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Brief Communications

Flammability limit of moderate- and low-stretched premixed flames stabilized in planar channel

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ABSTRACT

The experimental study of flammability limits of counterflow premixed methane-air flames in a planar micro channel is described in the paper. Combustion occurs in the gap between quartz plates which are connected with two countercurrent slot burners. The proposed counterflow burner allows investigation of the flame structure at low flow rates which are outside the applicability range of conventional counterflow burners at the normal gravity conditions. It was found that the heat return from combustion products to unburned mixture through the heat conducting plates is an essential effect at low gas flow rates.

1. Introduction

The knowledge about flammability limits of stretched flames is important for fundamental combustion research and it is also relevant to the development of clean combustion technologies, such as lean gas burning and others. The flammability limits of counterflow flames at high and moderate flow rates were investigated in early experimental and theoretical works [1–5] in the conditions of normal gravity. The experimental investigations of flammability limits at low stretch rates in normal gravity conditions are complicated due to natural convection resulting in additional heat losses. The quenching mechanisms of low-stretched flames were clarified and the flame extinction limits were determined in the course of microgravity experiments [6,7]. Further investigations of counterflow flames in microgravity conditions [8–11] revealed existence of various non-planar and unstable combustion modes. Although microgravity experiments yield valuable information about flame structure they are expensive and need special facilities like drop tower, airplane, etc.

One of the ways to overcome the buoyancy effect is the stabilization of flame in a planar micro channel. The quenching mechanism of diffusive and partially premixed flames stabilized in a planar channel was investigated in the papers [12,13]. It was shown that such system allows investigation of the flame in the normal gravity conditions. At the same time, the heat exchange between gas and the channel walls can cause additional heat losses from the flame to the channel walls. The influence of the heat losses on the flame is especially important in small size channel. The intensive heat losses to the channel walls cause the flame quenching in the channel with diameter smaller than critical one. On the other hand, as it was demonstrated in papers [14–17], the effective heat recirculation through the heat conducting walls can extend the flammability limits and allows flame propagation in narrow channels. The small spacing between plates prevents development of natural convection. The gas preheating via heat conducting channel walls decreases the ratio of densities of burned and unburned gases and this effect hampers the development of the natural convection too. At the same time, if the gap between plates is large enough the natural convection is appeared.

The present brief communication contains results of experimental investigation of the counterflow flames stabilized in the planar micro channel. The aim was to study both heat recirculation and stretched flow effects on flammability limits in the condition which prevent developing of natural convection.

2. Experimental setup

Experimental setup consists of counterflow burner, mass flow controllers and AD/DA converter connected to PC. Two slot-jet burners with nozzles 40 mm × 5 mm were mounted in horizontal plane opposite to each other at the distance 2L = 50 mm. The slot-jet counterflow burner is similar to that used in the work [18]. To

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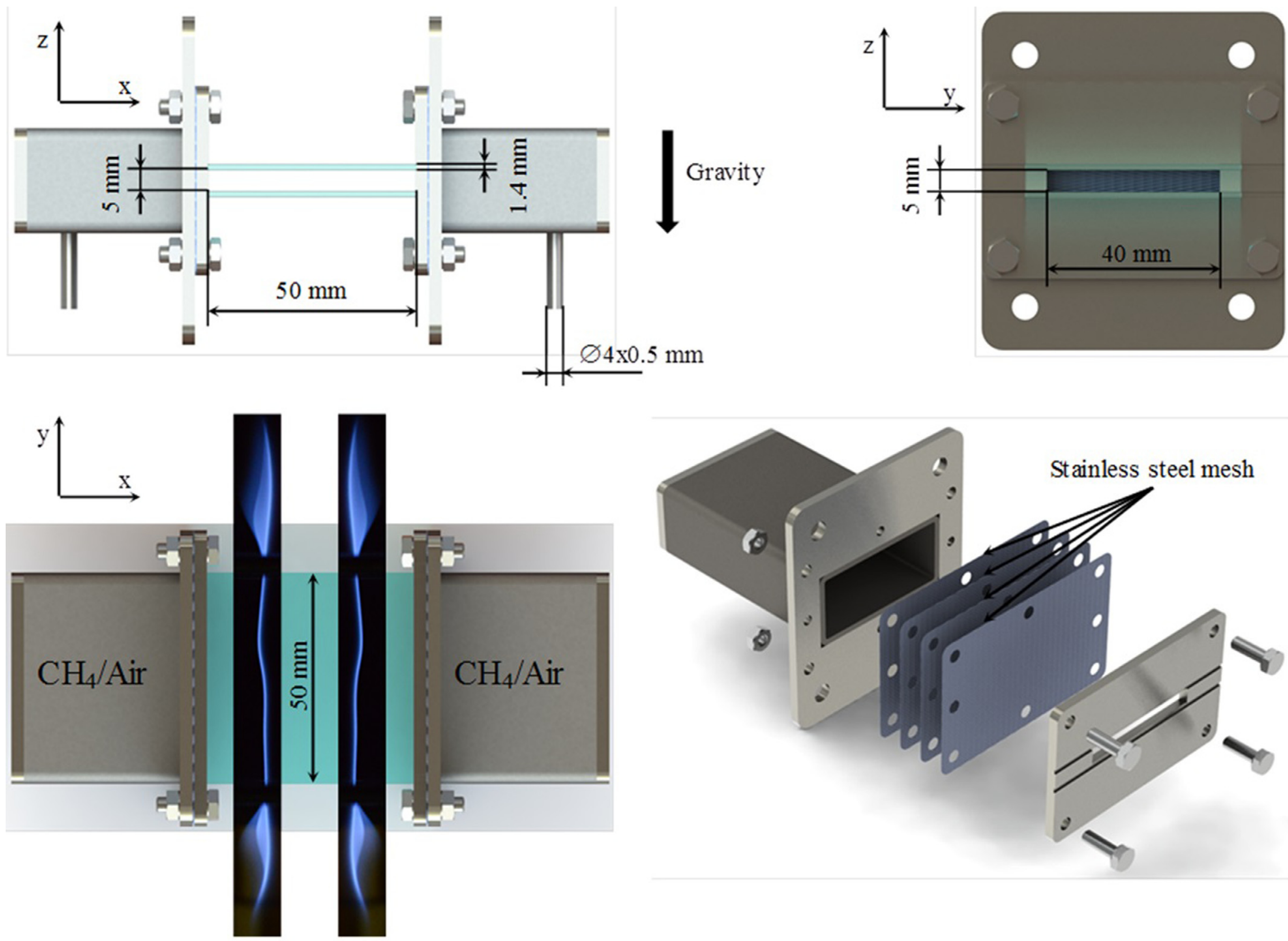

