Heat transfer in the flow with forced pulsations in a rib-roughened channel

I A Davletshin¹,², I M Gazizov² and A A Paereli¹

¹ Federal Research Center “Kazan Scientific Center of RAS”, Kazan, 420111, Russia
² Tupolev Kazan National Research Technical University – KAI, Kazan, 420111, Russia

E-mail: davlet60@mail.ru

Abstract. Heat transfer in pulsating air flow in a rib-roughened channel has been studied experimentally. Heat transfer was estimated using the technique of simultaneous wall heating and wall temperature measurement by the same copper tracks. Distributions of heat transfer coefficient over the channel wall in steady and pulsating regimes of flow have been obtained. 30% augmentation of heat transfer compared with the steady flow values has been revealed in pulsating flow. The frequency range of (0–100) Hz and the relative amplitude of forced velocity pulsations of 0.3 have been studied.

1. Introduction
Heat transfer enhancement in channels can be based on flow turbulization in a thin near-wall region, shedding of large vortices and boundary layer breakdown. The enhancement in this case is associated with turbulent transport dominating over the molecular one and is determined by the scale of vortical structures and their velocity. Ribbed channel is one of the techniques utilized to arrange such a flow.

Heat transfer can be augmented by a proper rib shape, spatial arrangement of ribs, or by forced flow pulsations [1–3]. For example, 60% augmentation of heat transfer if compared to the steady flow case was obtained in [1] for a single orifice in pulsating flow. Besides, the authors mentioned the displacement of maximal heat transfer coefficient towards the orifice and observed a five-fold increase in local heat transfer coefficient in the orifice near field. The shifted maximum of the heat transfer coefficient was also mentioned in [4] for the case of acoustically disturbed flow past a square rib at different frequencies and amplitudes of disturbances. But thermal-hydraulic performance in their case was not comparable with [3]. Periodic blowing-suction through the step edge is another way to manipulate the flow structure. Such an approach has been thoroughly studied for the case of backward-facing step flow [5, 6]. The main attention was paid to the flow structure control, and, in particular, an average of 30% reduction of the reattachment length has been observed in this case. Heat transfer enhancement by periodic flow disturbance through the backward-facing step edge was studied in [7]. The authors obtained 40% augmentation of heat transfer coefficient in the near wake of the step at the Strouhal number of 0.275.

The review of papers on the flow structure and heat transfer in separated pulsating flows has shown that the majority of results have been obtained on the basis of numerical simulation. At the same time, experimental studies mostly considered single obstacles with some certain combinations of the flow
unsteadiness parameters. Thus, experimental research of thermal performance in configurations implemented in real power engineering devices is a relevant problem.

2. Experimental setup and procedure
Heat transfer in pulsating flow in a rib-roughened channel was studied on the setup shown in figure 1. The setup was equipped with a smooth inlet 1 with flow constriction of 4:1 and a test section 2. The latter was a 1.2-m long rectangular channel with a cross section of 0.115×0.15 m². One of the walls was covered with square spanwise ribs 3 made of 9.5×9.5×150 mm³ aluminum bars. Part of this wall was considered as a measurement section 4 for heat transfer study. The ribs were glued to the wall using thermal grease to minimize heat resistance between the wall and the ribs. Flow pulsations following close to harmonic law were generated by a flap of pulsator 5. The flap was mounted on the motor shaft. The pulsation frequency was set by the shaft speed adjusted using the Vacon 10 frequency converter. To maintain the stable average air flow rate, a 1.5-m³ receiver tank 6 was mounted behind the pulsator. A set of critical flow nozzles 7 allowed the flow rate adjustment by opening a proper nozzle. The flow rate was generated by a compressor 9 operating in a suction mode. Thus, the air with environmental parameters was supplied to the channel inlet. Its temperature was measured by a Pt100 platinum resistance thermometer 10 located in the smooth inlet.

