Modeling of Bluff-Body Stabilized Combustion with Detailed Chemistry

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Abstract

Presented is the mathematical approach for studying bluff-body flame stabilization in confined flows with open boundaries. The approach is based on the Favre averaged conservation laws, a standard k-ε model of turbulence, presumed probability density function closure for the mean reaction rate, and 'non-reflecting' boundary conditions at open boundaries. A mechanism of flame stabilization and blow-off based on unambiguously defined characteristic residence and reaction times is suggested.

Objectives

The objective of the study is the development of the computational approach for modeling turbulent premixed and non-premixed flame stabilization on bluff bodies in partially confined flows. The approach should be capable of providing appropriate quantitative information on flame stability limits in terms of the fuel-air ratio, approaching stream velocity, pressure, temperature, turbulence, bluff-body shape and size, and the combustor blockage ratio. The study will be used for better understanding the mechanisms of flame stabilization and for elaborating the combustion control strategies in subsonic ramjet burners.

Formulation

Mathematically, the model is based on the Favre averaged conservation equations of mass, species continuity, momentum, and energy for the compressible turbulent premixed reactive flow, supplemented with the averaged thermal and calorific equations of state for chemical species. A standard k-ε model is employed as a turbulence closure. For modeling mean reaction rates, a presumed probability density function (PDF) method is developed, based on the three-parameter single-point bimodal PDF of temperature, $\tilde{P}(T,\overline{T})$ in the turbulent flame brush:

$$\tilde{P}(T,\overline{T}) = \begin{cases} \dfrac{T_c - \overline{T}}{T_c - T_0} & \text{at} \quad T = T_0 \\ P_T(T,\overline{T}) & \text{at} \quad T_0 + \Delta_1 < T < T_c - \Delta_2 \\ \dfrac{\overline{T} - T_0}{T_c - T_0} & \text{at} \quad T = T_c \end{cases}$$

The three parameters include (1) the probability density $P_T(T,\overline{T})$ of the event that the instantaneous temperature T takes the value between the initial T_0 and the final T_c flame temperatures at a given mean temperature $\overline{T}$, and (2) and (3) the 'thickness' of PDF modes, Δ_1 and Δ_2 in the vicinity of the initial and final flame temperatures. The mean reaction rate for the *j*th species is then taken in the form

$$S = \sum_j \int_{T_0}^{T_c} D_j W_j(T) P(T,\overline{T}) dT$$

$$P(T,\overline{T}) = \tilde{P}(T,\overline{T}) / \int_{T_0}^{T_c} \tilde{P}(T,\overline{T}) dT$$

where $W_j(T)$ and D_j are the rate of production/consumption of *j*th species taken from laminar flame calculations with due regard for the detailed kinetic mechanism and the heat of decomposition of *j*th species to atoms, respectively.

A set of initial conditions includes the specification of velocity, pressure, temperature, turbulence parameters and species concentrations in the computational domain. Ignition is simulated by enveloping the bluff-body by hot combustion products, to avoid the generation of intense ignition-induced pressure disturbances. No-slip constant temperature boundary conditions at rigid walls are adopted. Non-reflecting pressure boundary conditions [1] are employed at open boundaries – combustor inlet and outlet – ensuring transparency to pressure disturbances generated inside the computational domain.

Computationally, the set of governing equations is solved by the finite volume method on generalized boundary-fitted curvilinear non-orthogonal computational grids applying FIRE platform, developed by AVL LIST GmbH, Austria. Various versions of computational grids, differencing schemes, and the pressure correction algorithm are employed to check the results in terms of numerically-induced errors and to optimize the computations.

Results

A two-dimensional combustor is a straight channel 0.2 m in height and 1 m in length. The premixed methane-air mixture of equivalence ratio $0.5 < \Phi < 2.0$ enters the combustor from the left and burns behind the bluff-body flame holder mounted 0.24 m downstream from the inlet cross section. Combustion products and the remaining unburned mixture leave the combustor through the outlet. Three types of bluff bodies are considered, namely V-gutters with angle 60^o, plates, and cylinders. The blockage ratio (BR) ranges from 0.1 to 0.5, corresponding to the characteristic cross-flow dimensions of the bodies of 0.02, 0.03, 0.05, and 0.1 m. The ranges of variation of approaching stream velocity, pressure, temperature and turbulence intensities are as follows: $5 < U_0 < 150$ m/s, $0.2 < p < 10$ bar, $293 < T_0 < 700$ K, $2 < U_0^{'} < 10\%$.

For tabulating laminar flame reaction rates $W_j(T)$, the detailed methane oxidation mechanism [2] containing 280 elementary reactions and 35 species (including C_2 hydrocarbons) is employed. The parameters P_T, Δ_1, and Δ_2 in the temperature PDF were preliminarily obtained by fitting the predicted and measured turbulent flame velocities in a constant volume stirring bomb [3]. At $T_0 = 293$ K, $0.2 < p < 10$ bar, and $0.7 < \Phi < 1.4$, the optimized values of P_T, Δ_1, and Δ_2 are: $2.0 \cdot 10^{-3}$, 250 K, and 250 K.

