Heat transfer and turbulent characteristics in a pulsating flow

N I Mikheev1,2, N S Dushin 1, I M Gazizov2

1 Federal Research Center “Kazan Scientific Center of Russian Academy of Sciences”, Kazan, 420111, Russia

2 A.N.Tupolev Kazan National Research Technical University – KAI, Kazan, 420111, Russia

E-mail: n.miheev@mail.ru

Abstract. Heat transfer coefficient was experimentally estimated in the separation region behind a spanwise rib in a channel with forced flow pulsations. The same channel but without the rib was used for SIV measurements of dynamics of flow velocity vector fields that yielded in variations of normalized turbulent energy production, diffusion and dissipation over the flow rate pulsation period. High sensitivity of convective heat transfer, turbulent production, diffusion and dissipation to the forced flow pulsations have been revealed.

1. Introduction

Turbulent flows with forced pulsations are encountered in many engineering applications, however not enough attention has been paid to momentum and heat transfer in such flows so far. This is primarily due to complex nature of such flows as well as to difficulties in experimental and numerical studies. The research of pulsating flows is certainly a challenging problem even in a smooth channel case. Suffice it to say that two additional dimensionless numbers characterizing the amplitude and frequency of forced pulsations are required to describe such flows if compared to the steady flow case. Therefore, the currently available theoretical and experimental data on hydrodynamics and heat transfer in turbulent pulsating flows in smooth channels and separated flows do not allow extensive generalization of results in this field and reliable prediction of pulsating flow parameters.

Studies of heat transfer in pulsating flows in smooth channels revealed both heat transfer enhancement [1, 2] and deterioration [3, 4] in pulsating flow regimes. The effect of forced pulsations can change its sign when low frequencies give way to high frequencies [5-7]. Heat transfer in turbulent separated flows is rather sensitive to forced flow pulsations [8-10]. The latter induce regular vortical structures behind the obstacles.

The currently available information on pulsating flows sheds light on the effect of forced pulsations on velocity profiles and shear stress [11-12] but is almost useless for understanding the role of forced flow pulsations in turbulent energy production, dissipation and diffusion. Studies of hydrodynamics and turbulent characteristics in unsteady flows have been constrained until recently by insufficient spatial and temporal resolution of optical methods used for measurements of velocity vector field dynamics. SIV measurement technique has been recently developed [13]. Its main difference from conventional PIV is that to trace the flow, smoke with continuous image intensity is used instead of separate particles. SIV significantly expands capabilities of experimental studies of high-speed processes and small-scale turbulence [14].
The present paper contains new experimental data on the effect of forced flow pulsations on convective heat transfer in the separation region behind a spanwise square rib mounted on a channel wall. Variation of turbulent production, diffusion and dissipation in the Reynolds stress transport equation over the phase of forced flow rate pulsations has been estimated experimentally. Only the results for a simpler case of turbulent boundary layer in a smooth channel are presented in this regard.

2. Experimental setup and procedure
Heat transfer behind the rib in pulsating air flows was studied on the experimental setup schematically shown in figure 1. The test section was a 1.2-m long rectangular channel with a cross section of 0.115×0.15 m² and a smooth inlet. The setup comprised a smooth inlet 1, a channel 3, and a measurement section 2 for heat transfer measurements.

![Figure 1. Test section: 1 – smooth inlet; 2 – heated wall; 3 – channel; 4 – pulsator; 5 – thermometer; 6 – hot-wire anemometer; 7 – rib.](image)

Flow pulsations close to harmonic law were generated by a rotating flap of a pulsator 4 at the channel outlet. The pulsation frequency was set by the adjustment of motor shaft rotation frequency in the pulsator. The amplitude of flow velocity pulsations was derived from readings of a hot-wire anemometer 6. The flow temperature was measured by a platinum resistance thermometer Pt100 5.

A square rib 7 with a cross section of 30×30×150 mm³ was mounted 472 mm downstream of the smooth inlet. The rib was made of an aluminum alloy; it was glued to the heated wall by thermal grease. The rib-to-channel height ratio was $h/H = 0.261$ (figure 2), where the rib height $h = 30$ mm, the channel height $H=115$ mm.

![Figure 2. Heated wall with a 30×30×150 mm³ rib (view through a transparent side wall of the channel).](image)

Time-averaged coefficients of local heat transfer were measured using a technique [15] that enabled heating the surface simultaneously with estimation of its local temperatures from the measurement of corresponding electrical resistance of heating elements. For this purpose, the measurement wall 2 was embedded into the test section wall (figure 1). Its main element was a 1.5-mm thick printed circuit board (PCB) with the length of 455 mm and the width of 230 mm (figure 2). The inward side of the PCB was covered with copper etched to form zigzag tracks 3. The tracks were
localized in rectangular 150×9.5 mm² sections. A total of 47 sections with tracks were located closely one after another in streamwise direction with the pitch of 9.5 mm. Each track had its own current leads allowing their parallel or in-series connection to the current source. Each element could be connected to its own current source. Central 80×9.5 mm² segments of tracks had electrical contacts located on the reverse side of PCB. They measured the voltage drop across a circuit element in order to estimate the heat release and electrical resistance of track segments and, hence, the temperature of corresponding wall sections using the resistance-temperature relationship.

