

THE INVESTIGATION OF THE INFLUENCE OF A DILUENT CONTENT ON A LENGTH OF A JET FLAME IN STILL AIR

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ABSTRACT

Experimental investigation of the influence of diluents of various chemical natures (helium, nitrogen, carbon, dioxide, pentafluoroethane, inhibitor AKAM) on a length of a vertical jet flame of hydrogen in still atmosphere was carried out. Experiments were executed on burners of an internal diameter 0.8 and 10 mm at various velocities of discharge of compositions H₂ + diluent. It was found that inhibitor AKAM and pentafluoroethane cause a sufficient increase of the length of the jet flame, but at the same time chemically inert agents change the flame length much more slowly. Empirical coefficients in the well-known semi-empirical formula for calculations of the flame length of the mixtures hydrogen-diluent at various velocities of discharge and a diluent concentration were re-evaluated. A two-zone structure of the jet flame of the composition hydrogen + inhibitor AKAM at concentrations of inhibitor AKAM from 3 to 10 % (vol.).

KEYWORDS: Hydrogen, Jet flame, Inhibition

INTRODUCTION

One of the most important parameters defining fire hazard of jets of combustible gases from technological equipment is a length of a jet flame appearing at an ignition of a released gas¹. This parameter determines of a size of a zone of a flame action on neighboring objects (zone of a maximum thermal influence). Geometrical characteristics of the jet flame are needed also for an assessment of thermal radiation intensity from the jet flame. Many investigations were aimed on a determination of sizes of the jet flames¹⁻¹⁸. Most of them were dedicated to influence gasdynamical (discharge velocity) and geometrical (diameter and shape of a nozzle) parameters on the characteristics of the jet flame. The influence of a composition of a discharging gas was studied insufficiently. The most complete investigation of this question was carried out in¹, but in this study an influence of additions of chemically inert diluents only (such as nitrogen and helium) was explored. At the same time it is interesting to investigate influences not only inert but chemically active additions to a flammable gas on a length of a jet flame. This task is decided in this work.

EXPERIMENTAL

Experiments were carried out using the following methodology. Production of a required composition of a gaseous mixture (hydrogen and diluent) was made by an introduction flows of components were measured by rotameters. After the mixer the investigated gaseous composition was supplied into a burner. The relative error of determination of the gaseous flows did not exceed 10%. Burners of internal diameters 0.8 and 10 mm were used. Content of the diluents was varied in the range from 0 to 15% (vol.). After establishing the required flow rates of the components the mixture was ignited by an open flame. A flame length was measured by a digital photo camera using a length scale placed near the flame. A black screen was placed after the flame in order to increase of a quality of photos and a decrease of errors of measurements. Photo registration of the flame was made with a rather large duration (3 to 5 s) for a reduction of an influence of fast change of parameters of the system (external gaseous pipelines) on measurements of the length of the jet flame. The photos were processing by

means of a computer. An error for a determination of the flame length did not exceed 10 mm. The following dilutions to hydrogen were used: nitrogen, carbon dioxide, helium (chemically inert agents) and pentafluoroethane and inhibitor AKAM (propylene C_3H_6) produced by the Institute of Structural Macro Kinetics of Russian Academe of Sciences. In all experiments the burners were placed vertically. Any external air flows (except convective flows generated by a flame) were eliminated as ventilation during the experiments.

RESULTS

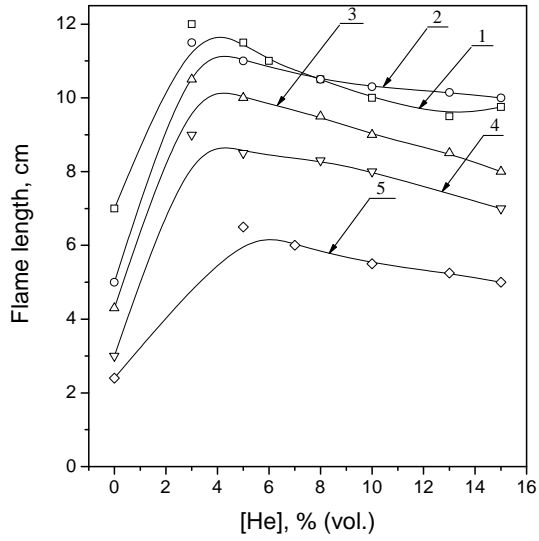
Let us consider firstly an influence of a chemically inert agent.

In Fig. 1 dependences of a flame length at combustion of a composition hydrogen-helium on a He concentration for various diameters of the burner and gas flow rates are presented. At low concentrations of the diluent (up to 4 to 5% (vol.)) a remarkable increase of the flame length occurs, which is replaced then by a slow drop. An elevation of a velocity of a gas discharge causes as a rule an increase of the flame length. Qualitatively close results were obtained for the cases of a dilution of hydrogen by nitrogen (Fig. 2) and carbon dioxide (Fig. 3).