Figure 1 shows the isotherms (uniform division of interval $[T_0, T_c]$ by 10 parts) of flames in the combustor with V-gutter flame holders of various size at $\Phi = 1$, $U_0 = 50$ m/s, $p = 1$ bar, $T_0 = 293$ K, $U_0^{'} = 2\%$, and time $t = 50$ ms after ignition. Only upper half-plane is shown. Smaller flame holders fail to support continuous combustion in the flow, and flame blows off. Flow velocity attains a maximum value above the flame holder, 60, 65, 72 and 106 m/s for cases *a*, *b*, *c*, and *d*, respectively. The optimum combustor BR, required for the highest flame stability in terms of U_0 is about 0.25-0.3, which agrees with experimental findings [4]. The predicted values of the limiting stream velocity of 50-60 m/s for a stoichiometric methane-air mixture are in a good agreement with measured values [5, 6].

Flame blow-off is a complicated transient phenomenon which is accompanied with periodic generation of intense pressure waves. Figure 2 shows the dynamics of temperature field in the combustor for the conditions of Fig.1*b* (time interval between frames is 2 ms). After ignition, the combustion zone is divided into two parts, the wake flame and the trail flame. The former tends periodically to 'catch' the latter, resulting in energetic jumps of a flame tong downstream the recirculation zone. However, due to expansions of the recirculation zone, an enhanced flow of unburned mixture repeatedly cuts the flame tong, resulting in splitting the flames.

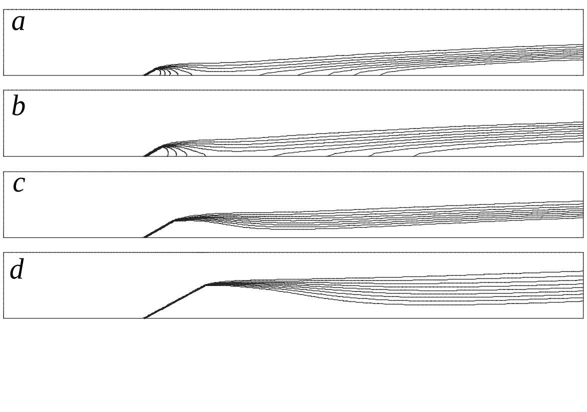
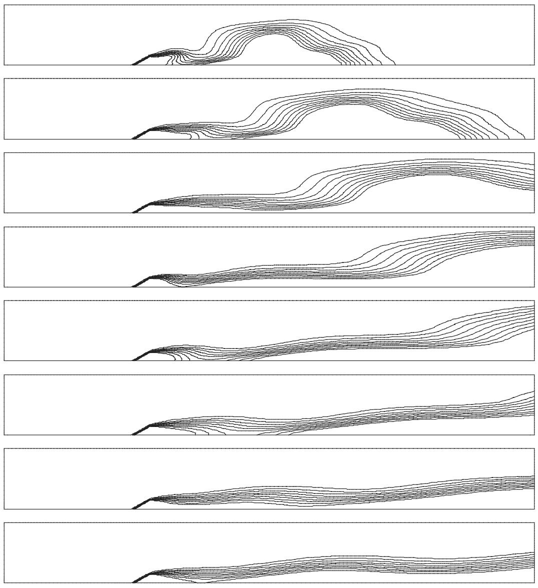


