HEAT AND MASS TRANSFER
AND PHYSICAL GASDYNAMICS

Laminar and Turbulent Modes of Combustion of Submerged Hydrogen Jets

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Abstract—Experimental data on the combustion of individual jets of hydrogen and methane in air are analyzed. A strong dependence of the relative flame height \( L/d_0 \) on the nozzle diameter \( d_0 \) is revealed. A direct application of the formulas well known in the practice of description of mass transfer to the calculation of flame parameters under conditions of both laminar and turbulent diffusion combustion revealed good agreement between the theoretical and experimental results: the divergence did not exceed 30%.

INTRODUCTION

It is the objective of this study to try and describe diffusion jet flames using the well-tested apparatus of the theory of heat and mass transfer in a multicomponent boundary layer. This theory, based on extensive experimental data and characterized by a well-developed methodology, may prove to be useful in developing theoretical models of the process of combustion of gaseous fuels issuing from nozzles to an oxidizer medium, in particular, under conditions of hydrogen flow into stationary air. The hydrogen/air interaction results in the formation of a fuel mixture on the jet periphery, which ignites from an external source and burns in a self-sustaining mode. The intensity of the entire process is defined primarily by the degree of mixing of combustible gas with oxidizer, i.e., by the process of mass transfer. The heat-and-mass transfer pattern of combustion in such diffusion flame may be represented as follows (Fig. 1).

Hydrogen flows with the mass velocity \( \rho_0U_0 \) upwards to a stationary air medium from a vertical cylindrical nozzle \( l \) (Fig. 1a) of diameter \( d_0 \). In so doing, in accordance with the jet theory [1], a jet flame consists of a conic central core 2, in which the initial flow velocity and concentration of hydrogen being injected are retained, and a diverging peripheral part 3. In the peripheral part, hydrogen is mixed with stationary air, is diluted with this air, and is decelerated as a result of momentum exchange. The velocity of the gas mixture decreases with increasing distance from the central core, as well as the hydrogen concentration, and the air concentration increases. When a hydrogen-air mixture with a concentration providing for its ignition (from a source such as a spark, heated wire, and so on) is formed on the boundary of a hydrogen jet, a combustion front or wave 4 arises in the neighborhood.
boundary layer of the jet. A medium consisting of almost pure fuel (hydrogen) is found on one side of this surface within the flame, and a medium of atmospheric oxygen – on the other side. The high difference between the concentrations in a layer of small thickness leads to intensive mass transfer. The curves of variation of the concentrations of hydrogen \(C_{\text{fuel}}\) and atmospheric oxygen \(C_{\text{O}_2}\) on different sides of the flame front in some cross section of the flame are given in Fig. 1b.

A significant amount of heat is released within the combustion wave. The temperature \(T_R\) rises to a level much higher than a thousand degrees. In so doing, high temperature gradients arise; high heat fluxes, which are proportional to these gradients and directed in both directions, heat up hydrogen \(T_{\text{fuel}}\) and air \(T_{\text{air}}\) approaching the combustion front and prepare them for ignition.

Quite a few publications were made [2–4], in which some or other approaches to theoretical analysis of efflux of burning jets are suggested. Of special interest are studies dealing with various modes of combustion, from laminar to developed turbulent. Unfortunately, the basic regularities of those modes could not yet be determined; no determining parameters and conditions of transition from laminar to turbulent flow were identified. In the overwhelming majority of cases, the differences between theoretical and experimental data turn out to be very significant.

**ANALYSIS OF PREVIOUS STUDIES**

Two studies [5, 6] are of interest, in which extensive experimental data are provided and ingenious procedures for their generalization are suggested. According to the first procedure, the length of jet flames was investigated under conditions of combustion of producer and coke gases flowing into air from cylindrical nozzles. The experiments were performed in a wide range of efflux velocities \(U_0\) and nozzle sizes \(d_0 = 10 \text{ to } 80 \text{ mm}\). Levchenko [5], who represented the obtained data in the form of dependence of \(L/d_0\) on the Reynolds number, observed a strong separation of points with respect to the nozzle size and gave up the use of the Reynolds number as the determining criterion. He suggested a generalization in the form of dependence of \(L/d_0\) on the Froude number \(Fr = \frac{U_0^2}{gd_0}\) determined by the nozzle diameter. However, a fitting parameter \(k\) appeared in the final formula

\[
\frac{L}{d_0k} = \left(\frac{U_0}{gd_0}\right)^{0.17}.
\]

This parameter is defined as the ratio of the mass flow rate of combustible gas in the jet to the flow rate of air “drawn” into the jet. For the producer gas, \(k\) was taken to be 0.65, and for the coke gas – \(k = 1\). Generally speaking, the value of \(k\) depends “on the physical properties of gas and on the conditions of flame development” and must be determined “experimentally in each case”. Therefore, one can hardly use formula (1) for practical calculations.

On the contrary, Annushkin [6] maintains that “the construction of the flame length dependence on the Froude number is devoid of physical meaning”. The very extensive experimental data were processed in [6] in the form of the empirical relation

\[
L = \frac{U_{LS}}{v\Re} + \frac{\rho_a}{13.5d_{a}^2(1 + L_0^2)}\Re \left(1 - \frac{1}{\Re}\right)^{0.25^{-1}},
\]

where \(d_a = d_{a0}\) is the diameter of isobaric cross section, \(U_{LS}\) is the rate of laminar combustion of stoichiometric mixture, \(v\) is the kinematic viscosity of gas in isobaric cross section, and \(\Re = \Re/\Re^*\) is the ratio of the actual number \(\Re\) of flowing-out medium to its value for an isentropically stagnant flow.

We can see that this formula is complex in calculation; furthermore, it includes an insufficiently clearly defined quantity \(U_{LS}\).

**BOUNDARY LAYERS IN A FLAME**

Although the process of combustion introduces specific features into the efflux of fuel jets into a space filled with oxidizer, there is reason to believe that the mechanism of this phenomenon has many a regularity in common with the transport of matter and thermal energy in the boundary layer on the surface of a solid subjected to a high-temperature chemically active gas flow. It will be remembered that it took thermal physicists almost a quarter of a century to reduce the plurality of semi-empirical formulas existing in engineering practice of the 1950s to clearly defined, physically transparent laws of heat and mass transfer which made it possible to predict with adequate accuracy the