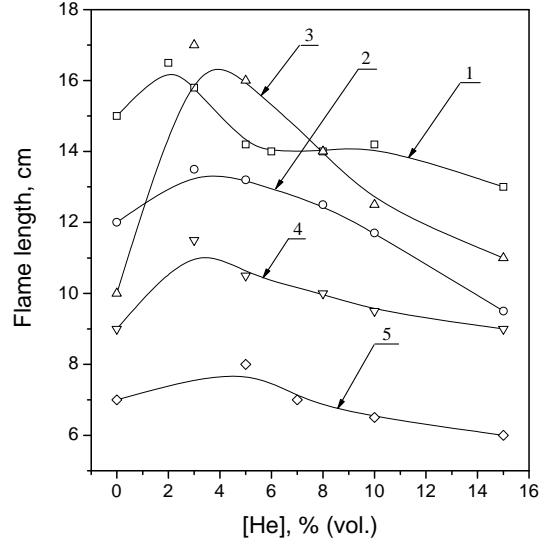
In Fig. 4 a dependence of the flame length on a flow rate of a gaseous mixture is shown, which is typical for a dilution by chemically inert agents (for example of a dilution by carbon dioxide). As a rule for all diluents examined, an increase of the flame length with an elevation of the gas velocity takes place. But sometimes some deviations from this rule occur, particularly at high concentrations of the diluents (see for example Fig. 2), and a nature of these deviations is not clear. A burner diameter did not influence qualitatively the results of measurements of the flame length.

There is some influence of a chemically inert agent on the flame length. For example, a replacement of helium (Fig. 1) by nitrogen (Fig. 2) will cause an increase of the maximum flame length. At a burner diameter 10 mm the maximum flame length for all gas discharge velocities and at a dilution by helium (Fig. 1b) exceeds by a factor 1.5 the appropriate value for nitrogen (Fig. 2b). But at the burner diameter 0.8 mm this tendency does not take place (compare Fig. 1a and Fig. 2a). Probably it is caused by a sufficiently higher diffusion. Coefficient of helium in comparison with nitrogen, which influences the flame length at low discharge velocities (burner diameter 10 mm). At the same time at high gas discharge velocities (burner diameter 0.8 mm) this tendency in the influence of the nature of diluents (helium or nitrogen) does not takes place. For carbon dioxide a qualitative character of the dependence of the flame length on diluent's concentrations and typical values of the flame length (Fig. 3) are analogous to those for nitrogen (Fig. 2). For the most part of the dependences of the flame length on the concentrations of the chemically inert agents it is typical an availability of a maximum in the area of the diluent's concentration 1 to 5% (vol.); the nature of this is not clear.

Let us now consider an influence of agents having inhibiting properties on the flame length of the hydrogen flare. In Figs. 5, 6 dependencies of the flame length at addition to hydrogen such agents as inhibitor AKAM and pentafluoroethane are presented. In the case of AKAM a sufficient increase of the flame length with an elevation of the inhibitor's concentration occurs (Fig. 5) in comparison with the chemically inert additives, for which (as it was mentioned above) an increase of the flame length at low concentrations of the agent is replaced by a decrease of this length at higher contents of the additives (Fig. 1 to 3). Another situation is observed for the case of pentafluoroethane. At a burner diameter $d_0 = 10$ mm a dependence of the flame length L_f on a content of the additive C_d (Fig. 6) is qualitatively analogous to that observed for AKAM (Fig. 5). But at $d_0 = 0.8$ mm the dependence of L_f on C_d is qualitatively analogous to the cases of the chemically inert additives (Fig. 1 to 3).

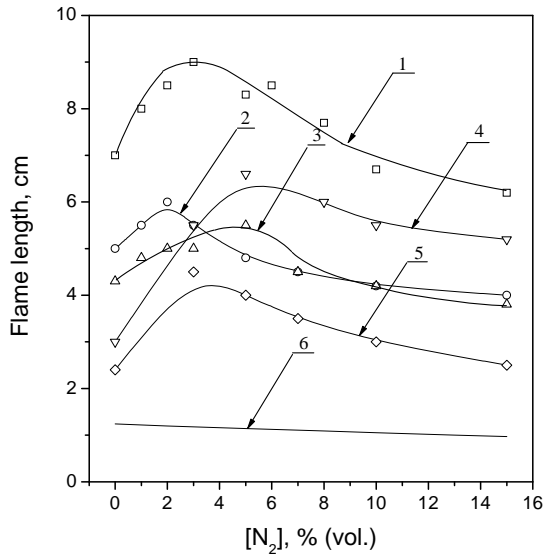


a)

