STUDY OF RADIATION HEAT TRANSFER AND THE TEMPERATURE STATE IN THE COMBUSTION CHAMBERS OF SMALL-SIZE GAS-TURBINE ENGINES (GTEs)

V. P. Lukash

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The experimental data on the radiation flux surface density distribution in the combustion chamber of a small-size gas-turbine engine are presented. Experiments are made at elevated pressures and temperatures of the stagnated flow at the chamber inlet. Satisfactory agreement between theory and experiment is obtained.

In recent years, both in our country and abroad, extensive studies have been made to improve the parameters and performance characteristics of small-size gas-turbine engines (SGTEs) used for helicopters, airplanes of local airlines, winged missiles, ground installations [1-3]. As compared to the large-size engines, the SGTEs have some specific features, and this makes one search for new ways to improve the parameters of engines of this class. In virtue of some design requirements, combustion chambers with reverse air flow in annular channels between the chamber body and the flame tube (countercurrent flow pattern, see Fig. 1) are mainly used in SGTEs. The SGTE combustion chamber with such a flow pattern is characteristic of: (1) low air velocities in annular channels (this deteriorates the convective heat removal from the flame tube surface); (2) the elevated value of the flame tube surface-to-its volume ratio (as against standard GTE chambers). This gives rise to an increase of the relative air flow rate to cool the flame tube walls, which is necessary to keep the wall temperature at an assigned level.

Under the above circumstances, solving the problem on the reliability and life of small-size combustion chambers, to a considerable extent, depends on the choice of an economic and effective cooling system for flame tube walls. The choice of the cooling system and the calculation of the thermal wall state are, in particular, based on reliable data on the magnitudes of the radiation heat fluxes from the fuel combustion products to the flame tube walls.

An experimental study of radiation fluxes has been made during independent bench tests of the combustion chamber of a particular small-size engine. Figure 1 shows the schematic of the annular chamber and the mounting places of beamed radiation radiometers. The flame tube is built with ordinary film cooling. The holes to "check" the flame by the radiometers are drilled at two wall places along the generatrix of the flame tube. In order to avoid the air flow from the annular channel inside the flame tube through these holes, the latter are connected with the outer body via the reducing bushes. The generatrix, along which the radiometers are arranged, passes along the nozzle axis.

The first (downstream in the flame tube) radiometer was mounted near the nozzle at a distance of about 40 mm from its cut and controlled flame radiation in the primary chamber zone along the beam path $l \approx 60$ mm. The second radiometer was placed approximately in the middle of the rectilinear flame tube section (before the flow turns) at a distance of 100 mm from the nozzle cut (at $l \simeq 75$ mm).

The design of beamed radiation radiometers used in the experiments is described in [4]. A differential many-junction ($\sim$25 junctions) copper-constantan thermocouple manufactured by the electrolytic coating method (wire thickness is 0.03 mm) serves as a sensing element of the radiometer. The body of the feeding element is fastened inside the copper unit, whose inlet is closed with a fluorite window (lens). The outer radiometer body is intensively cooled with water, the inner cavity is blown through by dried air (or nitrogen), thus preventing the hot gases from penetrating there. The viewing angle of the beamed radiation radiometer is $\simeq$2-3°. The radiometers are calibrated on a tube model of a perfectly black body, with the help of which it is possible to achieve radiation fluxes with a density up to $\sim$500 kW/m^2.

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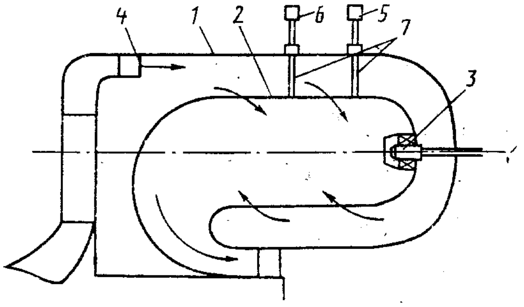

Fig. 1. Schematic of the combustion chamber of the small-size gas-turbine radiometer-equipped engine: 1) chamber body; 2) flue tube; 3) swirl nozzle; 4) compressor air supply; 5) 1st radiometer; 6) 2nd radiometer; 7) reducing bush.

The temperature level of the flame tube walls was determined by chromel-alumel thermocouples incorporating 0.3-mm-diameter electrodes; in all, 50 thermocouples (in the circumferential and longitudinal direction) were mounted on the flame tube. Two thermocouples were specially embedded into the inner shell of the flame tube radiometers. The indications of these thermocouples allow a contribution of the wall section radiation to the total radiation flux recorded by the radiometers to be taken into account.

Experiments are made over the range of the stagnated flow densities in the chamber $P^*_{ch} = (5\text{-}16) \cdot 10^2$ kPa, the stagnated flow temperatures at the chamber inlet $T^*_{ch} = 500\text{-}670$ K, of air excess coefficients $\alpha_{ch} = 2.6\text{-}5.6$, and of the reduced velocity at the chamber inlet $\lambda_{ch} = 0.1\text{-}0.13$.

From consideration of the data on the temperatures of the flame tube walls it follows that the wall temperature level is rather high and amounts to ≈ 1200 K near the nozzle and ≈ 1000 K far from it; this level decreases with increasing α_{ch} and decreasing P^{*ch}, T^*_{ch}.

Figure 2 plots the values of the surface radiation density E^* fixed by the radiometers in two mentioned cross-sections of the flame tube. In this figure, the local cross-section-mean values of the air excess coefficient $\alpha_{fi} = \alpha_{ch} G_i/G_a \simeq \alpha_{ch} \Sigma F_{ih}/F_h$ (where G_i is the air flow rate in the flame tube in the i-th cross-section; G_a is the total air flow rate through the chamber; F_{ih} is the total hole area from the swirler to the i-th cross-section; F_h is the total hole area of the flame tube). The quantities α_{f1} and α_{f2} calculated in terms of the hole areas are equal to $\alpha_{f1} = 0.192\alpha_{ch}$ and $\alpha_{f2} = 0.68\alpha_{ch}$.

