FLAME PROPAGATION AND DEFLAGRATION-TO-DETONATION TRANSITION IN A SEMICONFINED FLAT SLIT COMBUSTOR WITH SEPARATE SUPPLY OF ETHYLENE AND OXYGEN

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Abstract: Continuous detonation engines (CDEs) are considered promising for aerospace applications. Detonation initiation in a CDE can be accompanied by a destructive explosion of the excess volume of the fuel mixture in the combustor. To eliminate this phenomenon, "mild" rather than "strong" detonation initiation is required. To softly initiate detonation in the CDE, it is necessary to ignite the mixture of a certain minimum volume sufficient for deflagration-to-detonation transition (DDT). In this work, the critical conditions for detonation initiation via DDT in a semiconfined slit combustor simulating a CDE combustor with a separate supply of ethylene and oxygen diluted with nitrogen (from 0 to 40 %(vol.)) at a fuel-to-oxygen equivalence ratio ranging from 0.3 to 2.3 are obtained experimentally. It turns out that in order to initiate detonation via DDT, it is necessary to ignite the mixture upon reaching the critical (minimum) height of the combustible mixture layer. Thus, for mild detonation initiation in an undiluted $C_2H_4 + 3O_2$ mixture filling such a slit combustor, the height of the mixture layer must exceed the width of the slit by approximately a factor of 12. In terms of the transverse size of the detonation cell λ, the minimum height of the layer of such a mixture in the experiments is $\sim 150\lambda$. Compared to experiments with premixed ethylene and oxygen, the critical layer height turns out to be 20% higher which is explained by the finite rate of mixture formation. With an increase in the degree of oxygen dilution with nitrogen, the critical height of the layer increases and the role of the finite rate of mixture formation decreases: the results no longer depend on the method of combustible mixture formation.

Keywords: continuous detonation engine; slit combustor; deflagration-to-detonation transition; ethylene–oxygen mixture; minimum height of the combustible mixture layer

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Figure Captions

Figure 1 Schematics of the experimental setup: (*a*) overall schematic; and (*b*) mixer schematic

Figure 2 Example of primary records for experiment No. 333 with $0.65C_2H_4 + 3O_2$ mixture; P_{fu} — pressure in the ethylene receiver; P_{ox} — pressure in the oxygen receiver; U_{fu} (*1*) and U_{ox} (*2*) — voltages on the electronic switch controlling the activation of the solenoid valves in fuel and oxidizer manifolds; t_{on} — delay time for turning on the solenoid valves (9 ms in this experiment); t_{off} — delay time for turning off the solenoid valves (26 ms in this experiment); and t_s — switching time (4 ms in this experiment). The time is counted from the ignition

Figure 3 Diagram illustrating the difference between the true height of the combustible mixture layer near the ignition point (spark gap) and its value estimated for conditions of uniform layer-by-layer fill. The line corresponds to the equality of these values

Figure 4 Visualization of slit fill using fine MgO particles (experiment No. 426); the images are taken from the central window in the bottom row of three windows in the slit combustor (see Fig. 8). The time interval between the frames is 10 ms. The time is counted down to ignition

Figure 5 Measured coordinates (X_{DDT}, Y_{DDT}) of DDT locations for $C_2H_4 + 3(O_2 + \beta N_2)$ mixtures at $\Phi = 1.00 \pm 0.06$ and $0 \leq \beta \leq 2/3$

Figure 6 Measured time histories of pressure: (*a*) and (*b*) layer of the maximum height $h_{\mathrm{est}} = 80 \pm 3$ mm with $X_{\mathrm{DDT}} = 385$ (*a*) and 725 mm (*b*); and (*c*) and (*d*) layer of height $h_{\mathrm{est}} = 153 \pm 2$ mm with $X_{\mathrm{DDT}} = 248$ (*c*) and 485 mm (*d*)

Figure 7 The measured dependences of the reaction front (glow) propagation velocity on the traveled distance: (*a*) and (*b*) layer of the maximum height $h_{\mathrm{est}} = 80 \pm 3$ mm with $X_{\mathrm{DDT}} = 385$ (*a*) and 725 mm (*b*); and (*c*) and (*d*) layer of height $h_{\mathrm{est}} = 153 \pm 2$ mm with $X_{\mathrm{DDT}} = 248$ (*c*) and 485 mm (*d*)

Figure 8 Video frames of flame propagation, DDT, and detonation propagation in the slit combustor: (*a*) experiment No. 529 — layer of the maximum height $h_{\mathrm{est}} = 80 \pm 3$ mm with $X_{\mathrm{DDT}} = 385$ mm, $Y_{\mathrm{DDT}} = 0$ mm, and $t_{\mathrm{DDT}} = 2.29$ ms; and (*b*) experiment No. 398 — layer of height $h_{\mathrm{est}} = 153 \pm 2$ mm with $X_{\mathrm{DDT}} = 248$ mm, $Y_{\mathrm{DDT}} = 17$ mm, and $t_{\mathrm{DDT}} = 0.86$ ms

Figure 9 Video frames of flame propagation, DDT, and detonation propagation in the slit combustor: (*a*) experiment No. 530 — layer of the maximum height $h_{\mathrm{est}} = 80 \pm 3$ mm with $X_{\mathrm{DDT}} = 725$ mm, $Y_{\mathrm{DDT}} = 6$ mm, and $t_{\mathrm{DDT}} = 3.63$ ms; and (*b*) experiment No. 120 — layer height of $h_{\mathrm{est}} = 153 \pm 2$ mm with $X_{\mathrm{DDT}} = 485$ mm, $Y_{\mathrm{DDT}} = 20$ mm, and $t_{\mathrm{DDT}} = 0.98$ ms