Figure 1



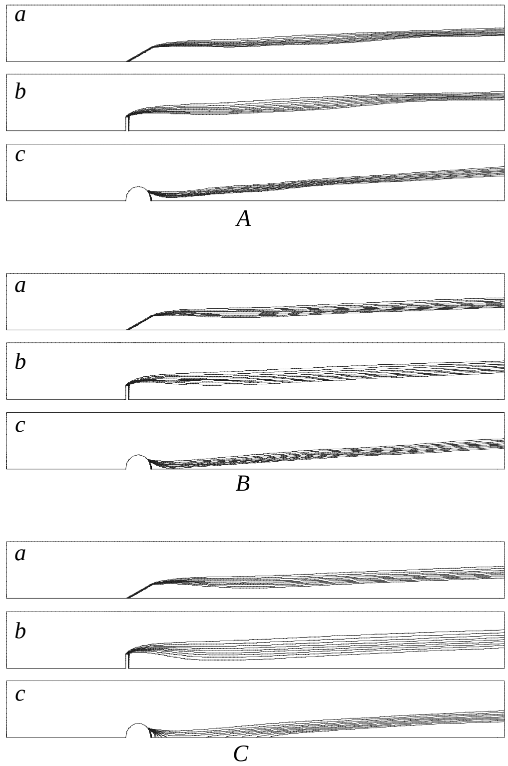


Figure 2

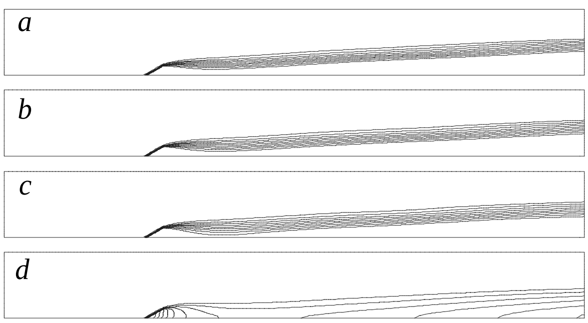
Figure 3

Figure 3 shows temperature fields in a combustor with V-gutter (*a*), disk (*b*), and cylinder (*c*) at $\Phi = 1$, $U_0 = 20$ (*A*), 30 (*B*), and 40 m/s (*C*), $p = 1$ bar, $T_0 = 293$ K, $U_0^{'} = 2\%$, BR = 0.25, and $t = 50$ ms. The most stable flame is provided by V-gutter. The examination of velocity profiles over the bodies indicates, that flame stability is directly related to the maximum velocity, which is highest for cylinder (68 m/s) and lowest for V-gutter (56 m/s).

Figure 4 shows the effect of combustor pressure on flame stability in terms of the temperature isotherms at

$t = 50$ ms after ignition ($\Phi = 1$, $U_0 = 20$ m/s, $T_0 = 293$ K, $U_0^{'} = 2\%$, BR = 0.15). Decrease in pressure from 1 bar (*a*) to 0.8 (*b*), 0.7 (*c*), and 0.5 bar (*d*) results in flame blow-off. This behavior is in line with experimental observations [7]. Pressure increase, other conditions being equal, results in the enhanced flame stability. At $p = 5$ bar, the limiting approaching stream velocity tends to 75 m/s compared to 50 m/s at $p = 1$ bar.

Figure 5 indicates a good correlation between measured [5] – *1* and [6] – *2* and predicted – *3* limiting flow velocities at various fuel-air ratios ($p = 1$ bar, $T_0 = 293$ K, $U_0^{'} = 2\%$, BR = 0.15). For comparing with experimental data, predicted maximum flow velocities over bluff-bodies were used to include the effect of partial confinement. The effect of inlet temperature and turbulence intensity on flame stability is also found to correlate with measurements.



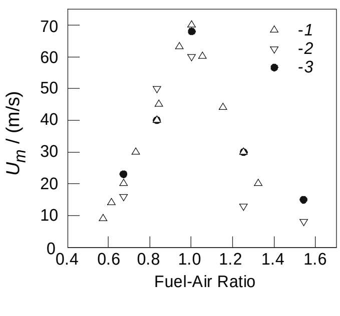


Figure 4

Figure 5

The Mikhelson-type stability criterion in terms of the ratio of the reaction time to the residence time in the recirculation zone is revised based on the examination of the flow in the wake of flame holders.

Behind the flame holder, there exists the limiting trajectory which separates non-turning and turning trajectories in the flow. Our analysis of numerous computations revealed that the turning point of the limiting trajectory is of significant importance for flame stability. When following the mean temperature evolution along the limiting trajectory, we observed that flame was definitely stable if the temperature attained the value T_* close to T_c ($T_* \approx 0.95T_c$) before reaching the turning point. If temperature T_* was attained after passing the turning point, the flame inevitably blew off though exhibiting a few violent longitudinal oscillations (see Fig. 2).

Quantitatively, these observations can be treated in terms of the characteristic residence time t_r and the characteristic reaction time t_c. Time t_r is defined as the time taken for the imaginary fluid particle to reach the turning point at the limiting trajectory. Time t_c is defined as the time taken for the fluid particle to attain temperature T_*. Then, the stability criterion will read

$$\frac{t_r}{t_c} = \mathrm{Mi} \geq 1$$

where Mi is the Mikhelson number. Table summarizes the calculated data for t_r, t_c, and Mi for the reactive flow patterns behind V-gutter flame holders of size H and apex angle 60$^{\mathrm{o}}$. In addition to the inlet velocity u_{in}, the calculated maximum flow velocity above flame holders, u_m is also presented. Signs "+" and "–" correspond to stabilized flame and unstable flame, respectively. Clearly, the Mikhelson number of unity separates the solutions with stabilized and unstable flames.

H cm	u_{in} m/s	u_m m/s	t_c ms	t_r ms	Mi	Stability
10.0	40	85	4.4	8.4	1.9	+
	50	106	6.4	7.6	1.2	+
	60	130	8.0	6.4	0.8	–
5.0	20	28	3.5	11.2	3.2	+
	40	57	4.4	8.8	2.0	+
	50	72	5.6	7.2	1.3	+
	60	87	7.6	6.0	0.8	–
2.0	20	23	4.4	8.8	2.0	+
	30	35	4.6	5.6	1.2	+
	40	47	6.4	4.8	0.75	–

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