As follows from the data in Fig. 2, the quantity E^*_1 (corresponding to the circulation zone radiation in the head chamber part near the nozzle) is noticeably greater than E^*_2 (determined by combustion product radiation in the mixing zone). As a rule, the quantities E^*_1 grow with elevating the parameters P^*_{ch} and T^*_{ch} (only the data on E^*_2 at $P^*_{ch} = 1000$ kPa, $T^*_{ch} = 650$ K have been obtained below the corresponding values of E^{*2} at $T^*_{ch} = 500$ K). Note that the results of the surface radiation density measured in the full-size combustion chamber (Fig. 2) are characteristic of a marked scatter of the values of E^* attributed to different factors: incorrect setting of the performance parameters in duplicate tests; insufficient good reproduction of the flow and combustion processes (determining the radiation level) in these cases; possible fouling of the fluorite window under unsatisfactory purification of the scavenging air, etc.

The maximum values of E^*_1 in the conducted runs of experiments are obtained in the chamber provided with a somewhat modified front facility at $P^*_{ch} = 13 \cdot 10^2$ kPa and $P^*_1 = 16 \cdot 10^2$ kPa, $T^*_{ch} = 650$ K, $\lambda_{ch} = 0.12$; these values are equal to 550 and 650 kW/m^2, respectively.

The obtained results on the radiation fluxes form the basis of calculations of the thermal state of the flame tube walls and of subsequent estimates of the chamber life. In addition to this, it should be noted that except for the flame self-radiation $E_{1s.r.}$, $E_{2s.r.}$, the radiation fluxes E^*1, E^*_2 measured by the radiometers incorporate the nonabsorbed (by the flame) radiation components of the opposite wall section and reflected (by this section) self-radiation. The estimates show that at $P^*_{ch} = 5 \cdot 10^2$ kPa the values of E^*_2 and E^*_1 (at $\alpha_{f1} = 1$) are by 15% greater than the corresponding values of $E_{2s.r.}$ and $E_{1s.r.}$, and at $P^*_{ch} = 10 \cdot 10^2$ kPa this difference amounts to 5-7%. The heat balance equations which are

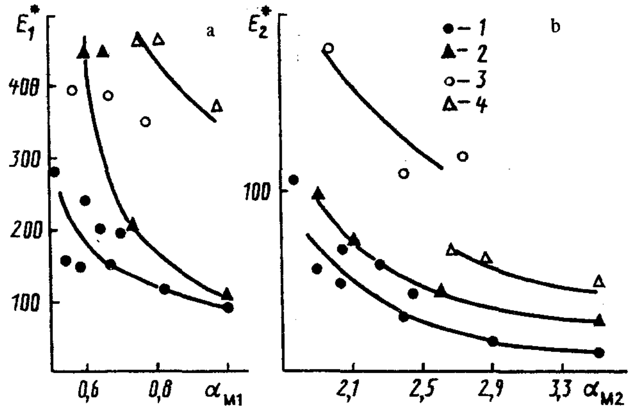

Fig. 2. Experimental value of the surface radiation density vs α_l [a) 1st radiometer indications; b) 2nd radiometer indications]: 1) T^*_{ch} = 550 K; 2) T^*_{ch} = 650 K, P^*_{ch} = 500 kPa; 3) T^*_{ch} = 500 K; 4) T^*_{ch} = 650 K, P^*_{ch} = 1000 kPa. E, kW/m^2; α, dimensionless quantity.

usually set up to determine the flame tube wall temperature must include the semi-spherical self-radiation flux quantity $q_{s.r.}$. The parameters of the emitting medium and the wall temperatures (in the circumferential and longitudinal directions of the chamber) vary, $q_{s.r.} \neq E_{s.r.}$; there where the values of $E_{s.r.}$ are maximum, $q_{s.r.} \leq E_{s.r.}$ and where the values of $E_{s.r.}$ are minimum there $q_{s.r.} > E_{s.r.}$; only under strong soot radiation when the flame emissivity $\epsilon_g \simeq 1.0$ does, $q_{s.r.} = E_{s.r.} = E^*$. Approximately, it may be assumed that, as in [4], $q_{s.r.} = (0.6\text{-}0.8)E_{s.r.}$

In conclusion, let us touch briefly on correlating the experimental data and those calculated for the case of gaseous combustion product radiation (CO_2, H_2O) by the methods from [5]. The calculations have been made for the operating conditions with $P^*_{ch} = 5 \cdot 10^2$ kPa, T^*_{ch} = 550-650 K, $\alpha_{l1} = 1.0$ and $\alpha_{l2} = 2.0$. For these parameters the contribution of soot particles to the total radiation flux is inconsiderable, and radiation heat transfer to the walls is mainly conditioned by triatomic gas radiation. It is found that the $q_{s.r.}$ data calculated within ±5-10% agree with the self-radiation fluxes determined in terms of the available experimental data under the mentioned operating conditions.

NOTATION

$q_{s.r.}$, semispherical self-radiation flux; E^*, surface radiation flux density measured by the radiometers; $E_{s.r.}$, surface density of the self-radiation flux of the flame; P^*_{ch}, stagnated flow density at the combustion chamber inlet; T^*_{ch}, stagnated flow temperature at the combustion chamber; α, air excess coefficient; α_{ch}, reduced velocity coefficient at the combustion chamber inlet; l, beam path length in the chamber. Indices: s.r. self-radiation; ch, chamber; l, local; *, stagnation; 1) first cross section of the chamber; 2) second cross section.

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