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INFLUENCE OF ABSORPTION OF THERMAL RADIATION IN THE SURFACE WATER FILM ON THE CHARACTERISTICS AND IGNITION CONDITIONS

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Abstract. The results of the mathematical modeling of homogeneous particle ignition process of coal-water fuel covered with water film have been presented in article. The set co-occurring physical (inert heating, evaporation of water film) and thermochemical (thermal degradation, inflammation) process have been considered. Heat inside the film has been considered as the model of radiation-conductive heat transfer. Delay times have been determined according to the results of numerical modeling of the ignition. It has been shown that the water film can have a significant impact on performance and the ignition conditions. It has been found that heating main fuel layer occurs in the process of evaporation of water film. For this reason, the next (after the evaporation of the water film) thermal preparation (coal heating, thermal decomposition of the organic part of the fuel) and inflammation occur faster.

1 Introduction

Prospects for the use of coal-water fuel (WCF) as the main thermal in the power plants and local boilers have been sufficiently justified [1, 2]. To date, the investigations of water-coal technologies are being carried out intensively both in Russia and abroad [3, 4]. However, despite this, the widespread adoption of WCF in the fuel and energy complex (FEC) has not yet occurred. The latter may be due to a number of objective and subjective reasons. Subjective reasons include economic factors (substantial cost advantage of gas over coal [5]) and technological reasons. The objective reasons are insufficient knowledge of the main thermo-physical processes (slow heating, evaporation of water) and thermochemical processes (thermal degradation, inflammation) occurring together during the thermal preparation of the WCF particles to inflammation [6-9].

Experimental studies of coal-water fuel drops ignition is difficult, due to the need for placement of equipment of high-speed video fixation in high-temperature gaseous atmosphere (combustion camera)[10]. Additional difficulties with the registration of the moment of ignition (the appearance of open flames) occur on the background of the furnace environment. For this reason, the use of mathematical modeling is the most appropriate for studying the thermal preparation and ignition of coal-water fuel particles. However, it

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should be noted that the main problem of mathematical description of such inhomogeneous and high-wet fuels is complex (joint) occurring of basic physical and chemical (inert heating, water evaporation, thermal decomposition of the organic part of the fuel, ignition) processes under conditions of high-temperature heating.

It is known that the processes of phase conversions (in particular water evaporation) are one the most difficult in terms of the mathematical formulation. This is because that the phase transition (in particular evaporation) occurs in a very narrow (much less than the linear dimension of the particle) constantly moving zone (front of evaporation) [13, 14]. The models [15-20], describing the phase transitions (such as evaporation) have been developed at present, but most of them are based on the considerably simplifying assumptions of modeling procedure. For example, there are such means as the equilibrium parameters (temperature, evaporation rate) of the phase transition at the boundary front [15], the use of the heat balance method [16] or damp-potential model [17]. Previously, it has been found [18] that two drop systems can be formed during WCF spraying. The first system is consisted of carbon particles coated by water film. The second system has only coal-water droplets. The ignition of coal-water droplets has been considered in detail in [19]. At the same time, the question of ignition of homogeneous coal particles coated with a film of water remains little studied [20]. A film of water can influence significantly on ignition conditions of these particles. This influence is caused by the high endothermic effect of the water vaporization (up to 2.5 MJ / kg) and the ability of the water to absorb and dissipate the radiation (dependent on incident wave spectrum) [21]. It is safe to say that the surface layer of water may have a significant effect on the characteristics of the particles and WCF ignition conditions. This is due to several factors. The first factor is the high endothermic effect of water evaporation and heat capacity of water. The second important factor is that water is optically thin environment (depending on the incident radiation of wavelength) [21]. Accordingly, in a high-temperature heating is expedient to take into account not only conductive but also radiative heat transfer within the film. The problem about emission of electromagnetic radiation (in a range of) to a thin film of water up to the present days has been hardly studied.

The aim of this study is mathematical modeling of heat and mass transfer processes during the ignition of coal particles coated by water film, taking into account the absorption of thermal radiation by water.

