THE EFFECT OF FLOW STRUCTURE ON THE COMBUSTION OF SOLID FUELS

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ABSTRACT

Among various aspects dealing with the influence of flow structure on the combustion characteristics of solid fuels,the effect of turbulent heat and mass transfer in the flame zone is studied in the present paper.The combustion in turbulent flow is considered by developing a model of interaction between turbulent and chemical reaction of combustion.Transport equation for turbulence heat flux defined in the Reynolds time-averaged form is taken into account including a source term describing the influence of chemical reaction.another mechanism of combustion reaction effect on turbulent heat transfer is analyzed by introducing a new characteristic period for the turbulent fluctuations,i.e.only fluctuations having a characteristic period that is smaller than corresponding characteristic period of reaction can affect the heat transfer in the flame zone.The local-isotropic assumption is carried out to reduce full transport equation for turbulent fluctuations of temperature to simple formulae.Hence,a new correlation for effective coefficient of turbulent heat transfer affected by chemical reaction is formulated.

The effect of erosive burning(increase of burning rate of solid fuel under blowing of burning surface)is studied numerically by boundary layer approach.Satisfactory agreement with measurements is obtained using proposed approach for the full transport equatin as well as for the local-isotropic assumption.

INTRODUCTION

The basic effect of turbulence on the combustion characteristics of solid fuel consists in the increase of solid fuel burning rate under blowing of burning surface by turbulent flow.This effect,that is known as a evasive burning,is widely studied in the theory of solid propellant combustion and,undoubtedly,has a significant role in the fire theory,especially being applied to the investigation of large fires where turbulence get to be one of the most crucial factors.

The mechanism,first proposed by Corner [1],attributes erosive burning effect by turbulent heat transfer in the flame zone that leads to increase heat flux into the solid fuel and,correspondingly,to increase burning rate.Dedicated to Zoldovich,it should be mentioned that same approach was proposed by him at the forties but accessible publication has appeared few decades later[2]. Considered problem stands close to the classical problem of turbulent combustion[3,4] including its peculiarities complicated by special features like a flow dynamics in the near wall region and interaction with burning surface of solid fuel.

A MODEL OF INTERACTION OF TURBULENCE
WITH CHEMICAL REACTION

To simplify the analysis developed in the presented paper following assumption are considered [5-7]:
- one single-step chemical macro-reaction of combustion is taken into account in the gas phase;
- following first assumption, only two species are considered in the gas phase: react ant α and reaction's product which mass fraction can be obtained as $(1-\alpha)$;
- using the similarity between distribution of temperature and mass fraction, the last one can be obtained as $\alpha/\alpha_s = (T_f-T)/(T_f-T_s)$, where s and f denote burning surface and flame respectively.

The mathematical model of solid fuel burning is described by boundary layer equations for the turbulent flow with chemical reaction of combustion. General form of these equations in Reynolds time-averaged form is:

$$\bar{\rho}\,\bar{u}\,\frac{\partial u}{\partial x} + \bar{\rho}\,\bar{v}\,\frac{\partial \bar{u}}{\partial y} = \frac{\partial}{\partial y}\Big[\mu_m\frac{\partial \bar{u}}{\partial y} - \overline{\mu'(\rho v)'}\Big]\frac{d\,\bar{p}}{d\,x} \tag{1}$$

$$\bar{\rho}\,\bar{u}\,\frac{\partial \bar{T}}{\partial x} + \bar{\rho}\,\bar{v}\,\frac{\partial \bar{T}}{\partial y} = \frac{\partial}{\partial y}\Big(\frac{\lambda_m}{C}\frac{\partial \bar{T}}{\partial y} - \overline{T'(\rho v)'}\Big) + \frac{Q}{C}\,\bar{\rho}\,\bar{W} \tag{2}$$

$$\frac{\partial \bar{\rho}\,\bar{u}}{\partial x} + \frac{\partial \bar{\rho}\,\bar{v}}{\partial y} = 0 \tag{3}$$

$$\bar{P} = R\,\bar{\rho}\,\bar{T} \tag{4}$$

Reaction's rate is described by Arrhenius -type formula:

$$W = A_g\frac{(T_f - T)}{(T_f - T)}\exp(-E_g/R_0 T) \tag{5}$$

Since dynamical turbulence is not affected by chemical reaction in present analysis, Reynolds stress in the momentum equation (1) is described simply as it is used for non - reaction flow:

$$\overline{\mu'(\rho v)'} = \mu\frac{\partial \bar{u}}{\partial y} \tag{6}$$

Concerning the parameters of turbulent heat transfer expressed by correlation — $\overline{T'(\rho v)'}$ in Eq.(1), previous studies [8,9] took into account conventional expression for non-reacting flow:

$$g_t = \overline{-T'(\rho v)'} = \frac{\lambda_t}{C}\frac{\partial \bar{T}}{\partial y} \tag{7}$$

