Combustion of liquid fuel in rectangular mini and microchannels

Valery V. Zamashchikov[1,3,a], Aleksey A. Korzhavin[1], and Evgeny A. Chinnov[2,3]

[1]*Institute of Chemical Kinetics and Combustion SB RAS, 630090 Novosibirsk, Russia*
[2]*Kutateladze Institute of Thermophysics SB RAS, 630090 Novosibirsk, Russia*
[3]*Novosibirsk State University, 630090 Novosibirsk, Russia*

Abstract. It is shown that flame spread rate can be high and comparable with velocities of flame propagation in the stoichiometric homogeneous gas mixture. The flame spread rate depends on velocity of oxidizer. It can either increase or decrease with arise of oxidizer velocity, depending on the oxygen content. The flame surface is significantly distorted with increase in average flame spread rate. It is shown that the flame spread rate can be significant and comparable with the laminar burning velocity of the stoichiometric homogeneous gaseous mixture.

1 Introduction

The trend towards a decrease in characteristic sizes of devices in various technical fields determines development of studies on hydrodynamic and heat transfer in mini- and microchannels. At a decrease in the height of flat channels the ratio of surface area to channel volume increases inversely to its minimal transverse size, and this causes high heat transfer intensity in the microsystems. In application to the processes occurring in reacting systems, for instance, burning of combustible liquids in small channels, heat transfer intensification can both improve and deteriorate the situation. Therefore, investigation of combustion processes in such systems is important for development of new applications and improvement of energy efficiency of available technical solutions.

To implement the combustion process, which includes the co-current motion of combustible liquid and gas it is important to get information about the regimes of two-phase flow in the considered channels. For instance, it is necessary to know in advance the conditions suitable for the separate flow, common for combustion.

It is shown in the review on the studies of the two-phase flows [1], that the flows in channels of different cross-sections depend significantly on channel transverse dimensions. According to analysis of the maps of air-water flow patterns in horizontal rectangular channels with height 0.1-1 mm [2-3], at low liquid and gas velocities, the phases flow separately.

Flame spread over pools of liquid with the flash temperature higher than ambient temperature was investigated by Ross and Miller [4, 5]. It is commonly assumed [6, 7] that liquid in the pre-flame area is heated through convective heat transfer, occurring due to the gradient of surface tension The space flame spreading is impossible in the conditions of restricted without oxidizer supply [8]. The pulsating flame spread regime implementation and mean flame spread rate depend on opposed air flow

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[a] Corresponding author : albor@kinetics.nsc.ru

velocities. Flame spread rates of an order of 0.5 cm/s were obtained. Increase in the flame spread rate oppose the oxidizing flow is possible by enriching the oxidizer with oxygen. Furthermore the flame spread rate depends on the channel height. In this connection the experiments were carried out in a narrow flat channel, the height of which may be varied, and with oxidizing flow that can be enriched with oxygen, n-butanol was used as combustible liquid.

In the present work, we have studied the flames propagating over the surface of n-butanol in micro- and minichannels. This experimental study was aimed at determination of the features of diffusion combustion of fuel film at the counter-current flow of oxidizer in a narrow flat channel.

2 Experimental setup

The flames, propagating above the surface of n-butanol in mini channels at $h > h_{cr}$, were studied. Here h_{cr} is quenching size for a slot. The channel height could vary, and it was an order less than its width. This was made to achieve the 2D structure of the flows and flame front, as far as possible.

