

Electrical Structure of the Jet of a Gas Mixture Flame

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Received January 15, 2013

Abstract—The combustion of the open flame of an air—domestic gas mixture in air is considered. The concept of the stoichiometric ratio for such a system is specified. The combustion of an enriched mixture, a stoichiometric mixture, and a depleted mixture are singled out. For each case, the structure of the flame and its variations under the condition of the transition of the combustion into the pulsating mode are found by electric and optic measurements. A significant role of the secondary (ambient, atmospheric) air for the stoichiometric flame combustion is noted.

Keywords: electrical breakdown, flame, flame jet structure, stoichiometry

DOI: 10.3103/S 1068375514030089

INTRODUCTION

The development of energy intensive technologies stimulates combustible minerals conservation. The efficiency of combustion depends on its corresponding organization. For example, practically all fuels (solid, liquid, and gaseous) burn in a pulsating combustion mode under defined conditions. The mode controlled in prescribed limits provides the efficiency of the fuel use in view of the acceleration of various heat—mass exchange processes (mixture formation, evaporation, and heat transfer) and an increase in the heat intensity of the furnace volume and the combustion efficiency of the fuel in comparison with steady-state stationary combustion [1—3].

Household technical equipment and commercial plants most often use gas mixture flames. The combustion mechanism for such flames is considered using an example of the flame jet of a propane—butane mixture. As noted in [4—5], the pulsating combustion mode for a propane—butane mixture occurs in a defined range of the fuel—oxidizer ratio and presents the intrinsic property of the flame jet, which leads to the characteristic changes in its structure.

Below, we consider the combustion of an open laminar ($Re \ll 780$) jet of a propane—butane mixture used as fuel (40% propane, 60% butane) in a vertically arranged burner with the forced feeding of the reacting components (air—oxidizer) within an air atmosphere under normal conditions (ambient temperature of 20°C, pressure of 768 mmHg).

EXPERIMENTAL TECHNIQUE

The schematic of the experimental device for the measurements is presented in Fig. 1.

The gas pressure was determined by reductor 12 in the range of 1.2—4.5 atm. The gas consumption was controlled by needle faucet 9. Air was supplied by compressor 14, and the air consumption was controlled by needle faucet 11. Air and gas were fed into the operating volume of the burner, where they were mixed, and the prepared homogeneous operating mixture was fed into a nozzle. The consumption of the source components was recorded by a set of parallel connected rotameters 18 and 19 (for the air oxidizer and the propane—butane combustible mixture, respectively).

The obtained flame has the typical structure of the flame of a Bunsen burner and is composed of two cones—the external and internal ones, the sizes, shape, and the ratio of the volumes of which depend on the ratio of the oxidizer—fuel in the source mixture. The internal cone is closed at a defined ratio of the oxidizer—fuel, forming a sharp vertex, and we observe the disappearance of the yellow glow characteristic for the presence in the flame of soot particles of the condensed phase, which are formed by an excess content of unburnt carbon in the flame jet. It is evident that this case corresponds to the stoichiometric ratio of the oxidizer—fuel [6] (if, in general, it is legitimate to introduce the conception of the “stoichiometric ratio” for organic fuel (the propane—butane mixture, benzene vapor, etc.) in view of the ambiguous sequence of intermediate chemical reactions).

