THE EFFECT OF TURBULENCE ON FLOW DEVELOPMENT IN HIGH-SPEED COMBUSTOR

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Two-dimensional (2D) numerical simulation of flow development in a TsAGI high-speed combustor equipped with fuel supplying pylons and backfacing step for flameholding is performed. The account for the effect of turbulence–chemistry interaction (TCI) is shown to change the dynamics of transient combustion processes in the combustor as compared to calculations without this effect. After ignition of the fuel–air mixture induced by pneumatic throttling of the flow at the end of the combustor, the arising combustion zone reaches the backfacing step significantly faster than calculated without TCI. These changes are shown to be caused by high-intensity fluctuations of static temperature in the preflame zone reaching 6%–10% (110–180 K) due to turbulence generation in this region. Such temperature fluctuations have a significant effect on the mean reaction rate leading to acceleration of transient processes.

Introduction

In scramjet combustors, the temperature and turbulence intensity of the air exceed 1000 K and 20%–25%, respectively. Under such conditions, combustion of hydrocarbon fuel is likely to occur in the mode with

combination of both frontal and volumetric reactions when thin reaction zones separating fresh mixture from combustion products coexist with wide zones of volumetric preflame reactions. Numerical simulations of turbulent combustion in such combustors are faced with the problem of calculating the mean reaction rates entering the averaged equations of chemical species continuity and energy conservation. This problem is often referred to as the problem of "turbulence – chemistry interaction" because for determining the mean reaction rate in a computational cell, one has to take into account the spatial inhomogeneity of chemical activity induced by turbulence [1].

In this paper, this issue is addressed by solving the problem of combustion development in the TsAGI high-speed combustor.

Problem Formulation

The combustor under consideration is a channel of rectangular cross section equipped with fuel-supplying pylons and backfacing step for flameholding which was investigated experimentally in TSAGI [2, 3] (Fig. 1). The supersonic air flow with Mach number $M \approx 2.5$ and static temperature $T \approx 530$ K enters the combustor from the left in Fig. 1. Despite the preheated air contains combustion products, the mass fraction of molecular oxygen in it is close to that in the standard air. At the end of the isolator (upstream from the backfacing step), there are three fuel supplying pylons each with 8 holes for injecting a liquid hydrocarbon fuel. The overall air-to-fuel equivalence ratio calculated using the air and fuel mass flow rates is 1.34. To initiate combustion, a short-term injection of high-pressure air (pneumatic throttling) through holes in the bottom wall of the combustor downstream from the backfacing step is used. Air injection leads to the formation of a pseudoshock,
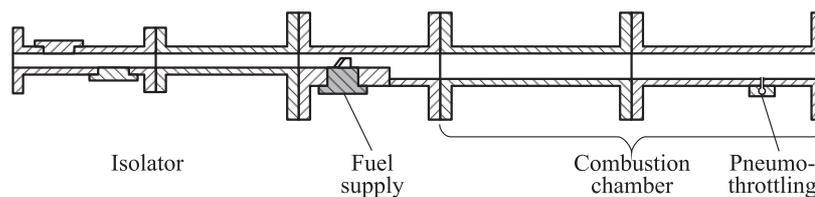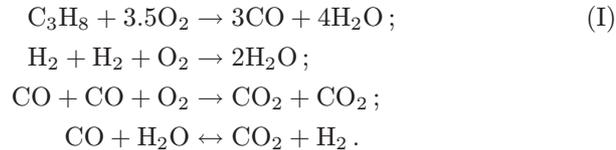

Isolator   Fuel supply   Combustion chamber   Pneumo-throttling

Figure 1 TsAGI combustor

the zone where transition from supersonic to subsonic flow occurs in a series of shocks interacting with separation zones. Flow deceleration in the pseudoshock leads to a local self-ignition of the fuel–air mixture followed by propagation of the arising reaction zone upstream together with the pseudoshock and flame stabilization at the backfacing step.