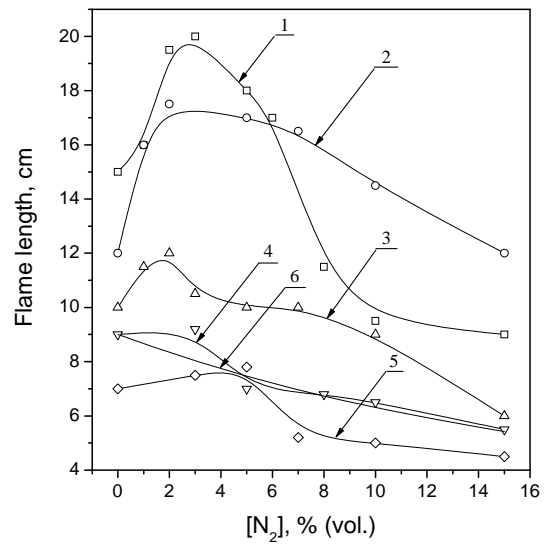


b)

FIGURE 1. Dependence of the flame length at combustion of a mixture H_2+He on a helium concentration for a burner diameter 10(a) and 0.8(b) mm and various discharge velocities V_m
 a) $V_m = 0.44(1), 0.37(2), 0.25(3), 0.23(4), 0.11(5)$ m/s; b) $V_m = 69(1), 59(2), 40(3), 35(4), 18(5)$ m/s



a)



b)

FIGURE 2. Dependence of the flame length at combustion of a mixture H_2+N_2 on a nitrogen concentration for a burner diameter 10(a) and 0.8(b) mm and various discharge velocities V_m
 a) $V_m = 0.44(1), 0.37(2), 0.25(3), 0.23(4), 0.11(5)$ m/s. Line 6 is a result of calculations by the formula (1) for $V_m = 0.44$ m/s and the values $a = 0.23, b = 0.017$;
 b) $V_m = 69(1), 59(2), 40(3), 35(4), 18(5)$ m/s. Line 6 is a result of calculations by the formula (1) for $V_m = 69$ m/s and the values $a = 0.23, b = 0.017$.

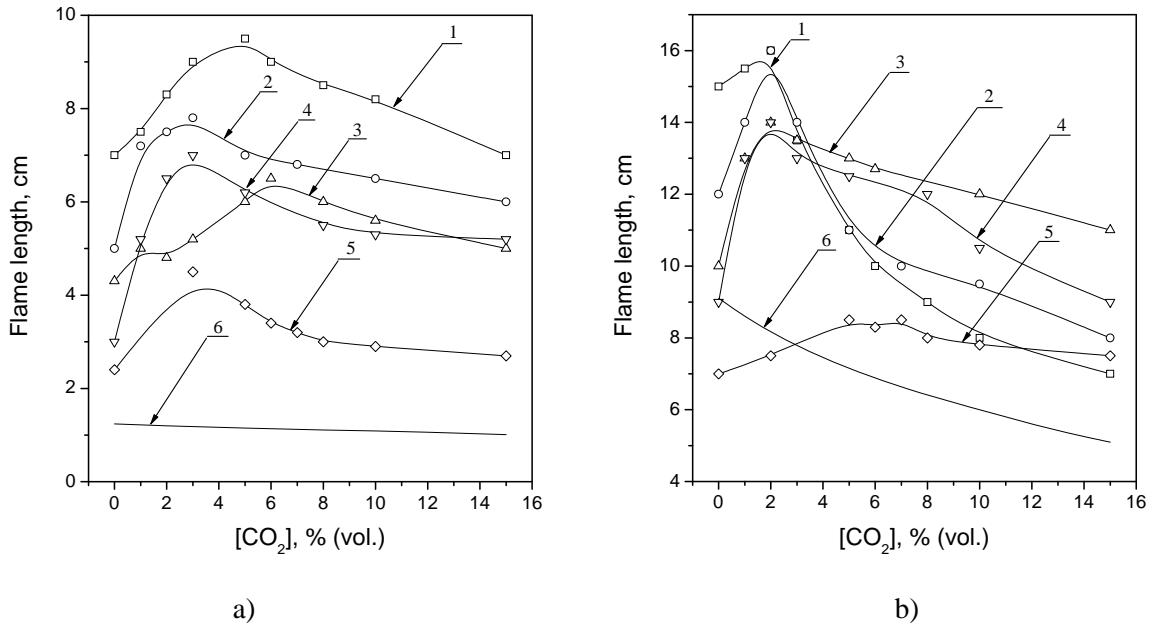


FIGURE 3. Dependence of the flame length at combustion of a mixture H₂+CO₂ on a carbon dioxide concentration for a burner diameter 10(a) and 0.8(b) mm and various discharge velocities V_m
a) $V_m = 0.44(1), 0.37(2), 0.25(3), 0.23(4), 0.11(5)$ m/s. Line 6 is a result of calculations by the formula (1) for $V_m = 0.44$ m/s and the values $a = 0.23$ and $b = 0.017$;
b) $V_m = 69(1), 59(2), 40(3), 35(4), 18(5)$ m/s. Line 6 is a result of calculations by the formula (1) for $V_m = 69$ m/s and the values $a = 0.23, b = 0.017$.