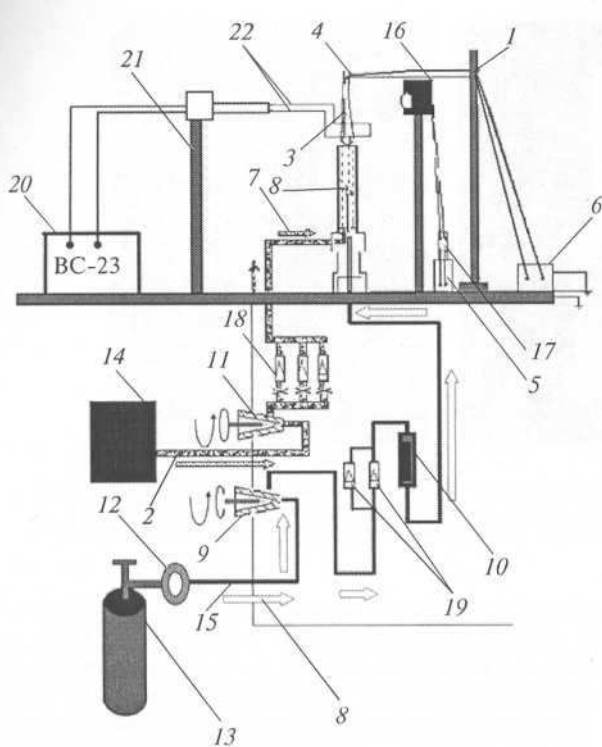


Fig. 1. Schematic of the experimental device: (1, 21) sub-stages; (2, 15) pipes; (3) investigated flame; (4) thermo-junction placed in the investigated flame; (5) S1-112A oscillograph; (6) V7-35 voltmeter; (7) direction of the air flow; (8) direction of the gas flow; (9, 11) needle valve; (10) flame damper (metal chips); (12) gas reducer for coarse adjustment; (13) gas vessel; (14) compressor; (16) photodiode; (17) amplifier; (18) rotameter unit measuring the air consumption; (19) rotameter unit measuring the gas consumption; (20) VS-23 high-voltage source; and (22) electrodes.

Such an optical approach to the determination of the concept of stoichiometry has an advantage with respect to the calculational determination of the stoichiometry based on the weight, molecular composition, etc., relationships, which in the last case is difficult, as it is impossible to take into account the effect of the secondary (atmospheric) air. Meanwhile, the presence of this secondary air affects the structure of the flame.

Nevertheless, referring to the parameters accessible to our measurement, we say that, at our organization of the flame jet (the burner geometry used and the consumption of the oxidizer and fuel), stoichiometric combustion (based on the above-mentioned optical postulate) occurs at a ratio of 600 units of the air volume and 140 units of the propane—butane mixture volume in the source combustible mixture. Photographs recording various combustion modes of the source mixture are represented in Fig. 2.

The stoichiometric mixture burns with a flame jet with a disappearing yellow glow within the upper part of the internal cone (Fig. 2a).

In the case when there is a gas excess in the source mixture with respect to the stoichiometric ratio (an enriched mixture), practically all the flame jet (especially its upper part) is colored by a yellow glow (Fig. 2b). In the case of a gas deficiency in the source mixture (a depleted mixture), the flame jet is structured and its glow has a dark blue color (Fig. 2c).

The described flame jet, beginning from the stoichiometric ratio and up to its extinction with decreasing the gas feed (at a fixed air supply), demonstrates optical pulsations of the brightness of the glow [4, 5], the amplitude and frequency of which increase with leaning of the source combustible mixture.

ELECTRICAL MEASUREMENTS

A great body of information concerning the structure of the flame jet can be obtained from electrical investigation of the flame.

Based on materials of monograph [6], one can mark out three aspects of the effect of charged particles in the flame upon it.

The first is that branched chain reactions with stages including many radicals proceed within the flame. This results in the appearance of higher concentrations of ions and radicals in carbon flames than at the equilibrium ionization in hot combustion products.

The second aspect concerns the conditions of the soot formation. All soot particles in the flame (condensed particles—the condensed phase) are charged at least at the presence of an electric field. This determines the possibility of the electric effect on the concentration and the disperse composition of the formed particles of the condensed phase and the processes of the soot formation based on electrical measurements.

The third aspect is the effect of charged particles (in particular, radicals incoming from the combustion zone) on the processes of the fuel pyrolysis and the formation of soot particles in this case, which result in the partial change of the structure of the energy distribution (an increase in the role of radiation) within the flame. This is especially characteristic for the case when fuel is supplied to the flame and it attains a high temperature mainly in the absence of oxygen or, at least, at its deficiency.

The described mechanisms lead to the appearance of electrical heterogeneities in the flame, which are localized in places of passing combustion reactions, and to the effect of these heterogeneities on the flame itself. It should be noted that the electrical changes in a flame are primary with respect to the temperature ones and have the greater rate.