The working section and scheme of equipment location are shown in Fig. 1. The working section consists of two parallel quartz plates, the distance between which (the channel height) h is set by two metal gaskets with the thickness from 1 to 0.5 mm. The oxidizing gas mixture was fed into the channel. The oxidizing mixture was prepared in the mixer of high pressure by partial pressures. The prepared mixture was fed to the flow controller El-Flow of Bronkhorst production. The accuracy of mixture preparation was 5%. The average velocity V of the oxidizer was determined as the ratio of the oxidizer flow rate to the cross-sectional area of the channel. The combustion process was registered from the top in the region between the liquid input and channel outlet by the digital video and photo cameras.
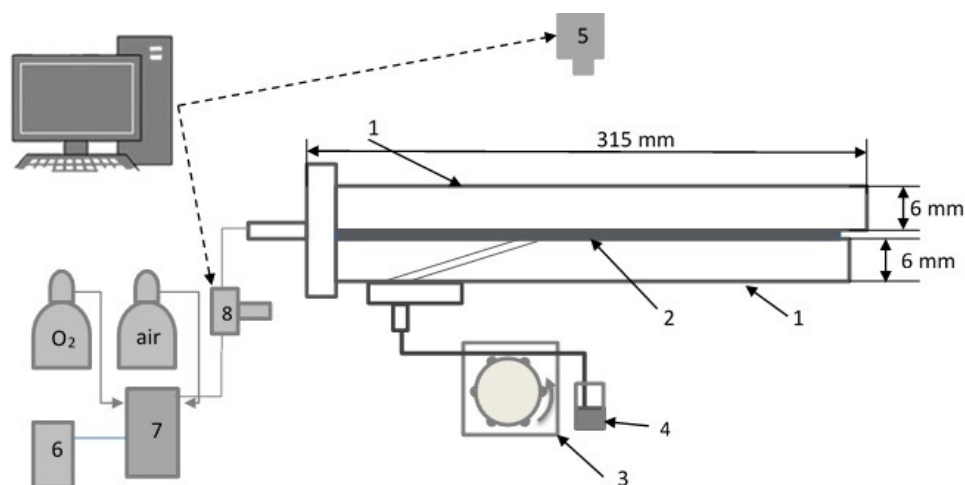
Figure 1. The scheme of setup. 1 – quartz plates, 2 – metal gasket, 3 – peristaltic pump, 4 – vessel with n-butanol, 5 – video camera, 6 – mixer of air and oxygen, 7 – gas control panel, 8 – gas flow controller El-Flow.

Ignition was performed by the naked flame at the channel outlet. After ignition we recorded the flame front coordinate and obtained the dependence of this coordinate on time. The flame velocity S was determined by inclination of this dependence. The accuracy of velocity measurements was 5%.

3 Results

Dependences of average flame propagation velocity on average gas velocity in the channels of 1 and 0.5-mm height at different oxygen content in the mixture are shown in Fig. 2. Average flame propagation velocity S determined on coordinate of the leading point of the flame in the beginning and final moments of flame propagation. As expected with increase in oxygen percentage in the oxidizer flame rate also increases. It is also seen in Fig. 2 that at addition of up to 60 % of oxygen into the oxidizer, dependences of flame velocity on average gas velocity are similar to those obtained in the higher channels [9]. However, for pure oxygen this dependence is changed to the opposite one (Fig. 2). Noteworthy also the average flame velocity in the oxygen flow in the channels with the height of 1 and 0.5 mm decreases with a decrease in the channel height, as it is expected.

Now as far as effect of environmental temperature on flame propagation velocity is concerned. Notice, according to [9] flame propagation velocity is dependent on environmental temperature. However flame propagation velocity is sensible to the temperature only at moderate oxidizer rates [9] and effect of temperature is weakened at increase in oxygen percentage in the oxidizer. Furthermore to avoid mistakes due to variation of environmental temperature the experiments were carried out at negligible variation of environmental temperature.

