EXPERIMENTAL STUDY OF HEAT TRANSFER IN A PULSATING COMBUSTOR

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The local and integral heat fluxes through the wall of a combustor operating in the pulsating regime have been investigated experimentally.

The interest in pulsating combustion is motivated by the opportunity of obtaining large heat-release rates and heat-transfer rates by comparison with conventional combustion equipment.

However, not enough theoretical and experimental work has been done to lend complete insight into the heat-transfer process associated with pulsating combustion.

The pulsating combustion chamber normally comprises a duct through which the combustion products move. It is well known that heat transfer is intensified in the pulsating combustor by the oscillations of the heat agent in the duct [1].

The published experimental and theoretical studies of nonsteady heat transfer in a duct contain conflicting data on the influence of pulsations of the heat agent flow on the heat-transfer process. Intensification has been observed in some cases [1, 2], and not in others [3], while in still other papers it has been demonstrated experimentally and theoretically that heat transfer deteriorates under conditions of heat agent oscillations [4, 5].

Some authors have noted both an increase and a decrease in the heat transfer rates, depending on the frequency and amplitude of the oscillations as well as the Reynolds number [6, 7].

The presence of large temperature differentials and periodic heat release in pulsating combustors complicates the investigation of nonsteady heat transfer. Also, the frequency and amplitude of sonic oscillations of the heat agent in pulsating combustors are determined by the geometry of the latter.

Hanby [1] has measured the local heat fluxes for the case of a tubular combustor closed at one end. The integral heat fluxes in a combustor configuration in the form of a duct with a connecting large volume have been investigated in a series of studies carried out at the Central Scientific-Research Institute for Boilers and Turbines (TsKTI) under the direction of B. D. Katsnel'son and A. A. Tarakanovskii.

The objective of the present study was to conduct experiments on the local and integral thermal characteristics of a pulsating combustor with the configuration of a duct connected to a large volume.

The experimental arrangement is shown schematically in Fig. 1.

The pulsating combustor 1 has two parts: the reactor 1a comprising a chamber with diameter $d_1 = 50$ mm and length $l_1 = 90$ mm; and the duct 1b with corresponding dimensions $d_2 = 20$ mm and $l_2 = 400$ mm. The fuel (commercial propane) and air are injected into the mixer 2 and fired in the reactor 1a. The mass flow of fuel and air are recorded by the rheometers 3. The combustor 1 is mounted vertically in the water reservoir 4, which has a volume of 15 liters.

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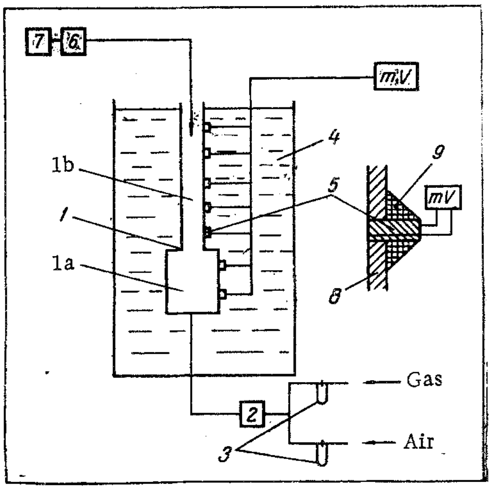

Fig. 1

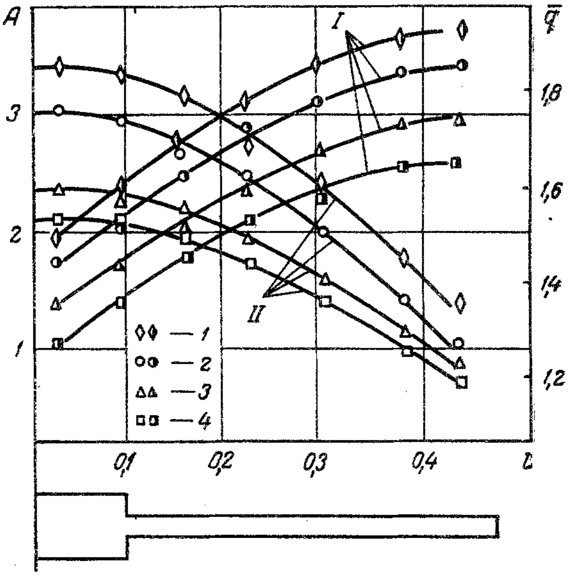

Fig. 2

Fig. 1. Experimental arrangement. 1) Pulsating combustor; 1a) reactor; 1b) duct; 2) mixer; 3) rheometer; 4) water reservoir; 5) heat-flux sensors; 6) acoustic probe; 7) oscilloscope; 8) combustor wall; 9) heat insulation.

Fig. 2. Distributions of parameter $\bar{q}$ (I) and acoustic pressure (II) along the pulsating combustor. Mixture flow rate Q = 580 cm^3/sec. 1) l = 0.058; 2) 0.053; 3) 0.045; 4) 0.006 m.

The local heat fluxes are measured with sensors operating on the "auxiliary wall" principle [8]. The sensors 5 are nickel rods with diameter d = 10 mm and height h = 20 mm. Copper wires are calked into the ends of the rod. The nickel rod and copper wires combine to form a differential thermocouple, which is precalibrated. The thermal conductivity of the nickel is taken from tables. The heat flux measurement error does not exceed 10%.

The surface of the sensors 5 in contact with the combustion products is carefully machined to conform to the inside diameter of the duct 8. This precludes the possibility of distortion of the boundary layer at the point where the heat fluxes are measured. The lateral surface of the sensors is protected by the thermal insulation 9.

Seven heat-flux sensors are planted on the surface of the combustor with a mutual spacing of 40 to 90 mm.

