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Investigation of Turbulent Reaction Fields by Ionization Measurements

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Information on the structure of the reaction field in turbulent diffusion flames is derived from ionization measurements. First, for laminar flames, it is shown that the reaction density is proportional to ion concentration. The distances between the respective peaks of subsequent flame fronts are shown. They prove to be larger than the length scales obtained from the velocity fluctuations. The velocity of flame fronts is calculated from correlation measurements with double probes. The relative velocities of flame front and flow are distinctly different from the laminar burning velocity.

Nomenclature

A	= flame surface
a,b	= constants
d	= burner diameter
f	= frequency
I	= ionization current
L	= macroscale
L_f	= distance between flame fronts (time mean value)
L_m	= macroscale
L_p	= distance between flame fronts (most probable value)
r	= correlation coefficient
T	= temperature
t	= time
u	= flow velocity
u_f	= velocity of flame fronts
$\dot{V}_R$	= methane consumption (with premixed air only)
x	= distance from burner exit
y	= distance from flame axis
$\overline{(\ )}$	= time mean value
$(\ )'$	= fluctuation value (instantaneous)
$\sqrt{\overline{(\ )^{\prime 2}}}$	= rms value

Introduction

INVESTIGATIONS of flames by ionization measurement have been conducted for many years. At first the presence or absence of the flame front at the measuring point was detected with Langmuir probes. This kind of measurement was started by Karlovitz et al.[1] and was often used to determine the position of premixed turbulent flame fronts.[2] Investigations of the degree of ionization were made in laminar, premixed, low-pressure flames to study the kinetics of ion production and ion recombination. Peters et al.[3] and Calcote et al.,[4] by measurement with a mass spectrometer, found that H_2O^+ is the most important component of methane flames.

A dependence of the degree of ionization on reaction density is reported by Fox and Weinberg.[5] They found the ionization to be proportional to the flame surface, but their constant depends on the type of fuel and on the fuel-air ratio.

In contrast to the great number of measurements made in premixed flames, only a few ionization measurements were performed in turbulent freejet diffusion flames. Ionization measurements in these flames were made by Lockwood and Odidi[6] in town gas flames and by Ahlheim and Günther[7] in natural gas flames. These flames consist of a system of thin flame fronts of irregular shape, distributed in the fluctuating field of eddies. This system can be observed only when no soot is produced inside the flame, since the high electric loads of the soot disturb the ionization field of the homogeneous reaction.

Experiment

In diffusion flames the conditions of mixing and heating of the mixtures entering the flame fronts change in time and locus and influence the degree of ionization. For observing the interdependence of reaction density and ionization, these conditions were simulated in laminar flames by varying of the methane-air ratio and the preheating temperature. The reaction density was defined as the total consumption of methane divided by the total flame surface. The result was a strong relation between the ionization measured locally and this reaction density (Fig. 1). The influence of premixing ratio and preheating temperature was very low. The following equation describes the dependence very well:

$$I=a(\dot{V}_R/A)^b$$

The constants a and b depend on the polarization voltage and on the geometry of the probe. Nevertheless, the ionization method is suitable not only for detecting flame fronts but also for measuring time mean values and fluctuations of reacting density.

The burner used for the diffusion flame was a 7.9-mm tube with a concentric tube for air; the airflow rate was 1.07 times the stoichiometric one. The fuel was natural gas containing about 4.7% hydrogen. The flame was stabilized at the burner mouth by a small annular oxygen stream surrounding the fuel jet. The gas velocity was 50 m/s and the air-gas velocity ratio was 0.29. The flame produced by this burner was soot-free.

The progress of combustion can be observed well from combinations of ionization and temperature. Figure 2 gives respective results for six positions along the axis of the flame. Near the burner exit, only a few temperature peaks occur which are always accompanied by ionization peaks. Further downstream, the frequency of temperature peaks increases more than that of ionization peaks. This increase in heat is caused by layers of hot combustion gas that do not react further but retain their heat content. This is expressed by the coefficient of correlation between temperature and ionization (Fig. 3). The high correlation at the beginning is caused by the coincidence of ionization and temperature. This coincidence decreases in the main reaction zone, and the correlation

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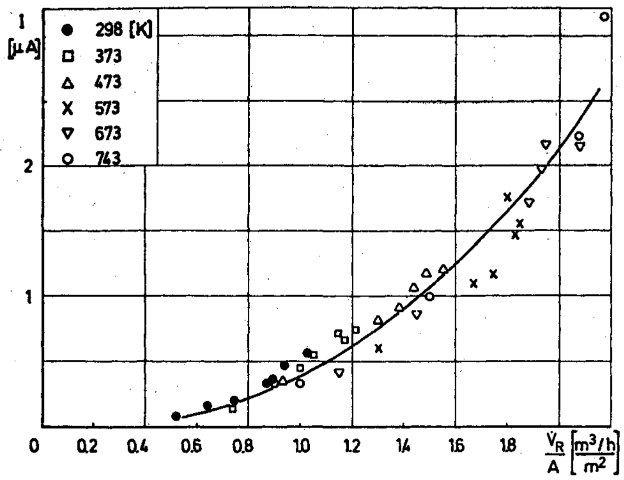

Fig. 1 Ionization and reaction density in laminar premixed and preheated methane-air flames.