Complex structure of the flame front was observed in channel with 0.5 mm height (Fig. 3). Probably because of film nonuniformity, the presence of liquid on the upper plate and small average film thickness (about 0.1 mm), the flame front is asymmetrical. Notice, if the oxidizer is pure oxygen, in the channel of 1-mm height the average flame velocity becomes comparable with the laminar burning velocity of the flame of homogeneous stoichiometric hydrocarbon-oxygen mixture (3 m/s) [10]. At that the flame propagates with pulsations and flame velocity amounts to 7 m/s; i.e. these values are higher than the laminar burning velocity of homogeneous gas flame.
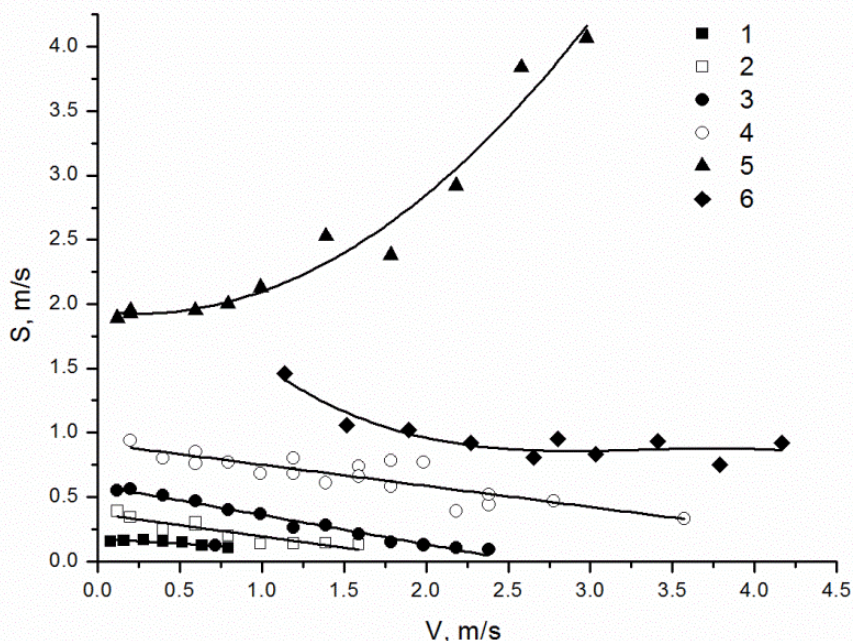
Figure 2. Average flame propagation velocity vs average gas velocity for different oxygen additive and channel heights. Channel height 1 mm (1-5), 0.5 mm – 6; ambient temperature 25.0-25.7°C. Oxygen additive in air: 1 - 24%, 2 - 30%, 3 - 40%, 4 - 60%, 5 – 6 pure oxygen (without air).
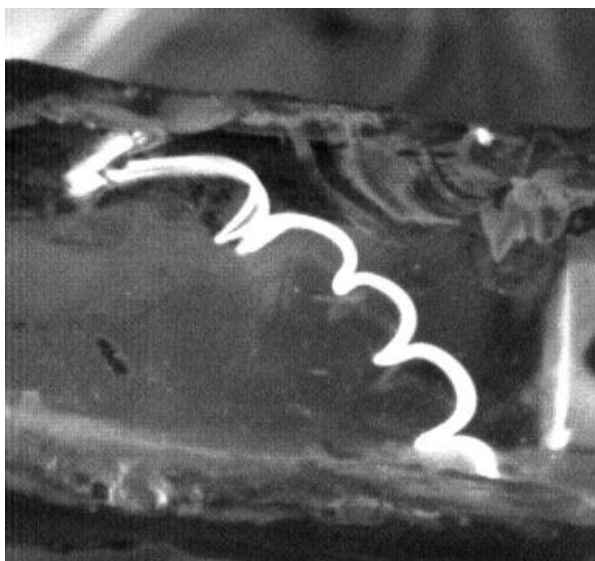
Figure 3. Flame in the channel of 0.5-mm height. Oxygen flow rate – $48 \cdot 10^{-6}$ m^3/s ($V = 2.3$ m/s).

4 Conclusions

Flame propagation against the oxidizer flow above the thin films of liquid fuel with vapor pressure below the lean limit in a narrow flat channel was studied experimentally.

It is shown that flame propagation velocity can be high and comparable with velocities of flame propagation in the stoichiometric homogeneous gas mixture.

The flame propagation velocity depends on velocity of oxidizer. It can either increase or decrease with arise of oxidizer velocity, depending on the oxygen content.

The flame surface is significantly distorted with increase in average flame propagation velocity.

Acknowledgments

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