DDT Test of Binary Fuel – Air Mixtures in an Obstructed Channel

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1 Introduction

The interest to the process of deflagration-to-detonation transition (DDT) in hydrogen-air mixtures sharply increased at the end of the last century after the known accidents at the atomic power plants. A tube (channel) equipped with periodically placed obstacles (e.g. rings) represents typical instrument for the DDT study under laboratory conditions. DDT in an obstructed channel is usually recognized as transition from fast deflagration to quasi-detonation [1]. In practice this transition becomes apparent when propagation velocity of the reactive front sharply increases from value of nearly $0.5D_{CJ}$ to $0.65D_{CJ}$ and higher up to D_{CJ} (D_{CJ} - Chapmen-Jouguet detonation speed) [2-5].

The benefit of the hydrogen combustion is a reason for development of prospective fuel compositions. The use of binary mixture of hydrocarbons and hydrogen is one of the possibilities to extend kinetics and thermodynamics fuel properties. The aim of the present work is experimental and theoretical investigation of the DDT in hydrogen-methane(propane)-air mixtures in channels with periodically placed obstacles.

2 Experimental details

The experiments were performed in detonation tube of D_0 = 54 mm in diameter and 2 m in length. The obstacles arrangement was placed in the initial run of the tube and consists of 14 orifice rings. The distance between the adjacent rings $L \cong D_0$ and the blockage ratio BR = 0.61. The mixtures of hydrogen-air as well as hydrogen-methane(propane)-air were prepared by partial pressure technique. The initial pressure was 1 bar. The main parameter to characterize the overall hydrocarbon-hydrogen-air mixture is the equivalence ratio φ, which takes into account the total amount of fuel (methane+hydrogen or propane+hydrogen).

For methane-hydrogen-air mixture:

$$\varphi = \frac{[H_2] + 4\cdot[CH_4]}{0.42\cdot(1-[H_2]-[CH_4])},$$

for propane-hydrogen-air mixture:

$$\varphi = \frac{[H_2] + 10\cdot[C_3H_8]}{0.42\cdot(1-[H_2]-[C_3H_8])},$$

where $[H_2]$, $[CH_4]$ and $[C_3H_8]$ are mole fractions of respectively hydrogen, methane and propane.

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Before experiment the tube was evacuated and filled by the mixture under investigation. The ignition was initiated by an exploding wire. Different combustion regimes including DDT were observed depending on the composition of combustible gas. The development of explosion process was recorded by pressure transducers placed along the tube.

The equivalence ratio was varied in the range of φ=0.5–3.5. Previously, a serie of experiments on DDT with similar binary fuel-air mixtures was performed in detonation tube of D_0 = 141 mm [6,7]. The described experimental setup with D_0 = 54 mm (including obstacles arrangement) reproduces the facility [6,7] on a scale of 1 to 2.6. Thus, a comparison of experimental data gathered at different tube diameters may be efficient for scaling analysis of the DDT dynamics.

3 Results and Discussion

It was assumed that transition to detonation occurs when the measured velocity of shock wave generated by accelerating flame achieves value of $0.65D_{CJ}$ or higher. Variation of the composition of binary fuel along with the equivalence ratio φ enables to draw a boundary between DDT and deflagration regimes. Figure 1 represents experimental results in terms of hydrocarbon mole fraction ([CH_4] or [C_3H_8]) and parameter φ. The content of binary fuel mixture can be specified with the help of the lines of the constant hydrogen mole fractions [H_2] that are also plotted in Figs. 1*a,b*. The boundary between DDT (solid symbols) and fast deflagration (empty symbols) represents a bell-shaped curve with maximum at nearly stoichiometric composition, i.e. at φ=1-1.5. Note that the DDT concentration limits broaden out as tube diameter increases from 54 mm to 141 mm.

The analysis of the influence of scaling factor on DDT in gaseous mixtures is usually based on the consideration of detonation cell size λ. There exists a gap in systematic data on parameter λ for a wide range of hydrogen-hydrocarbon compositions. To overcome this difficulty one can apply model [8] for binary fuel – air mixtures. Model verification was performed by comparison between calculated values of λ and experimental data of [9] for hydrogen-methane/propane-air mixtures. It was selected Konnov mechanism [10], since it describes the experimental results [9] within 20% deviation.