Figure 10 Video frames of flame propagation and DDT in the slit combustor filled with a layer of $C_2H_4 + 3(O_2 + (3/5)N_2)$ mixture of the maximum height $h_{\mathrm{est}} = 380 \pm 3$ mm: (*a*) experiment No. 812 — nonuniform ignition along the height of the layer with DDT at $X_{\mathrm{DDT}} = 530$ mm, $Y_{\mathrm{DDT}} = 0$ mm, and $t_{\mathrm{DDT}} = 2.37$ ms; and (*b*) experiment No. 813 — uniform ignition along the height of the layer without DDT

Figure 11 The measured dependences of the reaction front (glow) propagation velocity on the traveled distance in the slit combustor filled with a layer of $C_2H_4 + 3(O_2 + (3/5)N_2)$ mixture of the maximum height $h_{\mathrm{est}} = 380 \pm 3$ mm: (*a*) experiment No. 812, DDT at $X_{\mathrm{DDT}} = 530$ mm; and (*b*) experiment No. 813, no DDT

Figure 12 Measured time histories of pressure by sensors P1 (*a*) and P2 (*b*) in experiments No. 812 (*1*) and No. 813 (*2*)

Figure 13 Measured time histories of pressure by sensors P3 (*a*) and P4 (*b*) in experiments No. 812 (*1*) and No. 813 (*2*)

Figure 14 Deflagration-to-detonation "go" and "no go" conditions as a function of the layer height and fuel-to-oxygen equivalence ratio in the $\Phi C_2H_4 + 3O_2$ mixture: *1* — DDT "no go;" *2* — DDT "go;" and *3* — conditional boundary separating the DDT "go" and DDT "no go" domains

Figure 15 Flame propagation in the $2.1C_2H_4 + 3O_2$ mixture (experiment No. 234) at $h_{\mathrm{est}} = 215$ mm and $h_{\mathrm{flame}} \sim 350$ mm

Figure 16 Flame propagation and DDT in the $1.8C_2H_4 + 3O_2$ mixture (experiment No. 545) at $h_{\mathrm{est}} = 255$ mm with $X_{\mathrm{DDT}} = 357$ mm, $Y_{\mathrm{DDT}} = 75$ mm, and $t_{\mathrm{DDT}} = 1.01$ ms

Figure 17 Flame propagation and DDT in the $1.5C_2H_4 + 3O_2$ mixture (experiment No. 613) at $h_{\mathrm{est}} = 170$ mm (flow rate 5.2 l/s) and $h_{\mathrm{flame}} \sim 250$ mm with $X_{\mathrm{DDT}} = 286$ mm, $Y_{\mathrm{DDT}} = 15$ mm, and $t_{\mathrm{DDT}} = 0.86$ ms

Figure 18 The height of the layer in which DDT is registered as a function of nitrogen dilution $(O_2 + \beta N_2)$: *1* — DDT "no go" conditions; *2* — DDT "go" conditions in all experiments with a probability of $p = 1$; *3* — DDT "go" conditions with a probability of $p = 0.1 \ldots 0.4$ (DDT in less than half of experiments in the series); and *4* — DDT "go" conditions with a probability of $p = 0.5 \ldots 0.9$ (in more than half of experiments in the series); dashed curve — approximation of the conditional boundary for the minimum layer height for DDT in the premixed fuel and oxidizer; and solid curve — approximation of the conditional boundary for the minimum layer height for DDT in the slit combustor with separate supply of fuel and oxidizer (two criteria: transition with a probability ranging from $p = 0$ to $p > 0$ and transition with a probability ranging from $p < 1$ to $p = 1$)

Figure 19 The ratio of the minimum height of the layer in which DDT is registered to the detonation cell size as a function of nitrogen dilution of the $C_2H_4 + 3(O_2 + \beta N_2)$ mixture: *1* — data from this work; and *2* — premixed fuel and oxidizer [26]

Table Captions

Table 1 The Chapman–Jouguet detonation parameters (velocity and pressure) in comparison with those recorded in the experiment and the minimum layer height at which DDT is registered for $C_2H_4 + 3(O_2 + \beta N_2)$ mixtures

Table 2 Probabilities of DDT and the minimum and maximum DDT run-up distances depending on the layer height for the $C_2H_4 + 3O_2$ mixture

Table 3 Probabilities of DDT and the minimum and maximum DDT run-up distances depending on the layer height for the $C_2H_4 + 3(O_2 + (1/9)N_2)$ mixture

Table 4 Probabilities of DDT and the minimum and maximum DDT run-up distances depending on the layer height for the $C_2H_4 + 3(O_2 + (1/5)N_2)$ mixture

Table 5 Probabilities of DDT and the minimum and maximum DDT run-up distances depending on the layer height for the $C_2H_4 + 3(O_2 + (1/4)N_2)$ mixture

Table 6 Probabilities of DDT and the minimum and maximum DDT run-up distances depending on the layer height for the $C_2H_4 + 3(O_2 + (1/3)N_2)$ mixture

Table 7 Probabilities of DDT and the minimum and maximum DDT run-up distances depending on the layer height for the $C_2H_4 + 3(O_2 + (2/5)N_2)$ mixture

Table 8 Probabilities of DDT and the minimum and maximum DDT run-up distances depending on the layer height for the $C_2H_4 + 3(O_2 + (1/2)N_2)$ mixture

Table 9 Probabilities of DDT and the minimum and maximum DDT run-up distances depending on the layer height for the $C_2H_4 + 3(O_2 + (3/5)N_2)$ mixture

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