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Combustion of liquid fuel in the flat micro- and minichannels

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ABSTRACT

Flame spread over the combustible liquid, *n*-butanol, with the flash temperature higher than the temperature of ambient medium was studied experimentally. Experiments were carried out in a narrow rectangular channel with an opposed flow of gaseous oxidizers and variable flow parameters ensuring separate flows of liquid and gaseous phases. The oxidizer composition was varied from air to pure oxygen. Dependences of *n*-butanol flame propagation velocity on oxidizer velocity were obtained at different channel heights. It was found that the flame propagation velocity depends on the oxidizer velocity and channel height. With an increase in the oxidizer velocity, the flame propagation velocity may increase or decrease depending on the oxygen content. It was shown that the flame propagation velocity could be significant and comparable with the laminar burning velocity of the stoichiometric homogeneous gaseous mixture.

1. Introduction

There is a revolutionary development of the mini- and microscale heat-exchange systems, which have proved to be much more energy efficient than macrosystems with the channel sizes of 3–100 mm. With a decrease in the thicknesses of flat channels, the surface to volume ratio of the channel increases and becomes inversely proportional to its minimal transverse size (height). This causes heat transfer enhancement in the microsystems. Combustion of liquid fuel in these small channels can have a wide range of applications, for example in thermoelectricity and power engineering. Therefore, investigation of combustion processes in such systems is important for development of new applications and improvement of energy efficiency of available technological solutions.

Flame spread over the pools of liquid with the flash temperature higher than the ambient temperature was investigated by Ross and Miller [1,2]. Under the conditions of large free space over surface of liquid, the flame propagates in either the uniform or the pulsating regimes with characteristic mean flame propagation velocity of about 0.15 m/s. The flame propagation velocity was found to be independent on the opposed air flow velocities. For flame propagation over the liquid with the flash temperature higher than the ambient temperature, the liquid has to be heated to increase vapor pressure in the gas phase. Due to high temperature of combustion products the liquid can receive substantial amount of heat from them. Increased vapor pressure should be not in the area of combustion products but ahead of the flame front. Therefore, it is necessary either to heat the liquid before the front or deliver the vapors somehow to the pre-flame zone. It is commonly assumed [1,3,4] that liquid in the pre-flame area is heated through convective heat transfer, occurring due to the gradient of surface tension (i.e., thermocapillary-driven [1]). Thermal vortices in the liquid phase in both the uniform and pulsating regimes have been observed at normal gravity and μg conditions [1]. However, it is clear that with an increase in the flame propagation velocity the vortices will not have enough time to form. If convective liquid flow is essential for the flame propagation process, then one could observe an upper limit of the flame propagation velocity. Related to this, the goal of the present work is investigation of the possibility of obtaining flame propagation velocities, which are much higher than the known values in the literature for such systems. For such flame propagation velocities, the flame spread mechanism may have to be reconsidered.

The flame spreading is impossible without oxidizer supply under the conditions of restricted space [5,6]. The pulsating flame spreading regime and mean flame propagation velocity depend on the opposed air flow velocities. Flame propagation velocities of the order of 0.005 m/s were obtained in [5,6]. An increase in the flame propagation velocity is possible by enriching the oxidizer with oxygen.

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Furthermore, the flame propagation velocity depends on the channel height. In this connection, the experiments were carried out in a narrow flat channel [7], whose height may be varied, and oxidizing flow can be enriched with oxygen. *n*-Butanol was used as the combustible liquid. The flames that propagate above the surface of *n*-butanol in mini channels at $h > h_{cr}$ have been studied. Here h_{cr} is the quenching size for a slot. For the hydrocarbon-air mixtures, the quenching size of a slot is about 2 mm [8,9].

There are two different phase flow patterns depending on the relationship of liquid and gas phases flow rates and geometry of channels. However, flame spread is possible only at some values of gas flow rates. For investigation of diffusion flame, it is useful to obtain separate liquid flow on the bottom plate of the channel and gas flow between liquid and upper plate. Patterns of air-*n*-butanol flow in a horizontal rectangular channel have not been investigated.

The analysis of air–water flow patterns in a horizontal rectangular channel with cross-section of 19.05×3.18 mm^2 [10] shows that the phases move separately at low liquid and gas velocities. The zone of smooth separated flow, where liquid can combust in the channel, is determined by the following condition: $U_{SG} < 0.3$ m/s, $U_{SL} < 0.08$ m/s, where superficial velocities of gas U_{SG} and liquid U_{SL} are calculated as the volumetric flow rate of gas or liquid divided by the area of channel cross-section. Characteristics of two-phase flow of the air–water mixture in a horizontal rectangular channel with the width of 65 mm and height of 2 mm have been investigated in [11]. The liquid films with smooth ($U_{SG} < 1$ m/s, $U_{SL} < 0.05$ m/s) or wavy surfaces ($U_{SG} > 1$ m/s, $U_{SL} < 0.05$ m/s) and dry patches were observed. The liquid film surface is characterized by two- or three dimensional waves.

