

# Heat transfer in a pulsating flow in a converging channel

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**Abstract.** Experimental research of convective heat transfer in a plane converging channel has been conducted. Distributions of heat transfer coefficient on the channel wall in steady and pulsating air flow have been obtained. Quasisteady behavior of heat transfer distributions has been revealed for the pulsating flow case.

## 1 Introduction

Hydrodynamic and heat processes in gradient flows have their own features. Gradient flows exhibit significant difference between the flow with adverse and favorable pressure gradients. Streamwise pressure gradient in the former case can lead to the flow separation while in the latter case it contributes to the boundary layer stabilization.

Practical relevance of flows in converging channels with favorable pressure gradient determines the need for investigation of processes in such flows [1-4]. It was established experimentally [1, 2] and numerically [3] that favorable pressure gradient promotes flow laminarization. This is accompanied by the reduced hydraulic loss and heat transfer deterioration: the corresponding coefficients drop below the turbulent ones but remain higher than those in zero gradient case. The Kays acceleration parameter is usually taken as a numerical characteristic involved in the analysis of gradient flows. The Kays parameter is estimated by the rate of velocity growth along the streamwise coordinate. Laminar-turbulent transition delay occurs at any value of this parameter. Starting from a certain Kays parameter, the flow remains laminar at any time. Reverse turbulent-laminar transition is even possible at high Kays parameters.

Hydrodynamic and heat processes in channels were studied under the combined effect of the pressure gradient and other factors. In particular, the behavior of flow parameters when different turbulence generating grids were installed in the channel were estimated experimentally [2]. The mesh space and blockage ratio altered the boundary layer and thermal boundary layer and caused earlier transition of heat transfer coefficient from laminar to turbulent values.

Optical methods in hydrodynamics have been developing in the recent years. Kinematic flow structure (fields of velocity, turbulence, vorticity) in different cases is investigated using PIV measurements. In particular, even extensive PIV measurements involving 16 cameras were carried out to obtain the flow structure [4]. However, at present, the

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conducted research is more valuable for the try-out of measurement technique for the considered class of problems.

It should be noted that the majority of available data on gradient flows deal with the steady flow case. Meanwhile, the available information on pulsating flows shows, for example, the changes in the profiles of velocity and shear stress during one period of pulsations [5].

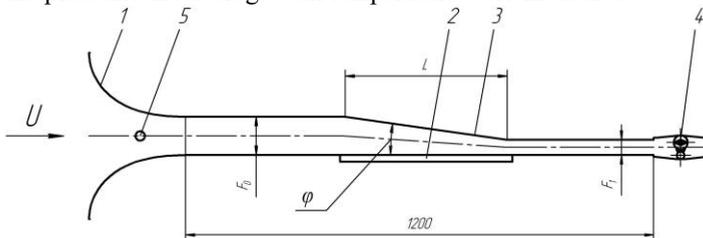
The parameters of separated flow are governed by forced pulsations. Depending on the frequency and amplitude of pulsations, large-scale vortices of different intensity are formed in the separation region. This is accompanied by variation in distributions of pressure, shear stress on the wall and heat transfer coefficient along the separation region. The reattachment length becomes half its initial size, heat transfer enhancement is observed particularly near the obstacle which causes flow separation [6].

Thus, the study of processes (including the heat processes) in gradient flows can yield new information on such complex flows.

## 2 Experiment

The paper deals with experimental estimation of the heat transfer coefficient in a converging channel with the angle of  $\varphi=4.5^\circ$  at steady and pulsating air flow regimes. The test section was a plane channel made of polycarbonate with the length of 1.2 m, width of 150 mm, inflow section height  $h_0=60$  mm and outflow section height  $h_1=24$  mm. This gives the ratio of inflow to outflow areas  $F_1/F_0 = 0.4$  (fig. 1). To turbulize the flow, a turbulence generating grid was installed and an abrasive strip was glued onto the channel perimeter between the channel inlet and the test section. The length of converging section was  $L=450$  mm. The distance between the channel inlet and the converging section inlet was 370 mm. The air flow was provided by a compressor operating in suction mode. Flow pulsations were generated by a special device – pulsator. Its cross section at the channel outlet was periodically blocked by a rotating flap 4. 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<sup>3</sup> 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 IRVIS RS-4 Ultra flowmeter downstream of the receiver tank.

A 450-mm long heat transfer wall was mounted across the whole channel for heat experiments in converging section. It 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. Total resistance of the plate and the average wall temperature were measured.



**Fig. 1.** Experimental setup: 1 – channel inlet; 2 – heat transfer wall; 3 – converging section; 4 – pulsator; 5 – thermometer

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 (not excepting the pulsating regimes).

The considered ranges of forced pulsation frequency and relative amplitudes of velocity were  $f = (6 - 12)$  Hz and  $\beta = A_0/U = 0.3 - 0.8$ , respectively. The frequencies were adjusted by the flap rotation rate. Amplitudes were estimated from velocity, measured by an optical method. The studied ranges of amplitudes and velocities were chosen according to the following considerations. The considered flows are influenced by two factors: pressure gradient due to the converging channel shape and forced flow pulsations. For the considered converging channel, it is in the specified ranges of frequencies and amplitudes that the pressure gradients caused by the channel geometry and wave structure of the pulsating flow are of the same level. Thus, both factors are relevant in the considered ranges of parameters. Under these conditions, the study of heat processes in pulsating gradient flows was of interest in terms of the combined effect of the specified factors.