The rib height \( h = 9.5 \text{ mm} \) (figure 2) yielded the ratio of the rib-to-channel height \( h/H = 0.083 \) \((H = 115 \text{ mm})\). The rib pitch was \( t/h = 20 \). Only one wall of the channel was ribbed. Two ribs were mounted upstream of the measurement region, i.e. measurements were made starting from the third rib.

Figure 1. Experimental setup: 1 – smooth inlet; 2 – test section; 3 – discrete ribs; 4 – measurement wall; 5 – pulsator; 6 – receiver; 7 – critical flow nozzles; 8 – valve; 9 – compressor; 10 – thermometer.

Figure 2. Discrete roughness: a – schematic of the channel; b – heated wall.
To arrange heat transfer between the wall and the air flow, the wall was heated by direct current supplied from accumulators with the emf \( E = 24 \) V.

3. Measurement method

Local heat transfer coefficient was measured using a technique that enabled to heat the surface simultaneously with estimation of its local temperature from the measurement of corresponding electrical resistance of the heating element. For this purpose, the measurement wall was embedded into the test section wall (fig. 2, b). It was a 1.5-mm thick printed circuit board (PCB) with the length of 455 mm and the width of 230 mm. The inward side of the PCB was covered with copper etched to form zigzag tracks. A total of 47 tracks were localized in rectangular 150×9.5 mm² sections. Each track had its own current leads allowing their parallel or in-series connection to the current source. Central 80×9.5 mm² segments of tracks had electrical contacts intended for voltage drop measurement. These contacts (copper tracks on the reverse side of PCB) were connected to terminals and further to a 14-bit L-card E14-140M analog-to-digital and a PC by shielded wires. Voltage measurements were performed 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. Prior to experiments, the dependence of electrical resistance of tracks on the temperature was calibrated.

The wall studied in experiments was electrically heated over the area of 455×150 mm² according to the boundary conditions of the second kind \( q = \text{const} \). 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 \( \Delta x = 9.5 \) mm along the channel and covering 80 mm across the channel, i.e. the area of 455×80 mm². Heat fluxes and wall temperatures were obtained from the measurements.

The external surface of the wall was thermally insulated.

Local heat transfer coefficients corresponding to streamwise coordinates \( x_i \) were derived from the heat balance equation:

\[
\alpha_i = \frac{q_i}{T_i - T_f} = \frac{U_i J_i - Q^*_i}{F(T_i - T_f)},
\]

where \( T_i \) is the local temperature of the wall; \( T_f \) is the flow temperature; \( U_i J_i \) is the heat generation rate of the current at the measurement section; \( Q^*_i \) is the heat loss; \( F \) is the section area. Heat loss comprised the heat loss through thermal insulation, radiation, thermal conductivity to the adjacent walls and heat fluxes between the adjacent tracks.

4. Results and discussion

The following parameters were considered in experiments: average flow velocity \( U = (1.7 - 4.9) \) m/s, Reynolds number \( Re = U d / \nu = (1.5 - 4.3) \times 10^4 \) (\( d = 0.13 \) m is the channel hydraulic diameter), forced pulsation frequency \( f = (0 - 100) \) Hz, relative amplitude of velocity pulsations \( \beta = A_i / U = 0.3 \).

Prior to the study of heat transfer in a rib-roughened channel, test measurements were conducted in steady air flow in a smooth channel. The latter was subsequently roughened with ribs. These experiments were followed by measurements in the steady flow in a rib-roughened channel.

Distributions of the heat transfer coefficient along the pitch are plotted in figure 3. Figure 3, b demonstrates the ratio, \( \alpha / \alpha_0 \), between the heat transfer coefficient in a rib-roughened channel and the corresponding coefficient in a smooth channel. Hereinafter, black square symbols on the x-axis of the figures correspond to appropriately scaled discrete roughness elements. Experimental data agree well with the well-known heat transfer coefficient distribution along the flow separation region, i.e. the coefficient is low in the corner immediately downstream of the obstacle, the maximal values are observed in the flow reattachment zone followed by heat transfer deterioration further downstream. We should particularly note here that heat transfer rises steeply immediately upstream of the ribs. The obtained data are in good agreement with the literature.
Heat transfer in pulsating flow in the rib-roughened channel was studied at three different air flow rates. The heat transfer coefficients were obtained at different frequencies and amplitudes of pulsations. Typical behavior of the heat transfer coefficient, $\alpha_t$, in steady and pulsating flow is shown in figure 4 together with the heat transfer augmentation, $\alpha/\alpha_{st}$, in pulsating regimes ($\alpha_{st}$ is the heat transfer coefficient in steady flow).

