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To cite this article: I A Davletshin et al 2017 J. Phys.: Conf. Ser. 891 012045

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Heat transfer in pulsating flows in the channels with pressure gradient

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Abstract. Heat transfer in channels with the pressure gradient has been studied experimentally. The considered rectangular channel had a diverging and a converging section. Air under atmospheric conditions at the channel inlet was considered as a heat-transfer fluid. Steady and pulsating flow regimes were studied at different frequencies and amplitudes of forced pulsations generated by a rotating flap periodically blocking the channel cross section. The effect of forced flow pulsations on heat transfer in channels with the pressure gradient has been described.

1. Introduction
Flows under pressure gradients, primarily in diverging and converging channels, frequently occur in engineering. Large variety of configurations can lead to major differences in hydrodynamic and heat processes in such channels. Integral characteristics of the channels (heat transfer, pressure drop) generally depend on the flow pattern. In regard to diverging channels, the case can be further complicated by flow separation [1]. Therefore, multiple studies deal with flow pattern examination. Optical technique of Particle Image Velocimetry (PIV), which has become very popular recently, allows measurements of the flow pattern in the form of 2D or 3D velocity fields [2, 3]. Studies of heat transfer in diverging channels are important from scientific and practical points of view [4].

Certain engineering structures employ complex channels, and the peculiarities in construction can alter the hydrodynamic and heat processes in a facility [5]. Authors [6, 7] showed that a combination of favorable/adverse pressure gradient and a sudden expansion resulted in decreased/enhanced heat transfer in the separation region. Thermal protection of facilities is a commonly encountered problem. The desired parameters are attained, among other, by optimization of the diverging channel geometry [8-10].

Flow pattern in converging channels with favorable pressure gradient is somewhat different from the one in diverging channels. No flow separation occurs in converging channels. Experimental [11, 12] and numerical [13] studies revealed that favorable pressure gradient promote flow laminarization. Pressure drop and heat transfer can decrease here: the corresponding coefficients drop below the turbulent ones, however they remain higher than zero-pressure-gradient values. Depending on the pressure gradient values, the laminar-turbulent transition can be delayed or the flow can remain...
laminar at all times. High pressure gradients can even cause reverse turbulent-laminar transition (relaminarization).

The information on processes occurring in gradient flows available so far has been largely related to steady flows. Meanwhile, hydrodynamics and heat transfer in unsteady, particularly pulsating, flows can be essentially different [14-16]. For example, depending on the conditions, forced pulsations can result in both heat transfer enhancement [17] and deterioration [18]. Large vortices can greatly affect the pulsating flow pattern. They can be observed even at steady regimes in the form of the separation region. In this case, interaction between the vortices and forced pulsations can further complicate the flow pattern [19]. It should be noted that flow pulsations themselves can cause the formation of regular vortices.

Thus, the study of heat transfer in the channel under the combined effect of pressure gradient and forced flow pulsations will contribute to the knowledge of main regularities in heat and mass transfer in such complex flows.

2. Experimental setup and procedure

An experimental setup with a plane 1.2-meter long test section is shown in figure 1. The inlet duct \( I \) in one plane was shaped according to the Bernoulli lemniscates curve. In the middle part of the channel there was a diverging (figure 1, a) or converging (figure 1, b) section \( \beta \) with the length \( L=196 \) mm. The channel width was \( 150 \) mm, diverging (converging) section inlet height was \( H_0=40 \) (100) mm, its outlet height was \( H_1=100 \) (40) mm. Diverging and converging sections were formed by inclination of one wall by the angle \( \varphi=17^\circ \). To turbulize the flow at the channel inlet (where the inlet duct was attached), a turbulence generating grid was installed and an abrasive was glued to the channel perimeter.

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 (the ones with and 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. The pulsation amplitude was derived from local velocities measured by an optical method.

The study of heat transfer of the test section with pressure gradient was carried out using a heat transfer section 2 with the length of 450 mm. 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 30-mm thick 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 the width of 100 mm. In fact, the copper layer acted as 33 resistance thermometers that measured local temperatures of the wall with the streamwise spacing of 13.6 mm.

The temperature of ambient air drawn into the channel was measured by a resistance thermometer 5 mounted in the inlet duct.

![Figure 1. Experimental setup with the diverging (a) or converging (b) section: 1 – inlet duct; 2 – heat transfer wall; 3 – diverging/converging section; 4 – pulsator; 5 – thermometer.](image-url)
Heat transfer studies were conducted as follows. The channel was heated by hot air before the measurements. Then, while the wall was being cooled by the air flow at the room temperature, the temperatures of heat transfer walls were measured during 100 seconds with the frequency of 200 measurements per second. Heat balance equations together with these data yielded the distribution of heat transfer coefficient along the channel which was considered time constant. Time-averaged heat transfer was estimated at pulsating flow regimes.

The experiments were conducted at the air flow rate of 120 m³/h. Average velocity, $U$, of the flow in the diverging section varied from 5.6 m/s at the inlet to 2.2 m/s at the outlet. In the case of converging section, quite the opposite, it varied from 2.2 to 5.6 m/s. Reynolds numbers based on the equivalent diameter, $d'$, were $Re=Ud'/\nu=2.4\cdot10^4$ (narrow sections) and $Re=1.8\cdot10^4$ (wide sections), where the corresponding $d'$ were 63.2 mm and 120 mm, respectively.

