolds number in the tube. Initial conditions with lower inlet perturbations increase the critical Reynolds number and favor heat transfer intensification in the stagnation point region. The heat transfer enhancement in the stagnation point region at Re_{cr} is 200–300% compared to the level of heat transfer in the turbulent mode that occurs in the vicinity of Re_{cr}. The obtained results may be useful in the design of advanced heat exchangers using impact jet flows.

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Conflict of interest

The authors declare that they have no conflict of interest.

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