The two-phase flow in the narrow short horizontal rectangular channels with 1 mm in height was studied experimentally in [12,13]. It is shown that with an increase in the channel width, the regions of the annular and separated flow patterns do not vary significantly. Under the influence of the gas flow, liquid is flowing as a smooth film on the bottom wall of the channel. Some liquid accumulates near the lateral walls of the channel due to the capillary forces. The wave motion of liquid is observed near the lateral walls with a further increase in the superficial gas velocity ($U_{SG} > 3$ m/s, $U_{SL} < 0.03$ m/s).

Investigation of the two-phase flow in a short horizontal channel of a rectangular cross-section with the height of 100–500 μm and width of 9–40 mm was presented in [14]. Data of [12–14] show that in the short channels with a decrease in their height, the zone of separated flow with smooth liquid film moves towards the area of the higher superficial gas velocities.

In the present work, we have studied the flames propagating over the surface of *n*-butanol in micro- and minichannels. The experimental study was aimed at determination of the features of diffusion combustion of fuel film at the counter-current flow of oxidizer in the narrow flat channels with the height from 0.2 to 4 mm. From the practical point of view, the main purpose of these experiments was determination of important parameters such as quenching distance (channel height) for flame penetration.

2. Experimental setup

The working section and scheme of equipment location are shown in Fig. 1. The working section consists of two parallel quartz plates (1), the distance between them (the channel height) *h* is set by two metal gaskets (2) with the thickness of 4, 2, 1, 0.5, 0.3, 0.23 and 0.2 mm. In experimental setup, the channel height could vary and its width was an order of magnitude higher than the height. The channel height was chosen considerably smaller than its width for formation of the 2D flame front. The length of the channel was 270 mm. The distance from the inlet of liquid into the channel to the outlet of the two-phase flow from the channel was 230 mm, Fig. 1. The channel width was 42 mm. The channels sizes were determined based on the data from [12–14].

The experimental setup included two computer-controlled circuits, which maintained the flow of liquid and gas phases. The liquid was driven by high precision peristaltic pump (3) and introduced into the main channel via flat nozzle (4). The flat nozzle was mounted in the bottom plate at the angle of about 11° relative the plate surface with the gap of about 150 μm over the whole width of the plate. The liquid flow rate in this experimental series was changed from $14.0 \pm 0.1 \cdot 10^{-9}$ m^3/s to $230 \pm 2 \cdot 10^{-9}$ m^3/s. In order to form liquid flow to the open end of the channel there was the moderate tilt of $1.3 \pm 0.3°$ of the channel plane relative to the horizon. The tilt was made to support the flow in the required direction, but not to affect the flame spread.

The oxidizing mixture was prepared in the high pressure mixer (5) by partial pressures. The accuracy of mixture preparation was 5%. The gas mixture was supplied into the central part of the channel (6) from the left. The gas flow rate was controlled and kept constant by the flow controller El-Flow (7) of Bronkhorst production. The gas flow rate was changed from 8 10^{-6} m^3/s to 1.5 10^{-4} m^3/s. 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 recorded from the top in the region between the liquid input and channel outlet by the digital video (8) and photo cameras. 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%. The environmental temperature for all experiments varied in the range 22–26 °C.

The liquid flow regime depends on the channel height. For the channels of 4 mm height, there is a range of liquid flow rates, where liquid flows as a film on the bottom plate even without gas supply. For the channel height of 2 mm, this range decreases, and liquid flows not only as a film, but also along the lateral walls filling up the whole height of the channel. In the channel heights less than 1 mm without gas supply and at low fuel flow rate, the liquid flows only along the lateral walls; with an increase in the fuel flow rate it fills up the whole channel. The average thickness of the liquid film in the channel of 4 mm height was measured by the mass balance [7]. The accuracy of its determination was 10%. In channels of 2 and 1 mm height, such measurements of film thickness gave a large error because the main mass of liquid was flowing along the lateral walls. In this case, the film thickness was measured by scattering the laser light with the wavelength of 532 nm. For this purpose, rhodamine was added into *n*-butanol. At first light scattering on the bottom plate surface and then on the film surface were recorded. The known angle of incidence of light allows one to determine the thickness of the film. In the channel of 4 mm height without gas flow, the liquid thicknesses have been also measured directly, when the upper plate was removed.

The temperature limit for *n*-butanol mixtures with oxygen was determined in the spherical 10-liter stainless steel bomb. The bomb was heated to the desired temperature. Then, it was filled with $5 \cdot 10^{-5}$ m^3 liquid (*n*-butanol) and oxygen was added up. The total initial pressure in the bomb was 1 atm. To mix the vapors of *n*-butanol with oxygen, they were kept in the bomb at least during 2 h. After that, the mixture was ignited in the center of the bomb by means of electric spark. Flame propagation was registered by a high-speed video camera and by the pressure dynamics measurements.