Fig. 1. Counterflow slot-jet burner.

construct the planar channel we made two slots on each burner below and above the nozzle to install quartz plates with a thickness of 1.4 mm and a length of 50 mm × 50 mm (see Fig. 1). To create the uniform flow we filled each burner's body by 1 mm ceramic balls and put four layers of stainless steel mesh before outlet. To maintain the constant temperature of inlet gas we mounted the water-cooling system on the burner's body. As a result, the inlet gas temperature did not exceed 50 °C during the experiments. To indicate the inlet gas temperature we mounted a K-type thermocouple in the center of the nozzle between two layers of stainless steel mesh. Another K-type thermocouple was connected to the center of bottom quartz plate to measure the plate temperature and confirm the established stationary combustion regime. Accuracy of the temperature measurement was ±1 °C, thermocouple controllers Omron E5CB were used. Two digital photo cameras were installed above and alongside of the counterflow burner.

Lean methane/air mixtures $0.6 \le \phi \le 0.8$ were used in the experiments. The extinction limit was determined by the following method. Mixture with equivalence ratio $\phi = 0.8$ was ignited at chosen value of velocity. Furthermore, the stationary state was established during several minutes and this process was controlled by thermocouple mounted on the bottom of the quartz plate. After that, the equivalence ratio was reduced on the value $D\phi = 0.01$ to establish new stationary state. We considered that the stationary state was established when the temperature change was less than ±0.1 °C/min. After measurements of flame characteristics we reduced equivalence ratio to study next stationary state.

3. Results and discussion

The flammability limits of methane/air premixed flames with equivalence ratio $0.6 \le \phi \le 0.8$ were investigated in the range of stretch rates from $44\,s^{-1}$ to $10\,s^{-1}$. The stretch rate is determined as $a = V/L$, where V is inlet gas velocity and the L is the half distance between burners. Various combustion modes were identified during the experiment. Direct photo of flat flames is shown in Fig. 2a (top view). The flame discontinuous at the edge of the quarts plate appears because the shafts holding the combustors obscure the flames in photos shown in Fig. 2a and b. The flame fronts were continuous in experiments.

With reduction of equivalence ratio the distance between flames decreased and at some critical value ϕ the flame fronts merged forming pattern resembling the single tube. Further reduction of equivalence ratio leads to decreasing of the “flame tube's” radius and at some value of ϕ the flame quenching occurs. Direct photos of the “flame tube” are shown in Fig. 2b (top view) and Fig. 2c (side view). The boundaries of the quartz plates and the contour of the “flame tubes” are marked by dashed lines. The “X” shape of the flame at Fig. 2c is the result of gas combustion outside the quartz plates.

Figure 3 shows the location of different combustion modes at the stretch rate/equivalence ratio plane. As can be seen from the figure, the “flame tube” exists in a wide region marked by solid circles in Fig. 3. The flame tubes exist if the stretch rate exceeds $30\,s^{-1}$. Below this boundary flame oscillations were detected