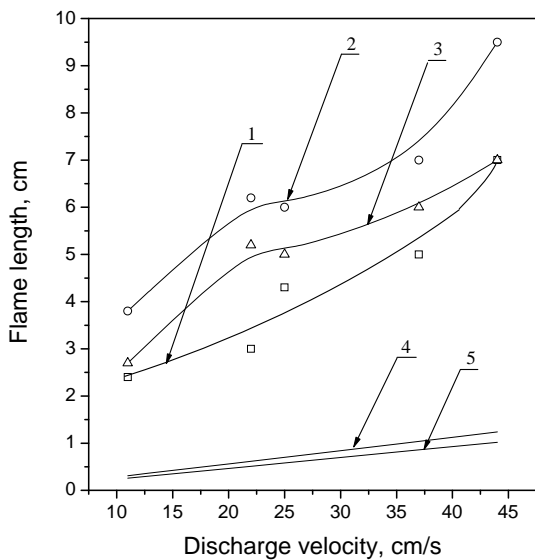


FIGURE 4. Dependence of the flame length at combustion of a mixture H₂+CO₂ on V_m at carbon dioxide concentrations 0(1), 5(2) and 15(3) % (vol.) for burner diameter 10 mm. Line 4 and 5 are the results of calculations by the formula (1) for the values $a = 0.23$ and $b = 0.017$ and CO₂ contents 0(4) and 15(5) % (vol.)

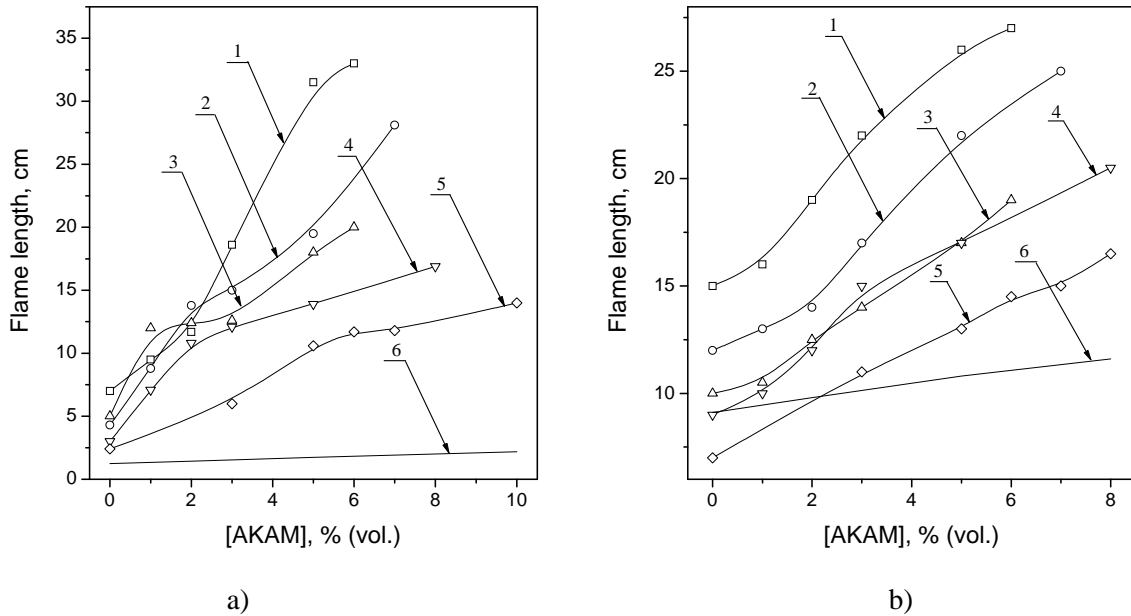


FIGURE 5. Dependence of the flame length at combustion of a mixture H_2+AKAM on the inhibitor AKAM concentration for a burner diameter 10(a) and 0.8(b) mm and various discharge velocities V_m
a) $V_m = 0.44(1), 0.37(2), 0.25(3), 0.23(4), 0.11(5)$ m/s. Line 6 is a result of calculations by the formula (1) for $V_m = 0.44$ m/s and the values $a = 0.23$ and $b = 0.017$;
b) $V_m = 69(1), 59(2), 40(3), 35(4), 18(5)$ m/s. Line 6 is a result of calculations by the formula (1) for $V_m = 69$ m/s and the values $a = 0.23, b = 0.017$.

