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THE NORMAL COMPONENT OF A GAS FLAME SPEED

We study the burning of an open flame of hydrocarbon fuel in the air atmosphere and introduce a method of determination of the flame speed normal component for a selected local diametrical slice. A distribution of speeds along the flame axis reveals the inner flame structure and its variation depending on the fuel-oxidant ratio.

Keywords: burning, hydrocarbon flames, normal component of the flame speed, local slices, flame structure.

A search for the conditions of efficient combustion of a fuel is one of the most important energy problems. In order to find such combustion modes, it is necessary to understand the mechanism of burning depending on the oxidant-fuel ratio, which can be described by the excess of the oxidant (air) α in a combustible mixture.

A mechanism of burning is closely related to the flame structure. For example, a pulse burning occurs at certain values of oxidant-fuel ratio α, which leads to the burning front degeneration into the burning zone. The electric breakdown voltage in this zone is lower than that in the nearby volumes of the flame [1], and the temperature is higher [2]. This may suggest a more complete combustion and thus a more efficient fuel utilization.

It should be noted that the mentioned methods (measurements of the temperature by a thermocouple and the breakdown voltage) assume the flame scanning, which makes it impossible to obtain a snapshot of the entire flame structure at once. The available optical methods are good for this purpose, but they require a complex experimental equipment [3].

An intensification of burning can be confirmed by an increase of the flame speed (more precisely, its normal component). The authors of work [4] suggested a method of digital processing of the flame photographic images and calculated the integral (over an entire surface of the burning front) values of the normal flame speed.

Our method allows one to determine the normal component of the local flame speed in any chosen diametrical slice of a flame.

In the present paper, we study the burning of an open laminar ($Re = 805$) torch of the prepared specimen of a gas mixture (fuel: 40% propane + 60% butane; oxidant: air) above an upright burner. The value of Re was calculated as $Re = vd/\nu$, where v is the linear flow speed in the burner (measured with rotameters), d is the inner diameter of the burner, ν is the kinematic viscosity (the reference data are taken from [5]).

The burning takes place in the air atmosphere under normal conditions (temperature 20 °C, pressure 768 mm Hg). The experimental setup, the flame structure, and its changes depending on α were described in [1, 2]. The fuel (propane-butane) and air were supplied to the mixer unit, by using two separate pipes. In order to prevent the spontaneous ignition, the temperature of the mixer unit was at 310 K level, which is much less than the ignition temperature as high as 700 K. The experimental setup was similar to one described in [1, 2]. Let us focus on the normal component of the linear burning velocity.

Figure 1 shows the photographic images of the torches above the burner with a nozzle diameter of 0.8 cm. The brightest inner cone is bounded by the narrow reaction front. The region of the pre-burning preparation of a combustible mixture (heating, decomposition, *etc.*) is inside this front, and the after-burning region is outside it.

The combustible mixture consumption varied within 1.2%, so the changes of the flame structure were obviously determined by a change in α. The digital image processing was as follows: the digital photographs of a flame were binarized with certain brightness threshold much like it had been done in [4]. The difference is that we used a sum of all three channels (RGB). Thus, the obtained silhouette of a flame was sliced into a number of layers (blocks) with a constant vertical step (Fig. 2, *a*). The lateral area of each block was calculated in the conic frustum approximation. From the calculated Re value, a laminar flow of the combustible mixture may be assumed. Consequently, by dividing a total mixture flow L (measured with rotameters) by the cross-section area of the flame base S_0^{cross} (Fig. 2, *b*), we obtain a specific mixture flow. Next, we take the difference between the cross-sections of two adjacent slices ($S_{i-1}^{\text{cross}} - S_i^{\text{cross}}$) and multiply it by the specific mixture flow to obtain the mixture discharge through the selected slice. Dividing this value by the lateral area of the same slice S_i^{block} directly yields the normal component of the burning speed in the i-th local slice of a flame, V_i^n. Applying the same procedure for all slices, we obtain a distribution of the normal component of the burning speed along the torch:

$$V_i^n = \frac{L}{S_0^{\text{cross}}} \frac{(S_{i-1}^{\text{cross}} - S_i^{\text{cross}})}{S_i^{\text{block}}}. \quad (1)$$

The proposed approach allows us to determine the value of V_i^n for the i-th local slice of a certain (predefined by the experimental conditions) size within a flame. It lets one solve the problem of geometrical localization of the reaction zone, and determination of its size. As a limiting case, the average value of flame speed normal component $\langle V^n \rangle$ for the inner cone as a whole can be found.

The results are presented in Fig. 3. The error of the V_i^n determination was estimated as follows:

$$\sigma_V \approx 2\pi R L (S_0^{\text{cross}})^{-2} \sigma_R, \quad (2)$$

where R is the flame cross-section radius, and σ_R is the error of the radius measurement by the image ($\sigma_R \approx 0.02$ cm).

