About the intensification of convective heat transfer from combustion products to the walls of a cylindrical shaped pulsing combustion chamber

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Abstract. Franke’s critical dependence determines the theoretical relationship for the numbers Nu for pulsating and stationary flow regimes. It is based on the heat exchange intensification hypothesis due to the interaction of the pulsating velocity profile and the boundary layer near the heating surface. The article presents the results of studies to test the efficiency of the Franke’s ratio for a given range of pulsed combustion chamber diameters, as well as to determine the influence of the geometric parameters of the chamber on the convective heat transfer from the combustion products to the walls of the chamber.

According to the ideas of the authors [1, 2], pulsating combustion is a self-oscillatory process that arises as a result of the interaction of the combustion zone (heat release, thermal resistance and burning velocity) and flow (pressure, velocity and entropy).

According to one of the hypotheses, the intensification of heat transfer during the washing of the heating surfaces by the pulsating flow occurs as a result of the interaction of the pulsating velocity profile and the boundary layer near the heating surface. The resistance of the pulsating flow, the velocity profile and the boundary layer on the channel walls determine the mass and heat exchange between the flow and the wall. According to G. Schlichting [3], the velocity profile of the pulsating flow is determined by the pressure gradient $\frac{\delta p}{\delta x}$. For cos- vibrations $\frac{\delta p}{\delta x}=\rho k \cos(\omega \tau)$, where $\rho$ – the density of the medium, kg/m$^3$; $k$ – a constant; $\omega$ – the angular frequency, s$^{-1}$; $\tau$ – the time, s.

The varying velocity profile causes oscillations of the heat sink from the flow to the wall, while a significant increase in the heat transfer coefficient is observed.

Based on the temporal and spatial distribution of the velocities of the stationary and pulsating flows in the tube, and also assuming that in the turbulent flow a pulsating boundary layer arises between the wall of the tube and the core of the flow oscillating as a solid body, Frank derived the theoretical relation on the basis of the Prandtl theory [4] for Nu numbers under pulsating and stationary flow regimes:

$$\frac{Nu_{fn}}{Nu_{fc}} = \frac{1+1.74(Pr_f-1)Re_f^{-1/8}}{1+1.02b^{1/8}Re_f^{1/10}Pr}\cdot\frac{Re_f^{3/8}Pr}{1.02b^{1/8}Re_f^{1/4}k},$$
where \( Pr_f = \frac{v}{\alpha} \) – the Prandtl criterion; 
\( v \) – the kinematic viscosity coefficient, \( m^2/s \); 
\( \alpha \) – the coefficient of thermal diffusivity, \( m^2/s \); 
\( Re_f = \frac{W_c d}{\nu} \) – criterion \( Re \) for stationary mode; 
\( W_c \) – the average velocity of the stationary flow in the chamber, \( m/s \); 
\( d \) – the diameter of the pipe, \( m \); 
\( \beta \) and \( b \) – are constants; 
\( Re_{f_p} = \frac{A \beta}{\nu} \) – criterion \( Re \) for a pulsating flow; 
\( A = \frac{\theta}{\omega} \) – the amplitude of pulsations, \( m \); 
\( \theta \) – the velocity amplitude, \( m/s \); 
\( \omega = 2\pi f \) – angular frequency of pulsation, \( 1/s \); 
\( k \) – the pulsation coefficient.

As can be seen from the equation, the increase in heat transfer depends on the criteria \( Pr_f \) and \( Re_f \), the pulsation coefficient \( k \) and the \( Re_{f_p} \) criterion. The effect of the \( Re_{f_p} \) criterion at a constant value of \( W \) is related to the change in the pipe diameter \( d \) and the kinematic viscosity coefficient \( \nu \). Heat transfer from the pulsating flow increases with an increase in the pulsation coefficient \( k \), and also with a decrease in the temperature of the gas flow and the value of \( Re_{f_p} \).

According to the equation for a certain tube diameter, there is an optimal relationship between the angular frequency \( \omega \), the average flow rate \( W \) and the pulsation coefficient \( k \), in which the heat transfer is maximized.

One of the research tasks was to check the reliability of the theoretical ratio of Nusselt numbers for a given range of the chamber diameter change, as well as to determine the influence of the chamber geometric parameters on the convective heat transfer from the combustion products to the chamber walls.

The experiments were carried out with a cylindrical combustion chamber 3, opened from one side (Fig. 1). Combustion in the chamber was achieved by installing, on the closed side of the chamber, a gas injection tunnel gas type 1 with a gas burner. The thermal power of the burner at a gas pressure in front of a nozzle of 0.1 MPa was equal to 40 kW. The excess air ratio was 1.

Fig.1. The scheme of the experimental setup

In chamber 3, pulsating combustion was achieved due to the installation of a combustible air mixture at the outlet of the injection gas burner 1 of a poorly flowing body - the vortex stabilizer 2 with a large cone angle.