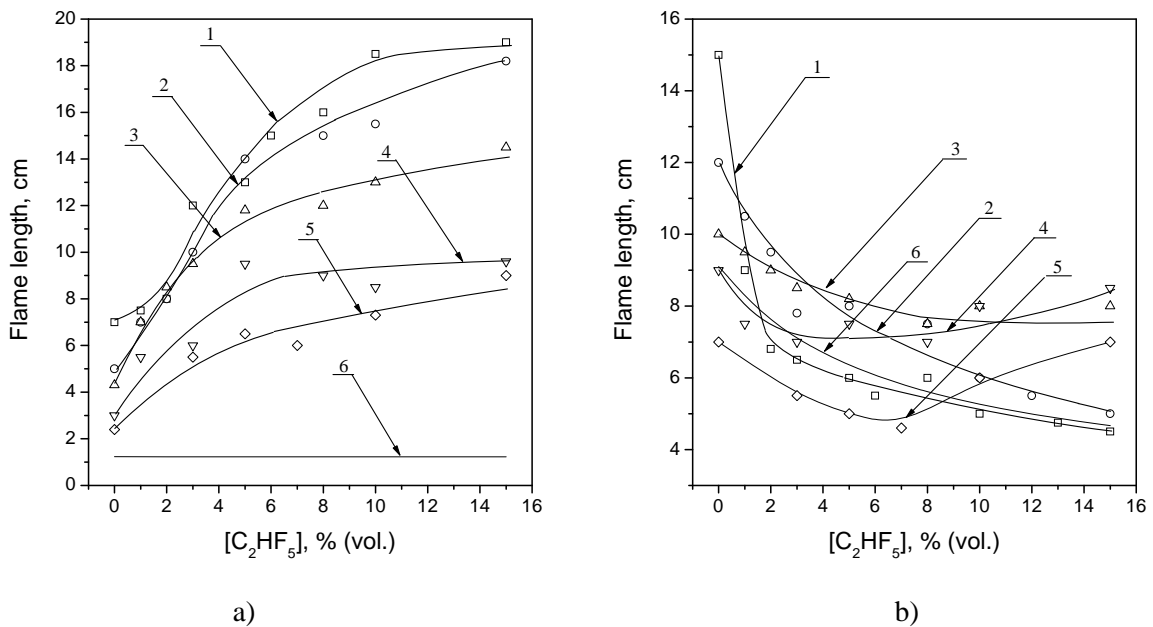
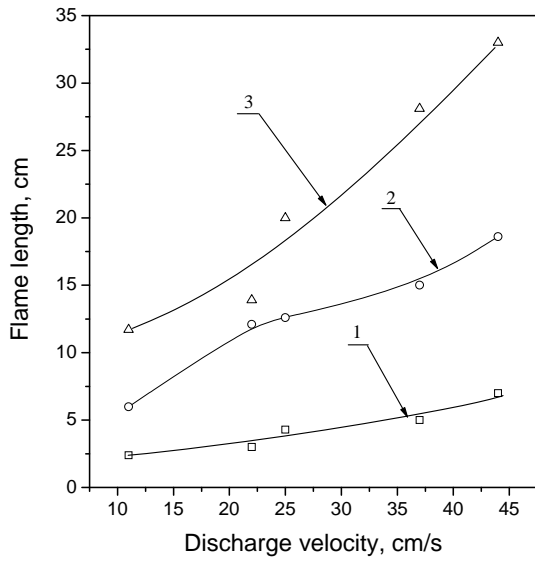
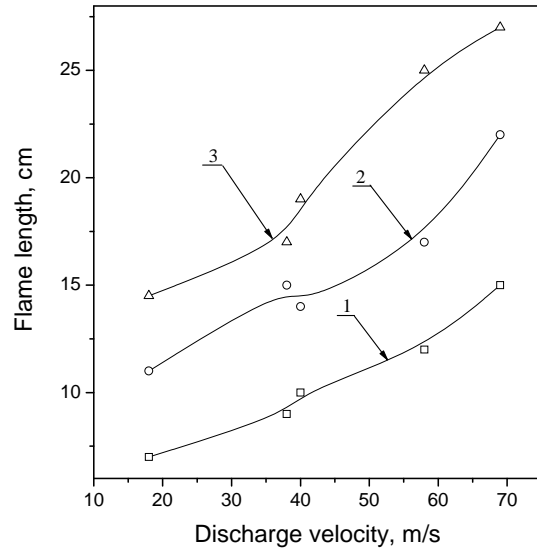


FIGURE 6. Dependence of the flame length at combustion of a mixture $H_2+C_2F_5H$ on a pentafluoroethane concentration for a burner diameter 10(a) and 0.8(b) mm and various discharge velocities V_m
a) $V_m = 0.44(1), 0.37(2), 0.25(3), 0.23(4), 0.11(5)$ m/s. Line 6 is a result of calculations by the formula (1) for $V_m = 0.44$ m/s and the values $a = 0.23$ and $b = 0.017$;
b) $V_m = 69(1), 59(2), 40(3), 35(4), 18(5)$ m/s. Line 6 is a result of calculations by the formula (1) for $V_m = 69$ m/s and the values $a = 0.23, b = 0.017$.