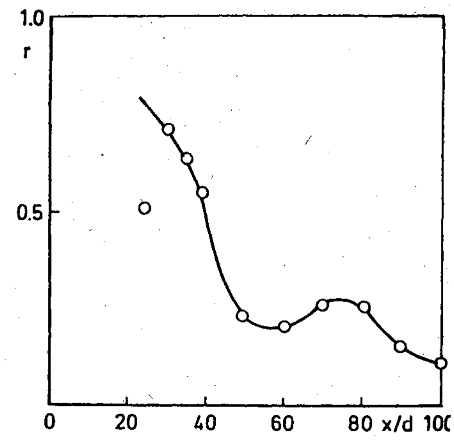

Fig. 3 Correlation of ionization and temperature along the flame axis.

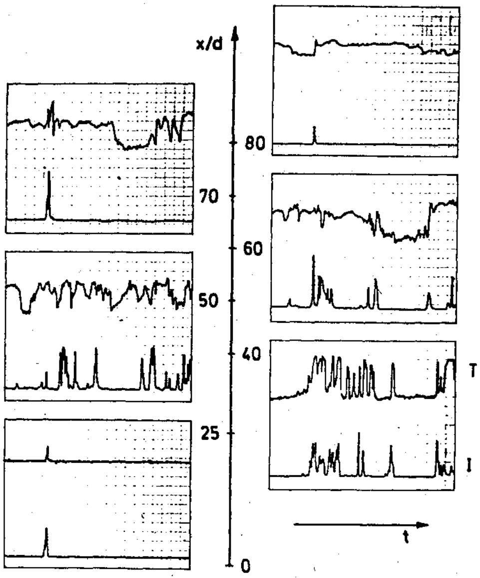

Fig. 2 Instantaneous ionization and temperature measured at different points on the flame axis.

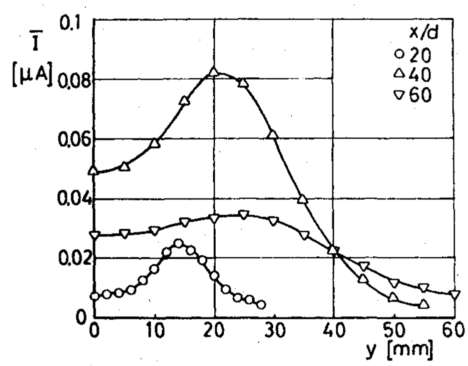

Fig. 4 Time mean values of ionization.

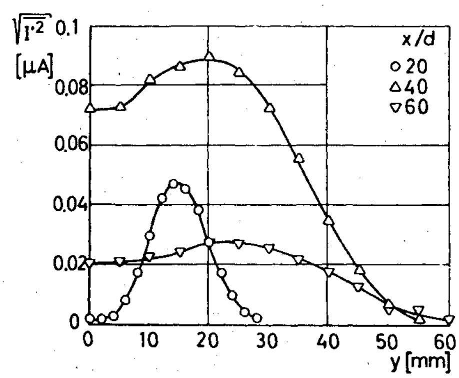

Fig. 5 Root mean square values of fluctuations of ionization.

coefficient becomes lower. The weak maximum at $x/d=80$ can be explained by the entrainment of cold air into hot gases still containing fuel and the resulting new reactions.

Measurements of time mean values of ionization show the progress of combustion very well (Fig. 4). The maximum at $x/d=20$ is caused by the holding flame. At $x/d=40$ the main reaction zone, with its high ionization, is extended across the whole flame cross section. The intensity of reaction then decreases to $x/d=60$. The flame ends at $x/d=100$.

The fluctuations of ionization (Fig. 5) describe the fluctuations of reaction density. They are influenced by the different heights of ionization peaks as well as by the frequency of these peaks. The turbulent reaction zone consists of a three-dimensional arrangement of nonreacting eddies containing fuel, air, and waste gas, with thin reaction fronts between eddies. This arrangement can be considered frozen as far as limited regions are concerned. Its movement over the probe produces the characteristic form of the ionization signal (Fig. 6). In the nonreacting eddies the ionization is zero interrupted by ionization peaks of different heights in diffusion flames.

