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HEAT AND MASS TRANSFER IN CHEMICAL TRANSFORMATIONS AND IN COMBUSTION

TURBULENT COMBUSTION OF GASEOUS FUELS

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Differences and similarities between the parameters of turbulence and turbulent viscosity of an isothermic jet and a burning-fuel torch have been analyzed on the basis of experimental data. It is proposed to use the dependences obtained for calculating the temperature fields in torches of gaseous fuels.

Keywords: *combustion, gaseous fuel, turbulence, viscosity, temperature fields.*

A torch is formed as a result of the ignition of a fuel jet the air. Unlike the process of efflux of an isothermic (classical) jet, this torch represents a fairly convenient object for observation because it glows brightly and is easily fixed on a standard photographic film. Therefore, the surprising thing is that there are not so many published works on the geometric, hydrodynamic, and physicochemical parameters of torches arising as a result of the ignition of different fuels and there is no a unity in the opinions of professionals on the criteria for processing of experimental data on them [1].

In Fig. 1, differences between the flows in an isothermic jet and in a burning-fuel torch are shown schematically: the cold core of the torch as if is enclosed in a shell of the products of reaction of the fuel with the air oxygen. As the distance between the jet and the exit section of a fuel nozzle increases, the temperature profile broadens and a temperature "plateau" is formed on it perpendicularly to the axis of the jet at the instant the fuel is burned completely.

Figure 2 shows results of measurements of the velocity profiles at several cross sections of a jet with combustion and without it and the dynamics of the change in the temperature profile of a burning hydrogen jet. It is clearly seen that the velocity profiles of both jets are similar despite the fact that the temperatures here and there increase by several times in the process of combustion.

The above-indicated high-temperature shell formed of the products of interaction of the fuel with oxygen not only does not increase the thickness of the torch δ, but even decreases it as compared to that of the isothermic jet (Fig. 3). Because of this, the velocity of the flow at the axis of the torch increases, and the velocity of the flow at the top of the torch is only two times lower than the velocity of the flow at the exit section of the nozzle, while the velocity of the flow in an ordinary jet decreases in inverse proportion to the distance between it and the nozzle exit section (x/d_0).

Such large differences between the hydrodynamic and geometric characteristics of a burning-fuel torch and an isothermic jet implicitly lead to the same large differences between their main parameters of turbulence. However, processing of our experimental data and those of foreigness on the turbulent flows in subsonic submerged jets has given fairly unexpected and universal results.

We will begin with the determination of the onset of the turbulent regime of flow. There is an opinion that the change from the laminar regime of flow in a jet to the turbulent one happens at fairly low Reynolds numbers, at least, as compared to the boundary layer on a plane plate. Figure 4 presents results of measurements of the height of a torch [2], from which the instant of the indicated laminar-turbulent change in the process of jet-torch combustion of hydrogen can be easily determined.

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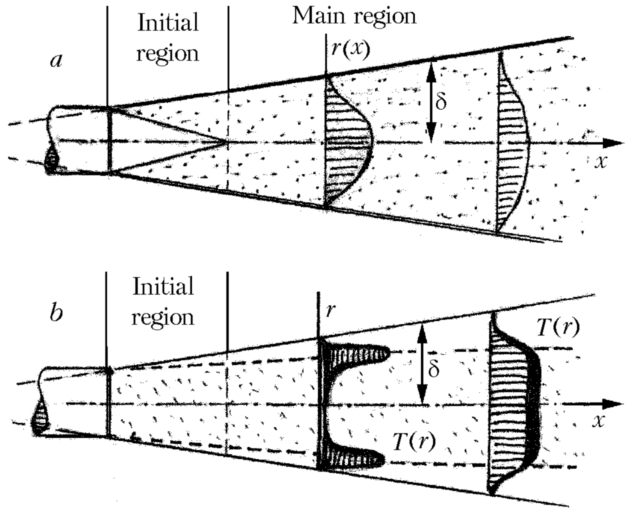


Fig. 1. Scheme of an isothermic jet (a) and a jet-torch "fuel stream" (b).