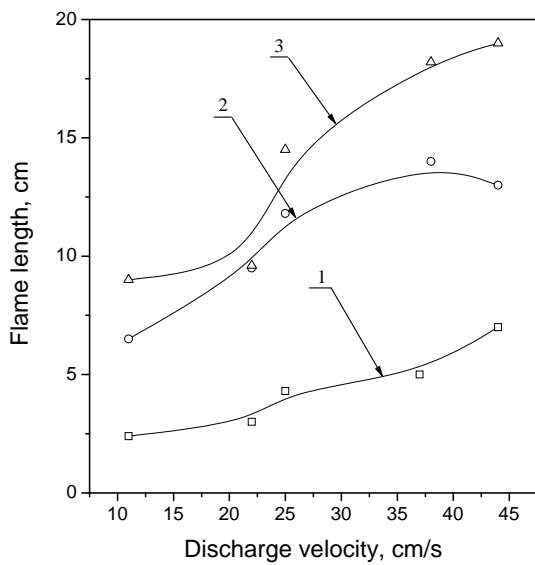


a)

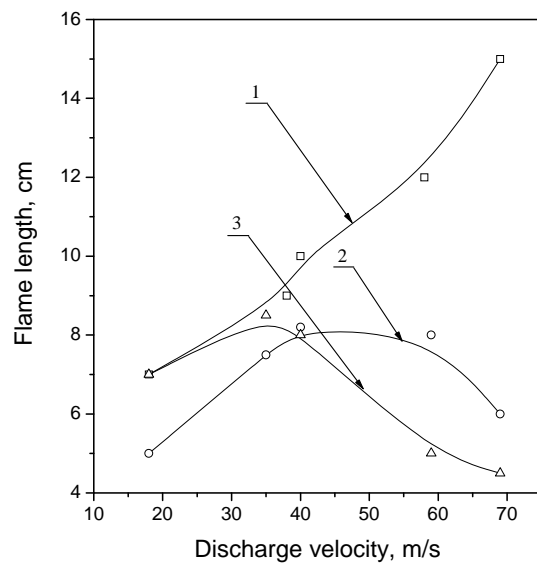


b)

FIGURE 7. Dependence of the flame length at combustion of a mixture H_2+AKAM on V_m at concentrations of the inhibitor AKAM 0 (1), 3 (2) and 6 (3) % (vol.) and a burner diameter 10 (a) and 0.8 (b) mm



a)



b)

FIGURE 8. Dependence of the flame length at combustion of a mixture $H_2+C_2F_5H$ on V_m for pentafluoroethane concentrations 0(1), 5(2) and 15(3) % (vol.) and a burner diameter 10 (a) and 0.8 (b) mm

In Figs. 7, 8 dependence of the flame length L_f on the gas discharge velocity V_m for mixtures hydrogen-diluent are presented. A qualitative character of these dependences is in the main analogous to that observed for such chemically inert agents as carbon dioxide (Fig. 4), that is an increase of L_f with an elevation of V_m occurs. An exception is data for combustion of the mixtures hydrogen-pentafluoroethane on the burner of diameter 0.8 mm, when a dependence of L_f on V_m has a maximum.

The sufficiently different structure of a visible part of the flame hydrogen-inhibitor AKAM in comparison with the hydrogen flame was observed, when the inhibitor concentration in hydrogen is higher than 3% (vol.) (Fig. 9). At the inhibitor concentration 2% (vol.) the flame in a near-nozzle area is characterized by a bright-yellow emission framing in the upper part by pale-violet area (Fig. 9a). Another picture takes place at the inhibitor concentration in hydrogen 3% (vol.) (Fig. 9b): the near-nozzle area of the flame has a pale-violet colour, and the upper part is bright-yellow. The bright-yellow emission is caused by an availability of hot soot particles formed due to conversion of the inhibitor AKAM, which is a mixture of hydrocarbons. It is not clear, however, why these soot particles at the AKAM concentration less than 3% (vol.) emit in the near-nozzle area, but at concentration higher than 3% (vol.) - in the upper part of the flame. It should be noted that such effect did not take place for other agents investigated in this work.

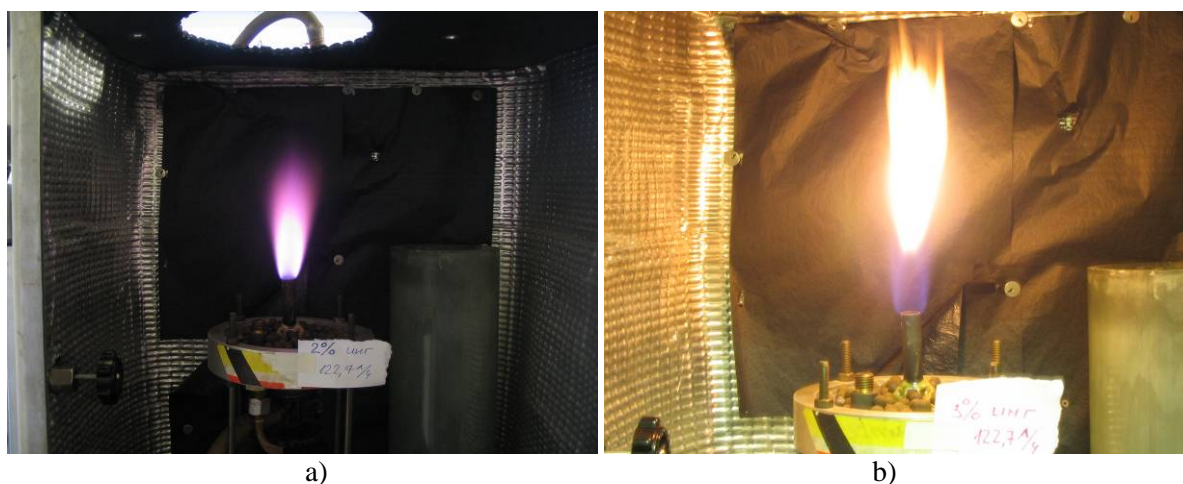


FIGURE 9. Influence of a concentration of the inhibitor AKAM on a shape of a jet flame of a mixture H_2 +AKAM for a burner diameter 10 mm and $V_m = 0.44$ m/s. AKAM concentration 2 (a) and 3 (b) % (vol.)