The average normal component of the flame speed $\langle V^n \rangle$ was also estimated from the lowest cross-section area (S_0^{cross}) and the total lateral area (S_0^{cap}). By taking the $\langle V^n \rangle$ as a reference value for each studied flame, it is possible to single out two distinctive zones: *a*) near the base of the inner cone, where it first touches the ambient (secondary) air; *b*) at the top of the inner cone.

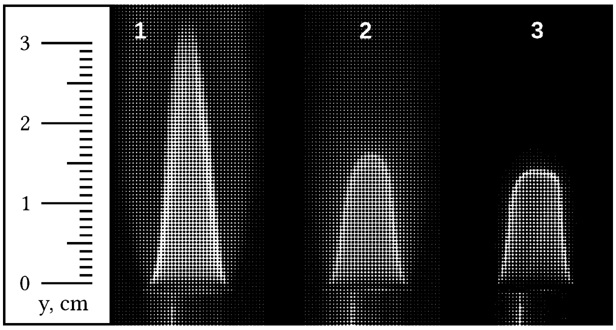
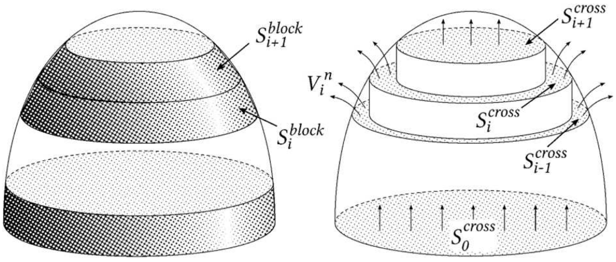


Fig. 1. Photographs of the inner cones of the propane-butane torch: 1) $\alpha = 0.93$; 2) $\alpha = 1.3$; 3) $\alpha = 1.38$



a *b*

Fig. 2. Illustration of the calculation of slice parameters

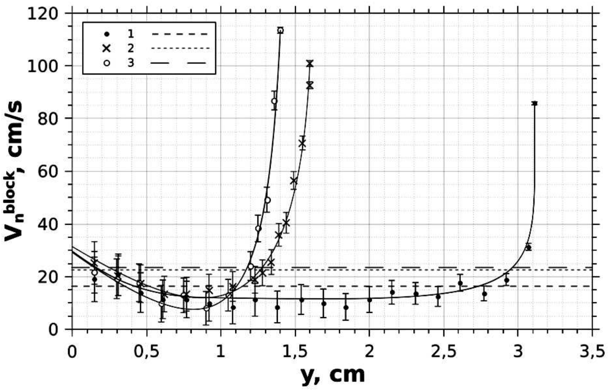


Fig. 3. Distribution of the normal component of the local flame speed along the torch for: 1) $\alpha = 0.93$; 2) $\alpha = 1.3$; 3) $\alpha = 1.38$. The dashed lines mark the corresponding average values $\langle V^n \rangle$: 13.6 cm/s *1*; 22.6 cm/s *2*; 23.6 cm/s *3*

Zone *a*) is characterized by the influence of the ambient (secondary) air, which is reflected by the increased values of V_i^n relative to $\langle V^n \rangle$. This influence decreases, as α increases (transition from curve *1* to curve *3* in Fig. 3.)

As for zone *b*), the local flame speeds increase with α because of the growing role of the kinetic reactions due to the excess of the oxidant and higher temperatures [2] (leading to a deeper decomposition of initial propane and butane molecules). For the sake of comparison, the portion of a mixture, which burns faster than $\langle V^n \rangle$, can be estimated. This portion is 10% for $\alpha = 0.93$, 29% for $\alpha = 1.3$, and 41% for $\alpha = 1.38$.

Thus, we suggest a method of determination of the local flame speed normal component V_i^n. Based on the obtained results, one may single out two zones within the inner cone of a flame, where local flame speeds are higher than $\langle V^n \rangle$: near the base of the torch and at the top of the torch. The higher V_i^n at the base of the cone are probably related to the contact with the ambient air, with its influence decreasing, as α increases. The higher values of V_i^n at the top of the cone can be caused by the kinetic reactions, whose role increases with α.

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НОРМАЛЬНА СКЛАДОВА
ШВИДКОСТІ ГОРІННЯ ГАЗОВОГО ФАКЕЛА

Р е з ю м е

Досліджено горіння відкритого факела вуглеводневого палива у повітряній атмосфері. Запропоновано методику визначення нормальної складової швидкості горіння виділених локальних об'ємів факела. Показано, що розподіл швидкостей уздовж факела полум'я (внутрішнього конуса) виявляє структуру факела та її зміну в залежності від співвідношення окисник–паливо у початковій пальній суміші.