Three-dimensional and 2D numerical simulations of flow in the combustor were previously conducted in [4–6]. It is shown based on 2D calculations in [6] that after termination of pneumatic throttling and a certain transition period, a quasi-steady combustion mode with periodic longitudinal vibrations of the combustion zone was established. Although the combustion zone was stabilized behind the backfacing step, it periodically slipped to the pylon causing a strong longitudinal displacement of the pseudoshock disposed in the isolator. Analysis of calculations in [6] shows that the turbulence intensity in the combustor at different stages of flow development was very large and attained 15%–20%. In such conditions, one could expect a substantial impact of turbulence on the mean reaction rate in a high-temperature flow, but calculations in [6] were made without consideration of this effect.

In this paper, this effect is taken into account. As in [6], 2D unsteady Reynolds averaged Navier–Stokes equations for the compressible reacting gas were used assuming that liquid fuel was instantaneously vaporized when getting into the channel.

In the calculations, the overall reaction mechanism of multistage oxidation of propane in air proposed in [7] was used:

$$C_3H_8 + 3.5O_2 \rightarrow 3CO + 4H_2O\,; \qquad (I)$$
$$H_2 + H_2 + O_2 \rightarrow 2H_2O\,;$$
$$CO + CO + O_2 \rightarrow CO_2 + CO_2\,;$$
$$CO + H_2O \leftrightarrow CO_2 + H_2\,.$$

The rate of (rate-limiting) reaction (I) was calculated based on the Arrhenius-type relationship for the bimolecular reaction:

$$w_I = -A_I\,[C_3H_8]\,[O_2]\exp\left(-\frac{E_I}{RT}\right) \qquad (1)$$

where A_I and E_I are the preexponential factor and activation energy of reaction (I); R is the gas constant; T is the temperature; and $[C_3H_8]$

and $[O_2]$ are the molar concentrations of propane and oxygen. The rates of other reactions were calculated using standard formulae of chemical kinetics. For simulating multistage self-ignition with low- and high-temperature chain branching phenomena, the following simplifying procedure was used in [7]: the preexponential factor A_I and activation energy E_I of reaction (I) in low- and high-temperature regions were determined independently based on comparison with experimental data. In order to separate the low- and high-temperature reaction regions, a so-called "switch-over" temperature T^* was introduced (775 K for propane). It was assumed that at $T < T^*$, parameters A_I and E_I are equal to their low-temperature values, whereas at $T \geq T^*$, to their high-temperature values. For other reactions in the overall mechanism, the values of preexponential factors and activation energies were not changed during transition through T^*. The Arrhenius parameters for all reactions in the mechanism were reported in [7].

Let us show, using reaction (I) as an example, how the mean reaction rate was determined in the course of calculations. For the mean rate of reaction (I) entering the averaged equations of species continuity and conservation of energy, one can approximately write based on Eq. (1):

$$\overline{w}_I = \overline{A_I[C_3H_8][O_2]\exp\left(-\frac{E_I}{RT}\right)} \approx A_I\overline{[C_3H_8]}\,\overline{[O_2]}\overline{\exp\left(-\frac{E_I}{RT}\right)}$$

where overbar denotes the mean value and it is assumed that nonlinearity in terms of temperature is considerably stronger than in terms of species concentrations. Mean concentrations $\overline{[C_3H_8]}$ and $\overline{[O_2]}$ are then determined from the solution of the corresponding averaged species continuity equations, and for calculating function $\overline{\exp(-E_I/(RT))}$, the analytical method of [1] is used.

In the method of [1], the temperature T in the turbulent flow is assumed to be a stochastic variable with Gaussian distribution, i. e., $T = \overline{T} + \eta\sqrt{\overline{T'T'}}$ where $\overline{T}$ is the mean temperature; T' is the temperature fluctuation; $\sqrt{\overline{T'T'}}$ is the variance of temperature fluctuations; and η is the standard Gaussian variable varying in the range from 0 to 1 and satisfying the probability density function

$$p(\eta) = \frac{1}{\sqrt{2\pi}}\exp\left(-\frac{\eta^2}{2}\right)\,.$$

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The mean value of nonlinear function $f(T) = \exp(-E_I/(RT))$ is determined as

$$\overline{f(T)} = \int\limits_{-\infty}^{+\infty} f\left(\overline{T} + \eta\sqrt{\overline{T'T'}}\right) p(\eta)\,d\eta\,.$$