Thus, the object of the electrical measurements in our investigations is the use of an electric field as a tool providing for the determination of the flame jet struc-

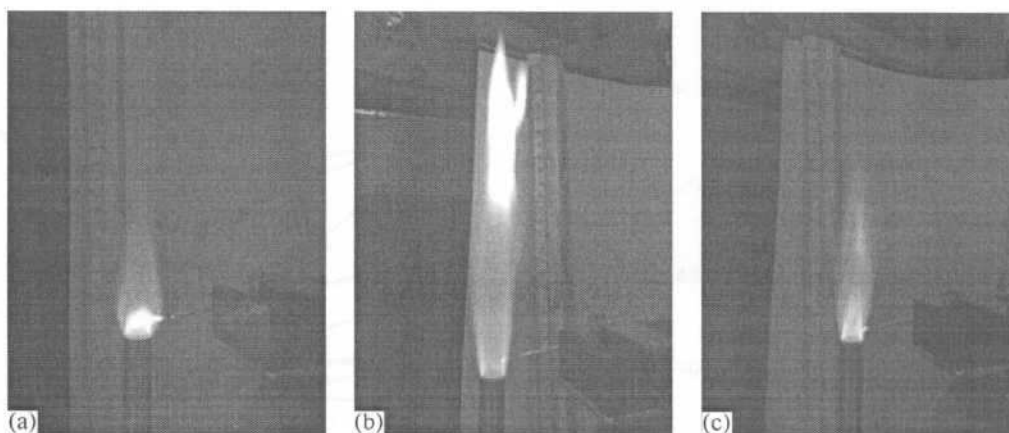


Fig. 2. Photographs of flame jets of the propane—butane mixture at various oxidizer—fuel ratios. (a) stoichiometric ratio (600 a.u. of air and 140 a.u. of propane—butane mixture); (b) enriched mixture (600 a.u. of air and 200 a.u. of propane—butane mixture); (c) lean mixture (600 a.u. of air and 80 a.u. of propane—butane mixture).

ture and the change in the structure with the changing the ratio of the oxidizer—fuel in the source mixture. It should be noted also the probably of greater susceptibility (in comparison with the temperature measurements) of the proposed method for electrical measurements taking into account the presence of the above-mentioned localized branched chain reactions within the flame, which generate excessive carriers of charges with respect to the ones present in hot combustion products at the equilibrium ionization.

A substage of the experimental device is equipped with a unit of electrodes placed in the opposite direction to each other in the horizontal place. The distance between them can be changed symmetrically from the center of their contact. We measured the voltage of the electrical breakdown in the flame of a propane— butane mixture between two platinum electrodes

0.5 mm in diameter. Measurements with a step of 1 mm were carried out along the line passing through the symmetry axis of the initial flame jet in horizontal planes placed at different distances from the nozzle exit section of the burner.

It should be noted that the breakdown voltage with the occurrence of the pulsating combustion mode in a lean mixture practically remains constant with a change in the distance between the electrodes in the reaction zone of the flame jet in the range of 1.5—8 mm, though it may somewhat vary in absolute value at the substitution of metals used as the electrodes. The mentioned fact allows us to consider that the breakdown voltage measured is characteristic for the flame state itself (the intensity of the reactions, the presence of radicals), and changes in it allow one to determine the flame jet structure.

The obtained results are represented for the stoichiometric composition (Fig. 2a) in Fig. 3, for the enriched mixture (Fig. 2b) in Fig. 4, and for the lean mixture (Fig. 2c) in Fig. 5.

As is evident from the graphs, the distributions for the enriched mixture and the stoichiometric composition pass through minimum breakdown voltages. Figure 6 reflects the positions of the voltage electrical breakdown minima along the flame symmetry axis depending on their position in the horizontal distribution of breakdown voltages.

