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Original Article

On Prognosis of Diffusion Combustion Process with Limited Discharge of its Products

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Abstract - In this paper, we introduce a model and an analytical approach for analyzing the diffusion combustion process with limited discharge of its products. In the analysis framework, we consider a combustion with the flame output through the opening. Different combustion regimes were investigated.

Keywords - Model of the combustion process, Analytical approach for analysis.

1. Introduction

Combustion is widely spread in nature (fires) and is used in everyday life and industry [1, 2]. The prognosis of combustion gives a possibility to control the considered process. Controlling combustion leads to obtaining the required results in industry and everyday life and decreasing destructive phenomena from spontaneous fires. The present paper's main aim is to formulate a model for the diffusion combustion process with limited discharge of its products. We analyzed different regimes of combustion. The accompanying aim of the present paper is to develop an analytical approach to the analysis of the considered process.

2. Method of Solution

In this paper, we consider a flame exit through a vertical opening with a continuous supply of fuel. We describe the combustion process by using the following system of equations

$$\begin{cases} \frac{\partial(\rho M_a)}{\partial t} = \frac{\partial}{\partial z}\left[\left(\frac{\mu}{S_C}+\frac{\mu_T}{S_{CT}}\right)\frac{\partial M_a}{\partial z}\right] - \rho V_a - \frac{\partial(\rho u_z M_a)}{\partial z} \\ \frac{\partial(\rho u_z)}{\partial t} = -\frac{\partial p}{\partial z} + \frac{\partial \sigma}{\partial z} + \rho g - \frac{\partial(\rho u_z^2)}{\partial z} \\ \frac{\partial(\rho E)}{\partial t} = \frac{\partial}{\partial z}\left[\left(\frac{\mu}{P_r}+\frac{\mu_T}{P_{rT}}\right)\frac{\partial E}{\partial z}\right] + \frac{\partial q_z}{\partial z} - \frac{\partial(\rho u_z E)}{\partial z} \end{cases} \quad (1)$$

Where u_z is the projection of the fuel intake velocity on the z-axis (fuel intake through a cylindrical pipeline and flame exit through a round hole are considered: the considerate situation is symmetrical); M_a is the mass fraction of the considered component; μ and μ_T is the viscosity and turbulent viscosity, respectively; p is the pressure; V_a is the rate of consumption of components as a result of combustion; q is the radiation heat flux; g is gravity acceleration; Sc and Pr are the Schmidt and Prandtl numbers; $\sigma = -\frac{2}{3}\frac{\partial}{\partial z}\left[pk + \left(\frac{\mu}{S_C}+\frac{\mu_T}{S_{CT}}\right)\frac{\partial u_z}{\partial z}\right]$; $E = \sum_a Y_a\left[E_0 + \int_{T_0}^{T} c_{pa}(T)dT\right]$ is the enthalpy of the mixture; Sc_T and Pr_T are the turbulent Schmidt and Prandtl numbers; k is the kinetic energy of turbulence; E_0 is the enthalpy of formation of the a-component; c_{pa} is the specific heat capacity of the a-component at constant pressure; T is temperature. The boundary and initial conditions for the system of Equations (1) are represented in the following form

$$u_z(0,t)=U_0,\ u_z(0,0)=U_0,\ u_z(z>0,0)=0. \tag{2}$$

We solved Equations (1) with conditions (2) by averaging functional corrections [3-5]. In the framework of the method, we replace the required functions on the right side of the above equations on their not yet known average values: $u_z \to \alpha_{1z}$. The replacement and integration on time give a possibility to obtain the following relation for the first-order approximation for the considered function in the following form

$$\begin{cases}\rho M_a=\rho_0 M_{a0}+\frac{\partial}{\partial z}\int_0^t\left(\frac{\mu}{S_C}+\frac{\mu_T}{S_{CT}}\right)\frac{\partial M_a}{\partial z}d\tau-\int_0^t\rho V_a d\tau-\alpha_{1z}\frac{\partial}{\partial z}\int_0^t\rho M_a d\tau\\ \rho u_{1z}=\rho U_0-\frac{\partial}{\partial z}\int_0^t p d\tau+\frac{\partial}{\partial z}\int_0^t\sigma d\tau+\int_0^t\rho g d\tau-\alpha_{1z}^2\frac{\partial}{\partial z}\int_0^t\rho d\tau\\ \rho E=\rho_0 E_0+\frac{\partial}{\partial z}\int_0^t\left(\frac{\mu}{S_C}+\frac{\mu_T}{S_{CT}}\right)\frac{\partial M_a}{\partial z}d\tau+\int_0^t q_z d\tau-\alpha_{1z}\frac{\partial}{\partial z}\int_0^t\rho E d\tau\end{cases} \tag{3}$$

