Features of liquid fuel burning in a narrow channel

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Abstract. The paper deals with experimental investigations of the surface perturbation effects on the flame propagation velocity along the surface of the liquid. It is revealed that at low velocities the effect is quite significant. Under certain conditions the flame even stabilizes for some time. The experiments were conducted to elucidate the mechanism of flame propagation. However, it was impossible to determine expressly the flame propagation mechanism along the surface, because this requires visualization of gas flows.

1. Introduction

Making the miniature power sources, which use the energy released during hydrocarbon combustion, is an urgent task since high intensity of heat transfer in microsystems allows creating the effective heat exchangers that can be useful for development, for example, of thermoelectric converters. The process of flame propagation over the surface of liquid on the bottom of a cylindrical tube was investigated in [1]. At that, liquid heating was observed under the flame front. In more detail, the processes occurring in liquid during flame propagation are studied in [2]. The authors observed the formation of a vortex in liquid that is ahead of the flame front and plays a large role in the mechanism of flame propagation. It is believed [2] that the cause of the vortex generation is the movement of liquid under the impact of uncompensated surface tension forces. These forces arise due to the temperature gradient along the liquid surface, resulted from the heating of the liquid by combustion products.

Experimental studies of liquid combustion in horizontal channels have shown [1, 3] that the flame velocity can vary in a wide range from millimeters per second to several meters per second. The estimates made in [3], have shown that at flame propagation velocities of the order of several meters per second, movement of the liquid due to thermocapillary forces is unlikely. In this regard, the question arises about the mechanism of formation of the combustible mixture in the flame front. In [3] the evaluations were carried out for a fairly thick layer of liquid. However, it can be assumed that due to the high temperature and high flame propagation velocity under the combustion front, only a very thin layer of liquid is able to warm up. The viscosity of liquid decreases with increasing temperature. Therefore, because of the resulting thermocapillary force, the upper liquid layer begins to slide over the cold and therefore more viscous portion of liquid. For this case, the estimates given in [3] are unjust, and thermocapillary mechanism may still be implemented. Heating of the fluid ahead of the
combustion front leads to an increase of the 1-butanol vapor flows into the oxidizer that leads to the formation of a combustible gas mixture.

Another possible mechanism of formation of the combustible mixture may be the following. Due to the large temperature difference between the combustion products and liquid (more than 1000 K) when near-surface liquid layer is heated (behind the combustion front, where the combustible products are situated), fuel vapors flow is formed. The stream flows around the flame, so that part of the stream is directed to the area ahead of the flame containing the oxidizer. Occurring turbulent mixing results in formation of the combustible mixture. Due to the rapid mixing, flame propagation velocity may be much higher than in the case of heat transfer through the liquid to the pre-flame area. The aim of this paper is to try to figure out the real mechanism of formation of the combustible gas mixture ahead of the combustion front.

2. Experimental setup

The experiments were carried out in a flat channel with the width of 4 mm and height of 42 mm (Fig. 1). Side walls were made of quartz plates.

In contrast to previous works, in this study, the bottom (lower part) of the channel was not a wide part [3], but a narrow one, and this allowed observing the combustion front and processes occurring in liquid. The oxidizer was fed from one side, while the other side was free. The barrier, preventing the leakage of fluid, was installed below the open side.

When air was used as an oxidizer, the flame entered to the channel and quenched. To exclude extinguishing, air was enriched with oxygen. To influence the processes occurring in liquid and combustion, a barrier was mounted on the channel bottom (Fig. 1).

3. Experimental results

In contrast to [3], in this case, the flame velocity did not depend on oxidant flow rate, at least up to the flow rate of 5 liters per minute, which agrees with the data obtained by other investigators at flame propagation over the liquid surface in sufficiently large volumes [2]. This can be explained by the fact that the effect of oxidant flow on combustion should increase with a decrease in the free space above the flame. As expected, the velocity depends on the proportion of oxygen in the oxidant mixture. With an increase in oxygen proportion, the velocity increases almost linearly.

At flame velocities higher than 11 cm/s, there is no visual disturbance of the liquid surface (formation of a roll ahead of the front). However, the region of liquid heating is observed (Fig. 2 a). This region expands with a distance from the combustion front. The fact that in this area the temperature actually increases is shown by thermocouple measurements. A 25-μm chromel-alumel thermocouple was used (it can be seen in Fig. 2). As the flame velocity increases with oxygen enrichment of air, the heating region observed under the front becomes thinner, and eventually it cannot be distinguished (Fig. 2b). To understand the mechanism of flame propagation, it is important to determine where the heating region is relative to the leading point of combustion wave: is it ahead of this point or not.