The dependence of electrical resistance of tracks, R, on the temperature was calibrated prior to experiments. The resistance-temperature relationship appeared to be close to the one typical of thermometers made of technically pure copper: in R=R₀(1+α(T−T₀)) corrected to T₀=0°C the temperature coefficient of resistance appeared to be α=0.0040°C⁻¹. The whole reverse side of PCB was covered with thermal insulation consisting of two 10-mm thick air chambers. External and dividing walls of chambers were made of aluminum foil. Such a design contributed to reduction of heat loss due to convective heat transfer and radiation from the heated PCB.

The wall studied in experiments was electrically heated over the area of 455×150 mm² according to the boundary conditions of the second kind q=const. The temperature was measured in the central part of the wall where the temperature field was supposed to be uniform in spanwise direction. In these conditions, the measuring part of PCB was essentially a set of resistance thermometers located with a pitch of Δx=9.5 mm along the channel and covering 80 mm across the channel, i.e. the area of 455×80 mm². Streamwise distributions of temperature on the heated wall were estimated from measurements.

Optical measurements using SIV technique yielding small-scale turbulence estimates were described in detail in [14]. To visualize the flow pattern, the air-aerosol mixture (MT-Gravity fluid with medium fog density) was supplied by Safex aerosol generator 5 to the channel inlet. The measurement area 6 was illuminated by a continuous diode-pumped solid-state laser KLM-532/5000-h. The flow pattern in the channel symmetry plane at the distance of L = 0.7 m from the channel inlet was recorded by a monochrome high-speed camera Fastec HiSpec 8 with the frame resolution of 665×110 pixel (scaling factor of 0.0625 mm/pixel) and a frame rate of 7083 1/s.

Period-averaged frame resolution in y* coordinates was 1 pixel = 0.8y*, interrogation window size equaled 16×16 pixel, period-averaged ratio of the resolved scale to Kolmogorov length scale was 1.6. Spacing between the grid nodes in which velocity vectors were estimated was 2 pixels along both coordinates.

3. Results and discussion

Experimental data on heat transfer in the wake of a spanwise rib mounted on the channel wall appeared to be rather sensitive to flow pulsations (figure 3). Normalized amplitude of velocity pulsations was constant in regimes with forced pulsation frequency, f, ranging from 5 to 100 Hz (figure 3) and equaled to 30% of the mean flow velocity. Time-averaged air flow rate through the channel ranged from 104.5 to 193.2 m³/h; the Reynolds number based on the rib height was 3.4×10⁷ to 6.2×10⁷. Bold line f=0 in the figure corresponds to the steady flow past the rib at the same flow rate. Forced flow pulsations contribute much to heat transfer enhancement in the rib near the wake within a certain range of forced frequencies (figure 3). The heat transfer coefficient at some frequencies was twice the steady flow values at the same average flow rate in the channel. By contrast, the effect of forced pulsations on the far field manifests itself in relatively moderate heat transfer deterioration. The obtained data are obviously not enough for extensive generalization of results using dimensionless numbers, therefore dimensional values are presented.

Flow visualization in [9] demonstrated fundamental rearrangement of flow structure in the separation region of the turbulent separated flow due to forced pulsations with some certain ratios of amplitudes and frequencies of pulsations. In the present paper, we quantify the effect of forced pulsations on turbulent characteristics. Pulsating flow in a smooth channel was considered, for which there are reliable experimental data for a steady flow case to compare with.
Figure 3. Heat transfer coefficient on the channel wall behind the rib in steady and pulsating flow regimes at Reh=3.4×10^3 (left) and Reh=6.2×10^3 (right).

Terms of the differential equation (1) describing energy transport for each component of the Reynolds stress tensor have been estimated from SIV measurements

\[
\frac{\partial}{\partial t}(\rho u_i u_j) + \rho \frac{\partial}{\partial x_k} \left[ u_k u_i u_j \right] = -\frac{\partial}{\partial x_k} \left[ \rho u_i u_j u_k + p \left( \delta_i \delta_j + \delta_j \delta_i \right) \right] - \frac{\partial}{\partial x_k} \left[ \mu \frac{\partial u_i}{\partial x_k} + \mu \frac{\partial u_j}{\partial x_k} \right] - \frac{\partial}{\partial x_k} \left[ \frac{\partial u_i}{\partial x_k} \frac{\partial u_j}{\partial x_k} \right] + \frac{\partial}{\partial x_k} \left[ u_i u_j + u_j u_i \right] + \frac{\partial}{\partial x_k} \left[ \frac{\partial u_i}{\partial x_k} + \frac{\partial u_j}{\partial x_k} \right] - 2\mu \frac{\partial u_i}{\partial x_k} \frac{\partial u_j}{\partial x_k} - p \frac{\partial u_i}{\partial x_k} \frac{\partial u_j}{\partial x_k},
\]

where \( C_{ij} \) is the convective term, \( D_{ij} \) and \( D_{ij} \) are diffusion terms, \( P_{ij} \) is the production term, \( \Phi_{ij} \) is the pressure-strain tensor, \( \epsilon_{ij} \) is the dissipation term. Pressure fluctuations were omitted since their effect in the smooth channel is negligible.

