Heat transfer and structure of a turbulized flow in a converging channel

I A Davletshin, A E Goltsman and A A Paereliy

Institute of Power Engineering and Advanced Technologies, FRC Kazan Scientific Center, Russian Academy of Sciences, 2/31 Lobachevsky str., Kazan, 420111, Russia

E-mail: davlet60@mail.ru

Abstract. The paper deals with experimental studies of convective heat transfer and kinematic flow structure in a plane converging channel. Different turbulence intensities were generated by a variety of arrangements at the channel inlet. Distributions of heat transfer coefficient over the wall of the converging channel were obtained in different regimes of the air flow. Optical measurements yielded the profiles of hydrodynamic parameters at characteristics locations.

1. Introduction

Flows in converging channels with favorable pressure gradients are often encountered in practice, which determines the relevance of the research into processes occurring in such flows [1-5]. Experiments [1, 2] and numerical studies [3, 4] have revealed that favorable pressure gradient promotes flow laminarization. The latter is accompanied by reduction in hydraulic losses and heat transfer: the respective coefficients fall below turbulent values exceeding, however, the coefficients typical of zero-gradient flows. When analyzing gradient flows, different acceleration parameters are usually taken as a numerical characteristic. In particular, laminar-turbulent transition is delayed at any values of Kays acceleration parameter. Starting from a certain Kays parameter, the flow always remains laminar, while reverse turbulent-laminar transition (relaminarization) may occur even at high values of Kays parameter.

Hydrodynamics and heat transfer in the channels were also studied under a combined effect of the pressure gradient and other factors. In particular, flow parameters in the channel with different grids (turbulizers) were estimated experimentally in [2]. Depending on the cell size and blockage ratio, the changes in dynamic and thermal boundary layers, as well as earlier transition of heat transfer coefficient from laminar to turbulent values were observed. Authors [4] performed numerical analysis of the effect caused by the zero-gradient entrance length on the flow parameters in a plane converging channel. Employing the pattern of friction coefficient to that end, they demonstrated that the entrance contributed to the delayed laminar-turbulent transition (longer entrance length delayed the transition).

Recently, rapid development of optical measurement methods has been observed in hydrodynamics. PIV measurements in a range of research areas are used to examine the kinematic flow structure: fields of velocities, turbulence, and vorticity. Such studies in gradient flows were carried out in [5]. New methods for optical measurement of flow structure are being developed [6, 7].

Some of the recently published papers demonstrated possible laminarization of turbulent flow by additional impacts on the flow [8]. Thus, we expect a combined effect of laminarization due to different factors in flows with large-scale turbulization in converging channels.
2. Experimental setup and procedure

Special experimental setup was developed for the research of hydrodynamics and heat transfer in the converging channel. The air with ambient parameters was supplied to the channel inlet. The flow rate inside the test section was provided by opening the proper number of critical flow nozzles (uncertainty in the flow rate did not exceed 0.25%).

The test section was a plain channel made of transparent material (polycarbonate) with the length of 1.2 m (fig. 1). Converging section 3 was located in the center of the channel. The channel width along the whole length was 150 mm. A smoothly shaped (in one plane) inlet 1 was attached to the channel entrance. The inlet was shaped according to Bernoulli lemniscates and provided the flow constriction of 5.5:1. Different turbulence promoting devices (5 and 6) were installed in the entrance where the smoothly shaped inlet was attached. We employed 4 different devices (arrangements):

1 – smooth channel;
2 – abrasive 6 with the grain size 630-800 µm over the perimeter of the entrance along a 70-m long section;
3 – abrasive and grid 5 (wire diameter 1.1 mm, grid spacing 6 mm) across the whole area of the entrance cross section;
4 – abrasive and grid with 30-mm long, 5-mm wide strips made of 24-mm thick polyethylene film; the strips were tied to the grid at the points of wire joints with a spacing of 24 mm in a staggered way.

Different arrangements allowed reproducing different turbulence intensities in the channel entrance. Flows in a converging channel with the angle of φ=8 degrees were considered. The angle was provided by the inclination of the upper wall. The channel height upstream of the converging part was \( H_0=100 \) mm, downstream of the converging part \( H_1=40 \) mm. Heat transfer measurements were conducted on the bottom wall 2, and hydrodynamics was measured near the same wall. Thermometer 4 was employed to measure air temperature at the inlet.

![Figure 1. Test section: 1 – inlet; 2 – heat transfer wall; 3 – converging part; 4 – thermometer; 5 – grid (grid with strips); 6 – abrasive; 7 – hot-wire anemometer; C1 and C2 – stations at which optical measurements were carried out](image)

3. Kinematic flow structure

First of all, turbulence intensity was experimentally estimated at the channel inlet downstream, immediately after the turbulence promoting device. To this end, a single-wire hot-wire sensor 7 was positioned at the channel axis at the distance of 100 mm from the inlet (fig. 1). Its readings yielded turbulent fluctuations in different regimes with different turbulence promoting arrangements. Bulk velocity at the inlet of converging section is \( U_0 = 1.9, 3.7 \) and 5.6 (the respective Reynolds numbers \( Re=U_0H_0/ν=12600, 24800 \) and 37500, where subscript 0 refers to the inlet of the converging section). The measurements have demonstrated that turbulence intensity in the smooth channel (without turbulence intensification) and in a channel with abrasive was \( Tu = 2 – 9\%\). Similarity in turbulence intensity ranges is attributed to the fact that roughness turbulizes primarily the boundary layer. But in
our case, measurements of flow velocity were performed in the flow core. Turbulization by the abrasive and grid increased turbulence intensity up to $Tu = 9 – 31\%$. Addition of strips promoted turbulence even further ($Tu=13 – 45\%$). In all the ranges, high turbulence intensities were observed for regimes featuring high flow rates (Reynolds numbers).