Distributions of the heat transfer coefficient, $\alpha$, in low-frequency pulsating flows are close to the steady flow ones. Growing frequency of pulsations displaces the peak of the heat transfer coefficient in the separation region towards the rib. Further increase in pulsation frequency makes the peak stabilize in the immediate vicinity of the rib.

Curves $\alpha/\alpha_{st}$ (figure 4, b) demonstrate that peak heat transfer augmentation in pulsating flow occurs close to the ribs within $\pm 4h$ from the latter and can be two-fold and higher. This agrees with the fact that regular vortices are formed behind the rib in pulsating flow, and they are able to significantly enhance mass and heat transfer in the separation region [3].

Heat transfer coefficient averaged over the area of the channel wall is a fundamental characteristic of flow:

$$\bar{\alpha} = \frac{1}{F} \int_0^F \alpha(F) dF,$$

Figure 3. Absolute (a) and normalized (b) heat transfer coefficient in steady flow: 1 – $Re = 1.5 \times 10^4$; 2 – $2.9 \times 10^4$; 3 – $4.3 \times 10^4$.

Figure 4. The heat transfer coefficient (a) and its augmentation (b) in pulsating channel flow at $Re = 1.5 \times 10^4$.
where $F$ is the area of the measurement section. The wall area excluding the surface of discrete roughness elements was taken as $F$. Augmentation of average heat transfer coefficient in pulsating regimes ($\overline{\alpha}/\overline{\alpha}_w$) is plotted in fig.5 vs the dimensionless frequency (Strouhal number) $Sh = f \cdot x_R/U$ (the reattachment length for the steady flow $x_R = 10 \cdot h$ was used in calculation). Such a curve featuring dimensionless parameters appeared to be universal for different flow rates (Reynolds numbers). Averaged increments of heat transfer demonstrated non-monotonous behavior consistent with the similar curve plotted in the separation region behind a single obstacle [3]. Peak heat transfer enhancement in pulsating flows was observed around the frequency $Sh = 0.6$ and reached 30%. The value of $\overline{\alpha}/\overline{\alpha}_w \approx 1.4$ at $Sh \approx 1$ should be considered as a random outlier.

5. Conclusions

Experimental study of heat transfer in a rib-roughened channel has revealed the following:
- the heat transfer coefficient behavior in separation region behind the ribs is non-monotonous with the peaks around reattachment points and upstream of ribs;
- maximal augmentation of heat transfer in pulsating flow has been observed close to the ribs within $\pm 4h$ from the latter;
- augmentation of area-averaged heat transfer coefficient in pulsating flow is non-monotonous and has a peak of up to 30% around $Sh = 0.6$.

Acknowledgments

This study was supported by the Russian Science Foundation (Project no.16-19-1036).

References

[1] Xie G, Zheng S, Zhang W and Sunden B 2013 *Applied Thermal Engineering* **61** 289–300
[2] Moon M A, Park M J and Kim K Y 2014 *International Journal of Heat and Mass Transfer* **71** 275–84
[3] Davletshin I A and Mikheev N I 2012 *High Temperature* **50** 412–9
[4] Cukurel B, Selcan C and Stratmann M 2015 *International Journal of Heat and Mass Transfer* **91** 848–60
[5] Das Gupta A, Zhao P and Ray S 2016 *54th AIAA Aerospace sciences Meeting* (San Diego, USA)
[6] Chun K B and Sung H J 1996 *Experiments in Fluids* **21** 417–26
[7] Rhee G H and Sung H J 2000 *Numerical Heat Transfer: Part A: Applications* **37** 733–53