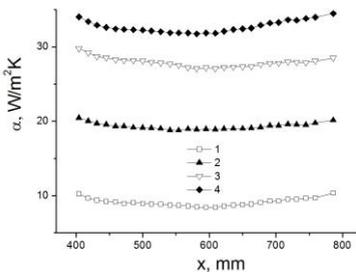
### 3 Results

First, heat transfer coefficients were measured in steady air flow in the converging channel section (fig.2, 3). Despite the streamwise acceleration, heat transfer deterioration was observed in the first half of the converging channel, while the second half of the converging channel exhibited typical streamwise heat transfer enhancement (fig. 2). In general, the behavior of these distributions is obviously formed by two factors: the growth of thermal boundary layer further downstream and its thinning under favorable pressure gradient. So, the first factor dominates in the first half, while the second one is prevalent in the second half.

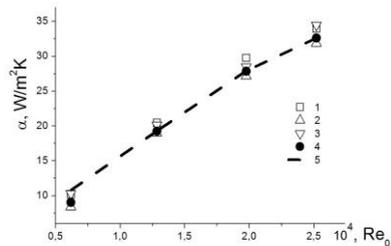
The research of the steady flow was carried out in the range of velocities at the converging channel inlet velocity  $U_0 = (1.5-6.3)$  m/s and Reynolds numbers  $Re_0 = U_0 h_0 / \nu = (0.6-2.5) \times 10^4$ . Reynolds numbers based on the actual velocity and streamwise coordinate were  $Re_x = Ux/\nu = (0.4 - 7.5) \times 10^5$ , Kays acceleration parameter  $K = (3.1-13) \cdot 10^{-6}$ ,

here  $K = \frac{\nu}{U^2} \frac{\partial U}{\partial x} = \frac{tg\phi}{Re_0}$  for the plane channel. According to [1-3], laminar flow

corresponds to these parameters. However, forced turbulization of flow by the turbulence generating grid and the abrasive provided heat transfer coefficients typical of turbulent flows (fig. 3).

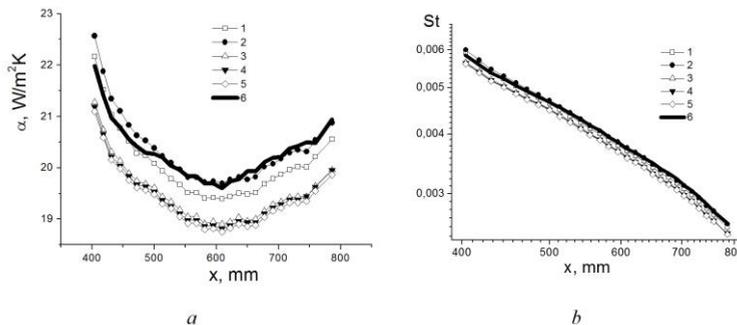


**Fig. 2.** Heat transfer coefficient in steady flow at inlet velocity  $U_0$ : 1–1.5; 2–3.2; 3–4.9; 4–6.3 m/s.



**Fig. 3.** Heat transfer coefficient: 1 –  $x=34$ ; 2 – 225; 3 – 416 mm; 4 – wall average; 5 –  $\alpha \sim Re_0^{0.8}$

Heat transfer at pulsating flow regimes was studied for a single flow rate (fig. 4) at which the average velocity at the channel inlet was  $U_0=2.9$  m/s ( $Re_0=1.2 \cdot 10^4$ ). The Stanton number was estimated using the actual values of the average air velocity in the converging channel  $St = \frac{\alpha}{\rho c U}$ , where  $\rho$  and  $c$  are air density and heat capacity, respectively. The measurements showed that heat transfer coefficient distributions in pulsating flows are quasi steady. Moreover, the values of  $\alpha$  appeared to be close to the steady ones with small deviation (up to 5%) towards the lower values. Such decrease can be explained as follows: when the velocity is periodic in time, the inequality  $(U^{0.8})_{aver} < U_{aver}^{0.8}$  (subscript “aver” means time average) is true for the curve  $\alpha \sim U^{0.8}$  typical of turbulent regimes (exponent less than 1). Hence, in quasisteady approximation, the heat transfer coefficient in pulsating flow should exhibit some decrease depending on the amplitude. Quasi steadiness here means that forced pulsations do not lead to qualitative changes in the flow structure if compared with the steady case.



**Fig. 4.** Heat transfer coefficient (a) and Stanton number (b) at the regimes: 1,2 – 6 Hz; 3,4 – 9 Hz; 5 – 12 Hz; 6 – steady; light symbols –  $\beta=0.3$ ; dark symbols –  $\beta=0.8$ .

## 4 Conclusions

It has been experimentally established that heat transfer coefficient in pulsating flows in converging channels remains close to the steady flow case. This statement is true at least for the flows in which the flow structure can be considered quasisteady.

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## References

1. W.M. Kays, D.W. Kearney, R.J. Moffat, *The turbulent boundary layer-Experimental heat transfer with strong favorable pressure gradients and blowing* (1970)
2. M.F. Blair, M.J. Werle, United Technologies Research Center East Hartford CT, 1981
3. E.P. Volchkov, M.S. Makarov, A.Yu. Sakhnov, *Int. J. Heat Mass Transfer* **55** 1126 (2012)
4. R. Hain, S. Schamowski, N. Reuther et al. *In Proc. 18th Int. Symp. on the Application of Laser and Imaging Techniques to Fluid Mechanics, Lisbon, Portugal* (2016)
5. A.E. Goltsman, I.A. Davletshin, N.I. Mikheev, A.A. Paereliy, *Thermophys. Aeromech.* **22** 319 (2015)
6. I.A. Davletshin, N.I. Mikheev, *High Temp.* **50** 412 (2012)