DISCUSSION

It is interesting to compare the obtained experimental data with results of theoretical studies. A detailed analysis of various approaches for calculation of a length of a jet flame was performed in ^{1,19}. In these investigations on the theoretical base ² and experimental data published in literature a semi-empirical formula for calculation of the flame length L_f of a vertical gaseous jet in still atmosphere was proposed:

$$L_f = H_s / (a + b/M) \quad [1]$$

where H_s is a length of a contour restricting of a mixture of a stoichiometric composition obtained by mixing of combustible gas and air; $M = V_m/C_s$ is Mach number for the mixture discharging from a nozzle; C_s is sound velocity in the discharging mixture; a and b are empirical constants.

The C_s value is calculated by a formula:

$$C_s = (\gamma P_0 / \rho_0)^{1/2} \quad [2]$$

where $\gamma = \sum \gamma_i C_i$ is an index for adiabat for the discharging mixture; γ_i and C_i are an index for adiabat and a mole fraction for the i -th component of the mixture; P_0 is pressure of the discharging mixture at the end of the nozzle (is accepted to be equal to atmospheric pressure); ρ_0 is density of the discharging mixture at the pressure P_0 .

The value H_s can be calculated by a formula:

$$H_s = 6.57 d_0 / (f(\rho_a / \rho_0)^{0.5}) \quad [3]$$

where d_0 is an internal diameter of a nozzle; ρ_a is density of air at the pressure P_0 ; f is a mass fraction of the discharging gas on a surface of a stoichiometric contour of its mixture with air, which is evaluated by a formula:

$$f = 1 / (1 + \beta(C_0/C_a) \cdot (\rho_a / \rho_0)) \quad [4]$$

C_0 and C_a are mole fraction of a flammable gas in the discharging mixture and of oxygen in air respectively; $\beta = n_C + n_H/4 - n_O/2$ is a stoichiometric coefficient of oxygen in the reaction of combustion of the flammable gas; n_C , n_H , n_O are numbers of atoms C, H, O in a molecule of the flammable gas (it is accepted that the molecule of the flammable gas contains only C, H, O atoms).

In ^{1,19} the values of the empirical coefficients a and b been determined to be equal: $a = 0.23$, $b = 0.017$. Results of calculation of the flame length using these values are presented in Figs. 2 to 6. It can be seen that theoretical curves describe at least a qualitative character of the dependence of the flame length on the concentration of the additive. Rather satisfactory quantitative agreement takes place only for some mixtures with the chemically inert agents at a burner diameter $d_0 = 0.8$ mm. In the case of the chemically active additives (AKAM, pentafluoroethane) the flame length increased much more strongly than it is predicted by the empirical formulas with inhibition of combustion of hydrogen. For the case of the chemically inert additives the effect of inhibition does not take place, and for the burner diameter $d_0 = 0.8$ mm (when the velocity of a discharge is high enough in comparison with velocities of convective flows) the theoretical data are rather close to the experimental one.

The values of the empirical coefficients a and b in the formula were improved [1] for more precise description of the dependence of the flame length on the burner diameter, gas velocity and composition of the mixture. For this purpose the coefficients a and b were determined using the experimental data of this study by the method of least squares. In this case formula [1] was rewritten by the way:

$$a + b(1/M) = H_s/L_f \quad [5]$$

Graphs characterizing validity of the relationship [5] for various additives are presented in Figs. 10 to 12. The appropriate values of the coefficients a and b are indicated in Table 1.

It can be seen that agreement between the theoretical and the experimental data for new values of the empirical coefficients a and b is much better than for the old values. The mean square deviations are rather low, but the correlation coefficients are high.