Where ρ (t=0)=ρ $_0$, M_a (t=0)=M_0, E (t=0)=E_0. Not yet known average value α_{1z} was calculated by using the standard relation [3-5].

$$\alpha_{1z}=\frac{1}{\Theta L}\int_0^\Theta\int_0^L u_{1z}(z,t)dzdt \tag{4}$$

Substitution of solutions (3) into relation (4) gives a possibility to obtain

$$\alpha_{1z}=\frac{1}{\frac{2}{\Theta L}\int_0^\Theta(\Theta-t)\int_0^L\frac{1}{\rho}\frac{\partial\rho}{\partial z}dzdt}\left(\sqrt{U_0^2-\frac{4\beta}{\Theta L}\int_0^\Theta(\Theta-t)\int_0^L\frac{1}{\rho}\frac{\partial\rho}{\partial z}dzdt}-U_0\right), \tag{5}$$

Where $\beta=\frac{1}{\Theta L}\int_0^\Theta\int_0^L\frac{1}{\rho}\frac{\partial}{\partial z}\int_0^t p d\tau\, dzdt-\frac{1}{\Theta L}\int_0^\Theta\int_0^L\frac{1}{\rho}\frac{\partial}{\partial z}\int_0^t\sigma d\tau\, dzdt-g\Theta-U_0$.

The second-order approximation and approximations with higher orders of the required projection of velocity could be obtained in the framework of the standard procedure [3-5]. In the framework of the procedure, one shall replace the required function on the right side of Equation (3) on the following sum: $u_z\to\alpha_{nz}+u_{n\text{-}1z}$. The substitution gives a possibility to obtain the system of equations to calculate the second-order approximation of projection u_z in the following form

$$\begin{cases}\rho M_a=\rho_0 M_0+\frac{\partial}{\partial z}\int_0^t\left(\frac{\mu}{S_C}+\frac{\mu_T}{S_{CT}}\right)\frac{\partial M_a}{\partial z}d\tau-\int_0^t\rho V_a d\tau-\frac{\partial}{\partial z}\int_0^t\rho(\alpha_{2z}+u_{z1})M_a d\tau\\ \rho u_{2z}=\rho U_0-\frac{\partial}{\partial z}\int_0^t p d\tau+\frac{\partial}{\partial z}\int_0^t\sigma d\tau+\int_0^t\rho g d\tau-\frac{\partial}{\partial z}\int_0^t\rho(\alpha_{2z}+u_{1z})^2 d\tau\\ \rho E=\rho_0 E_0+\frac{\partial}{\partial z}\int_0^t\left(\frac{\mu}{S_C}+\frac{\mu_T}{S_{CT}}\right)\frac{\partial E}{\partial z}d\tau+\frac{\partial}{\partial z}\int_0^t q_z d\tau-\frac{\partial}{\partial z}\int_0^t\rho(\alpha_{2z}+u_{1z})E d\tau\end{cases} \tag{6}$$

Not yet known average value α_{2z} was calculated by using the following standard relation [3-5].

$$\alpha_{2z}=\frac{1}{\Theta L}\int_0^\Theta\int_0^L[u_{2z}(z,t)-u_{1z}(z,t)]dzdt \tag{7}$$

Substitution of relations (3) and (6) into relation (7) gives a possibility to obtain a relation to determine the required average value in the following form

$$\alpha_{2z}=-\frac{U_0^2}{\Theta L}\int_0^\Theta(\Theta-t)\rho dt\Big/\left[1+2\frac{U_0}{\Theta L}\int_0^\Theta(\Theta-t)\rho dt\right] \tag{8}$$

The projection of the fuel intake velocity u_z was calculated as the second-order approximation in the framework of the method of averaging function corrections. The second-order approximation is usually a good approximation for qualitative analysis and obtaining quantitative results. The results of the analytical calculation were checked by comparing them with the results of the numerical simulation.