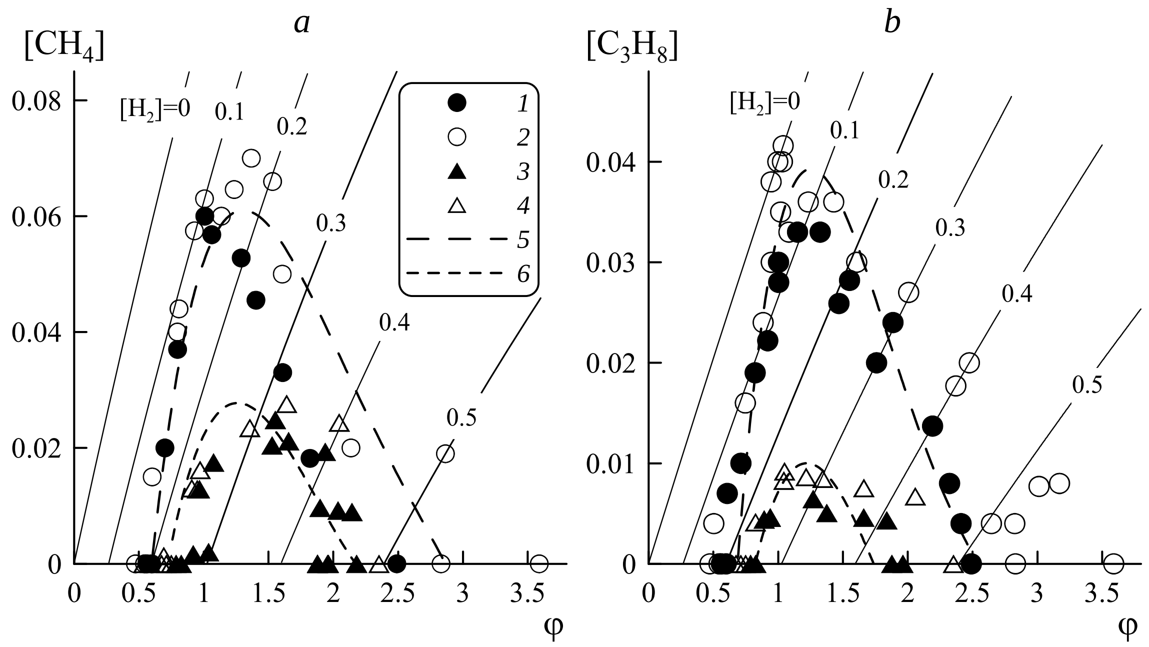

Figure 1. Concentration limits of DDT. *a*) hydrogen-methane- air; *b*) hydrogen-propane- air. *1* – DDT in 141 mm tube, *2* – deflagration in 141 mm tube, *3* – DDT in 54 mm tube, *4* – deflagration in 54 mm tube, *5* – contour of constant size of detonation cell at λ=70 mm (*a*) and λ=42 mm (*b*), *6* – contour of constant size of detonation cell at λ=27 mm (*a*) and λ=16 mm (*b*).

The contours of constant size of detonation cell are represented in Fig. 1 by dotted curves. The values of λ were selected in accordance with the following reasons: 1) maximum approach to experimentally found boundary between DDT and fast deflagration; 2) maintenance of the scaling factor 1 to 2.6. The contours of λ=const for hydrogen-methane-air mixtures are plotted in Fig. 1*a* at λ=70 and 27 mm. It is seen that these contours describe boundaries DDT – deflagration satisfactorily excluding reach compositions in 141 mm tube. Note, that the selected sizes of detonation cell are close to the orifice diameter of ring obstacles, namely, *d*=90 (for 141 mm tube) and 33.7 mm (for 54 mm tube). This is in agreement with data [4], where it was suggested that DDT is possible if $\lambda \leq d$. For the mixtures of hydrogen-propane-air represented in Fig. 1*b* the contours of λ=const are plotted at λ=42 and 16 mm. These values are 1.7 times lower than that for hydrogen-methane-air mixtures. The decrease of critical λ parameters demonstrates lower sensitivity of hydrogen-propane-air mixtures to DDT.

