Heat transfer at the stagnation point of the impinging laminar jet

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Abstract. Heat transfer of an impinging axisymmetric jet at low Reynolds numbers (Re = 250-5000) at the obstacle stagnation point was studied experimentally. An air jet from a long tube was flowing onto a flat heated plate at a constant wall temperature. The distance from the jet beginning to the obstacle was h/d = 20. A connection of thermal parameters (averaged and pulsating) at the stagnation point for the flow at the initial cross-section of the jet was established. For the laminar flow, an increase in heat transfer of more than 200% was observed in the jet in comparison with the turbulent flow. Comparison of the obtained data on heat transfer revealed a significant discrepancy with the well-known correlation formula for impinging jets.

1. Introduction

Heat transfer in impinging jets is well studied. The complexity of the problem is caused by a large number of parameters that affect heat transfer [1,2]: Reynolds (Re) and Prandtl (Pr) numbers, distance from the nozzle to the surface (h/d), intensity of jet turbulence (Tu), shape and size of the nozzle and the state of its edge, shape of the cooled surface, etc. One of the determining parameters is Reynolds number (Re=Ud/ν), which is determined for axisymmetric jets by the average flow rate velocity U=4V/π*d², nozzle diameter d and kinematic viscosity ν (V is the volumetric flow rate). The formula for calculating heat transfer near the spreading point of a flat obstacle is as follows:

\[ \text{Nu}_0 = C \text{Re}^m \text{Pr}^n \left( \frac{h}{d} \right)^p \]

where \( \text{Nu}_0 \) = αd/λ, α is the heat transfer coefficient, λ is the coefficient of air heat conductivity, coefficients C, m, n, p vary in the works of different authors [1-2]. In practice, to cool the heated surfaces effectively, the jets flowing from nozzles (contoured confusers) at high Reynolds numbers (Re> 5000) were studied. The study of the heat transfer process when cooling devices by various technologies has also established the optimal range of distances from the nozzle to the surface (h/d = 4-6). At that, the tasks, not optimal from the viewpoint of heat transfer and technology, remained unexplored: low Reynolds numbers (Re <5000), outflow from the tubes, large distances from the nozzle to the obstacle (h/d>10). It was previously shown in [3] that the laminar round jets have significantly greater range than the turbulent ones. There are relatively few publications dealing with the study of heat transfer at low Reynolds numbers (Re<5000) [4-5]. Dependence (1) leads to a monotonic increase in the Nusselt number with an increase in the Reynolds number (m = 0.4–0.6),
also at \( Re < 5000 \), which is confirmed by some experimental data [4-5]. It is shown in our experiments that the initial velocity profile in the jet (parabolic or top-hat) has a significant effect on heat transfer in the impinging jet [6]. Recently, interest in heat transfer in microdevices, which are characterized by low Reynolds numbers (\( Re < 5000 \)), has increased [7]. In this regard, the problem of studying laminar impinging jets has again become urgent. The first step of this task is studying the thermal characteristics at the stagnation point. For jet flows, there is a problem of classification from the viewpoint of the flow regime (laminar, transitional, and turbulent) [8]. In our works, when a jet flows from long tubes, we hold the criterion associated with the flow regime in the initial cross-section of the jet. Thus: 1) the jet is laminar if the flow is laminar in the initial cross-section of the jet; 2) the jet is turbulent for the turbulent boundary layer in the initial cross-section of the jet; 3) the jet is transitional if a laminar-turbulent transition is observed in the final cross-section of a long tube. In this regard, this work is aimed at the experimental study of heat transfer in the vicinity of the frontal point of a circular impinging air jet at low Reynolds numbers (250 < \( Re < 5000 \)). At that, significant attention is paid to laminar jets and comparison of heat transfer at the stagnation point for the laminar and turbulent impinging jets.

2. Experimental method

In this work, physical modeling of the heat transfer problem is carried out. The scheme of experiment with the impinging jet is shown in figure 1. The working gas under pressure is fed from the compressed air line and regulated by valve 1. Then, the gas passes through precision flowmeter 2 (Bronkhorst company) and through a flexible hose (internal diameter of 15 mm) it enters tube 3 (internal diameter \( d = 3.2 \) mm, length \( l = 1 \) m). The jet flows into the airspace under room conditions. The distance from the jet beginning to obstacle 5 is \( h = 60 \) mm (\( h/d = 20 \)).

