MATHEMATICAL MODELING OF TURBULENT COMBUSTION OF HYDROGEN IN A BOUNDARY LAYER

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Turbulent flow in a boundary layer with injection of hydrogen through a permeable plate into an external air flow is modeled. To calculate turbulence characteristics the Lam–Bremhorst modification of the k–ε model is employed. Calculations are made both with and without account for the non-unity of the Lewis number. In determining the concentrations of the intermediate and end combustion products and the temperature the assumption of chemical equilibrium is made. The obtained distribution of turbulent pulsations allows the conclusion of flow laminarization under combustion conditions to be made.

Introduction. A considerable number of theoretical [1-3] and experimental [4-8] works are devoted to the problem of combustion in a turbulent layer. In many of them a modified k–ε model is used to predict combustion in turbulent flows, and a global reaction with a finite rate is used to calculate its chemical part [1, 3]. In [9] the authors note, by the way, that in modeling turbulent combustion of ethanol in a boundary layer use of the kinetic mechanism exerts a considerable influence on the distribution of the concentration of the chemical components and the temperature of the flame front.

In addition to simplifications of the chemical processes, in calculations of turbulent flows in some cases molecular heat conduction and molecular diffusion are neglected compared to turbulent transfer [10] or the assumption \( Pr = Sc = 1 \) is adopted. Even for calculation of laminar flows with heat and mass transfer the assumption \( Pr = Sc = 1 \) is made in some problems, e.g., in [2] in the calculation of a flow under combustion conditions. Calculations in a simplified mathematical statement require less time and in many cases lead to satisfactory agreement with experimental data. On the other hand, in multicomponent media the diffusion coefficients of individual components can differ from each other by severalfold (by comparison, the Schmidt numbers in dilute mixtures of hydrogen and ethanol with air are 0.2 and 1.3, respectively). The Prandtl number, though being weakly related to the temperature, can depend on the composition (for a hydrogen–air mixture with different hydrogen concentrations the Prandtl number varies from 0.7 to 0.45) [11]. As a result, the Lewis numbers \( Le = Pr/Sc \) of individual components of a mixture can differ from unity by severalfold.

The non-unity of the Lewis number can exert a considerable influence on calculation results. For instance, in [12, 13] in the calculation of combustion a strong influence of the Lewis number on the flame temperature is noticed. In boundary layers with injection or evaporation of a reagent from a plate the processes in the viscous sublayer, where molecular diffusion and heat conduction are of importance, play a crucial role. Therefore the assumption \( Le = 1 \) made for prediction of the flow with combustion of hydrogen can lead to erroneous results.

Furthermore, it is of interest to investigate the mutual influence of turbulence and combustion. In experimental works in measuring turbulent pulsations it is observed that in combustion of different fuels the relative value of turbulent pulsations decreases [4, 7] over some initial section [4]. Flow laminarization and subsequent turbulization are also a matter of concern in the present work.

Mathematical Statement of the Problem and Method of Solution. In this work we use a k–ε turbulence model with allowance for laminarization effects [14]. The choice of this modification of the widely adopted k–ε model has been motivated by the fact that on a flat plate it produces more satisfactory results for turbulence.
Table 1 gives the quantities of $\Phi$, the diffusion coefficients $\Gamma_\Phi$, and the source terms $S_\Phi$, where

$$\mu_t = \rho C_\mu f_\mu \frac{k^2}{\varepsilon}, \quad C_1 = 1.44, \quad C_2 = 1.92, \quad C_\mu = 0.09, \quad \sigma_k = 1.0, \quad \sigma_\varepsilon = 1.3,$$

$$\Pr_t = \Sc_t = 0.9, \quad G_k = \mu_1 \left(\frac{\partial u}{\partial y}\right)^2, \quad f_1 = 1 + (0.05/f_\mu)^3,$$

characteristics [15] as compared to other modifications. The equation for each variable, namely, the longitudinal velocity $u$, the enthalpy of the mixture $h$, and the mass concentrations of the components $c_i$, and for the turbulence quantities, namely, the kinetic energy of turbulence $k$ and its dissipation rate $\varepsilon$, can be represented in the generalized form

$$\left(\frac{\partial}{\partial t} + u \frac{\partial}{\partial x} + v \frac{\partial}{\partial y}\right)\Phi = \frac{\partial}{\partial y}\left(\Gamma_\Phi \frac{\partial \Phi}{\partial y}\right) + S_\Phi.$$

(1)