Study of radiation heat transfer during combustion of liquid fuel in a rectangular channel

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Abstract. An experimental study of radiation heat transfer during combustion of a flammable liquid in a narrow rectangular channel is performed. The emission spectrum of combustion products and the absorption spectrum of butanol-I are obtained. The case when the temperature of the combustible liquid is lower than the flash point is investigated. A comparative analysis of emission and absorption spectra shows that they do not intersect well, and the radiative heating of the liquid during diffusion flame propagation along the surface cannot be too large.

1. Introduction
In a narrow channel, at the bottom of which a combustible liquid is poured, after initiation of combustion, a diffusion flame torch is formed on its slice [1]. When the oxidizer is supplied through the other end of the channel, under certain conditions, the flame separates and propagates along the channel towards the oxidizer flow [1]. There is a lower limit on the oxidizer flow rate starting from which the flame can propagate [2, 3]. The lower limit is due to the lack of oxygen necessary to maintain combustion. The experiments [1-5] showed that the flame velocity depends on the oxidizer velocity, the oxygen content in oxidizer, the thickness of the liquid layer, and the type of combustible liquid. The flame velocity can vary over a wide range [1-5]. At low velocities, the flame propagates in a pulsating regime. With an increase in velocity, an almost uniform flame propagation is observed. It is shown that the flame velocity increases significantly when air is enriched with oxygen [1].

It is known from previous studies [6, 7] that at low flame velocities in the liquid, thermal and hydrodynamic waves form under the combustion front, as a result of which the liquid warms up and a combustible mixture is formed in front of the flame. At high velocities, when a hydrodynamic wave is not observed in the liquid, the mechanism of formation of the combustible mixture in front of the combustion wave is not fully understood. Unlike a flame propagating through a homogeneous gas mixture, for a flame above the surface of the liquid, additional time is required for evaporation and mixing of the vapors with the oxidizing agent. The temperature of the combustion products is quite high, so when the flame propagates, the liquid radiates in front of the flame. In this case, there may be enough time for heating the liquid.

The aim of this work is to analyze the possibility of heating a liquid in front of a combustion wave by radiation from combustion products in a narrow rectangular channel.
2. Experimental setup

The experiments were carried out in a rectangular channel measuring 270x42x4 mm³, on the bottom of which a n-butanol flammable liquid was poured (see Fig. 1). The working section consisted of two parallel quartz plates (1), the distance between them was set by two metal gaskets 4 mm thick (2). A nozzle (4) with a width of about 150 μm was placed in the bottom plate at an angle of ≈11°, through which liquid was supplied by peristaltic pump (3) into the space between the plates. As an oxidizing gas mixture from (5), air with the addition of oxygen supplied through gas flow inlet (6) to the central part of the channel was used. To control the flow of gas El-Flow of Bronkhorst flow controller (7) was used. The combustible fuel was set on fire at the exit of the channel. The combustion process was recorded by digital video and photo cameras (8). After combustion initiation, the dependence of the coordinate of the flame front on time was measured. The infrared absorption spectrum of butanol-1 was measured by a Fourier spectrometer. In calculating the flux density of the infrared radiation of the flame, it was assumed that the main contribution was made by water and carbon dioxide molecules. The details of the experiment are described in [1, 2].

![Figure 1. The scheme of experimental setup: 1 – quartz plates, 2 – metal gasket, 3 – peristaltic pump, 4 – flat nozzle for liquid supply, 5 – mixer of air and oxygen, 6 – gas flow inlet, 7 – gas flow controller El-Flow of Bronkhorst, 8 – video camera [1]](image)

3. Theory

We consider a flame with a cylinder (see scheme in Fig. 1) emitting light whose flux density is \( j \).

![Figure 2. Scheme illustrating analytical calculations](image)
The length of the cylinder is $a$, $h$ is the distance from the center of the cylinder to the surface of the liquid, $y$ is the distance from the projection of the center of the cylinder on the liquid surface to the liquid element $dy$. We define the angle as $\tan \alpha = \frac{y}{h}$. And find $d\alpha = \frac{hdy}{y^2 + h^2}$ and $dl = d\alpha \sqrt{(y^2 + h^2)}$. Thus, we obtain

$$dl = \frac{hd}{\sqrt{(y^2 + h^2)}},$$ then $dS = \frac{a}{\sqrt{(y^2 + h^2)}}$ (1).

Find the energy flux $I$ through the surface $dy \cdot a$:

$$I = j dS = \frac{ja}{\sqrt{(y^2 + h^2)}},$$ then $\frac{I}{dy} = \frac{j}{\sqrt{(y^2 + h^2)}}$ (2).

Let the cylinder move with speed is $v$. Then the energy passing over the unit surface during time $dt$:

$$dQ = \frac{jvdt}{\sqrt{(v^2t^2 + h^2)}}$$ (3).

Integrating the expression over time, we obtain equation:

$$Q = \int_0^\tau \frac{jvdt}{\sqrt{(v^2t^2 + h^2)}},$$

where $\tau = \frac{v}{j} \ln \frac{v\sqrt{v^2 + h^2}}{h}$ (4).

It follows from the obtained approximate equation for $Q$ (4) that the greater the flame velocity $v$, the less the influence of radiation heat transfer. However, when air is enriched with oxygen, along with the flame velocity, flux density of emitting light $j$ also increases. In addition, the flame propagates through an increasingly heated liquid ($\tau$ increases). However, a noticeable change in the flame velocity is not observed [1]. Note that the evaluation does not consider the thermal conductivity of the liquid and the absorption of light by the oxidizing agent.

4. Results

To clarify the contribution of radiative heat transfer, it is necessary to compare the spectrum of the flame radiation with the absorption spectrum of the liquid (see Fig. 3). Butanol-1 was used as a combustible liquid in [1]. The infrared absorption spectrum of butanol-1 is shown by a line with squares in Fig. 3. It was measured with a Bruker Vector 22 Fourier spectrometer, liquid layer thickness 50 μm. The line shows the calculated IR spectrum of flame emission. When calculating the flux density of the IR radiation of the flame, it was assumed that the main contribution was made by water and carbon dioxide molecules. The calculations were carried out as follows. Initially, the IR absorption spectrum was calculated for a stoichiometric mixture of butanol-1 with oxygen at a temperature of 3000K. The calculation was performed using the Spectra program of the IAO SB RAS [8]. Then, using the Planck formula, the spectral radiation density of a heated gas layer 1 cm thick was estimated.

Figure 3 shows that the absorption spectrum of butanol does not overlap well with the emission spectrum of the heated gas. The main radiation power is concentrated in the vibrational frequency band of the CO$_2$ molecule by 4.3 μm, where the absorption coefficient of liquid butanol is close to zero. In this regard, to verify the assumption of radiative heat transfer, an experiment with deuterated butanol C$_4$D$_9$OD or C$_4$H$_9$OD seems promising. Deuterated alcohols have an intense absorption band in the range 2000–2500 cm$^{-1}$ [9].
Figure 3. The emission spectrum of the flame (a line with squares) and the absorption spectrum of butanol-1 (line)

5. Conclusions
An experimental verification of the hypothesis regarding the possibility of heating a liquid in front of a combustion wave by radiation of combustion products in a narrow rectangular channel is carried out. The emission spectrum of combustion products and the absorption spectrum of butanol-1 are measured. An analytical estimate for the radiation flux density is obtained. From equation it follows that the greater the flame velocity the less the influence of radiation heat transfer. Study based on analysis of absorption and emission spectra shows that the radiative heating of a liquid by combustion products during diffusion flame propagation most likely does not have a large effect on this process.

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