Heat transfer at a stagnation point of impinging round air jet at low Reynolds numbers

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Abstract. This work presents experimental investigation of average and pulsation thermal characteristics at the stagnation point of a round impinging air jet at low Reynolds numbers. In the experiments, the average and pulsation values of heat flux, heat transfer coefficient and Nusselt number were measured. At low Reynolds numbers (Re<4000), in contrast to the known monotonous increase in heat transfer, a non-monotonic change in heat transfer is shown. With an outflow from the tube, a significant increase in Nusselt number is observed in comparison with the case, when the jet flows from a nozzle, and this increase can be 300-500%.

1 Introduction

The impinging jets are widely used for efficient cooling of heat-stressed sections in different fields of engineering [1-2]. However, there are some unresolved issues concerning heat transfer at interaction of the jet with the surface. The complexity of the problem is caused by the large number of parameters influencing hydrodynamics and heat transfer. It is known that heat transfer in the impinging jets depends on Reynolds number (*Re*), Prandtl number (*Pr*), relative distances from the nozzle to the surface (*h/d*), degree of jet turbulence (Tu), and others [1-4]. One of the most important parameters is the Reynolds number ($Re=Ud/\nu$); for the round jets it is determined by superficial velocity U, initial jet diameter d and kinematic viscosity ν. Correlation dependence for calculation of heat transfer in the region of the stagnation point of a flat plate is usually written as

$$Nu_0 = C\,\mathrm{Re}^m\,\mathrm{Pr}^n\left(\frac{h}{d}\right)^p \tag{1}$$

where coefficients C, m, n, p vary in the studies of different authors [1-4]. A monotonous increase in the Nusselt number at a growth of Reynolds number (m=0.4-0.8) follows from formula (1), and this is proved by experimental data of [1-5]. To solve the problem of efficient cooling of heat-stressed sections, the jets with high Reynolds number (Re>10000) at small distances to the obstacles (h/d<6) were studied mainly. Few papers [5-8] deal with

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the study of heat transfer at low Reynolds numbers (Re<4000) usually at $h/d<10$. In this regard, the aim of the current work was the study of average and pulsation characteristics of heat transfer in a vicinity of the stagnation point of the impinging round air jet at low Reynolds numbers.

2 Experimental setup and measurement method

The experimental equipment included a setup and measurement system. Working gas was air. The following devices were used as a jet source: a) tube with inner diameter d=3.2 mm, length l=1 m with an inlet of the type "sudden contraction", b) profiled nozzle with inner diameter d=3.2 mm and length of 35 mm with the contraction degree of 20. The distance from the jet beginning to as obstacle was h/d=18-20. The heat exchange section, which receives the impinging jet, is a homogeneous copper plate with the diameter of 190 mm and thickness of 50 mm. A small heat flux sensor (HFS) of the gradient type with the size of 2x2x0.2 mm was mounted at the stagnation point of the plate [9]. The plate was heated using the electric heater, the boundary condition on the copper plate surface was close to T_w = const. To measure the level of turbulence in the initial jet cross-section, DISA 55M heat-wire anemometer was used. In the course of experiment, the following parameters were measured: instantaneous value of the heat flux, gas flow rate through a tube or nozzle, temperatures of the plate T_w (40-50°C) and jet T_j (24-27°C) in the initial cross-section, and barometric pressure. Average Q and mean square q values of the heat flux were determined by the measured time series of instantaneous heat flux values (the sample size of up to 1×10^4). The average heat transfer coefficients α_0 and mean square pulsations of heat transfer coefficient α_0' were determined respectively by Q and q and temperature difference between the wall T_w and jet T_j. The parameters of air (kinematic viscosity ν and heat conductivity coefficient λ) required for calculation of the jet Reynolds numbers and Nusselt number ($Nu_0 = \alpha_0 d/\lambda$) were determined by the flow temperature in the initial cross-section of jet T_j.

3 Experimental results and discussion

Experimental data for local heat transfer coefficient at the stagnation point of the plate are shown in Fig.1. For the outflow from the nozzle, monotonic dependence of average heat transfer coefficient α_0 on jet Reynolds number is observed in the range of Re=200-20000 (Fig.1a). At the same time, for the outflow from the tube, the behavior of α_0 is significantly different. There are three characteristic zones. The following phenomena were registered in these zones: an increase in α_0 in the first zone (Re<3320), considerable decrease in α_0 in the second zone (Re=3320-3500), and growth of α_0 in the third zone (Re>3500). Thus, a non-monotonic change in the average heat transfer coefficient α_0 was determined in the range of low Reynolds numbers (Re<4000). For the outflow from the nozzle, the level of pulsations is low and approximately constant over a wide range of Reynolds numbers (Fig.1b). At the same time, for the outflow from tube at Re=3320, there is a significant extreme α_0', which correlates with the maximum of α_0.