The following mechanism proposed by the authors of [7] for the combustion of a gas flame jet is considered as conventional: the boundary of the internal and external cones corresponds to the flame front, and the external cone is afterburning the excess fuel (essentially in the form of CO and H) and the source fuel undecomposed or incompletely decomposed at diffusion into the reaction area of the oxidizer of the sec-

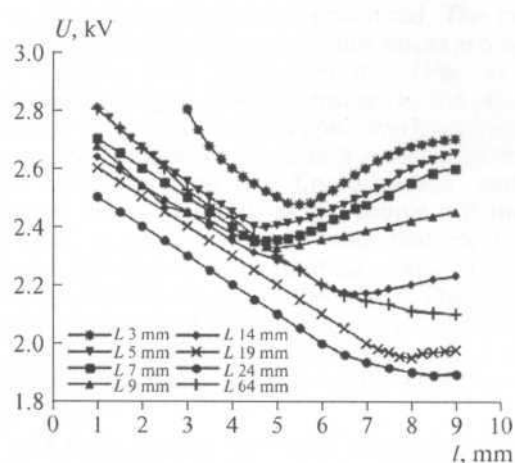


Fig. 3. Distribution of the breakdown voltage in the horizontal section of the flame jet for the stoichiometric mixture (flame image, Fig. 2a).

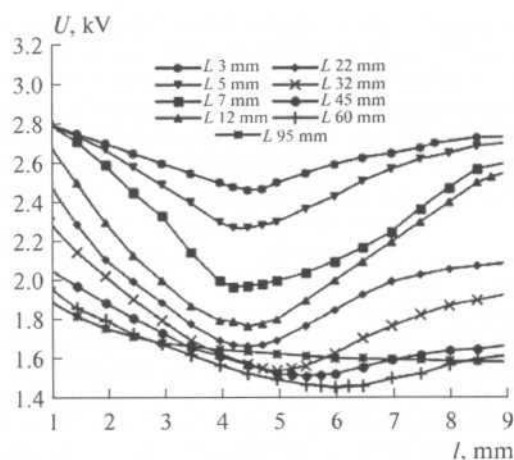


Fig. 4. Distribution of the breakdown voltage in the horizontal section of the flame jet for the enriched mixture (flame image, Fig. 2b).

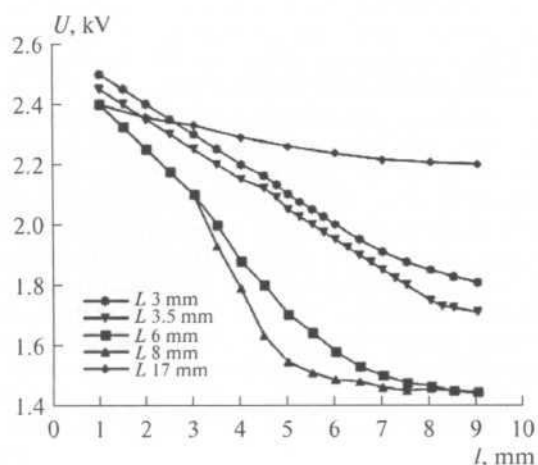


Fig. 5. Distribution of the breakdown voltage in the horizontal section of the flame jet for the lean mixture (flame image, Fig. 2c).

ondary (ambient) air. The combustion is additionally maintained by hot gases and active centers—free radicals formed in the area adjacent to the combustion front.

As is evident from the represented graphs, in the case of the stoichiometric ratio of the oxidizer—fuel, the set of minimum electric breakdown voltages attained in various sections of the flame jet forms a geometrical surface coincident (or close) with the surface of the internal cone of the flame jet (Fig. 2a). Such a surface corresponds to the combustion front, and the internal completely formed cone (closed in the upper part), to the occurrence of the pulsating combustion mode.