Forcing frequencies $f=0–20$ Hz were considered at two levels of relative amplitudes of velocities $\beta=A_1/U$~0.3 and $\beta$~0.8. These values were chosen due to the following considerations. Pulsating flow in a diverging (converging) channel can be characterized by two pressure gradients. The first one is governed by the channel geometry, and the second one is due to the wave structure of the pulsating flow. There can be different ratios of these parameters in the considered flow. The regimes with one and the same order of these gradients were studied here. Otherwise, it would have been possible to tentatively relate the flows to pulsating zero-pressure-gradient flows or steady gradient flows.

3. Results and discussion

Initially, test experiments were conducted in a smooth channel with the cross section of 150×115 mm² and the length of 1.2 m at steady flow regimes. The obtained heat transfer coefficient distributions agreed well with a classical concept of heat transfer in the entrance region of the channel. Thus, the employed method demonstrated its efficiency in the considered class of problems.

Figures 2 and 3 show the distributions of heat transfer coefficients over the channel length. The inlet section of the channel (where the inlet duct was attached) was taken as the origin $x=0$. Dotted lines indicate the boundaries of converging and diverging sections. Since the heat transfer wall was longer than the diverging (converging) section, the data on heat transfer was obtained also in the region upstream of the diverging (converging) section.

First of all, the heat transfer in steady gradient flows was studied experimentally. The heat transfer coefficient, $h$, in the steady flow in the diverging channel decreased over the channel length, which is obviously attributed to the reduction in the flow velocity (figure 2, line 7). Some nonmonotonicity in distribution of $h$ over the diverging section is probably associated with the flow separation or the proximity of such phenomenon. Indeed, at the outlet-to-inlet area ratio $H_1/H_0=2.5$ and the angle $\varphi=17^\circ$, the considered diverging channel is at the boundary between the geometries corresponding to separation-free and separated flows [20]. When the amplitude of velocity pulsations was low ($\beta$~0.3), the heat transfer coefficient distributions in pulsating flows appeared to be close to the steady ones. However, nonmonotonicity of curves became more pronounced. Increase in the amplitude up to $\beta$~0.8 promoted this non-monotonous behavior. This can be attributed to the enhancement of vortex motion in the separation region of the pulsating flow in the diverging channel. The figures show that 15% heat transfer augmentation in pulsating flow if compared with the steady flow values is also observed upstream of the diverging section inlet. This effect is possibly due to heat and mass transfer enhancement in the inlet duct and in the entrance section of the channel.

Similar heat transfer enhancement (up to 20% in pulsating flow) was also evidenced in the entrance section upstream of the converging channel (figure 3). Here, unlike the case of diverging channel, monotonous increase in heat transfer coefficient was observed throughout the whole converging section at all the considered regimes of flow due to streamwise increase in the flow velocity. At small amplitudes of velocity, the distributions of $h$ can be considered quasi-steady with slight enhancement. The increase in the amplitude leads to heat transfer coefficient amplification. However, the latter should be rather attributed to the heat transfer enhancement in the entrance.
section of the channel. The unsteady and steady heat transfer coefficients, $h$, move closer to each other along the converging section.

Considerable deterioration of heat transfer was observed downstream of the converging section, which was probably due to considerable rearrangement of flow pattern in this region. This flow pattern can be characterized, for example, by hydrodynamic and thermal boundary layers on the opposite walls reaching the channel axis downstream of the converging section. This holds true for steady and low-amplitude pulsating regimes. However, in high-amplitude pulsating flows immediately downstream of the converging section, the decrease in heat transfer coefficient is followed by its growth in streamwise direction. Such behavior may be attributed to the local separation region and large vortices formed in this area. Vortices regularly shed from the corner edge between the converging section and the constant cross-section channel are able to considerably enhance heat transfer in this part of the channel.

![Figure 2](image2.png)

*Figure 2.* Heat transfer coefficient in the diverging channel at the following forcing frequencies: 6 (1, 2), 12 (3, 4), 20 Hz (5, 6), steady flow (7): light symbols (1, 3, 5) at $\beta$~0.3, dark symbols (2, 4, 6) – $\beta$~0.8.

![Figure 3](image3.png)

*Figure 3.* Heat transfer coefficient in the converging channel. See figure 2 for notations.

Thus, experimental study of heat transfer in the channels with forced flow pulsations and pressure gradient demonstrated the following:
- quasi-steady behavior of heat transfer coefficient along the channel at low amplitudes of velocity fluctuations;
- high amplitudes of pulsations can enhance heat and mass transfer when separation regions (vortices) exist (or start forming) in the channel;
- the flow history upstream of the diverging (converging) section can significantly affect the convective heat transfer in this section. In the considered case it was expressed through heat transfer enhancement in pulsating flow in the entrance region of the constant cross-section channel.

Acknowledgments
This study was supported by the Russian Science Foundation (Project no.16-19-10336).

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