2 Formulation of the problem

The following physical model of the ignition has been accepted. At the initial time ($t = 0$), a drop of WCF particles coated by water film enters the conditions corresponding to the combustion chamber of the boiler unit. Under the influence of high-intensive radiative-convective heat flow film of water begins to evaporate. As a result, the particle size decreases. As a result of intense radiation and convection heating is initiated by water evaporation. The mass velocity of the "dehydration" (and hence the endothermic effect) depends on the temperature of the surface water film. Radiation heat exchange between the coal particles and the external environment is carried out at high temperatures (T>1000K). The part of the thermal radiation is absorbed by the water film.

Boiling water occurs by heating the system boundary "coal – water" to vaporization temperature. The process of thermal decomposition and ignition is initiated after removing of the film particles WCF in a continuing heating process. It is assumed that particles on the surface of carbon oxidation reaction occur: It is assumed that the coal is composed predominantly of carbon, respectively, on the particle surface oxidation reaction proceeds as follows:

$$\mathrm{C} + \mathrm{O}_2 = \mathrm{CO}_2 + 402{,}4kJ$$

The mathematical formulation of the problem, the corresponding stated higher of physical model is a non-stationary system of differential equations in partial derivatives:

- the energy equation for a homogeneous coal:

$$C_1\rho_1\frac{\partial T_1}{\partial t}=\lambda_1\cdot\frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2\frac{\partial T_1}{\partial r}\right]\pm\sum Q_i\cdot W_i \qquad (1)$$

$$t>0,\ 0<r<r_1.$$

- the energy equation for the film of water:

$$C_2\rho_2\frac{\partial T_2}{\partial t}=\lambda_2\cdot\frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2\frac{\partial T_2}{\partial r}\right]-C_sW_v\frac{\partial T_2}{\partial r}+q_r\cdot\exp(-\chi_\lambda\cdot r) \qquad (2)$$

$$t>0,\ r_1<r<r_0(\tau).$$

- the equation of chemical kinetics for homogeneous part of fuel:

$$\frac{\partial\eta}{\partial t}=\left[1-\eta(r,t)\right]\cdot k_0\cdot\rho\cdot\exp\left[-\frac{E}{R\cdot T(r,t)}\right] \qquad (3)$$

$$t>0,\ 0<r<r_1$$

The system of equations (1-4) has been solved with the following boundary conditions and closing ratios:

$$0<r<r_0,\ T(r,0)=T_0,\ \eta(r,0)=\eta_0$$

$$-\lambda_2\frac{\partial T_2}{\partial r}\bigg|_{r=r_0}=\alpha\cdot[T_e-T_2(r_0,t)]+\varepsilon_2\cdot\sigma\cdot[T_e^4-T_2^4(r_0,t)]-Q_vW_v \qquad (6)$$

$$-\lambda_1\frac{\partial T_1}{\partial r}\bigg|_{r=r_1}=\alpha\cdot[T_e-T_1(r_1,t)]+\varepsilon_1\cdot\sigma\cdot[T_e^4-T_1^4(r_1,t)] \qquad (7)$$

$$\frac{\partial T_1(0,t)}{\partial r}=0 \qquad (8)$$

There is (4) the boundary condition of the fourth kind at the interface of the “homogeneous coal — water film”, taking into account the radiation heat transfer in the system “homogeneous coal — environment” and the thermal effect of vaporization:

$$\lambda_1\frac{\partial T(r,t)}{\partial r}\bigg|_{r=r_1-0}=\lambda_2\frac{\partial T(r,t)}{\partial r}\bigg|_{r=r_1+0}+q_r-W_vQ_v \qquad (4)$$

$$T_1(r_1;t)=T_2(r_1;t)=T_{w-c}(t)$$

The radiant heat flux on the boundary of the system interface “homogeneous coal — water film”, has been calculated from the mathematical expression of the law of Bouguer [22]:

$$q_r=\varepsilon_1\cdot\sigma\cdot\left[T^4(r_1,t)-T_e^4\right]\cdot\exp\left[-\chi_\lambda\cdot\left(r_0(\tau)-r_1\right)\right] \qquad (5)$$