To determine the integral in the right-hand side of this equation, the Gaussian quadrature is used:

$$\overline{f(T)} \approx \sum_{k=1}^{n} f\left(\overline{T} + \eta_k\sqrt{\overline{T'T'}}\right) c_k \tag{2}$$

where, e. g., for $n = 5$, the nodes η_k and coefficients c_k are given by the relationships:

$$\left.\begin{array}{c} \eta_1 = -\sqrt{5 + \sqrt{10}}\,; \quad \eta_2 = -\sqrt{5 - \sqrt{10}}\,; \quad \eta_3 = 0\,; \\[2mm] \eta_4 = \sqrt{5 - \sqrt{10}}\,; \quad \eta_5 = \sqrt{5 + \sqrt{10}}\,; \\[2mm] c_1 = \dfrac{1}{60}(7 - 2\sqrt{10})\,; \quad c_2 = \dfrac{1}{60}(7 + 2\sqrt{10})\,; \quad c_3 = \dfrac{8}{15}\,; \\[2mm] c_4 = \dfrac{1}{60}(7 + 2\sqrt{10})\,; \quad c_5 = \dfrac{1}{60}(7 - 2\sqrt{10}) \end{array}\right\} \tag{3}$$

with

$$c_1 + c_2 + c_3 + c_4 + c_5 = 1\,.$$

It follows from Eqs. (2) and (3) that $\overline{f(T)} \neq f(\overline{T})$ and $\overline{f(T)} = f(\overline{T})$ only at $\sqrt{\overline{T'T'}} = 0$ (in [6], $\overline{f(T)} = f(\overline{T})$ was assumed).

The variance of temperature fluctuations $\sqrt{\overline{T'T'}}$ in the turbulent flow is determined from the solution of an additional equation (see, e. g., [8]):

$$\frac{\partial\rho\overline{T'T'}}{\partial t} + \frac{\partial}{\partial x_j}\left(\vec{u}_j\rho\overline{T'T'}\right) = \frac{\partial}{\partial x_j}\frac{\mu_t}{\sigma_t}\frac{\partial\overline{T'T'}}{\partial x_j} + C_g\mu_t\left(\frac{\partial\overline{T}}{\partial x_j}\right)^2 - C_d\rho\frac{\varepsilon}{k}\overline{T'T'}$$

where t is time; x_j is the component of spatial coordinates; ρ is the density; $\vec{u}_j$ is the component of the velocity vector; μ_t is the turbulent viscosity; k is the turbulent kinetic energy; ε is the dissipation of the turbulent kinetic energy; $\sigma_t = 0.85$; $C_g = 2.86$; and $C_d = 2.0$.

Similar to [6], the calculations are made using the finite-volume method of SIMPLE (semiimplicit method for pressure linked equations) type with the first-order approximation in time and space, wall functions at rigid walls, and the k–ϵ-model of turbulence. In the course of calculations, grid resolution was changed to obtain grid-independent results.

Results of Calculations

Figure 2 shows the calculated snapshots of static temperature at the initial stage of combustion process development in the combustor in the period from 0.5 to 2.5 ms after triggering pneumatic throttling without (Fig. 2*a*) and with (Fig. 2*b*) TCI taken into account. The cold cross-flow air jet inducing ignition is clearly seen at all snapshots at the right end of the combustor. The account of TCI changes the dynamics of the processes in the combustor: the combustion zone reaches the backfacing step much faster (in 2.0 ms) and slips toward the pylon. The reason for this change in the process dynamics is analyzed in Figs. 3–5.