A detailed study of the kinematic flow structure was carried out at two characteristic locations: 100 mm downstream of the inlet of converging part (location $C_1$) and in the middle of the converging part (location $C_2$). Fields of velocities and Reynolds stresses in the converging channel at different turbulence intensities were measured by an optical method of Smoke Image Velocimetry (SIV) based on digital processing of videos of flow pattern behavior [6, 7]. SIV estimates the vector fields of velocity from the analysis of displacements of turbulent structures visualized using an aerosol. The minimal interrogation window size was $16\times6$ pix (the latter side was normal to the wall). Such measurements allowed us to analyze the effect of pressure gradient on hydrodynamics of turbulent flows. Experiments were carried out at the Reynolds number $Re=16700$.

SIV measurements provided the profiles of streamwise velocities, $U$, fluctuations of streamwise, $U'$, and transverse, $V'$, components of velocity and Reynolds stresses, $U'V'$. Different arrangements for turbulization induced several different flow patterns. This was evident through certain segregation of velocity profiles upstream of the converging part. Profiles in the smooth channel appeared to be the fullest which is typical of the initial part of the boundary layer in a channel. Turbulization by the abrasive and grid resulted in flow stagnation near the wall. When strips were added, the reduced velocities were observed deeper inside the flow core. The velocity profiles almost coincided in the converging part of the channel.

Profiles of turbulent characteristics in the channel entrance reflect the impact of turbulization arrangements: more intense turbulization led to higher turbulence intensity and Reynolds stresses (fig. 2, $a$).
However, a somewhat different (in some regimes even reverse) pattern was observed in the converging part of the channel (fig. 2, b). In particular, when the initial turbulence intensity of flow turbulized by the abrasive, grid and strips was high, lower turbulence (compared to other regimes) was observed further downstream in the converging part of the channel. This effect is probably due to a number of mechanisms of turbulence development in the flow. First, turbulence in the channel entrance immediately downstream of turbulizer should be viewed as non-equilibrium. Under these circumstances, we can expect the turbulence intensity to approach its equilibrium values (i.e. to reduce). As far as the smooth channel is concerned, the turbulence intensity should obviously increase in downstream direction. Second, favorable pressure gradient induces the trend to flow laminarization [1]. And third, large-scale turbulization of flow (by the strips) is able to flatten the velocity profiles (make them more filled), reduce the turbulence intensity and even laminarize the flow [8]. But such laminarization is observed only at moderate Reynolds numbers. However, in this case, the effect of reduction of turbulent characteristics can be attributed to the combined influence of both factors. And depending on the factors ratio, flow patterns can be different, which was documented in experiments.

4. Heat transfer
Heat transfer was measured in the channel with the geometry identical to hydrodynamic measurements. Unlike the latter, a heated wall was embedded into the central part of the straight wall, and the inlet was equipped with a thermometer intended for flow temperature measurements (fig. 1). The experiments...
were carried out at approximately the same Reynolds number and identical turbulence intensity at the channel inlet.

Time-averaged local coefficients of heat transfer were measured using a self-developed technique that allows simultaneous heating of the surface and estimation of its local temperatures from the measurements of related electric resistances of heating elements. Detailed information on the method was provided in [9].

In experiments, the wall was electrically heated in the converging part of the channel starting from its inlet according to the boundary conditions of the second kind \( q = \text{const} \). Bulk velocity at the inlet of the converging channel was \( U_0 = 1.9 \text{ m/s (Re}=12600) \).

Distributions of heat transfer coefficients along the converging channel were obtained experimentally. The data were plotted in figure 3, where dashed lines demonstrate the boundaries of the converging part. Non-monotonic distributions of heat transfer coefficient are to be attributed in this case to the influence of two factors. First, since the wall was heated starting from the inlet of the converging channel, the entrance length with declining heat transfer developed at the inlet. Second, flow acceleration in converging channel resulted in heat transfer enhancement.

As far as the effect of turbulization on convective heat transfer is concerned, heat transfer coefficient in the smooth channel was the lowest. Augmentation of turbulence intensity generally led to heat transfer enhancement. The regime with maximum turbulization (abrasive + grid + strips) should be considered as an exception. Here, we observed somewhat weaker heat transfer compared to other regimes with enhanced turbulence. This fact agrees well with the kinematic flow structure, when large-scale turbulization (by strips) at the channel inlet results in decreased turbulence characteristics in the converging part of the channel.

Distributions of heat transfer coefficients have shown that turbulization on the whole led to heat transfer enhancement by up to 10% compared to the smooth channel.

![Figure 3. Heat transfer coefficient: 1 – smooth channel; 2 – abrasive; 3 – abrasive+grid; 4 – abrasive+grid+strips](image)

**Conclusions**

The paper has demonstrated that turbulization in most cases leads to increased values of turbulence characteristics. However, large-scale flow turbulization (by strips) did not further the transition to turbulent flow, but rather somewhat delayed it. This effect can be attributed to a more uniform velocity profile or its increased stability. The latter is more relevant for the initial part of the boundary layer in the channel, which is in line with the considered cases. A favorable pressure gradient may also contribute to this effect.

Heat transfer measurements have demonstrated that turbulization intensification results in heat transfer enhancement. And heat transfer in case of large-scale flow turbulization (by strips combined
with abrasive and grid) in the majority of regimes appeared to be somewhat weaker than in conditions of moderate turbulization by the abrasive and grid. This result is consistent with kinematic flow structure.

Thus, according to the obtained experimental data, it is possible to enhance the effect of flow relaminarization or further delay the laminar-turbulent transition in the flows with favorable (negative) pressure gradient when large-scale mixing (turbulization) is introduced into the flow.

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