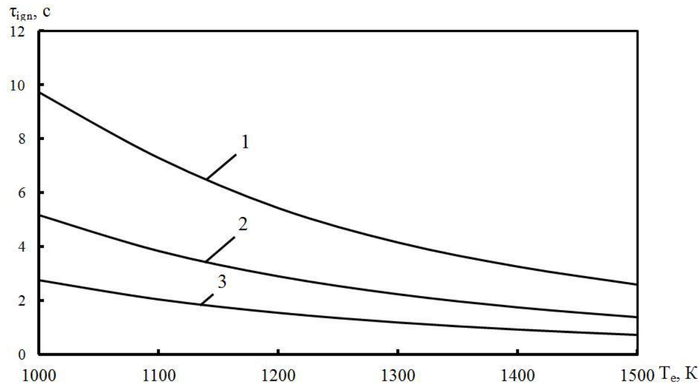

Fig. 1. The dependence of the ignition delay times of the ambient temperature at a rate (δ) particles: 1-δ=0, 5·10^{-3}m; 2-δ =0,3·10^{-3}m; 3-δ =0,2·10^{-3}m.

The rate of chemical reactions has been calculated from the mathematical expression of the Arrhenius law:

$$W_i = k_i \cdot \rho_i \cdot \exp\left(-\frac{E}{R \cdot T\left(r,t\right)}\right) \tag{9}$$

The rate of chemical reactions has been calculated from the mathematical expression of the Arrhenius law:

$$W_{td} = \left(1-\eta\left(r,t\right)\right)\cdot k_0 \cdot \rho \cdot \exp\left(-\frac{E}{R\cdot T\left(r,t\right)}\right) \tag{10}$$

The designations: T_0— is the initial temperature of the particles, K; T_e — is the temperature of the environment, K; $T_{w\text{-}c}$ — is the temperature at boundary section of the “coal — water”, K; r_1 — radius of coal particle, m; r_0 — external WCF particle radius, m; σ — is a constant radiation of a black body; α — coefficient of convective heat transfer, $W/(\text{m}^2\cdot\text{К})$; λ_1 — the coefficient of thermal conductivity of the homogeneous part of the WCF, $W/(m\cdot\text{К})$. λ_2 — the coefficient of thermal conductivity of water, $W/(m\cdot\text{К})$; C_1 — specific heat homogeneous part of WCF, $J/(kg\cdot\text{К})$; C_2 — the specific heat of water, $J/(kg\cdot\text{К})$; W_{eva} — mass the rate of water evaporation, $kg/(\text{m}^2\cdot\text{s})$; Q_{eva} – is the thermal effect of the water evaporation , J/kg; Q_i — is the thermal effect of chemical reaction, J/kg; k_i — preexponent of chemical reaction $1/\text{s}$; E_i – the activation energy of a chemical reaction, $J/mole$; χ_λ — average-spectral coefficient of radiation absorption 1/m.

The mass evaporation rate has been calculated from the expression [23]:

$$W_v = W_0 \cdot \exp\left[\frac{Q_v\cdot\mu\cdot\left(T_s - T_f\right)}{R\cdot T_f\cdot T_s}\right] \tag{11}$$

Where: $\boldsymbol{T_1}$ — is the temperature at the boundary of evaporation, K; $\boldsymbol{T_0}$ — is the temperature of the liquid corresponding to the freezing point, K; $\boldsymbol{W_0}$ — the velocity of evaporation at temperature, $\boldsymbol{kg/(\mathbf{m}^2\cdot \mathbf{s})}$; $\boldsymbol{\mu}$ — molar mass of water vapor, $\boldsymbol{kg/mole}$; R — universal gas constant, $\boldsymbol{J/(mole\cdot K)}$.