Figure 3 shows a fragment of the combustion zone in terms of a snapshot of the mean static temperature 0.8 ms after triggering pneumatic throttling and Figs. 4 and 5 show the distributions of the mean static temperature (*1*) and temperature fluctuations (*2*) along the horizontal lines *1* to *6* shown in Fig. 3. At this time instant, the mean static temperature in the flow approaching the combustion zone (left edges of lines *1* to *6* in Fig. 3) reaches 1050 K in the upper part of the channel ($X = 0$ in Fig 4*a*) and gradually increases to 1250 K at the bottom part of the channel in the vicinity to the wall ($X = 0$ in Fig. 5*c*), whereas the static temperature fluctuations relatively far away from the combustion zone are quite small: $T' = 4$–5 K at $X = 0$ for all lines *1* to *6*. However, in the flow region close to the combustion zone, the amplitude of static temperature fluctuations is greatly increased. Thus, along line *1* which does not intersect the combustion zone, the amplitude of static temperature fluctuations is 30 K at the mean value of 1350 K (see Fig. 4*a*), and along lines *2* to *6* it attains 175 K (line *2*), 180 (*3*), 180 (*4*), 125 (*5*), and 50 K (*6*), correspondingly, at the mean value of ~ 1800 K, which can be treated as the combustion front isotherm (the lower white line in Fig. 3). Thus, the intensity of static temperature fluctuations in this case reaches
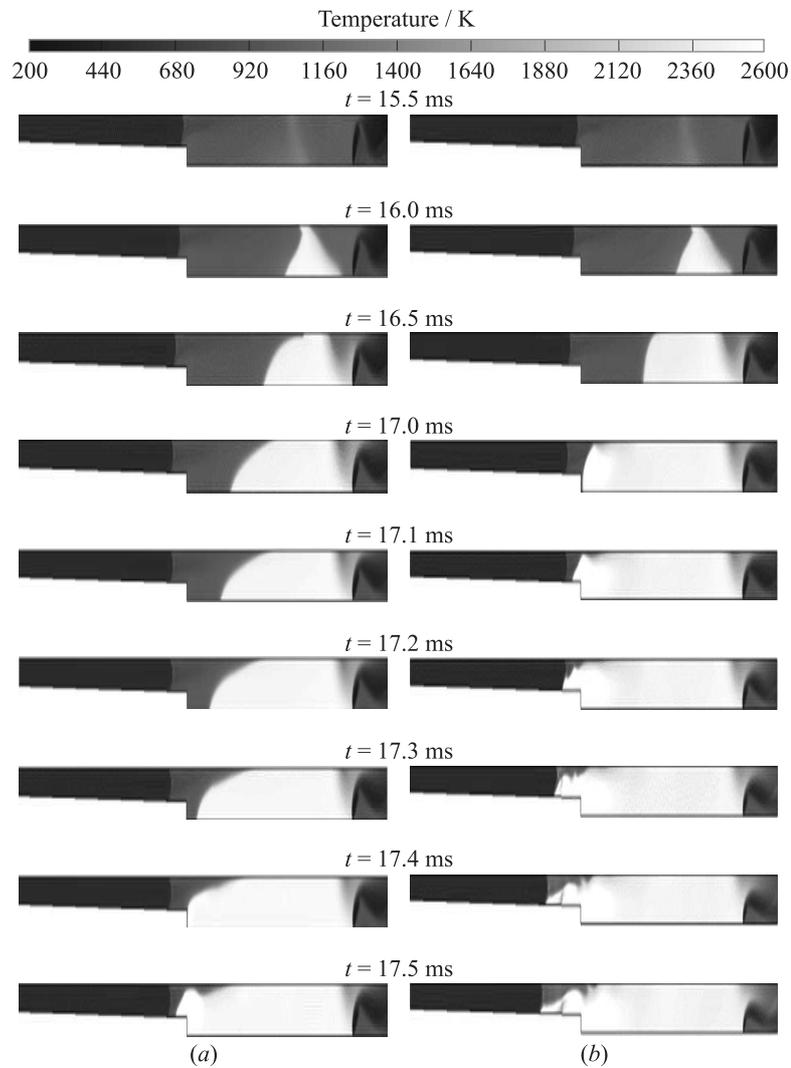
Temperature / K

200   440   680   920   1160   1400   1640   1880   2120   2360   2600

$t = 15.5$ ms

$t = 16.0$ ms

$t = 16.5$ ms

$t = 17.0$ ms

$t = 17.1$ ms

$t = 17.2$ ms

$t = 17.3$ ms

$t = 17.4$ ms

$t = 17.5$ ms

(a)   (b)

