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HEAT AND MASS TRANSFER IN CHEMICAL TRANSFORMATIONS AND COMBUSTION

EXPERIMENTAL INVESTIGATION OF THE LENGTH OF A FREE DIFFUSION JET OF FUEL GASES DILUTED WITH INERT GASES

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Experimental investigation of the length of single burning jets of methane and hydrogen previously diluted with an inert gas (nitrogen or helium) was carried out. Efflux of fuel gases into the atmosphere occurred through cylindrical extension pieces 4 and 8 mm in diameter. The Reynolds numbers at the cut of a piece varied in the range from 400 to 12,000. A clearly defined dependence of the jet length on the quality of the added inert gas is obtained. The correlation of experimental data made it possible to recommend formulas for engineering calculations of free laminar and turbulent jets.

Keywords: *combustion, flame, jet length, inert gas, dilation.*

Introduction. Investigation of the combustion of single jets of gaseous fuels outflowing into an oxidant (air) volume that create so-called diffusion jets are rather numerous (e.g., [1, 2]), and corresponding computational formulas were suggested for their calculation. Meanwhile, in practice fuel gases are often diluted with noncombustible (inert) gases. Examples of the use of fuel gases ballasted with an inert gas, mainly nitrogen, in industry and in the home are a lot. This first of all applies to a producer gas (N_2 up to 52 vol. %), a blast-furnace gas (up to 60%), and gases of chemical industries. One of the techniques of decreasing ejections of nitrogen oxides at thermal electric power plants is a two-stage combustion of a natural gas, when first a "rich" mixture greatly deficient in air is burnt and later it is mixed with an additional amount of air (secondary) to form a lean mixture which is burnt out completely. As a result, at the first stage the temperature is substantially lower than the stoichiometric one and the medium is regenerating, hindering the formation of nitrogen oxides; at the second stage there is an excess of oxygen, but the temperature is moderate and a little amount of NO_x is formed. Combustion of the fuel at the second stage proceeds with a considerable content of N_2 (and CO_2) in a burning gas.

The presence of nitrogen in a gaseous fuel must, of course, influence the process of combustion, at the height of jets including. The authors are unaware of any relevant investigations. There is only information on the lower and upper limits of the ignition of such mixtures that first of all are of interest for fire-prevention undertakings.

The aim of the present work is to study the length of burning flame jets of methane and hydrogen diluted with nitrogen or helium during their efflux into an air space.

Experimental Setup and Technique. Investigations were carried out at the M. V. Keldysh Research Center on an experimental setup shown schematically in Fig. 1. A fuel gas (methane or hydrogen) from cylinders 1 entered a mixer 2 into which an inert gas (nitrogen or helium) was supplied from cylinders 3 in needed quantities. This was arranged beforehand; the mixture was held for several hours, and its composition was controlled by taking samples and analyzing them. It is known that on dilution of fuel gases with neutral ones a concentration can be attained at which combustion would be impossible; therefore in investigating the processes of combustion the range of concentrations was obviously in excess of this limit.

The thus prepared mixture was fed by a pipeline with a regulating valve 4 to a burner 5. The flow rate of the mixture was measured with the aid of an RM-02-type rotameter 6 installed on the pipeline (small flow rates) and

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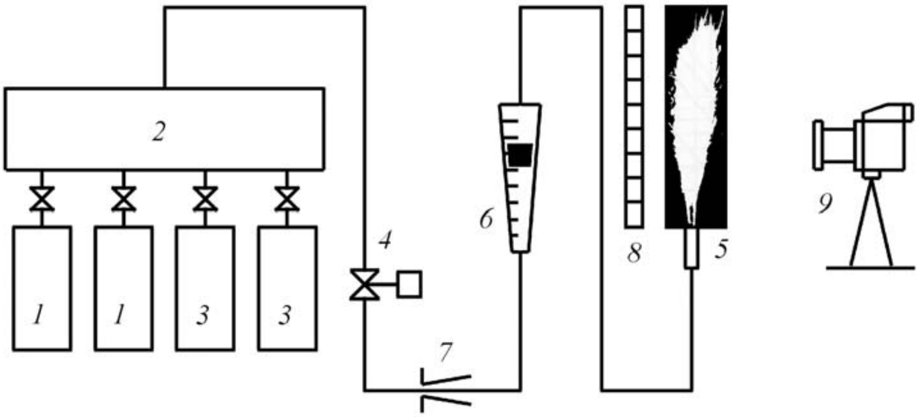


Fig. 1. Schematic diagram of the experimental setup.