The amplitude of the pressure oscillations in the combustor 1 is measured with the acoustic probe 6, whose output signal is fed to the calibrated oscilloscope 7. The pressure amplitude is measured at the sites of the heat-flux sensors. Because of the impossibility of dynamic calibration the relative amplitude of the acoustic pressure is measured. The pressure amplitude measurement error is 8%.

The temperature of the combustion products is measured with a Chromel-Alumel thermocouple. To provide a basis for comparison of the thermal characteristics the pulsating combustor is also driven in the conventional, "uniform" combustion regime by means of fittings for the absorption of acoustic energy. The integral heat flux from the combustor walls is determined from the heating of the water in the reservoir 4. The water temperature is measured with a thermometer.

Stable pulsating combustion is observed in the range of concentrations $\varkappa$ = 0.035 to 0.075 at mixture flow rates Q = 200-1300 cm^3 sec. The flow rate is determined with 6% error. The pressure oscillation amplitude is a maximum for the stoichiometric fuel concentration. With an increase in the flow rate Q of the mixture the pressure amplitude is observed to increase. The frequency of the acoustic oscillations in the pulsating combustor is 180 ± 10 Hz, does not depend on the concentration or flow rate of the mixture, and corresponds to the fundamental natural frequency of the duct with the attached volume.

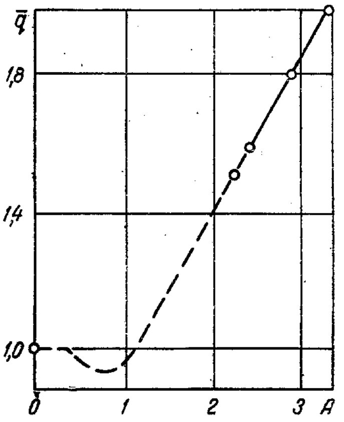

Fig. 3

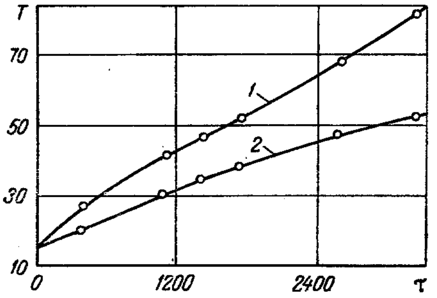

Fig. 4

Fig. 3. Parameter $\bar{q}$ versus pressure amplitude for Q = 580 cm^3/sec.

Fig. 4. Water temperature in reservoir versus combustor operating time. 1) Pulsating combustion regime; 2) "uniform" regime; T in °C, τ in sec.

Figure 2 gives plots of the pressure in the pulsating combustor for various concentrations at one value of the mixture flow rate Q = 580 cm^3/sec. The acoustic pressure maximum occurs in the reactor. The pressure amplitude is constant in the reactor and decreases along the duct, becoming a minimum at the open end.

In the pulsating combustion regime complete combustion occurs in the reactor 1a, whereas in the "uniform" regime complete combustion is observed in the duct 1b. The heat-release rate of the combustion volume attains 20 MW/m^3 in the pulsating regime.

The heat-transfer coefficient cannot be determined by the given procedure. The local heat flux through the combustor walls is measured in the present investigation. To determine the influence of the pressure oscillations on the heat transfer we introduce the dimensionless parameter $\bar{q}$, which is the ratio of the local heat flux through the combustor wall in the pulsating (q_p) and "uniform" (q_u) combustion regimes: $\bar{q} = q_p/q_u$. In essence, $\bar{q}$ represents the relative gain of the heat flux.

Figure 2 gives the variation of the parameter $\bar{q}$ along the combustor for various values of the acoustic pressure level. The lengthwise distribution of $\bar{q}$ in the combustor emulates the velocity distribution. The results indicate the decisive influence of the velocity amplitude on the variation of the heat flux through the wall, as is consistent with earlier results [1, 2, 6].

Inasmuch as the pressure and velocity curves are shifted by a quarter-wavelength, the pressure amplitude in the reactor 1a is proportional to the velocity amplitude at the open end of the duct 1b.

The influence of the pressure amplitude on the variation of the heat flux is shown in Fig. 3. The parameter $\bar{q}$ measured at the open end of the duct is plotted on the vertical, and the pressure amplitude A in the reactor 1a on the horizontal axis; the latter amplitude is proportional to the velocity amplitude at the open end of the duct 1b.

It is seen that the parameter $\bar{q}$ increases linearly with the pressure amplitude, consistent with the quasisteady-state theory of nonsteady heat transfer and with the results obtained in [1]. It is important to note that the continuation of the curve (dashed part) does not pass through the point ($\bar{q}$ = 1; A = 0) corresponding to "uniform" combustion; this result also concurs with the paper cited above.

The integral heat flux from the combustor is determined from the heating rate of the water in the reservoir. Figure 4 gives the dependence of the water temperature on the operating time of the combustor. The upper curve (1) corresponds to the pulsating combustion regime, and the lower curve (2) to the "uniform" regime. It is seen that the heating rate of the liquid is higher in the pulsating regime than in the "uniform" regime: $(\partial T/\partial \tau)_p > (\partial T/\partial \tau)_u$.

From the data of Fig. 4 we determine the ratio of the efficiencies of the two combustion regimes: $\mathrm{eff}_p/\mathrm{eff}_u = 1.8$. The average heat flux over the length of the combustor (Fig. 2) increases by a factor of 1.8 in the pulsating regime.

The increased efficiency of the pulsating regime is evinced by a decrease in the temperature of the combustion products at the exit from the duct as the pressure amplitude increases.

Using the tabulated chemical composition and heat capacities of the combustion products, we determine the heater efficiency, which turns out to be 90 to 95% for the pulsating regime and 45 to 55% for the "uniform" regime.

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