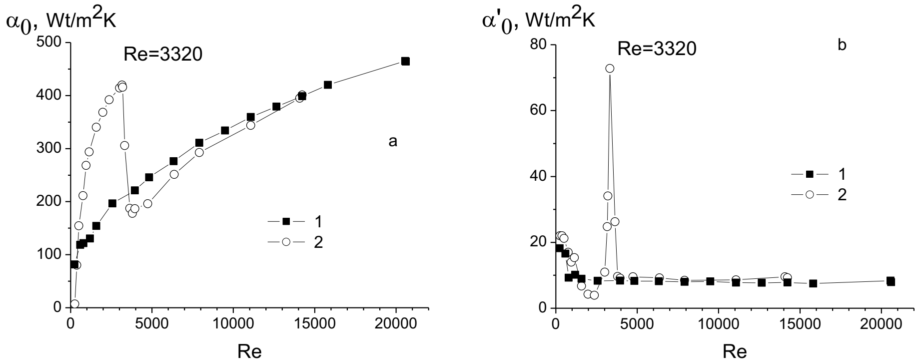

Fig. 1. Average (a) and pulsation (b) value of the local heat transfer coefficient at the stagnation point of the plate: *1* — nozzle, *2* — tube (*h/d* = 20).

The measured level of turbulence in the initial cross-section of the impinging jet is shown in Fig.2a. For the jet outflow from the nozzle, the level of velocity pulsations is low and it is Tu<1% in the range of Re=250-20000. For the jet outflow from the tube, the character of turbulence behavior is different. As in Fig. 1, there are three zones. An insignificant decrease in velocity pulsations (Tu<1%) is registered in the first zone (Re<3300), in the second zone (Re=3300-3500), there is the extreme of velocity pulsations at Re=3320, which is 12%, and in the third zone (Re>3500), there is a monotonous decrease in pulsations (Tu<2%).

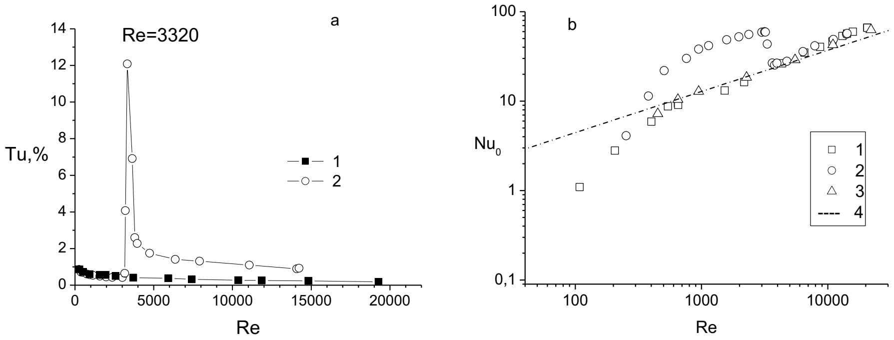

Fig. 2. Dependence of turbulence degree (a) and Nusselt number (b) on Reynolds number: 1 — nozzle, 2 — tube; 3 – data of [7], 4 – calculation by (1).

Data using the Nusselt number for the average heat transfer Nu_0 are shown in Fig.2b. Line 4 in the figure corresponds to dependence (1) with coefficients C=5.25 m=0.5 n=0.33 p=0.77 [1-2]. Data of [7] for heat transfer were obtained in the range of Reynolds numbers Re=450-22000 for air. According to the figure, experiments of [7] are consistent with correlation dependence (1). Our data for the jet outflow from the nozzle are also described by dependence (1) at Re>400, however, for Re<400, there is significant deviation from (1). For the jet outflow from the tube, the character of a change in heat transfer depending on Re number is non-monotonic. As in Figs. 1, 2a, there are three zones. At low Reynolds numbers (Re<400) the data are substantially lower than dependence (1). In the range of

Re=3300-3500, there is a significant increase in Nusselt number in comparison with the case, when the jet flows from a contoured nozzle, and it can be 300-500%. Experimental data are consistent with dependence (1) only in the range of Re>4000. The reason for this behavior of heat transfer at the stagnation point at Re<4000 is the effect of initial conditions of jet formation. For a long tube at Re<3300, velocity distribution in the initial jet cross-section is close to the Poiseuille profile. For the case of a contoured nozzle, the velocity profile at outlet cross-section has a “shock” character with thin boundary layers. In literature, the effect of initial velocity profile for the impinging jets was studied only for high Reynolds numbers (Re>4000). Experiments carried out at IT SB RAS on the range of axisymmetric free jets [10] demonstrate a strong effect of the initial velocity distribution. For the flow from the nozzle, parameters shown in Figs.1, 2 have monotonous dependence on the Reynolds number. At that, a change in the Nusselt number depending on the Reynolds number at Re>400 is consistent with known dependence (1) and experiments of [7].

4 Conclusions

According to the research, heat transfer at the stagnation point of the impinging jet depends not only on similarity criteria (Re, Pr, *h/d*, Tu), but also on the method of jet formation. At interaction of an axisymmetric air jet flowing from a long tube with a flat surface, a non-monotonous change in heat transfer near the front point is observed at low Reynolds numbers (Re<4000). In this case, there is a significant increase in Nusselt number in comparison with the case, when the jet flows from a contoured nozzle, and it can be 300-500%. At Reynolds numbers Re>4000, the difference in heat transfer for two versions of jet formation, decreases asymptotically.

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