Figure 2 Comparison of predicted snapshots of static temperature at the initial stage of combustion development without (a) and with (b) TCI taken into account. Vertical scale of the combustor is changed; pneumatic throttling is triggered at 15 ms
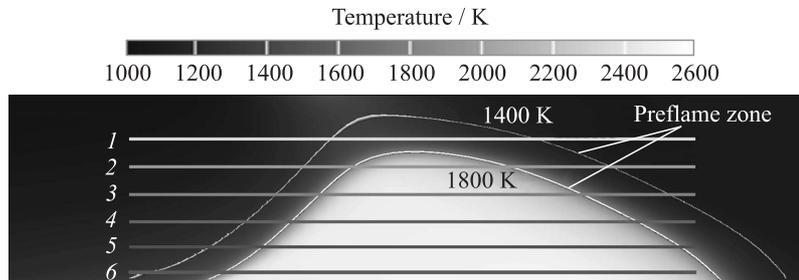
Temperature / K

Figure 3 Fragment of the combustion zone (snapshot of the mean static temperature) at a time instant 0.8 ms after triggering pneumatic throttling. Lines *1* to *6* are the cross sections for the graphs in Figs. 4 and 5

the value of 10%. It should be noted that the maximum amplitude of static temperature fluctuations is achieved downstream of the combustion zone in the fragment under consideration. The maximum intensity of static temperature fluctuations upstream of the combustion zone does not exceed 110 K (6%) in the given fragment at a given time.

Processing of the calculation results shown in Fig. 3 allows plotting the distribution function of static temperature fluctuations in the preflame zone, the region in Fig. 3 bounded by two white lines: isotherms 1800 and 1400 K. Such a distribution function is shown in Fig. 6 as a fraction of the total area of preflame zone $\delta S/S$ vs. the intervals of static temperature fluctuations in the selected range. For example, $\delta S/S = 9.3\%$ for static temperature fluctuations with an amplitude of 40 to 50 K and $\delta S/S = 2.3\%$ for the fluctuations with an amplitude of 150 to 160 K.

The increase of static temperature fluctuations in the preflame zone is associated with turbulence generation in this zone because of large velocity gradients. The amplitude of turbulent velocity fluctuations in the preflame zone reaches ~ 40 m/s and turbulence intensity $u'/\overline{u}$ is as high as 15%–20% there. Note that outside the preflame zone, velocity fluctuations are even higher (~ 50 m/s): they are caused by the recirculation flow behind the backfacing step upstream from the zone and by flow deceleration ahead of the pneumatic-throttling jets downstream from the zone. Processing of the calculation results similar
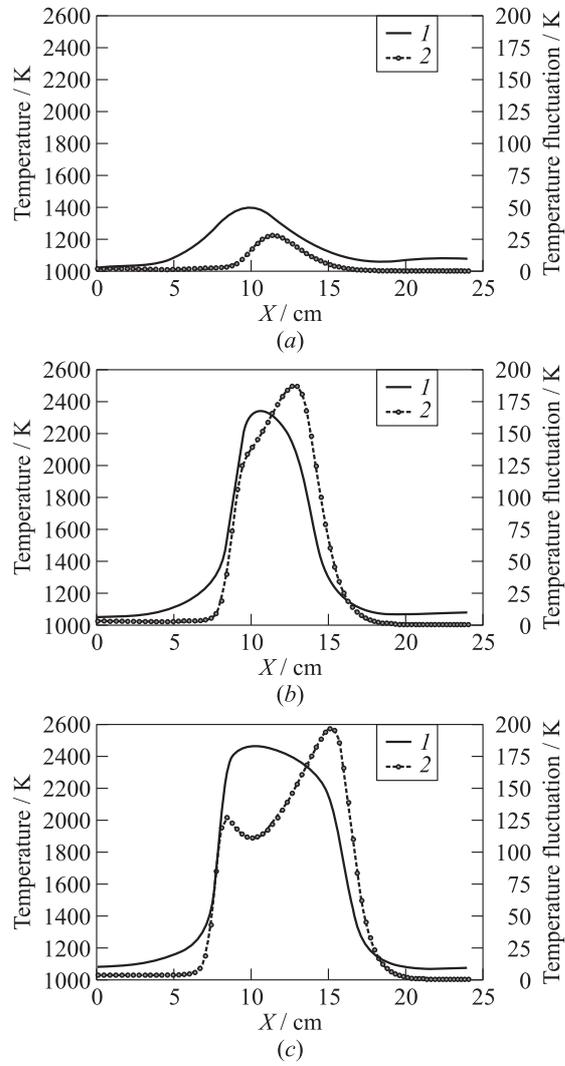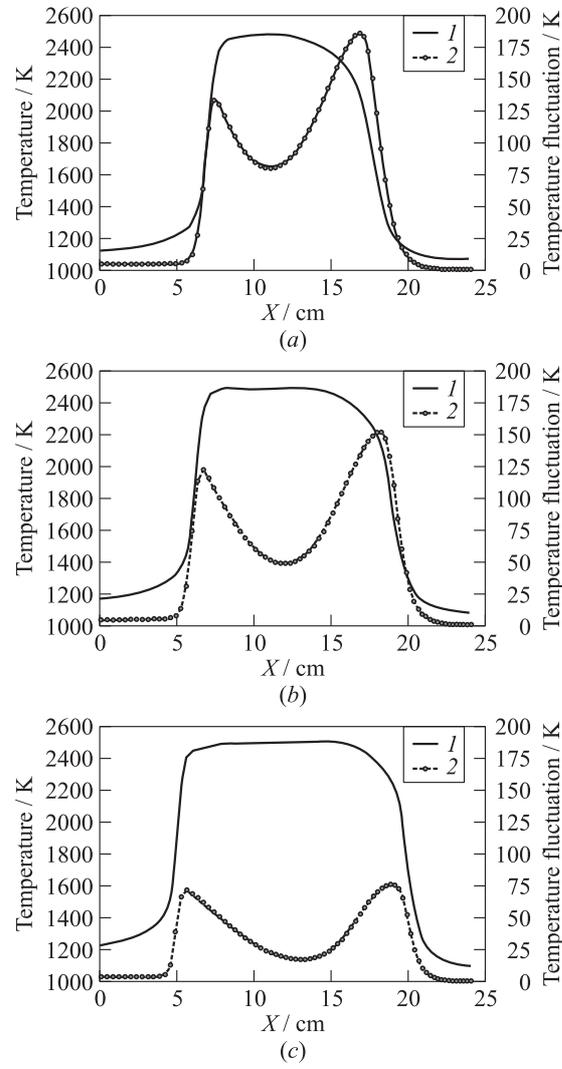
Figure 4 Predicted distributions of the mean static temperature (*1*) and the static temperature fluctuations (*2*) along the horizontal lines *1* (*a*), *2* (*b*), and *3* (*c*) in Fig. 3