In presenting analysis the influence of chemical reaction on the turbulent heat transfer is determinate by considering equation for turbulent heat flux g $=-\overline{T'(\rho v)'}$. Chemical reaction affects turbulent heat transfer by following mechanism. Relaxation process of heat transfer in the flame zone is define by new characteristic period $t\tau$ which can be estimated as $t\tau \sim 1/\bar{W}$. Hence, turbulent fluctuation which period is greater that $t\tau$ can not affect the distribution of temperature in the flame zone because chemical reaction and

heat conduction are more faster processes to determinate temperature profile than turbulence. Applying this reasoning we define parameter $k\tau$ as a turbulence energy of fluctuation which period is limited by $t\tau$:

$$k_r = k \phi \ (t_r/t_0) \tag{8}$$

Here to is characteristic period of entire spectrum of turbulent fluctuations. Defining $to \sim k/\varepsilon$ and meaning $t\tau \sim 1/\overline{W}$, we receive that $t\tau/to \sim \varepsilon/k\overline{W}$. To provide condition $\phi(0) \longrightarrow 0, \phi(1) \longrightarrow 1, \phi(\infty)=1$, correlation function ϕ is approximated as

$$\phi = 1 - \exp\left(- B \frac{\varepsilon}{k\overline{W}} \right) \tag{9}$$

where B is empirical constant.
Hence, equation for turbulent heat flux $g_t = - \overline{T'(\rho,\upsilon)'}$ is defined as following

$$\rho u \frac{\partial \ g_t}{\partial \ x} + \overline{\rho} \ \overline{v} \frac{\partial \ g_t}{\partial \ y} = \frac{\partial}{\partial \ y} \left(\frac{\lambda_m}{C} + C_1 \ \mu_t \right) \frac{\partial \ g_t}{\partial \ y} +$$

$$C_2 \ \overline{\rho} \ \mu_t \ \left(\frac{\partial \ \overline{u}}{\partial \ y} \frac{\partial \ \overline{T}}{\partial \ y} \right) - C_3 \frac{\rho \ \varepsilon}{k \ \phi} \ g_t [\ 1-\delta \quad] \tag{10}$$

where

$$\delta = \frac{1}{C_3} \ \frac{k \ \phi}{\varepsilon} \ \frac{Q}{C} \frac{\partial \ \overline{W}}{\partial \ T} \tag{11}$$

and C_1 , C_2 , C_3 , are empirical constants.
Considering assumption of local-isotopic turbulence, Eq.(10) can be significantly simplified. Defining $\mu = c \ \rho k^2/\varepsilon, \mu \frac{\partial \ \mu}{\partial \ y} = -\overline{\mu}' \ (\overline{\rho} \ \overline{\upsilon})' = C_4 \ \overline{\rho} \ k$ and keeping only the generation and dissipation terms Eq.(10) can be transposed to simple formula :

$$g_t = \frac{\mu_t}{Pr_t} \frac{\phi}{1 - \delta} \frac{\partial \ \overline{T}}{\partial \ y} \tag{12}$$

where $Pr = C_3 C\mu/C_4 C_2$.
Eq.(12) differs from the Eq.(7) for turbulent heat flux in the non-reacting flow by the factor $\phi/(1-\delta)$ . . Here ϕ describes an influence of chemical reaction on the turbulent heat transfer by the proposed mechanism and $(1-\delta)$ -by the direct influence of source term caused by chemical reaction. The coefficient of turbulent heat transfer can be expressed from Eqs.(7),(12) as

$$\lambda_t = \frac{C \ \mu_t}{Pr_t} \frac{\phi}{(\ 1 - \delta \ )} \tag{13}$$

To complete the set of equation,turbulence model should be taken into account.Here well-known k-ε model is used [10].

Solid propellant burning rate is calculated as [11]:

$$m_s = \left(\frac{\rho_p \lambda_p T_s R_0 A_p}{E_p [C_p(T_s - T_n) - Q_p/2]} \right)^{1/2} \exp(-E_p/2R_0 T_s)$$

Here subscript   p   denotes the solid fuel parameters.

RESULTS

An influence of chemical reaction on the turbulent heat transfer in the flame zone is shown in Fig.1-3.Since temperature increases monotonously moving away from burning surface,according to Eqs.(10)-(11),chemical reaction generates additional turbulent heat flux g in the pre-flame zone where $\partial \overline{W}/\partial \overline{T} > 0$ ($\delta > 0$) and decrease g on the descending part of function $W(T)$ where $\partial \overline{W}/\partial \overline{T} < 0$ ($\delta < 0$) .

As the results presented in Fig.1 show,generation of g by chemical reaction is almost negligible while suppression is significant.Last conclusion can be carried out obviously from the analysis of curve 3 in Fig.2.The coefficient of turbulent heat transfer which distribution is shown in Fig.3 is expressed from Eq.(7) as

$$\lambda_t = C g_t \left(\frac{\partial T}{\partial y} \right)^{-1} \tag{14}$$

Fig.3 shows significant influence of chemical reaction on the turbulent heat transfer in the flame zone.Moreover,in the point y=0.3 mm which corresponds to the point of maximum heat release(see curve 3 in Fig.1), turbulent heat transfer level is even lower than molecular thermal conductivity.Comparing curves 1 and 2 in Fig.2 and,also the same curve in Fig.3,fairly good suitability of the local isotropic assumption can be concluded.

Measurements of erosive burning of stick propellant in the wide range of blowing velocity produced by Vilyunov [12,13] have shown that erosivity coefficient $\varepsilon = m_s/m_s^o$ (m_s , m_s^o are the burning rates of solid fuel under blowing and without it respectively) can be described uniformly as a function of dimensionless parameter which was marked,as Vi dedicating to discoverer. the expression for this parameter is

$$V_i = \frac{(8 \rho_c \tau_s)^{1/2}}{m_s^o}$$

where ρ_c is core flow density , τ_s is shear stress on burning surface.

Fig.4 shows substantial disagreement between measurements and predicted results obtained neglecting influence of interaction between chemical reaction and turbulence while presented model has good agreement.

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