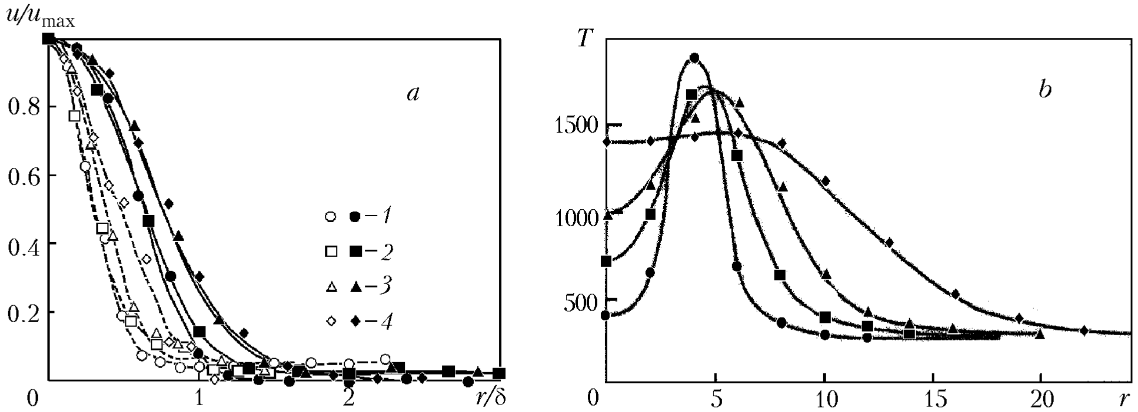


Fig. 2. Velocity (a) and temperature (b) profiles at the cross sections of a jet (dashed lines) and a torch (solid lines): x = 30 (1), 60 (2), 90 (3), and 160 mm (4). T, K; r, mm.

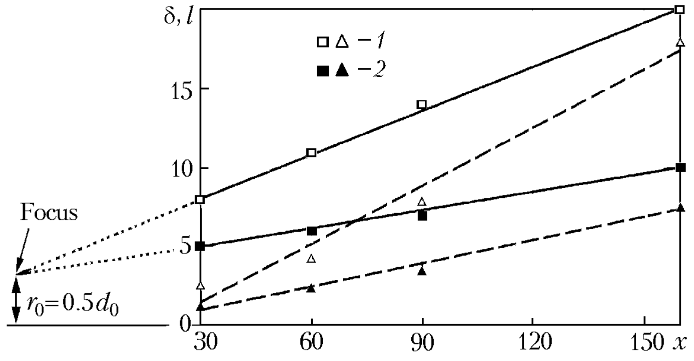


Fig. 3. Dependence of the thickness of a torch δ (solid lines) and the scale of turbulence l (dashed lines) on the axial coordinate x: 1) without combustion; 2) with combustion. The points correspond to the approximated values of δ and l inside the nozzle. δ, l, x, mm.

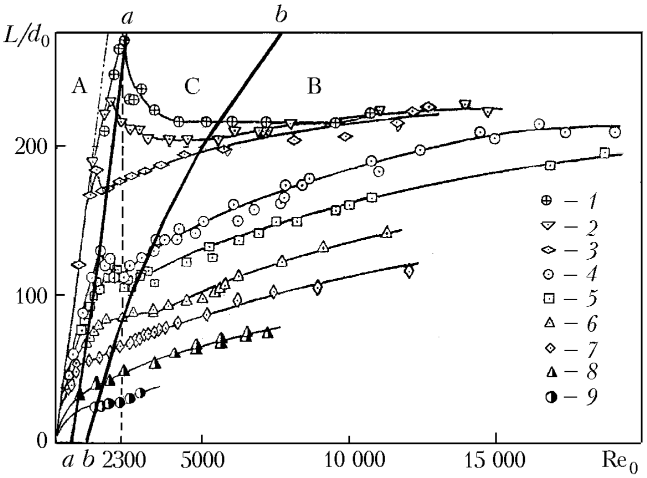


Fig. 4. Dependence of the dimensionless height of the torch (L/d_0) on the Reynolds number Re_0: d_0 = 1.45 (1), 1.9 (2), 2.9 (3), 4.0 (4), 6.0 (5), 10.75 (6), 15.5 (7), 21.0 (8), and 51.7 mm (9); a–a, boundary of the laminar-combustion region (A); b–b, boundary of the turbulent-combustion region (B); C, region of change from the laminar combustion to the turbulent one.

For nozzles of different diameters, the Reynolds numbers of the laminar-turbulent change fall within the range 1000–2000. A large number of models have been proposed for description of developed turbulent flows. Of them, the Prandtl–Kolmogorov model including three functional parameters, the Reynolds friction stress τ_t, the kinetic energy of turbulence K, and the shift length (scale of turbulence) l, is, in our opinion, preferable for jets. The calculation of the latter is the aim of the present work.