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Figure 5 Predicted distributions of the mean static temperature (*1*) and the static temperature fluctuations (*2*) along the horizontal lines *4* (*a*), *5* (*b*), and *6* (*c*) in Fig. 3
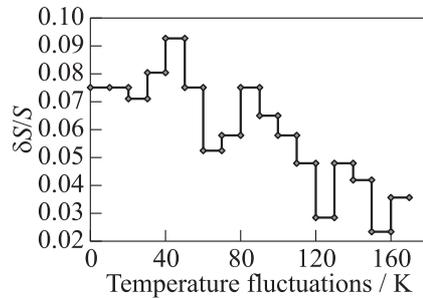
Figure 6 Distribution function of static temperature fluctuations in the preflame zone

to the procedure applied in Figs. 3–5 allows getting the distribution function for turbulent velocity fluctuations in the preflame zone similar to that shown in Fig. 6. Thus, it appears that $\delta S/S = 2\%$ for velocity fluctuations with an amplitude of 10 to 20 m/s and $\delta S/S = 48\%$ for those with an amplitude of 30 to 40 m/s.

Concluding Remarks

Combustion development in the TsAGI combustor has been simulated numerically with the effect of TCI taken into account. The inclusion of TCI was shown to change the dynamics of combustion processes in the combustor. After ignition of the fuel–air mixture by means of throttling of the flow at the end of the combustion chamber, the arising combustion zone reaches the backfacing step and slips to pylons significantly faster than calculated without TCI. The reasons for these changes in the combustion dynamics were investigated. It was found that the intensity of turbulent fluctuations of static temperature in the preflame zone with large gradients of mean flow velocity may reach 6%–10% (110–180 K), which is caused by turbulence generation in this zone with the intensity up to 15%–20%. Such temperature fluctuations have a significant effect on the mean reaction rate leading to acceleration of combustion processes.

Acknowledgments

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