Behavior of heat transfer in pulsating flow in the channel entrance region

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Abstract. Convective heat transfer in the entrance region of a plane channel has been studied experimentally. Steady and pulsating air flow regimes have been considered. Heat transfer distributions over the channel wall have been obtained. Non-monotonous behavior of heat transfer coefficient has been revealed at some frequencies and amplitudes of forced flow pulsations. It was accompanied by heat transfer enhancement that was almost double for the local heat transfer coefficients. This may result from generation of vortices in the inlet duct in conditions of flow pulsations.

1. Introduction
Forced pulsations of flow can significantly alter the flow pattern, hydrodynamic and thermal characteristics of flow. Undoubtedly, this has an impact on the operation of different engineering devices [1] and living organisms [2]. Theoretical and experimental research of pulsating flows is motivated by the relevance of problems in this area. When setting up an experimental investigation, a certain flow velocity (pressure) law should be provided. The latter is be responsible for the pattern of pulsating flow. This problem is rather challenging on its own. First, the velocity law is to be provided by a device (pulsator) that generates forced pulsations of flow [3]. Second, acoustic properties of the working medium and channel geometry promote pulsations (resonance) or their attenuation. Third, the pulsator location within the channel can also influence the flow pattern [4]. In general, the study of processes in pulsating flows requires taking into account at least two other factors: frequency and amplitude of pulsations. There is some information on pulsating flows available nowadays that shows the effect of pulsations on velocity profiles, shear stress, laminar-turbulent transition, etc. [5-7]. But due to multi-factor nature of problems in this area, the obtained results are often partial and limited to the considered case. This can result in the situation when some results seem contradictory. For example, both heat transfer enhancement [1, 8] and deterioration [9] have been revealed at pulsating flow regimes.

One of the factors influencing the flow pattern (in particular, the one of pulsating flows) is vortex shedding. Vortices can exist even in a steady flow in its separation region. Then this region somehow interacts with forced pulsations [10] making the flow pattern even more complex. In general, vortices in pulsating flows can originate under the emerging variable moments of forces.

Flow parameters depend both on the object geometry (wall, diverging channel, orifice, etc.) and its location in the channel due to the wave structure of pulsating flow. In particular, the response of flow parameters to the forced pulsations has certain peculiarities in the entrance region of the channel and in the developed flow. Thus, investigation of the effect of flow pulsations on the distribution of heat
transfer coefficients in the entrance region will contribute to the establishment of main regularities in such flows. The present work is mainly focused on interaction of flow pulsations with the processes in the inlet duct.

2. Experimental setup and procedure
An experimental setup with a 115×150 mm\(^2\) 1.2-meter long plane test section (figure 1) was used for the experiments. The inlet duct \(I\) in one plane was shaped according to the Bernoulli lemniscates curve.

Air flow pulsations were generated by a pulsator 4, whose outlet cross section was periodically blocked by a rotating flap. Adjusting the blockage of the windows (with or without the flap) provided the required air flow rate and the amplitude of velocity pulsations. A receiver tank with the volume of 1.3 m\(^3\) was installed between the test section and the compressor. It damped the velocity (pressure) pulsations further downstream. The air flow rate was measured using an ultrasonic flowmeter downstream of the receiver tank. The pulsation amplitude was estimated using the flow velocity values measured by an optical method.

The temperature of ambient air entering the channel was measured by a resistance thermometer 5 mounted in the inlet duct. Heat transfer in the entrance section was studied on a wide wall (150 mm) of the 450-mm long section of the channel. The latter was a plate (printed circuit board) made of composite epoxy material with the width of 1.6 mm. To eliminate the heat loss, the outer surface of the plate was covered with polystyrene layer. Copper layer on the plate surface was etched to form a single strip. The strip was functionally divided into 33 sections with the length of 13 mm and width of 100 mm. Thus, the copper layer acted as 33 resistance thermometers that measured local temperatures of the wall with the streamwise spacing of 13.6 mm.

To obtain more detailed distribution of the heat transfer coefficient, the heat transfer section was installed alternately downstream of the channel inlet and in the middle part of the channel. Heat transfer experiments were arranged as follows. Channel walls were heated by a hot air flow prior to the measurements. Then, while the wall was being cooled by the air flow at the room temperature, the temperatures of heat transfer wall were measured during 100 seconds with the frequency of 200 measurements per second. Heat balance equation together with these data yielded the distribution of heat transfer coefficient along the channel which was considered time constant. Hence time-averaged heat transfer was estimated at pulsating flow regimes.