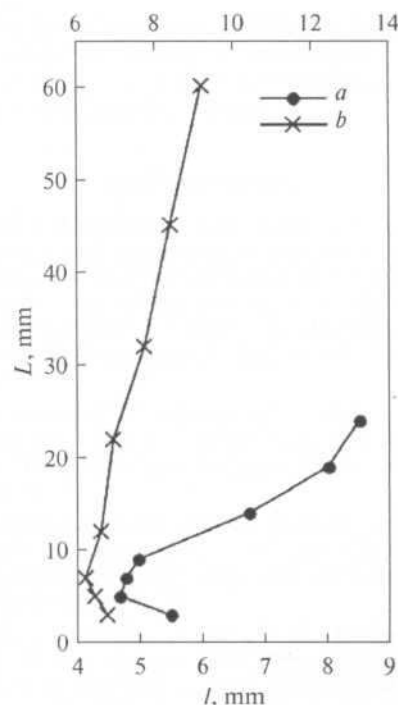


Fig. 6. Vertical distributions of the location of the minimum breakdown voltages of the flame jet along the symmetry axis as a function of their position in the horizontal distributions. (a) stoichiometric ratio; (b) enriched mixture.

RESULTS AND DISCUSSION

The obtained results allow one to state that the changes occurring in the flame jet at the transition of the source mixture composition from enriched to lean have the following character.

The flame of the enriched mixture (Fig. 2b) has great linear sizes and is little structured. The breakdown voltage within it maintains low values at a significant distance from the burner face (Fig. 4). The breakdown voltage can be determined by the presence in the flame of excess radicals preserved from the reaction in the combustion front as a result of branched chain reactions and by fine-dispersed particles appeared during pyrolysis of the source mixture. In any case, there is a need to note that electrically charged chemically active particles exist practically along the total flame jet in the flame. They may be beyond the scope of optical boundaries of the flame jet. The limiting component is the air of the primary combustible mixture. The role of the secondary air is insignificant.

With fixing the level of the air supply and decreasing the level of the gas supply, one can attain the stoichiometric ratio of the air—propane—butane mixture. In this case, a closed internal flame cone forms (Fig. 2a), the presence of which corresponds to occurring of the pulsating combustion mode in the flame.

The electric breakdown voltage in the boundaries of the external cone also increases in comparison with the enriched mixture (Fig. 3), which indicates more complete combustion of the gas. The structure of the flame jet is determined by the balance of three components: the primary and secondary air and the combustible gas. The secondary (ambient) air significantly affects the shape of the internal flame cone.

The further decrease in the level of the gas supply (leaning of the mixture) results in a decrease in the linear sizes of the flame jet (Fig. 2c) and broadening of the reaction front into a zone. The electric breakdown voltage increases in the boundaries of the external cone and decreases in the boundaries of the small one (Fig. 5). The amplitude and frequency of the recorded optical pulsations of brightness [5] depend on the ratio of the oxidizer—gas and the geometrical flame-jet structure determined by this ratio. The limiting component is the content of propane—butane in the primary combustible mixture.

Thus, the transition from the stoichiometric ratio to the lean mixture causes a rise in the combustion temperature, which conditions an increase both in the amount of radicals supplied by the excess oxidizer and in the heat flow towards the motion of the combustible mixture. This prohibits the preliminary preflame preparation of the latter and the geometrical broadening the reaction front, which is transformed in the zone. As the mixture is leaned, the linear sizes of the combustion zone increases, and its arrangement in the flame jet is closed to the nozzle. For example, based on the data of papers [8, 9], the linear sizes of the zone may attain 6—8 mm in the direction of the motion of the flow. At the same time, the pulsating combustion mode is attained, the mechanism of which [5] is determined by the presence of local volumes in the source mixture with the oxidizer—fuel ratio differing from the average.

CONCLUSIONS

(I) The electrical and optical measurements determined the flame jet structure corresponding to the transition of the combustion into the pulsating mode occurred with the formation of the closed internal cone of the flame jet.

(II) It is noted that, with transition to the pulsating combustion mode, the flame front broadens in the combustion zone, the size and arrangement of which depend on the oxidizer—fuel ratio in the source mixture.

(III) Consideration is given to the role of the ambient air in the formation of the fuel jet structure burning in the mode of the stoichiometric ratio.

(IV) A conception of the stoichiometric ratio is proposed based on the optical structure of the flame jet for organic fuels characterized by the ambiguity of the set of intermediate chemical reactions.

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Translated by S. Ordzhonikidze