The Investigation of Flame Propagation in Gaseous Mixtures in Large Semiopen Tube

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ABSTRACT

Experiments have been made for investigation of a flame accelerating during its propagation in gaseous mixtures of propane - butane - air in the large-scale semiopen horizontal tube (diameter 1.45 m, length 100 m) with combustion initiated near the closed end of the tube. We found, that in most experiments the flame velocity, S, increases linearly with a distance, L, from the end of the tube. At a distance 15-20 m from the closed end of the tube the change of the regim of flame propagation may take place with the appropriate change of the proportionality coefficient between S and L. The experiments showed that combustion process duration, in a fixed tube cross - section, which is detected by photodiodes and electric potential transducers, decreases exponentially with the distance from the closed end of the tube. The exponent index does not depend on a combustible mixture composition. The linear relationship between the flame velocity and the distance from the closed end of the tube was qualitatively explained based on the concept on a flame accelerating due to formation of an elongated flame front.

Keywords: flame acceleration; horizontal tube; gaseous mixtures.

INTRODUCTION

Investigations of flame propagation in gaseous mixtures in tubes are very important to develop combustion theory and in practice. The peculiarities of a flame accelerating in tubes are now rather unclear in order to predict consequences of gaseous explosions in a tube geometry confinement. This is necessary to ensure the fire and explosion safety in the process industries. Many works have been aimed on the investigation of a flame accelerating during its propagation in tubes (see, for example, [1-16]). These works found, that flame velocity is influenced by such factors as diameter and length of the tube wall roughness, obstacles in the path, kind and position of ignition source ets. The interesting effect, revealed in [5, 13, 16] for semiopen tubes of various diameters, is the exponential dependence of flame velocity, S, on time from ignition of gaseous mixture, or quite the same, the linear relationship between S and a distance, passed by the flame from the closed end of the tube. This phenomenon is caused mainly not by flame turbulence but by formation of elongated flame front along the tube axis [5, 13, 16]. In the previous works [1-16] the experiments have been carried out as a rule on laboratory - scale apparatus (with the exception of [7, 8, 15, 16]). This fact makes use these experimental data difficult for real industrial objects.

This work is aimed at determining of flame acceleration in large industrial size pipes

EXPERIMENTAL

The basis of the experimental apparatus is the large-scale horizontal tube with diameter 1.45 and length 100 m. This tube has a set of small perforations (diameter up to 0.03 m) for detectors for measurement of a flame propagation. These detectors were photodiodes and passive flame electric potential detectors. The experiments have been carried out with gaseous mixtures of a various composition. The oxidizer equivalence ratio α was selected as a parameter, which describes the mixture composition. The value of α is described by the formula

$\alpha = (C_a / C_c) / (C_{as} / C_{cs})$,

where C_a, C_c are concentrations of air and combustible gas in the mixture investigated; C_{as}, C_{cs} are concentrations of air and combustible gas in the stoichiometric mixture. The lean ($\alpha \approx 1.3$), near stoichiometric (($\alpha \approx 1.0$) and rich ($\alpha \approx 0.7$) mixtures were used in experiments. Combustible mixtures were prepared by introducing of combustible gas (propane-butane composition) into the closed part of the tube isolated by a polyethylene diaphragm. The mixture introducing was made through numerous perforations placed in the top of the horizontal tube along its axis. The concentration of the combustible gas was tested in various parts inside the tube by means of an interferometric device SHI-7. The interferometer was calibrated for the gas investigated (propane-butane mixture with concentrations of C_3H_8 75-85% (mass.) and C_4H_{10} 15-25% (mass.)). It has been shown in many preliminary measurements that concentration of combustible gas was rather uniform (the maximum difference in concentrations did not exceed 0.3% (vol.)).

Along the tube we placed some photodiodes and passive electric potential transducers. The electric potential detectors were in the form of steel wires with diameter 1.5 and length 10 mm or steel plates with length 3 and width 1 cm. These detectors were introduced into the gaseous mixture at various distances from the closed end. Signals from the electric potential detectors were amplified by an amplifier with input resistance $10^7\ \Omega$ and registered by oscilloscope. This registered also signals from photodiodes. Photodiodes were placed outside the tube and were connected with an internal cavity of the tube by a little channel with diameter 8 and length 50 mm. The photodiodes were protected against the flame by covering the end of the channel with transparent glass plate. At the described positions of the photodiodes, the view angle of each photodetector is narrow enough to register a flame arrival with a relatively high precision.

The combustion initiation was made by a fused nichrom wire placed at a distance 0÷0.8 m from the closed end of the tube.

Conditions of experiments are presented in Table 1.