Evaluation of behavior of the hybrid fuel – air mixtures under different conditions requires information on the size of detonation cell over wide range of relative and absolute concentrations of the components. Figure 2 represents the results of calculation of the parameter λ by model [8] for mixtures of hydrogen-methane-air (Fig. 2*a*) and hydrogen-propane-air (Fig. 2*b*). As seen, in the frame of the selected variables (cell size – mole hydrocarbon concentration) the curves plotted at fixed hydrogen concentration are divided into pair of sets: 1) at $[H_2] < 0.296$ the dependencies are U-shaped (dotted curves); 2) at $[H_2] \geq 0.296$ the plots transform into lines of monotonic increase of parameter λ (solid lines). It will be recalled that concentration $[H_2] = 0.296$ corresponds to stoichiometric condition in hydrogen-air mixture. Dependences family represented in Fig. 2 express the change of detonation cell size due to addition of hydrocarbon to hydrogen-air mixture. If the base mixture is lean, i.e. $[H_2] < 0.296$, then hydrocarbon addition first leads to decrease of value of λ due to the approach of total fuel content to stoichiometric conditions. After reaching some minimum value the parameter λ starts to increase since mixture becomes rich. Thus, for fixed hydrogen content (in lean H_2-air mixture) there exists two different values of hydrocarbon concentration that supply the mixtures by identical detonation cell size. If $[H_2] \geq 0.296$, then any hydrocarbon addition produces rich mixture and value of λ is always increased.

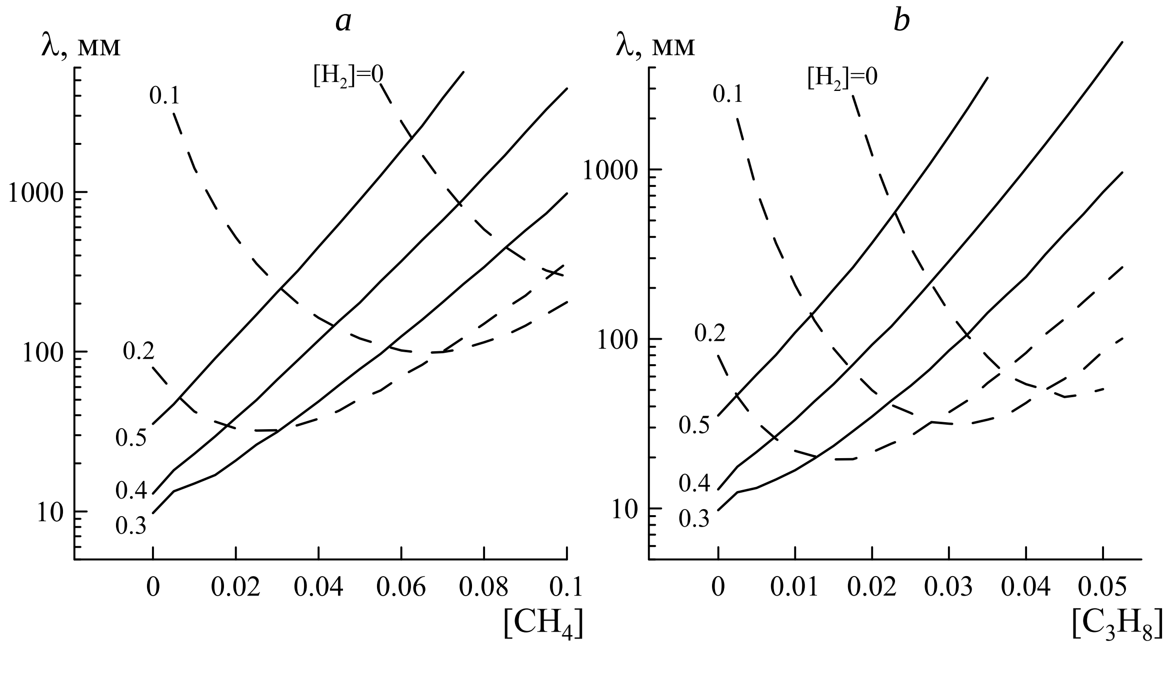

Figure 2. Detonation cell size in mixtures of hydrogen-methane-air (*a*) and hydrogen-propane-air (*b*).

4 Concluding Remarks

The results of experiments on deflagration-to-detonation transition in hydrogen-methane/propane- air mixtures in 54 mm tube were compared with the data gathered in 141 mm tube. It was shown that limits of DDT depend both on the relation between components in binary fuel hydrogen-methane(propane) mixture and scale of the setup. The peculiarities of the DDT process in binary fuel – air mixtures are determined by the behavior of detonation cell size.

Acknowledgements

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