Heat transfer section 5 was made in the form of a copper disk with a diameter of 190 mm and thickness of 50 mm. The disk was heated using electric heater 6. The boundary condition on the obstacle was close to condition \( T_W = \text{const} (T_W = 55-60^\circ C) \). On the plate surface at the spreading point, thin-film heat flux sensor (HFS) 4 with a size of 2x2x0.2 mm was installed [9]. The temperature of the plate and jet in the initial cross-section were measured by thermocouples made of a wire with a diameter of 0.2 mm (chromel-copel material). The heat flux sensor and thermocouples were connected to the data acquisition system through a preamplifier and analog-to-digital converter (L-Card E14-140).
ADC). This scheme allows measuring the instantaneous heat flux in the frequency band of up to 3 kHz and calculation of average $Q$ and rms value $q$ of the heat flux by the time series (sample size of $1 \times 10^4$). The average values of heat transfer coefficient $\alpha$ and rms values of pulsations of the heat transfer coefficient $\alpha'$ were determined by $Q$ and $q$, respectively, and the difference between the wall $T_W$ and jet $T_J$ temperatures. The air parameters necessary to calculate the Reynolds (Re) and Nusselt (Nu) numbers (kinematic viscosity $\nu$ and heat conductivity coefficient $\lambda$) were determined from the temperature of the air flow at the nozzle outlet. The following parameters were measured in the experiments: the time series for the instantaneous heat flux value, the gas flow rate through the nozzle or tube, the plate and jet temperatures in the initial cross-section, and the barometric pressure. To determine the initial dynamic conditions, we used a DISA 55M hot-wire anemometer with a miniature DISA 55P11 probe (tungsten wire, filament diameter of 5 $\mu$m).

3. Results

It is known that the flow in a jet depends substantially on the initial conditions. In this regard, at the first stage, much attention was paid to the control of the initial conditions. The experimental data at the outlet of a long tube with varying Reynolds numbers are presented in figure 2 for the cross-section $x = 0.5$ mm ($x$ is the longitudinal coordinate, measured from the end of the tube along the jet axis). The data for the average and rms values of the longitudinal velocity component are shown there. It follows from the experiments that up to Re $= 3160$, the velocity distribution ($U/U_m$) along the jet radius agrees well with the Poiseuille formula ($U_m$ is the velocity on the axis). At Re $> 3160$, the velocity profile deviates from the parabolic, at Re $> 3800$ it becomes sharper and tends to the developed turbulent profile in the tube for high Reynolds numbers (see Re $= 6360$). The distribution of turbulence intensity ($Tu = u/U_m * 100\%$) along the jet radius correlates with a change in the average velocity. At Re $< 3160$, the Tu maximum is located on the jet axis and is 0.4-0.7%, in the region of Re $~ 3340$, three extrema are observed, and at Re $> 3800$, the velocity pulsation profile corresponds to the turbulent flow in the tube with maximum $Tu = 9.8\%$ in the near-wall region (see Re $= 6360$). The presented distribution of dynamic parameters suggests the following. Up to Re $= 3160$, the flow in the jet source is laminar; in the range Re $= 3160-3800$, the flow is transient. If value Re $= 3800$ is exceeded, the turbulent flow regime is registered. Such a change in parameters agrees well with the scenario of a laminar-turbulent transition in axisymmetric tubes [10].

![Figure 2. Distribution of velocity (a) and turbulence intensity (b) in the initial cross-section of an axisymmetric jet: 1-3 experiments, 4 - Poiseuille profile; (1-Re=1260, 2-3340, 3-6360).](image-url)

At the second stage, there were experiments to study heat transfer at the spreading point of the impinging jet. The use of the heat flux sensor allowed obtaining both average and fluctuation characteristics of thermal parameters. So, figure 3 shows the experimental data for both average and pulsating heat fluxes ($Q$, $q$) and heat transfer coefficient ($\alpha$, $\alpha'$). The values for turbulence level $Tu$ on the axis in the initial cross-section of the jet are also shown there. As it can be seen from figure 3, for
all parameters, three characteristic sections with varying Reynolds numbers, namely, laminar, transitional, and turbulent can be distinguished. The first section (Re <3160) is a laminar jet. Monotonic growth of Q and \( \alpha \), and approximately constant level of q, \( \alpha' \), and Tu are registered there. The turbulent range of Reynolds numbers (Re> 3800) is characterized by a small change in all parameters. The most significant transformation of the diagrams occurs in the region of the laminar-turbulent transition (3160<Re<3800). In this section, Q and \( \alpha \) decrease sharply, and a maximum of fluctuations in velocity and thermal characteristics is observed. It should be noted that the level of heat transfer for the maximum in the laminar jet is almost two times as high as that in the turbulent flow.