RESULTS

Figure 1 shows typical dependencies of the coordinate of the leading part of the flame front L (distance from the closed end of the tube) on time t. From Fig.1, it can be seen that the flame accelerates during its propagation along the tube. By a differentiation of the function L = f (t), the values of the flame velocity S were determined. Typical dependencies of the S values on L are shown in Fig.2. In accordance with [5, 13, 16], these dependencies are close to linear. This fact is equivalent to an exponential increase of a flame velocity with time. In some experiments the linear relationship between S and L

$$S = KL \qquad (1)$$

was realized with a constant K value during the whole combustion process ($K \approx 12\ s^{-1}$). However, in the most of experiments an abrupt change of the K value occurs at a distance 15-20 m from the closed end of the tube. In the initial part of a flame propagation, where formation of the elongated flame front takes place [13, 16, 18], the coefficient K has the maximum value ($K \approx 10\text{-}15\ s^{-1}$) but then this coefficient becomes 4-9 s^{-1} when the abrupt change occurs.

In some experiments, the electrodes of electric potential detectors were placed at some distances from tube walls inside the combustible gaseous mixtures. It has been found, that the deeper electrodes register signals of the flame arrival earlier, the electrodes placed near tube walls. The signals from these deeper electrodes appear in many cases earlier, than signals from photodiodes placed at the same tube cross-section. These effects demonstrate two phenomena: first, the elongated form of the flame front, and, second, a possible availability of a ionization zone ahead of the luminous flame front.

Table 1. Conditions of experiments

N	Length of the part of the tube, occupied by a combustible mixture, m	Distanse of an ignition source from the closed end of the tube, m	Oxidizer equivalence ratio	Distance from the detector to the closed end of the tube, m		Depth of the location of the electrode of the electric potential detector, cm
				photodiodes	electric potential-detectors	
1	31	0.75	1.0	10; 50		
2	31	0	1.0	10; 50		
3	11	0	1.0	15;25	4; 10	9; 9
4	11	0.75	0.7	4; 15; 25	4; 10	9; 9
5	11	0	1.4	-	4; 10	9; 9
6	11	0.80	0.8	7; 15; 20	4; 10	9; 9
7	51	0.80	1.0	7;10;30;50	4; 10	27; 9
8	31	0.80	1.0	7;10;30;50	4; 10	9; 9
9	31	0	1.0	7;10;30;50	4; 10	9; 9
10	31	0	0.5	7;10;30;50	4; 50	27; 9
11	31	0	0.9	7;20;30;50	4;4;10	9;27;9
12	51	0	0.8	7;20;30;50	4;4;10	9;63;9
13	51	0	1.4	7;20;30;50	4;10;10	9;27;9
14	51	0.80	0.8	7;20;30;50	4;10;10	9;27;9
15	31	0.80	0.8	7;20;30;50	10; 10	9; 63
16	31	0.80	1.0	7;20;30;50	10; 10	9; 63
17	21	0.80	0.7	7;15;25;30	20; 20	9; 63
18	21	0	0.7	7;15;25	20; 20	9; 63

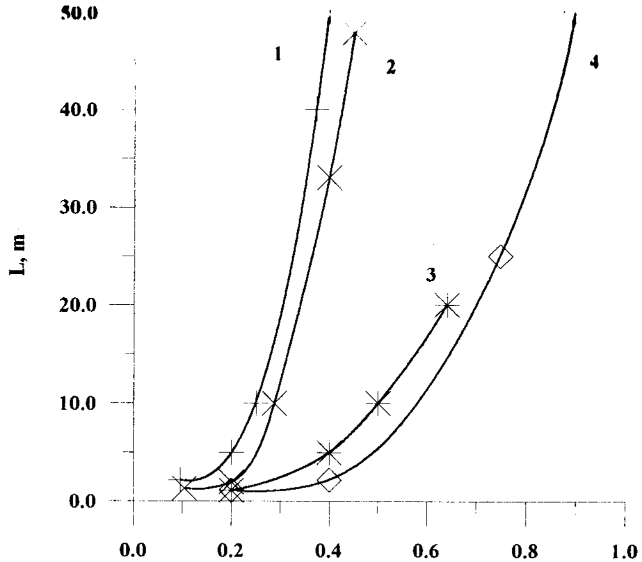

Fig. 1. The typical dependences of coordinate L of the leading part of the flame front on time t. 1-experiment N 4; 2-experiment N 12; 3-experiment N 3; 4-experiment N 7.