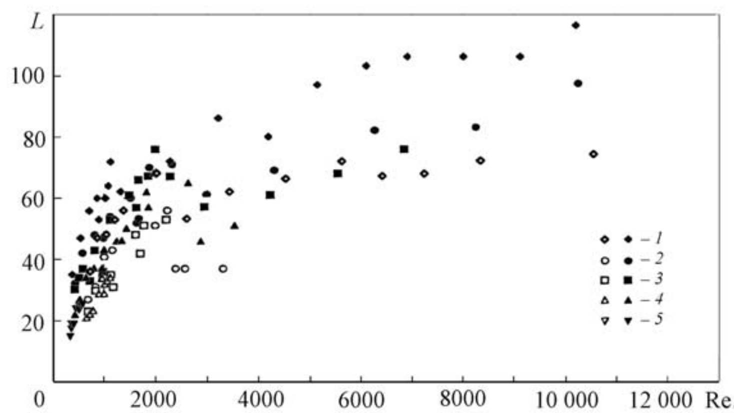


Fig. 2. Dependence of the flame jet length L on the Re_0 number for CH_4–N_2 mixtures of different compositions: 1) a_0 = 0.90; 2) 0.6; 3) 0.55; 4) 0.45; 5) 0.30; light points, d_0 = 4 mm; dark points, 8 mm. L, mm.

a flow metering nozzle 7. The gas was ignited by a special device. Cylindrical pipes 4 and 8 mm in diameter and with a relative length of 15 diameters were used as combustion nozzles.

The height of flame jets was determined by projecting them onto a scale ruler 8 installed behind the nozzle. Usually, in analogous investigations the length (height) of the visible zone of the flame jet encompasses the temperatures from the highest one (the theoretical temperature of combustion for a given fuel gas) up to 800–900 K, which corresponds to the red-orange and red parts of the spectrum. Special investigations, carried out in [3], of the dependence of the measured portion of the flame jet on the method of fixing (visual, black-white photo, video- and digital cameras) showed that the black-white photography underestimates the height of a luminous flame, which can be attributed to the lowered sensitivity of the photomaterial used in the red parts of the spectrum, whereas the findings of the rest methods are well correlated with the visual one. Therefore, in the experiment a digital camera was used as a recorder 9; it is convenient for the subsequent input of data into a computer for their processing.

In the experiments we measured: the mass and volumetric rates of flow of the gaseous mixture, the velocity of the gaseous mixture efflux from a nozzle, and the length of the luminous (visible) part of the flame jet. The length and the shape of a flame were photographed with equal exposures.

Results of Investigations. Our research subjects were single vertical flame jets of a burning methane or hydrogen in binary mixtures with nitrogen or helium issuing into a nonperturbed air volume at room temperature. Under examination were mixtures of methane with nitrogen, methane with helium, hydrogen with nitrogen, and hydrogen with helium on variation of the volume content of the fuel gas a_0 from 0.90 to 0.20. Experiments were carried out at Reynolds numbers Re_0 based on the conditions at the nozzle cut, from 400 to 12,000, i.e., in laminar, transient, and turbulent combustion regimes.

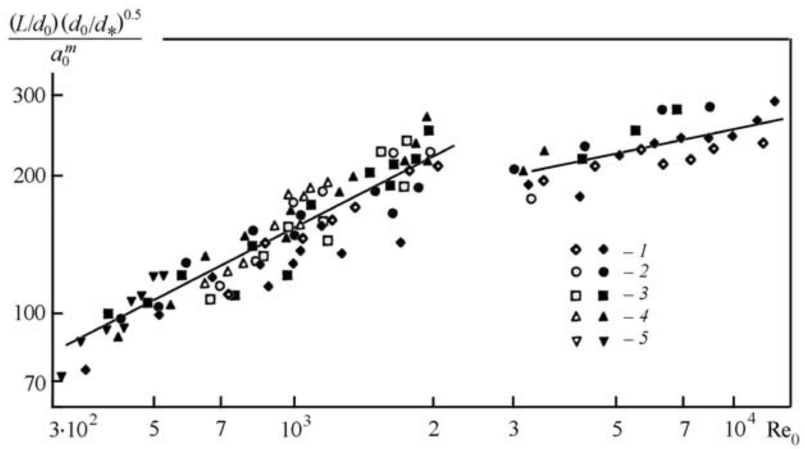


Fig. 3. Correlation of experimental data on combustion of methane-hydrogen mixtures. Designations 1–5 are same as in Fig. 2.