**Figure 3.** Dependence of heat flux (a), heat transfer coefficient (b) and intensity of turbulence (a, b) on the Reynolds number in the impinging jet.

High time resolution of the heat flux sensor allowed measuring the time series of instantaneous heat flux value. Such data are presented in figure 4 for two Reynolds numbers. The first oscillogram was measured for a laminar jet (Re = 2370 <3160), and the second one was measured for a turbulent jet (Re = 6360> 3800). In both cases, there are no significant peaks in the time series. It can be noted that in the first version, the heat flux level at the spreading point on the plate is approximately Q~16 kWt/m\(^2\), and in the second version it is much lower: Q~10 kWt/m\(^2\). Another feature of the diagrams is the different level of heat flux pulsations on the wall: for a laminar jet q~150 Wt/m\(^2\), and for a turbulent jet it is much larger and is approximately q~350 Wt/m\(^2\).

**Figure 4.** Variation of the local heat flux at the plate stagnation point in time:

a) Re=2370, b) Re=6360.

The results of experimental and calculated data on heat transfer are compared in figure 5. The line shows the calculation by the correlation formula (1) with parameters C = 5.25, m = 0.5, n = 0.33, and
p = 0.77 [1] for the distance from the nozzle to the wall h/d = 20. The experimental data of other authors (h/d = 20) are also presented: [4] for the nozzle and [11] for the microjet with a size of 50 μm. As it follows from the figure, the experimental data of [4] and our experiments at Re > 3800 are in good agreement with dependence (1). On the other hand, our data at low Reynolds numbers and experiments for the microjet [11] are in good agreement with each other, but do not correspond to formula (1). By analogy with the results presented in figure 3, we can also distinguish three heat transfer regions at the frontal point: at Re < 3160, it is laminar, at 3160 < Re < 3800, it is transitional, and at Re > 3800, it is turbulent. In the turbulent region, the experimental and calculated data correlate with each other both qualitatively and quantitatively. The growth rate of the Nusselt number for the laminar zone is significantly higher than for the turbulent region. For the laminar region, the correlation formula (1) requires modification.

![Figure 5](image-url)

Figure 5. Comparison of experimental and calculated data on heat transfer at the stagnation point of an impinging jet (h/d=20): 1 – tube jet experiment, 2 – microjet experiment [11], 3 – nozzle jet experiment [4], lines – theory (1).

Discussion and Conclusions
From the viewpoint of the problem of heat transfer intensification, the heat transfer maximum on the plate is interesting. As it follows from our results, the heat transfer extremum at the point of impinging jets stagnation corresponds to the laminar regime, i.e., the case before the laminar-turbulent transition in the jet source (long tube). In our experiments, the critical Reynolds number is Re = 3160. It has been previously established that the laminar-turbulent transition in this tube occurs according to the alternation scenario: when the regions with a laminar flow alternate with the regions of a turbulent flow with formation of turbulent spots (puff) [12]. It is known that the critical Reynolds number in tubes can reach Re = 10^7 and depends on the initial conditions at the tube inlet, roughness size, etc. [10]. Thus, to obtain the maximum heat transfer at the stagnation point of the obstacle, it is necessary to drag out the laminar-turbulent transition in the jet source. Another important issue is the presence of a transition point in the jet itself, that is, at a distance from the jet beginning to the obstacle. In [3], it was shown that the laminar round jets have a significantly greater range than the turbulent ones. In our experiments, the distance from the beginning of the jet to the obstacle was h/d = 20. According to visualization, the laminar jet does not decay at Re < 3160. Thus, the laminar-turbulent transition mechanism in the jet is also an essential parameter in this problem.

To sum up, the interaction of an axisymmetric air jet flowing from a long tube with a flat obstacle has been studied experimentally. Heat transfer at the stagnation point of the impinging jet at low Reynolds numbers (Re = 250-5000) for the distance to the obstacle h/d = 20 has been investigated. A relationship between thermal parameters (averaged and pulsating) at the stagnation point for the flow at the initial cross-section of the jet has been established. For the laminar flow of the jet, a noticeable
increase in heat transfer by more than 200% as compared with the turbulent flow regime in the jet at close air flow rates is observed. The obtained data on heat transfer at low Reynolds numbers are consistent with the experimental data of other authors, but do not correspond to the well-known correlation formula for impinging jets. Application of the obtained results for other distances to the obstacle requires studying the mechanism of the laminar-turbulent transition of jets flowing from long tubes.

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