The experiments were carried out in the range of forced pulsation frequency \(f=0\text{–}140\ \text{Hz}\) and two levels of relative velocity amplitudes \(\beta=U/U\sim 0.3\) and \(\beta\sim 0.8\).

![Figure 1. Experimental setup: 1 – inlet duct; 2 – heat transfer section; 3 – channel; 4 – pulsator; 5 – thermometer.](image-url)
3. Results and discussion

Primary experimental data included the voltage, $V$, and the current, $I$, in the stripes of heat transfer section. Their behavior in time, $\tau$, is shown in figure 2 for the steady flow case. When the strips were connected in series, the same current passed through them (figure 2, b).

This primary information yielded time variations of strip resistance $R_i = V_i/I$. Then the temperature of strips (heat transfer wall sections), $T_i = T_i(R_i)$, was estimated using the known relation between the electrical resistance of copper conductor and the temperature. Resistance for the cold condition had been measured in advance. A heat balance equation was constructed for the measured wall and air temperatures and known thermophysical properties of fiberglass laminate wall of appropriate shape. The equation yielded heat transfer coefficient on the wall $\alpha_i = \alpha_i(T_i, T_f, \rho, c, \delta)$, here $T_f$ is the air flow temperature; $\rho, c, \delta$ are the density, heat capacity and thickness of the heat transfer plate. Heat transfer coefficient distribution was estimated for each value of forcing frequency.

At the first stage of experiments, heat transfer was measured in the steady air flow. The obtained distributions of heat transfer coefficient at these regimes agree well with canonical data on heat transfer in the entrance region of the channel. Peak heat transfer coefficients, $\alpha$, were observed at the channel inlet with monotonous decrease further downstream.

![Figure 2. Voltage (a) and current (b) in the strips of heat transfer section in steady flow.](image)

For the case of smooth-inlet channel, heat transfer coefficients were studied for the average flow velocity $U=1.8$ m/s (Reynolds number based on equivalent diameter of the channel $Re=1.5 \times 10^5$). Experimental data are demonstrated for two frequency ranges (figure 3, a, b) for clarity. The inlet section of the channel (where the inlet duct was attached to the channel) was taken as $x=0$. All figures contain the distribution of heat transfer coefficient in the steady flow (solid line 8) for comparison. Two data groups along x-coordinate refer to two measurement cycles with different location of heat transfer wall: in the entrance region and further downstream.

In general, the experiments demonstrated heat transfer enhancement at pulsating flow regimes in the channel entrance region, in particular immediately downstream of the inlet duct. At low frequencies of up to $f=12$ Hz (figure 3, a) and/or low amplitudes $\beta \sim 0.3$ (figure 3, b) the behavior of heat transfer coefficient distributions were similar to the ones in steady flow with slight deviations in values. The flow pattern can obviously be considered as a quasisteady one. The increase in forced pulsation frequency up to $f=50$ Hz (figure 3, b) significantly changes the behavior of heat transfer coefficient: it becomes non-monotonous with several maxima and minima, and double heat transfer enhancement is observed. This fact can testify to generation of large-scale vortices in the inlet duct. Their behavior in the entrance region obviously causes such non-monotonous distributions of the heat transfer coefficient.
transfer coefficient. Further monotonous reduction of the heat transfer coefficient down to the steady-flow values downstream along the channel may result from breakup of these vortices.

![Figure 3](image)

**Figure 3.** Heat transfer coefficient at low-frequency (a) and high-frequency (b) regimes with frequencies 12 (1), 16 (2), 20 (3), 40 (4), 50 Hz (5) at $\beta \sim 0.8$, 70 (6), 140 Hz (7) at $\beta \sim 0.3$ and in steady flow (8).

In general, decrease in heat transfer coefficients down to the steady-flow values was observed along the channel at all the considered frequencies. At the distance of $x \sim 1$ m (~8 equivalent diameters) the difference did not exceed 8%.

### 4. Conclusions

Thus, when studying hydrodynamics and heat transfer from objects located in channels with forced flow pulsations, not only the wave structure of the pulsating flow should be taken into account but also the flow history. The latter largely depends on the interaction between the pulsating flow and the inlet duct at least in the entrance region. It seems likely that vortices will form here depending on the frequency and amplitude of forced flow pulsations.

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