The configuration of nonreacting substances and the flame fronts between them can be described by eddy scales of the flowfield and by the distances between flame fronts. To get the latter information the probe is used as a flame front detector. Supposing a frozen arrangement of eddies and flame fronts to exist, the mean value of distances between flame fronts can be calculated from the flow velocity and the frequency with which flame fronts pass the measuring point. To count the flame fronts one must set a trigger level. This trigger level is arbitrary, but the measured frequency was found to remain constant over a wide range of levels. A suitable level for the actual apparatus and flame was 0.1 μA.

The profiles of the flame front frequencies (Fig. 7) are similar in shape to those of the time mean values and the fluctuations of ionization (Figs. 4 and 5), because all of them depend in a similar way on the distribution of the reaction fronts and are influenced by the frequency. The maximum in the profiles at $x/d=20$ and $x/d=40$ shows the position of the reaction zone. At $x/d=60$ the reaction zone has become nearly homogeneous across the jet.

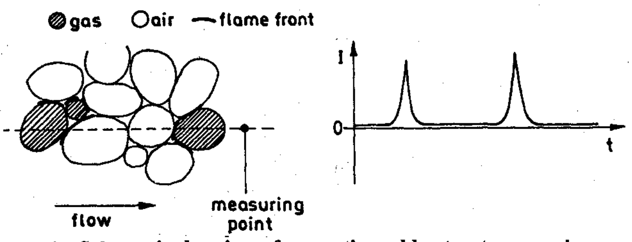

Fig. 6 Schematic drawing of a reacting eddy structure moving over the measured point.

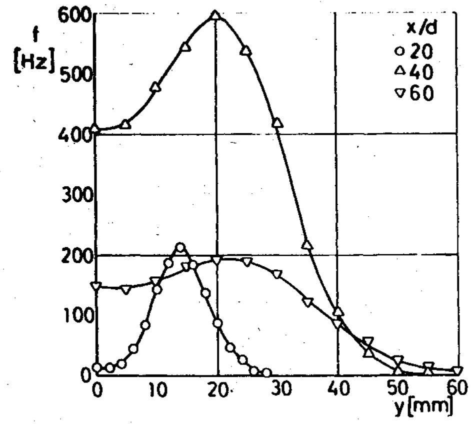

Fig. 7 Flame front frequencies.

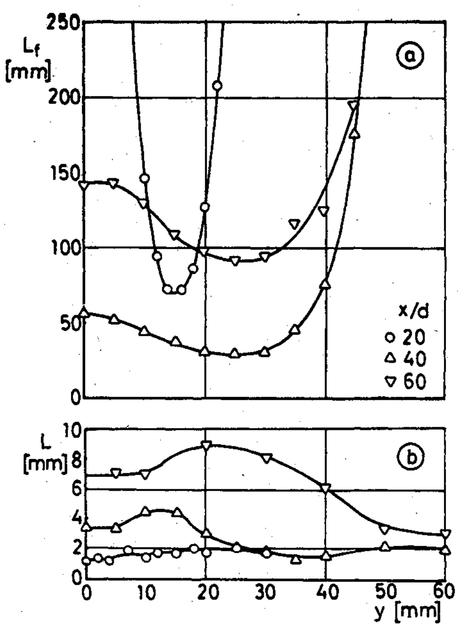

Fig. 8 Top: Time mean values L_f and most probable values L_p of distances between flame fronts. Bottom: Macroscales L_m (from Ref. 8).

The time mean values and the most probable values of distances between flame fronts are shown in Fig. 8a. The latter were calculated from the time distance between subsequent flame fronts and flow velocities measured by Seifert.[8] The time mean values are low in the reaction zone but increase rapidly when leaving this zone. The most probable values are far lower than the time mean values and decrease at greater radii. The macroscales (Fig. 8b) calculated by Seifert[8] from velocity fluctuations are much different. The great difference between the distances of flame fronts and the macroscales can be explained by the structure of the reaction zone. It is supposed that eddies contain fuel, air, waste gas, and their

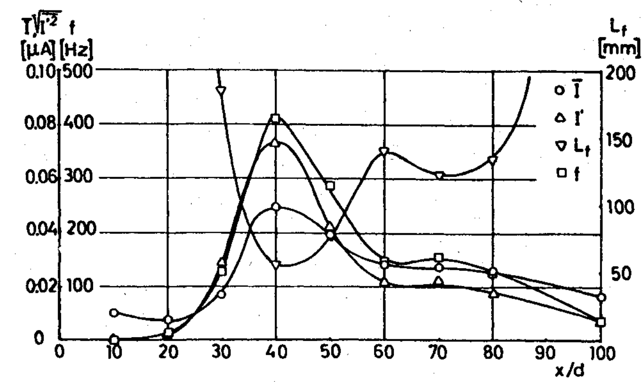

Fig. 9 Time mean values and root mean square values of ionization, frequencies of flame fronts and distances between flame fronts along the flame axis.