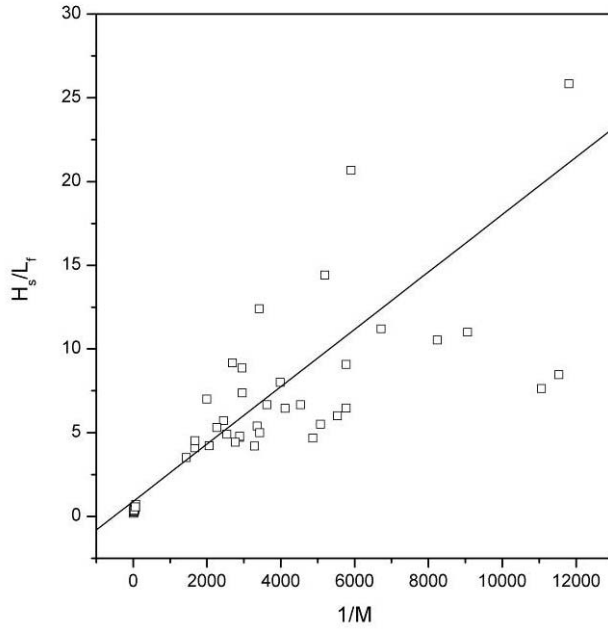


FIGURE 10. Dependence of a reduced flame length H_s/L_f for a mixtures H_2 +inert diluent (CO_2, N_2, He) on reciprocal Mach number of a discharging gas

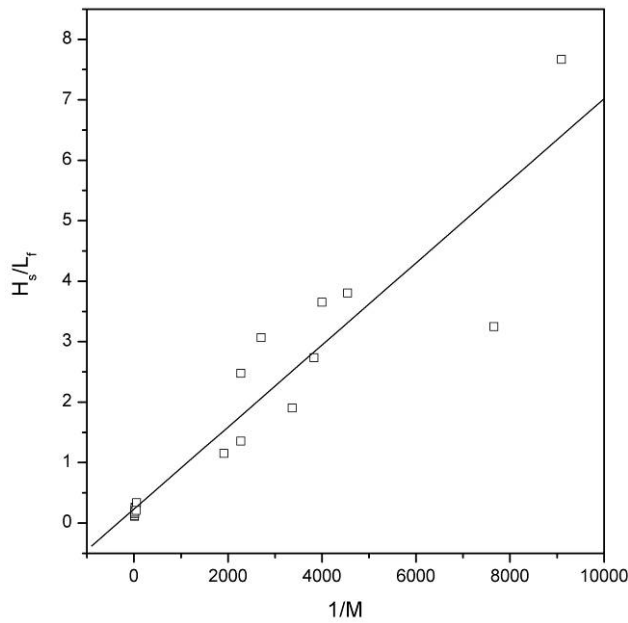


FIGURE 11. Dependence of a reduced length of a flame on Mach number at dilution of hydrogen by inhibitor AKAM

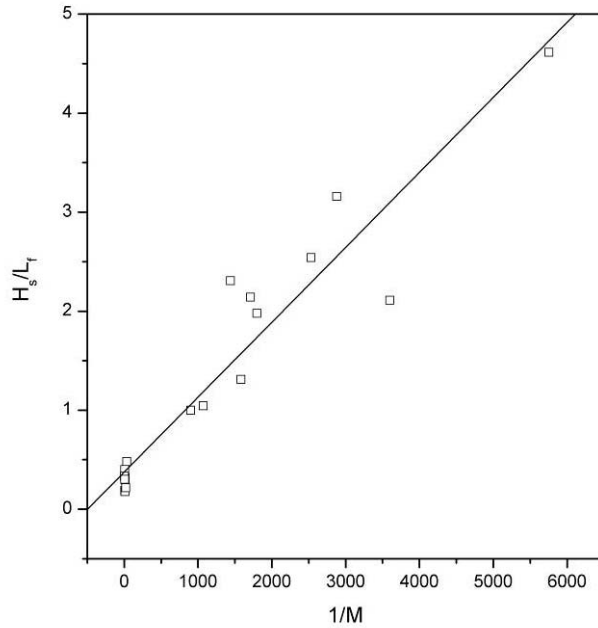


FIGURE 12. Dependence of a reduced length of a flame on Mach number at dilution of hydrogen by pentafluoroethane

TABLE 1

Additive		Helium	Nitrogen	Carbon dioxide	Pentafluoroethane	AKAM
Coefficients	a	1.0	0.9	0.5	0.4	0.2
	b	$1.3 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	$8 \cdot 10^{-4}$	$7 \cdot 10^{-4}$
Absolute mean square deviation of the (H_s/L_f) value		4	3	3	0.4	0.7
Coefficient of correlation		0.76	0.91	0.92	0.95	0.93

CONCLUSIONS

In this study experimental investigation of the influence of additives of various chemical natures to hydrogen on a length of a vertical diffusion flame was executed. Such diluents as helium, nitrogen, carbon dioxide, pentafluoroethane, inhibitor AKAM were tested. Experiments were carried out on burners with internal diameters 0.8 and 10 mm at various discharge velocities of a composition H_2 + additive. It was found that the inhibitor AKAM and pentafluoroethane cause a substantial increase of the flame length, but the chemically inert agents differ the flame length much more slowly. The empirical coefficients in the expression for the calculation of the flame length were determined, which give a possibility to increase an accuracy of an evaluation of the length of a hydrogen flame in still atmosphere in dependence on the velocity and concentration of the additive. A two- zone structure of the flame of hydrogen diluted by the inhibitor AKAM at its content in H_2 higher than 3% (vol.) was revealed.

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