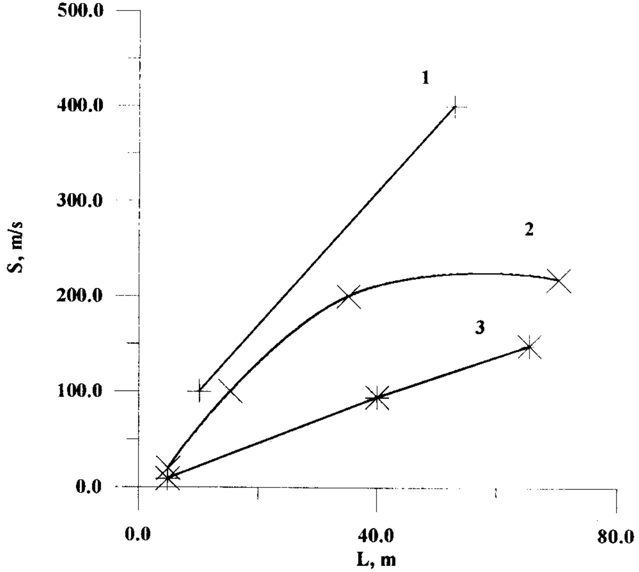

Fig.2. The typical dependences of the flame velocity S on coordinate of the leading part of the flame front L. 1-experiment N12; 2-experiment N18; 3-experiment N10.

In our experiments we recorded the times of the beginning and finishing of signals from the photodiodes and the electric potential detectors. A difference τ between two times characterizes a duration of combustion processes in gaseous mixtures in fixed tube cross-sections, where detectors are placed. Typical dependences τ on the distance from the closed end of the tube L are presented in Fig.3. It can be seen, that τ decreases exponentialy with the increase of the L value:

$$\ln\tau = A - BL, \qquad (2)$$

where A and B are coefficients. The determined A and B values are presented in Table 2 for various experiments.

From Table 2 it can be seen, that the B coefficient is close to 0.03 m^{-1} for most experiments and does not depend significanly on mixture composition and the length of the tube part occupied by the combustible mixture. At the same time a coefficient $C = \exp(A)$ in an expression

$$\tau = C\exp(-BL), \qquad (3)$$

which is followed from (2), is determined sufficiently by mixture composition. It is unexpected that the C value has a maximum at near stoichiometric mixtures ($C\approx760$ ms), for which laminar burning velocity has the maximum value. For rich ($\alpha\approx0.7$) and lean ($\alpha\approx1.3$) mixtures the C value decreases to ≈ 500 ms.

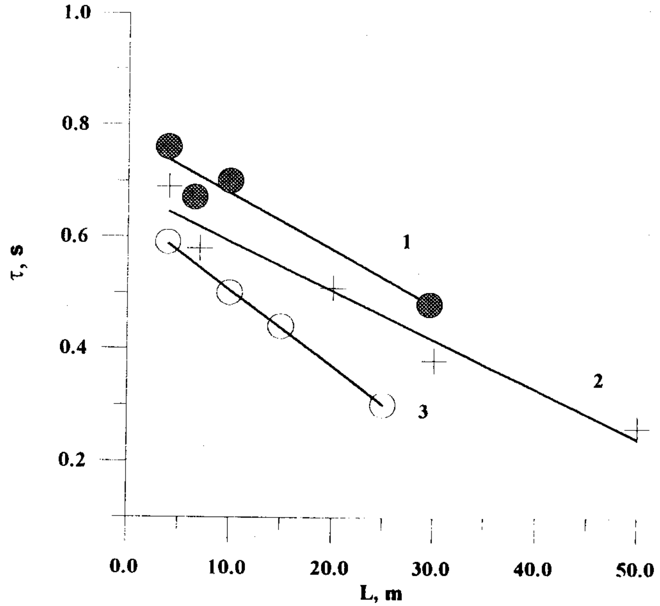

Fig.3 The typical dependences of combustion duration in a given cross-section of the tube t on a coordinate L. 1-experiment N9; 2-experiment N11; 3-experiment N3.

Table 2. The results of the determination of A, B and C coefficients in dependences (2) and (3)

Experiment N accourding to Table 1	Oxidizer equivalence ratio α	Length of the part of the tube, occupied by a combustible mixture, m	Coefficients		
			A	$B \cdot 10^2$, m^{-1}	C, ms
3	1.0	11	6.6	2.5	740
4	0.7	11	6.3	2.8	550
6	0.8	11	6.2	5.0	490
7	1.0	51	6.8	3.6	900
8	1.0	31	6.6	5.6	740
9	1.0	31	6.6	3.0	740
11	0.9	31	6.7	2.7	810
12	0.8	51	6.5	3.0	670
13	1.4	51	6.25	2.7	520
15	0.8	31	6.1	1.8	450
16	1.0	31	6.5	2.0	670

DISCUSSION

Earlier Fialkov, et al. [16] mentioned that the measured high values of a flame velocity S (several hundreds $m \cdot s^{-1}$) can not be explained by a turbulence generated by a flame front only. The tube used in our experiments is rather smooth, therefore the role of obstacles in flame acceleration is negligible. Radiative mechanism [17] also does not present any satisfactory explanation of the observed phenomena, because on the basis of this mechanism it is very difficult (or even impossible) to interpret the linear relationship between the flame velocity S and the distance from the closed end of the tube.