These regimes were most thoroughly examined in experiments with methane mixtures and less thoroughly (especially a laminar regime) in experiments with hydrogen. As a rule, the presence of inert gases led to a decrease in the flame jet height L, but without changing the general trends noted in [2]. This is shown, on primary processing at $L = f(\mathrm{Re}_0)$ for CH_4–N_2 mixtures, in Fig. 2: the points corresponding to the nozzle with d_0 = 8 mm lie higher than those for d_0 = 4 m, and the value of L decreases with increase in the content of inert gases. The dependence of L on the Re_0 number in the laminar regime (up to $\mathrm{Re}_0 \le 2000$) is much steeper than for the turbulent one ($\mathrm{Re}_0 \ge 3000$). In the transient zone at Re_0 = 2000–3000 any definite dependence is absent.

More rigorous dependences were obtained in further processing of the data. According to the recommendations of [2], for both regimes of combustion we used relations of the following type:

$$\frac{L}{d_0} = A\ \mathrm{Re}_0^n \left(\frac{d_0}{d_*}\right)^{-0.5}, \tag{1}$$

where d_* is a certain diameter of the nozzle below which the points corresponding to the region of turbulent combustion lie on one line $L/d_0 = f(\mathrm{Re}_0)$ irrespective of the nozzle size d_0. In [4] such a size was d_0 = 3 mm, precisely which was adopted in [2] as d_*. At $d_0 \neq d_*$ in the laminar region and $d_0 > d_*$ in the turbulent one the following correction to the nozzle size $(d_0/d_*)^{-0.5}$ is introduced.

The processing of the data presented in Fig. 2 yielded the following formulas for the region of laminar combustion of CH_4–N_2 at Re_0 = 400–2000:

$$\frac{L}{d_0} = 4.90 \cdot \mathrm{Re}_0^{0.5} \left(\frac{d_0}{d_*}\right)^{-0.5} a_0^{0.85}, \tag{2}$$

and the region of turbulent combustion:

$$\frac{L}{d_0} = 41.3 \cdot \mathrm{Re}_0^{0.2} \left(\frac{d_0}{d_*}\right)^{-0.5} a_0, \tag{3}$$

where a_0 is the volumetric fraction of a fuel gas (methane) in these mixtures.

The results turned out to be close to those obtained earlier in [3], where the constant coefficients A were equal to 4.15 and 38.7, respectively (of course, at a_0 = 1). A comparison of the computational formulas with experiment is given in Fig. 3.

The correlation of the experimental data for the CH_4–He mixture was made similarly. In this case, agreement with the data of [3] at a_0 = 1 is practically complete:

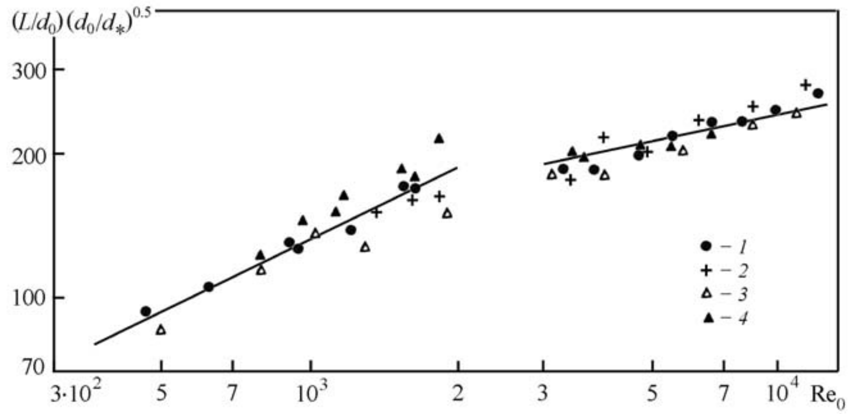


Fig. 4. Correlation of data on combustion of methane-helium mixtures: 1) d_0 = 8 mm, a_0 = 0.85; 2) 8 and 0.65; 3) 8 and 0.6; 4) 4 and 0.85.