3 The results

Figure 1 shows the dependence on the delay time of ignition homogeneous water coal particles coated with a water film, the temperature of the environment. The sizes of the particle have been varied in the range of $\delta = 0,2 \div 0,5 \cdot 10^{-3}$ m at a film thickness $\Delta=0,05\cdot10^{-3}$m.

Dependency analysis (fig. 1) shows that the temperature of the external oxidant has a significant impact on the dynamics of the processes of thermal preparation and ignition of WCF particles. So we can say that for a particle with the diameter of $\delta = 0,5\cdot10^{-3}$ m temperature increase at 500K (from 1000 K to 1500 K), accelerates significantly ignition [approximately 3 times (delay time decreases from 10 seconds to 3)]. The latter can indicate the important role of the complex processes of evaporation of water film radiative-convective heat transfer, the heating up of base layer of fuel and the thermal decomposition of the organic carbon in the temporal characteristics of the thermal preparation steps. At the same time it should be noted that in the case of ignition of WCF drops with the diameter $\delta = 0,2 \cdot 10^{-3}$ m, the degree of this influence is negligible, which may also indicate the important role of the temperature distribution along the radius of the particle. Consequently, the application of balance-type models [16] during the predictive modeling of ignition of fuel can lead to large errors in determining the ignition delay times.

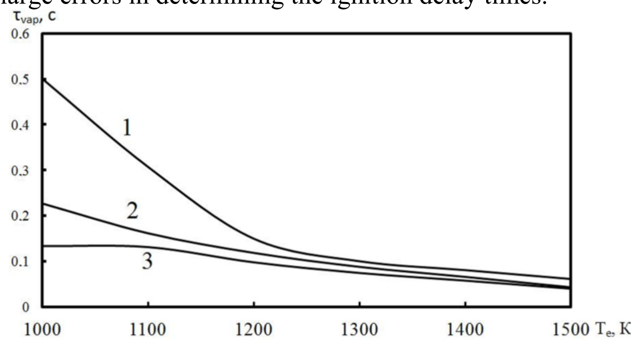

Fig. 2. The dependence of the evaporation times particle diameters rum ($\delta = 0,5 \cdot 10\text{-}3$m) on the ambient temperature at a film thickness (Δ): 1-0,15·10-3 m; 2- 0,1·10-3 m; 3-0,05·10-3 m.

Figure 2. shows the dependence of the evaporation times (particles of coal-water fuel with the diameter $\delta = 0,5 \cdot 10^{-3}$ m) on the ambient temperature by varying the thickness of the water film ($\Delta = 0,05 \div 0,15\cdot10^{-3}$ m). The analysis of the graph shows that the evaporation of water film can affect the dynamic of the thermal preparation. At this evaporation time of water film can take up to 10% of the total induction period. This is because in a small film thickness and penetration depth of the water heat radiation layer increases temperature of the latter which is much faster than excluding radiative intra-film heat transfer. Accordingly, it can be concluded that heating the base layer of fuel occurs in the water film evaporation process and the subsequent ignition takes place faster. The analysis of the curves (1) — (3) shows that at high temperatures (T_e>1200K) difference of evaporation time of a film is negligible, despite the substantial (more than 3 times) changes in Δ. At the same time difference in values τ_{vap} increases significantly at ambient temperature T_e<1200K. The latter indicates a significant effect of intra-film radiative heat transfer.

4 Conclusion

The basic temporal characteristics of processes of heat and ignition homogeneous preparation of coal-water fuel particles coated with a water film have been determined according to the results of numerical modeling. It has been found that the water film can affect significantly the dynamic of the thermal preparation. At this evaporation time of water film can take up to 10% of the total induction period. Radiative intra-film heat transfer plays a significant role this is due to the fact that it is under conditions of high heat. Accordingly, it can be concluded that heating of the base layer of fuel occurs in the water film evaporation process and steps of thermal preparation (inert heating, the thermal decomposition of organic fuel, ignition) proceed significantly faster than without the water film.

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