One of possible mechanisms of flame acceleration at its propagation from closed to open end of the tube is formation of an elongated flame front, which occurs in a following manner [13, 19]. At a point of initiation of combustion near the closed end of the tube initialy a spherical flame front is formed. But at approach of a flame front to tube's walls an extension of combustion products takes place mainly to the open end of the tube, and therefore the flame front obtains an elongated form. An elongated front at a flame propagation in a tube has been experimentally revealed in [20].

Let us consider, according to [19], a process of a propagation of a leading part of a flame front in a tube at ignition near the tube's closed end. We shall consider the flame front as a cylinder with radius close to tube radius r and height equal to L (coordinate of the leading part of the flame front). An increment of combustion products volume dv which takes place during a time interval dt can be described by a formula:

$$dv = FS_u (E_i - 1)dt, \tag{4}$$

where F is area of the flame front; S_u is laminar burning velocity; E_i is coefficient of extension of combustion products.

The F can be described by an expression (at L >>r):

$$F = 2\pi r\, L. \tag{5}$$

Assuming, that extension of combustion products occurs only to the open part of the tube, we can obtain the following expression for velocity S of the leading part of the flame front

$$S = \frac{1}{\pi r^2}\frac{dV}{dt} = \left[\frac{2S_u(E_i - 1)}{r}\right] L. \tag{6}$$

For stoichiometric hydrocarbon - air mixtures for our tube $K = 2S_u (E_i - 1)/r \approx 7 s^{-1}$, which is close to values 10-15 s^{-1} obtained experimentally at initial phase of flame acceleration. Thus the elongated flame front, which has been revealed experimentally in [20], is probably the cause of flame acceleration at initial phase of the process. This explanation has certainly a qualitative character, but it allows to understand the mechanism of flame acceleration at its propagation in a smooth tube at ignition of combustible mixture near the closed end of the tube.

As it has been mentioned above, at L=15-20 m the abrupt change of the K value occurs in most experiments. Probably this effect is connected with a change of a regime of a flame propagation characterized by a decrease in the extent of a flame elongation. For more detail explanation, additional theoretical and experimental investigations are required.

A flame luminosity in a fixed cross-section of the tube is a characteristic of duration of combustion process at this part of the tube. The duration of a signal from an electric potential detector is close to the duration of the signal from the photodiode placed in the same tube cross-section, that is, the signal from electric potential detector is also a characteristic of occurance of combustion process. However it is necessary to note, that the signal from the electric potential detector in most experiments begins earlier than the signal from the photodiode. This effect is not connected with inertia of the devices used in our experiments. The probable reason of this phenomenon is an availability of an ionization zone ahead of the luminous flame front. This zone can be stipulated by two processes: first, chemiionization ahead of the luminous flame front, and, second, diffusion of electrons from the luminous flame front. In the framework of our investigation it is impossible to reveal a mechanism of this phenomenon exactly.

It can be seen from the relationship (3) between the combustion process duration τ and the distance from the closed end of the tube L, that combustion near the closed end of the tube (near the ignition point) continues, when combustion in more remote cross-sections has finished. This shows that the higher mass burning rate of the gaseous mixture in remote parts of the tube probably is caused by a higher flame front turbulence compared with the tube end near the ignition source.

An evaluation of a flame velocity S by means of the formula (6) shows that the S value reaches the detonation wave velocity (≈1800 $m \cdot s^{-1}$) at a distance near 180 m from the closed end of a hypothetic tube with diameter 1.45 m. This value will be reached after 660 ms from the initiation of combustion process. The luminosity duration τ at this distance will be equal to 4 ms (results of calculations according to formula (3)). At this time moment the luminosity (that is the combustion process) near the closed end of the tube will continue (as it has been mentioned above, the luminosity duration at this point is nearly equal 760 ms for the stoichiometric mixture).

CONCLUSIONS

On the basis of the experiments the following conclusions can be made.

1. The regularities of a flame acceleration and propagation in the large-scale semiopen tube with ignition near the closed end of the tube have been experimentally investigated. We found that flame velocity S increases linearly with distance L from the closed end of the tube. At the distance 15-20 m the change of a regime of a flame propagation occurs with the appropriate change of the proportionality coefficient between S and L.

2. We found, that combustion duration in a fixed cross-section of the tube decreases exponentially with distance from the closed end of the tube. The exponent index does not depend remarkably on composition of a combustible mixture. The observed effect is stipulated by an increase of mass burning rate of gaseous mixture due to turbulence of a flame front.

3. The linear relationship between flame velocity and the distance from the closed end of the tube can be qualitatively explained on the basis of flame acceleration caused by formation of elongated flame front.

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