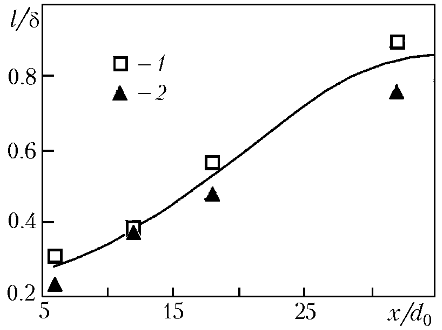
Unlike the boundary-layer flow along a plane plate, $\tau_t \to 0$ and the kinetic turbulent energy $K \neq 0$ at the axis of a jet; therefore, the ratio $(\tau_t/\rho K)$ is not invariant for the jet. However, as the experimental data show, the condition $\left(\frac{\tau_t}{\rho K}\right)_{\max} \approx 0.3$–$0.32$ is fulfilled at extremum points the Reynolds stresses, which is typical for the greater part of the flow in tubes and in boundary layers. This gives grounds for the selection of the proportionality coefficient C_μ in the expression for the friction coefficient τ_t:

$$\tau_t = -\rho\,(\overline{u'v'}) = -\rho C_\mu l\sqrt{K}\left(\frac{du}{dr}\right), \quad C_\mu = \left(\frac{\tau_t}{\rho K}\right)^2_{\max} \approx 0.09\text{–}0.1\,.$$

The velocity gradient $\left(\frac{du}{dr}\right)$ will be determined by the known Schlichting formula for the self-similar profile of the flow in a jet:

$$\frac{u}{u_{\max}} = \left[1 - \left(\frac{r}{\delta}\right)^{\frac{3}{2}}\right]^2, \text{ from where } \left(\frac{du}{dr}\right)_{\max} = -1.4 \cdot \frac{u_{\max}}{\delta}\,.$$

The thicknesses of a jet and a torch as functions of the axial coordinate are presented in Fig. 3. The initial dependences for the maximum velocity $u_{\max}$ and the thickness δ are given in [3]. At a large distance from the axis of an isothermic jet and the axis of a torch, where K = const, a different equality is fulfilled:



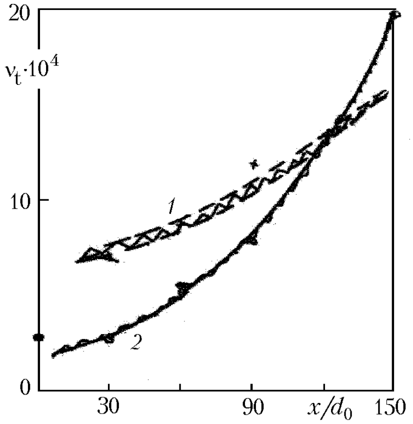


Fig. 5. Dimensionless ratio l/δ as a function of the coordinate x/d_0: 1) without combustion; 2) with combustion.

Fig. 6. Kinematic viscosity ν_t as a function of x/d_0 in the isothermic jet (1) and in the torch (2). x, mm; ν_t, m^2/sec.

$$\sqrt{K} = -C_k l \left(\frac{du}{dr}\right)_{\max} .$$

Here, the proportionality coefficient is equal to $C_k = \left(\frac{\tau_t}{\rho K}\right)_{\max} \approx 0.32$, which satisfies to the condition

$$C_k = C_\mu \left(\frac{\rho K}{\tau_t}\right)_{\max} .$$

The scales of turbulence l of an isothermic jet and a torch were found to be very different. More unexpected is the fact that the ratios l/δ for the jet and the torch are identically dependent (with an error of no more than 20%) on the longitudinal coordinate (x/d_0) (Fig. 5).

The scale of turbulence l is of importance because it is precisely this parameter that mainly determines the coefficient of kinematic viscosity in jet streams:

$$\nu_t = C_\mu C_k l^2 \left(\frac{du}{dr}\right)_{\max} .$$

Since the dependences $\delta(x)$ and $u_{\max}(x)$ for an isothermic jet and a torch are different, their kinematic viscosities ν_t are also very different (Fig. 6): in the jet, the kinematic viscosity is larger at the exit section of the nozzle, and then it changes not as sharply with increase in the ratio x/d_0 as compared to that of the torch-jet stream.

CONCLUSIONS

1. An analysis of the results of our experiments showed that the parameters of turbulence and turbulent kinematic viscosity of an isothermic jet and a burning-fuel torch change by mechanisms that have both differences and similarities.

2. The dependences obtained can be used for calculating the dynamics of the change in temperature fields in torches of different gaseous fuels as well as for estimation of the volume of harmful effluents.

NOTATION

C_μ, C_k, proportionality coefficients; d, diameter of a tube, m; $K = \frac{1}{2}\rho(u'^2 + v'^2 + w'^2)$, kinetic turbulent energy, m^2/sec^2; L, height of the flame of a torch, m; l, scale of turbulence, m; u, linear velocity, m/sec; u'^2, v'^2, w'^2, components of pulsating velocities, m/sec; r, radius, m; Re, Reynolds number; T, temperature, K; x, coordinate, m; δ, thickness of the torch, m; ν, kinematic-viscosity coefficient, m^2/sec; ρ, density, kg/m^3; τ_t, friction stress, $kg/(m \cdot sec^2)$. Subscripts: max, maximum; t, turbulent; 0, initial.

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