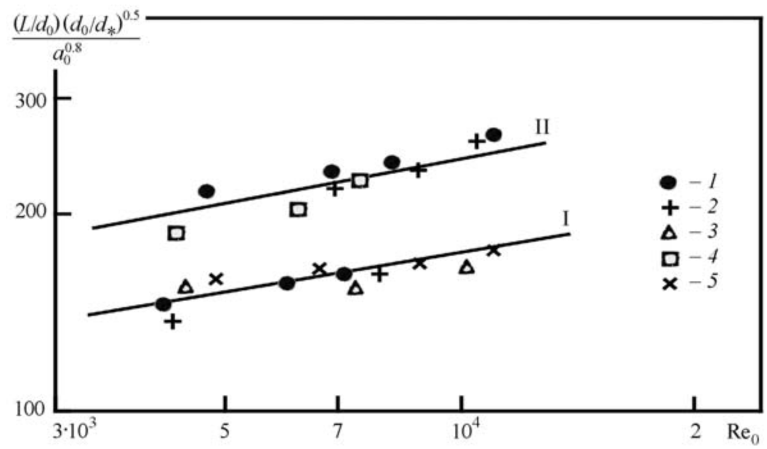


Fig. 5. Correlation of data on combustion of hydrogen-nitrogen (I) and hydrogen-helium (II) mixtures (the ordinata of line II is augmented 3 time, d_0 = 8 mm: 1) a_0 = 0.6; 2) 0.5; 3) 0.33; 4) 0.2; 5) 0.25.

for a laminar flame

$$\frac{L}{d_0} = 4.18{\cdot}\mathrm{Re}_0^{0.5}\left(\frac{d_0}{d_*}\right)^{-0.5}, \qquad (4)$$

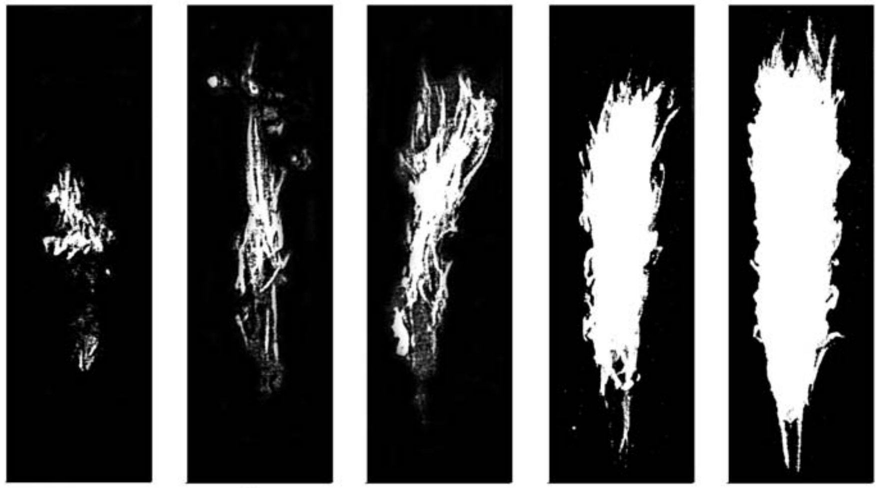
for a turbulent one

$$\frac{L}{d_0} = 38.9{\cdot}\mathrm{Re}_0^{0.2}\left(\frac{d_0}{d_*}\right)^{-0.5}. \qquad (5)$$

However, while for the CH_4–N_2 mixtures the flame height was practically proportional to the volumetric fraction of CH_4 in a mixture, for the CH_4–He mixtures such a dependence was practically absent. It may quite be that in mixtures with helium the influence of the latter was insignificant because of its small mass (the maximum weight content of He did not exceed 0.14), whereas the decrease in Re_0 with the increase in the mixture viscosity [5] led to a marked decrease in the calculated value of L/d_0.

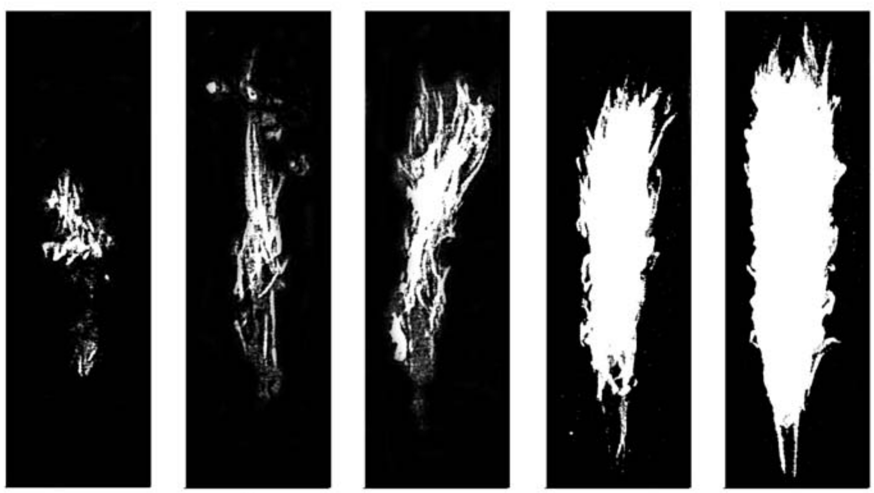
A comparison of the results calculated by Eqs. (4) and (5) with experimental data is presented in Fig. 4.