During the experiments, the influence of the geometric parameters of the chamber on the convective heat transfer from the combustion products to the walls of the chamber was clarified. Therefore, three cylindrical pipes of different diameters were used as combustion chambers. With an unchanged length of the chamber, their internal diameters were 0.092; 0.148 and 0.206 m. In determining the convective heat transfer for the characteristic size, the diameter of the chamber was adopted.

Determination of the functions of the heat transfer coefficient \( \alpha \) and the Nusselt number was carried out by the method described in the source [5]. For each diameter of the chamber, the rate of heating of the chamber walls, the acoustic parameters of the gas flow, and the gas flow rate in the chamber were determined. The heating rate was recorded by temperature sensors installed along the entire length of the chamber. Figure 2 shows the heating rate diagram of five sections of the chamber in the pulsed combustion regime. Measurements of the investigated signals were carried out in stationary and pulsed-burning regimes. In both cases, the local values of the heat transfer coefficient \( \alpha \) were determined.
Fig. 2. Graphs of the rate of heating of the i-th section of the chamber in the regime of pulsating combustion

The results of the experiments were presented in the form of the value of the heat transfer coefficient $\alpha$ along the length of the chamber for the stationary and pulsating operating regimes of the three chambers. The characteristic convective heat transfer graphs are shown in Fig. 3.

Fig. 3. Typical heat transfer graphs for a chamber with a diameter of 0.148 m

An analysis of the results of experimental studies made it possible to draw a number of conclusions. It is established that in the regime of pulsing combustion, the value of the heat transfer coefficient $\alpha$ is much higher than in the stationary combustion regime. As can be seen from Fig. 3, during passing from one combustion regime to another, the heat transfer coefficient increases almost three times. It is noted that an increase in the heat transfer coefficient is associated with an increase in the velocity pulsations. In experiments with a chamber $d = 0.092$ m, the vibrational velocity of the gas flow reached 16 m/s. Calculation of the vibrational velocity of the gas flow during pulsating combustion was carried
out on the basis of data obtained by measuring the pulsations of the gas flow pressure. The vibrational velocity in a plane traveling wave was found by the method of [6]. Figure 4 shows the characteristic graphs of the vibrational velocity of the gas flow: a solid line for harmonics with a frequency of 45 and 135 Hz in the pulsed combustion mode, an intermittent line for harmonics with the same frequencies in the steady-state combustion mode. When analyzing the diagrams of the vibrational velocity of the gas flow, it is established that in the regime of pulsating combustion considerable oscillations are generated in the chamber (up to 9 m/s). The highest values of the heat transfer coefficient $\alpha$ (up to 40 ... 50 W/m$^2$K) were fixed at the maximum values of the vibrational velocity. Consequently, an increase in the heat transfer coefficient $\alpha$ is due to a significant increase in the vibrational velocity of the gas stream.

\[ \alpha \sim d^{-0.15} \]

Fig. 4. Characteristic diagram of the vibrational velocity of the gas stream for a chamber with a diameter of 0.148 m

It is established that the diameter of the chamber does not significantly affect the heat transfer. Figure 5 shows the dependence of the average heat transfer coefficient $\bar{\alpha}$ average length on the chamber for the regimes of stable pulsating combustion. It is seen that as the diameter of the chamber $d$ increases, the average heat transfer coefficient $\bar{\alpha}$ decreases insignificantly. The calculations showed an approximate dependence $\bar{\alpha} \sim d^{-0.15}$.

Fig. 5. Dependence of the average length heat transfer coefficient over the length of the chamber from the diameter of the chamber

Using the data obtained during the experiments and the calculated average values of the heat transfer coefficient $\bar{\alpha}$ an adequate normal equality of the Nusselt numbers was observed under pulsating and stationary gas flow regimes. The data were based on the data of the average constant speed $W$ and the maximum oscillation amplitudes $\delta$, obtained in the regime of stable pulsating combustion at the maximum heat transfer.

The obtained results of the Nusselt number ratios for different chamber diameters for pulsating and stationary operating modes are given in the table 1.
Table 1. Experimental and calculated ratios of Nusselt number values

| Internal diameter of the chamber, m | Nн/Нс experimental | Nн/Нс calculated | Degree of conformity of experimental and calculated values, % |
|-----------------------------------|---------------------|------------------|-------------------------------------------------------------|
| 0.092                             | 3.4                 | 2.7              | 20                                                          |
| 0.148                             | 3.1                 | 2.6              | 16                                                          |
| 0.206                             | 3.9                 | 3.3              | 15                                                          |

As can be seen from the table, the ratio of the values of Nusselt numbers for stationary and pulsating combustion regimes obtained experimentally (for chambers with internal diameter d = 0.092, 0.148 and 0.206 m) correspond to the same values obtained by calculation, with the error indicated in the table.

It allows to assert that the known criterial dependence applied to the proposed scheme of the pulsing combustion chamber is reliable, and in the range of the investigated diameters (0.092...0.206 m) it can be used for preliminary chamber calculations.

References

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