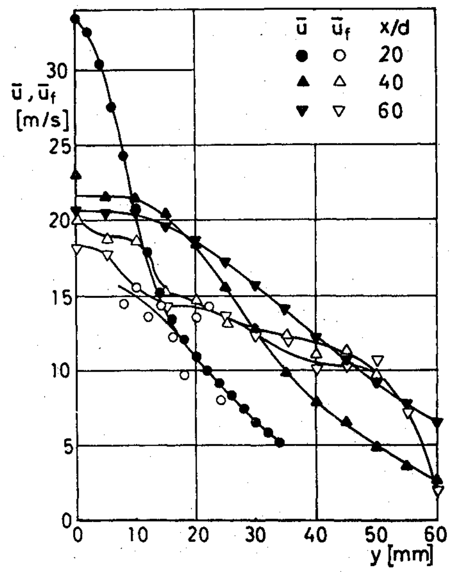

Fig. 10 Flame front velocities and flow velocities.

Table 1 Distances between flame fronts related to macroscales (from Ref. 8) on the axis and at the radius of minimum distances between flame fronts

x/d	20	40	60
L_f/L	1987.5	16.5	21.8 on the axis
	42.5	13.9	12.6 at the radius of L_f minimum

mixtures. Flame fronts can occur only between eddies containing air and fuel; all other pairs of eddies cannot react (see Fig. 6).

The ratio of distances between flame fronts and the macroscales of flow (Table 1) probably depends on the concentrations of fuel, air, and waste gas. A field in which the time mean stoichiometric mixture of fuel and air exists and no combustion products are present should produce the greatest number of flame fronts relative to the number of eddies.

Along the flame axis combustion progress is shown by the time mean values and the fluctuations and frequency of ionization in a similar way (Fig. 9). The distances between flame fronts indicate the main reaction zone by a minimum.

In addition, it would be interesting to know if flame fronts move relative to the flowfield. In turbulent premixed flames Suzuki, Hirano, and Tsuji[9] found a difference between the flow velocity and the velocity of flame fronts that was similar to the laminar flame speed.

These authors measured the velocity of the flame fronts by cross correlation with a double ionization probe. From measurements of time delay in three directions the velocity and direction of flame fronts were calculated. The difference between the velocity of flame fronts and the flow velocity measured by Seifert[8] was found to be important (Fig. 10). Maximum values were about 5 m/s. Near the axis the direction of this movement is always upstream. At the beginning of the main reaction zone ($x/d=40$) and at greater radii, the movement of flame fronts in the flow changes its sign to downstream.

In a premixed flame the movement of flame fronts in the flow was explained by the laminar burning velocity.[9] In the diffusion flame the relative velocity reaches up to 5 m/s, but the maximum laminar flame speed of natural gas is 0.43 m/s. This difference can be explained by two effects. In diffusion flames, gas and air can be preheated before reaction by conduction and by mixing with combustion products. It is estimated that in this way the burning velocity can increase up to 1.5 m/s. The turbulent burning velocity cannot be considered here, since it concerns the flame as a whole, whereas here the real single layers of burning substance are considered. So the whole difference cannot be explained by means of the burning velocities. The second reason for the great difference in flame front velocity and flow velocity must be found in the structure of the turbulent reaction zone.

Whereas flow velocity is measured continuously, the measurement of flame front velocity depends on the occurrence of a flame front. But the occurrence of a flame front itself is correlated with a nearly stoichiometric mixture. The initial flow velocity of fuel is high and that of air is low. The stoichiometric mixture consists of about a ten times greater mass of air than of fuel. So it may happen that the local flow velocity of gas may be bigger than that of air and that the flame front for this reason moves with a lower velocity than the time mean value observed at the respective point. Direct measurement of this correlation seems very difficult, but results of Wittmer,[10] who seeded gas and air alternatively in observing a jet flame with laser-Doppler anemometry, give evidence of velocity differences between the substances.

Conclusions

Ionization measurements give important information on the intensity and structure of the reaction zones in flames. A strong relationship between ionization and reaction density was found in laminar flame fronts. In turbulent diffusion flames the position and the intensity of the reaction zone are shown by the time mean values and the rms values of ionization and by the frequency of flame fronts. The structure of the reaction zone is expressed by the comparison of distances between flame fronts and macroscales of flow as well as by the velocities of both. Measurements of the correlation of ionization and temperature show the progress of combustion along the flow path. The results are in accordance with the assumed eddy structure of the turbulent reaction zone.

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