3. Discussion

In this section, we analyze the changes in the densities considered over time. Figure 1 shows typical dependences of the considered densities on time at different values of the mass fraction of the considered component Ma. Figure 2 shows typical dependences of the considered densities on time at different values of the rate of the consumption of components as a result of combustion Va. Dependences of densities of the considered gases are qualitatively similar to dependences in Figures 1 and 2.

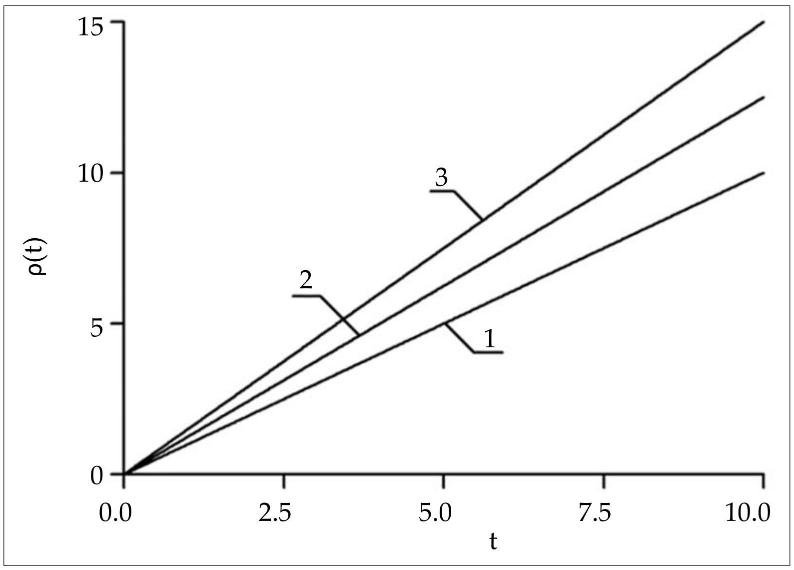

Fig. 1 Typical dependences of the considered densities on time at different consumption values of the mass fraction of the considered component M_a. Increasing the number of curves corresponds to increasing the value of parameter M_a.

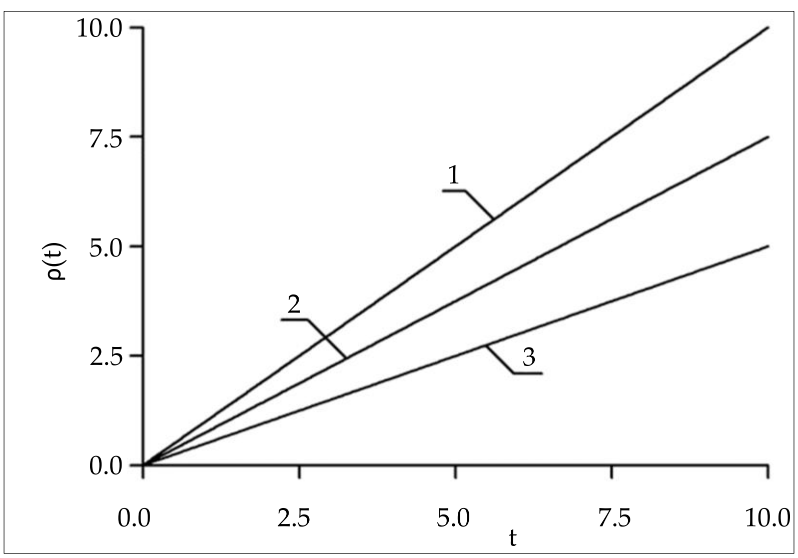

Fig. 2 Typical dependences of the considered densities on time at different values of the consumption of components as a result of combustion V_a. Increasing the number of curves corresponds to increasing the value of parameter V_a.

4. Conclusion

In this paper, we introduce a model and analytical approach to the analysis of the combustion process. We investigate regimes of combustion at different values of appropriate parameters.

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