However, thermocouple measurements did not allow this, since, first, when the thermocouple approaches the surface, the latter is bent, and second, the near-surface heated layer can be so thin that the thermocouple does not measure the actual temperature profile near the liquid surface. It should be noted that when measuring the gas temperature, i.e., in the case, when the thermocouple was located above the surface, the temperature profile obtained by the thermocouple was considerably shifted relative to the combustion front because of thermocouple inertia.
For the existence of a combustion wave, it is important that a combustible mixture be formed before the front. The combustible mixture is formed at mixing the vapors with an oxidant, if vapor concentration is higher than the limiting value. The authors of [2], in the mechanism of flame propagation proposed by them, have determined the role of thermo-capillary phenomena. Due to the temperature gradient formed along the surface and temperature dependence of surface tension coefficient, a force is generated that moves the heated liquid into the pre-flame region. A thermocapillary wave is formed in liquid, and it moves together with the flame along the liquid surface. As a result, vapors of heated liquid, mixing with an oxidant, form a combustible mixture before the flame.

It is obvious that liquid surface bending affects the processes taking place in liquid and gas, and thus, flame propagation. To study the effect of surface bending on the flame velocity, a cylinder or parallelepiped was placed on the channel bottom. On the one hand, the barrier bent the surface of the liquid, on the other hand, the liquid layer thickness decreased. The thickness of the liquid layer begins affecting the velocity of combustion wave, when it is comparable with the characteristic heating thickness (in this case the liquid can move) of the near-surface layer under the flame front. The thickness of the heated layer in turn depends on the flame propagation velocity. The curvature of the surface influences both processes occurring in the liquid and those occurring in the gas phase.

When the flame approaches the barrier: a) it slows down; b) its slope relative to the gravity vector changes; c) its position changes, although insignificantly, relative to the liquid surface; d) its length decreases; e) brightness of its image decreases. The shlierten-image brightness should be related to the flame temperature, so it decreases in the flame front.

The shape of the flame depends on the vapor flow from the liquid surface and oxidant flow. Since the flame velocity in this case does not depend on the oxidant flow rate, it can be assumed that combustion takes place at low gas velocities, i.e., in almost resting gas. In this case, most likely, there is diffusion mixing of vapors and oxidant with formation of a combustible mixture ahead of the combustion front. The greater the surface curvature (determined by the ratio between the thickness of

![Figure 2. Photos of flame propagation front.](image-url)
the liquid layer and the height of the obstacle) and the lower the flame velocity, the stronger is the effect of barrier on the flame propagation velocity. During the flame propagation, the barrier should not have a significant effect on the flame velocity until the flame approaches the barrier. When the flame comes close to the barrier, firstly the surface bends, and secondly, the liquid layer thickness changes. These two factors influence the temperature of the near-surface layer.

Diffusion of vapors should also depend on the surface curvature, and the value of this flux should depend on the temperature of the near-surface layer. Dependence of the flame velocity on coordinate and position of the barrier are shown in Fig. 3. The flame spreads from right to left. It can be seen that the velocity decreases, when the flame rises to the barrier. Due to liquid surface curvature, the flame, when moving along the surface, passes the region, where the liquid layer thickness increases first, and then decreases. From the point of view of vapor diffusion and liquid heating ahead of the flame front, the velocity should increase and then decrease, but this is not observed. This can be explained as follows. As mentioned above, the liquid layer thickness starts influencing the flame propagation velocity, when it is comparable to the characteristic thickness of the liquid layer heated under a flame front. If at the distance far from the barrier, characteristic thermal thickness is less than the liquid depth, then the increase in the latter when approaching the obstacle has little effect on the velocity. When the depth decreases and becomes comparable with the characteristic thermal thickness, the flame propagation velocity is reduced that in turn leads to an increase in the characteristic thermal thickness, and this leads to a further slowing of the flame. However, we cannot exclude that the flame velocity is determined by the average characteristics, which are not affected by such a change in thickness.

At the place, where the velocity is minimal (Fig. 3), the flame becomes more vertical, it lengthens and its brightness increases. Under some certain conditions (when a parallelepiped is used as a barrier), the flame is stabilized in this place for some time. This behavior can be explained as follows. First, the liquid layer thickness under the flame is small there. Consequently, it is poorly heated due to the heat flux into the solid phase. Second, liquid heating ahead of the front leads to an increase in the vapor flow into the gas phase, but this flow is directed away from the flame by virtue of geometry (fig. 4).
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The stabilization of the flame is of practical importance. On the barrier

The stabilization was observed when oxygen flow rate changed

The oxygen was used as the oxidizer. The stabilization was observed when oxygen flow rate changed

4. Conclusion

Thus, the barrier has an effect on the flame propagation. It affects the processes occurring in the liquid and gas phases. However, the experiments carried out in the presence of a barrier do not give an unambiguous answer about the mechanism of flame propagation.

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