Variation of normalized turbulent energy production, diffusion and dissipation for the tensor component \( u'v' \) written in wall coordinates is shown in figure 4

\[
P^* = \frac{P}{U_t \left( \phi \right)}, \quad \epsilon^* = \frac{\epsilon}{U_t \left( \phi \right)}, \quad D_r^* = \frac{D_r}{U_t \left( \phi \right)}, \quad D_r^* = \frac{D_r}{U_t \left( \phi \right)}.
\]

Such a representation allows analyzing the effect of forced unsteadiness on turbulent energy transport in terms of comparison with the steady flow with its established concept of the budget of turbulent production, diffusion and dissipation in turbulent kinetic energy transport equation. Phase-averaged friction velocity, \( U_t \left( \phi \right) \), is used for normalization in (2).

Figure 4 shows variation of normalized production, diffusion and dissipation (ordered top-bottom) in the Reynolds stress transport equation over the period of flow rate pulsation (over the phase angle counted from the time when the free stream velocity reaches the average velocity in acceleration phase) for tensor components \( u'u' \), \( u'v' \), and \( v'v' \) (left to right). These data were acquired for the average velocity of 4.24 m/s at the external edge of the boundary layer, normalized amplitude of forced pulsations of 0.28 and the frequency of 40 Hz. Similar results obtained in the steady boundary layer are shown to the right of unsteady flow images with the same color palette (shown in the middle) for comparison. Note that Mikheev et al. [14] confirmed reliability of SIV measurements of turbulent characteristics in the steady flow by extensive comparison with the reliable experimental and DNS data from literature. In particular, those measurements included new data on dissipation obtained with unprecedented spatial resolution that agree well with DNS.
Maximum values of production and dissipation terms of turbulent kinetic energy transport equation (figure 4) correspond to the phase angle range from 250° to 315°, i.e. to the range within which the streamwise pressure gradient (flow acceleration) changes its sign. Turbulent production \( P'(u'u') \) and dissipation \( \varepsilon'(u'u') \) attain their maxima around these phase angles. These maxima can reach almost five times the values observed in steady boundary layer. On the other hand, \( P'(u'u') \) and \( \varepsilon'(u'u') \) are minimal in the phase of peak flow rate (90°).

Forced flow pulsations also make the terms of turbulent diffusion of velocity fluctuations, \( D_T^+ \), change by many times. For example, while turbulent transport of \( u'u' \) fluctuation energy in steady flow is directed from the peak production zone \( y^*=10...15 \) (sign of \( D_T^+ \) changes in this zone) towards both the wall and the core flow, the sign of \( D_T^+ \) in the pulsating flow changes with the phase of forced pulsations.

4. Conclusions
High sensitivity of convective heat transfer in the separation region behind a spanwise rib to forced flow pulsations has been revealed in experiments.

Experimental data on variation of normalized production, diffusion and dissipation of Reynolds stress transport equation terms over the period of flow rate pulsations have been obtained in the boundary layer of the pulsating flow for the first time ever.

SIV technique is now ready for the studies of mechanisms underlying the enhancement of transfer processes as well as for the research of turbulent characteristics in unsteady flows.
References
[1] Galitseiskiy B M, Ryzhov Yu A and Yakush E V 1977 Heat transfer and hydrodynamics in oscillating flows (Moscow: Mashinostroenie) (in Russian)
[2] Wang X and Zhang N 2005 Int J Heat Mass Tran 48(19) 3957-3970
[3] Yuan H, Tan S, Zhuang N and Tang L 2014 Int Commun Heat Mass 53 14-17
[4] Plotnikov L V and Zhilkin B P 2017 Int J Heat Mass Tran 115 1182-1191
[5] Kim S Y, Kang B H and Hyun J M 1993 Int J Heat Mass Tran 36(17) 4257-4266
[6] Moschandreu T and Zamir M 1997 Int J Heat Mass Tran 40(10) 2461-2466
[7] Mehta B and Khandekar S 2015 Int J Therm Sci. 91, 157-166.
[8] Cukurel B., Selcan C.., Stratmann M. 2015 Int J Heat Mass Tran 91 848-860
[9] Davletshin I A and Mikheev N I 2012 High Temp 50(3) 412-419
[10] Amiri S, Taher R and Mongeau L 2017 Experimental Thermal and Fluid Science 85 22-36
[11] Gündogdu M Y and Carpinlioglu M Ö 1999 JSME Int Journal. Series B, Fluids and Thermal Eng 42(3) 384-410
[12] Miau J J, Wang R H, Jian T W and Hsu Y T 2017 Proc. R. Soc. A (The Royal Society)
[13] Mikheev N I and Dushin N S 2016 Instr and Exp Tech 59(6) 882-889
[14] Mikheev N I, Goltsman A E, Saushin I I and Dushina O A 2017 Exp Fluids 58(8) 97
[15] Dushin N S, Mikheev N I, Gazizov I M and Davletshin I A 2017 Rus Aero 60(4) 583-590