Experiments with mixtures of hydrogen with nitrogen and helium were carried out on a nozzle 8 mm in diameter and mainly in the region of turbulent combustion. In both cases one could observe a clear exponential depend-



a *b* *c* *d* *e*

Fig. 6. Photographs of a CH_4–N_2 flame made with different exposures: a) 1/60 sec; b) 1/30; c) 1/16; d) 1/4; e) 1.



a *b* *c* *d* *e*

Fig. 7. Change in the luminosity of a flame in transition from a laminar regime of combustion to a turbulent one: a) $\mathrm{Re}_0 = 385$; b) 753; c) 2154; d) 4088; e) 7253. H_2–N_2 mixture, $a_0 = 0.6$, exposure 8 sec.

ence on the volumetric fraction of hydrogen: with increase in the amount of an inert gas the flame jet height decreased proportionally to $a_0^{0.8}$. The computational formulas obtained as a result of the processing of data differ only by a constant factor:

for the H_2–N_2 mixture

$$\frac{L}{d_0} = 26.4 \cdot \mathrm{Re}_0^{0.8} \left(\frac{d_0}{d_*}\right)^{-0.5} a_0^{0.8}, \tag{6}$$

for the H_2–He mixture

$$\frac{L}{d_0} = 38.1 \cdot \mathrm{Re}_0^{0.8} \left(\frac{d_0}{d_*}\right)^{-0.5} a_0^{0.8}, \tag{7}$$

The somewhat lower value of this factor in Eq. (6) as compared to Eqs. (3), (5), and (7) cannot be explained as yet. A comparison of these results with experimental data is given in Fig. 5. It should be noted that in all the cases (Figs. 3–5) the experimental points are grouped around the predicted curves with a scatter not exceeding (except for some cases) ±15%, which should be accepted as satisfactory.

The use of a digital camera to fix the flame length allowed us to obtain a large number of photographs, even a preliminary analysis of which made it possible to note some specific features of the processes of flame jet combustion. Thus, while in [3] the black-white photography with a short exposure (of the order of 1/500–1/100sec) made it possible for laminar flames of methane in air to reveal very luminous thin cylinders of irregular shape "sitting" at the nozzle cut from which a flame jet of known spindle shape is formed, when increasing exposure by superposition, an analogous digital camera-aided photograph (with an exposure of 1/60 to 1 sec) of the formation of a turbulent flame jet has shown that under this flame there are shapeless shreds ejected upward (Fig. 6) that finally, on superposition in time, yield the same known picture of a flame.

Just as in [3], all the tests were carried out with methane. The sharp increase, fixed by the digital camera, in the luminosity of a hydrogen-nitrogen flame jet (Fig. 7) in transition from a laminar regime of combustion to a turbulent one seems to be the result of the anisotropicity of the flame.

CONCLUSIONS

1. Experimental investigation of the length of flame jets formed in burning of mixtures of methane and hydrogen with inert gases (nitrogen and helium) in a stagnant air was carried out. Flame jets were fixed on taking their photographs using a digital camera.

2. The correlation of experimental data made it possible to obtain computational dependences of the relative height of a flame jet on the Reynolds number and the volumetric fraction of the fuel gas in the mixture.

3. A change in exposure from 1/60 to 1 sec has shown that underlying the formation of an ordinary visible turbulent flame jet are periodic ejections of bright burning formations which are disconnected and shapeless.

NOTATION

a, volumetric content of a fuel gas; *d*, nozzle diameter, m; *L*, flame jet length, m; *m*, exponent of the Reynolds number; Re, Reynolds number. Subscripts and superscripts: 0, exit section of the nozzle; *, characteristic value of diameter (3 mm).

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