Combustion of a coal dust suspension in a pipe during the swirl

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Abstract. This manuscript presents the research on the combustion problem of a coal dust suspension in a pipe under the swirl flow condition. The physico-mathematical model is based on the approaches of the mechanics of multiphase reacting media by R. I. Nigmatulin. The solution to the problem is performed in a two-dimensional axisymmetric formulation. Godunov's scheme is used to solve the equation system of the model. The paper provides the results of the parametric analysis of the problem and data on the influence of the flow swirl on the gas temperature fields in the pipe at the initial stage of combustion. The presence of a significantly swirl flow leads to the incomplete combustion of coal dust in the pipe.

1. Introduction
Swirl combustion is currently one of the most important engineering problems in combustion physics. There is a hypothesis about increasing the combustion efficiency of the reacting gas mixtures in the swirl combustion chambers [1], as well as improving the efficiency of the fuel burning devices [2–5]. The combustion of the gas suspensions in vortex burners is the object of thorough investigation for a number of authors. The swirling is believed to lead to the heat transfer intensification and, consequently, to the increase in efficiency of the dispersed fuel combustion. The Reynolds equations [3] or the Navier-Stokes equations [1], which take into account the turbulent sources, are usually used to simulate the swirling flows. The choice of the turbulence model depends on the combustion conditions.

In the present study, it is proposed to model the swirl flow in a cylindrical pipe by taking into account the angular component of the flow velocity. The aim of the research is to determine the influence of the angular component on the flow and combustion characteristics of a coal dust gas suspension in the pipe.

2. Mathematical model and solution method
We have solved the combustion problem of a coal dust suspension in the air in a two-dimensional axisymmetric formulation. The system of equations describing the motion of the suspension takes into account the axial and radial change of the flow velocity and it is supposed that the derivative of the flow velocity due to angular component is equal to zero. It is assumed that before the process begins, the pipe is filled with a cold air and there are no particles of coal dust. The right end of the pipe is open, whilst the left end is the inlet of the coal dust suspension heated to a high temperature. The incoming coal dust-air flow is swirling. The diffusion and thermal conductivity processes in the gas phase are neglected. The heated particles of coal dust are known to be capable of chemical reaction. The first-order heterogeneous oxygen reaction proceeds on the particle surface. The rate of the
The reaction is limited by the mass transfer coefficient $\beta$ [7]. The model takes into account the interaction between particles and gas phase.

The physical-mathematical formulation of the problem is based on the approaches of the mechanics of multiphase reacting media by R.I. Nigmatulin [6] and on the previously developed physical-mathematical model of the coal dust suspension combustion in the air [7]. Under the formulated assumptions, the model includes the following conservation law equations for the gas and particles:

$$\frac{\partial \rho_g}{\partial t} + \frac{\partial (\rho_g u_g)}{\partial x} + \frac{\partial (\rho_g v_g)}{\partial r} = rG,$$  \hfill (1)

$$\frac{\partial \rho_g u_g}{\partial t} + \frac{\partial (p_g + \rho_g u_g^2)}{\partial x} + \frac{\partial (p_g v_g)}{\partial r} = -r \tau_g + rG u_g,$$ \hfill (2)

$$\frac{\partial \rho_g v_g}{\partial t} + \frac{\partial (p_g + \rho_g v_g^2)}{\partial x} + \frac{\partial (p_g u_g)}{\partial r} = -r \tau_g + rG v_g + \rho w_g^2,$$ \hfill (3)

$$\frac{\partial \rho_g w_g}{\partial t} + \frac{\partial (p_g + \rho_g w_g^2)}{\partial x} + \frac{\partial (p_g u_g)}{\partial r} = -r \tau_g + rG w_g - \rho_s w_g v_g,$$ \hfill (4)

$$\frac{\partial \rho_{oa}}{\partial t} + \frac{\partial \rho_{oa} u_g}{\partial x} + \frac{\partial \rho_{oa} v_g}{\partial r} = -r \alpha \rho G,$$ \hfill (5)

$$\frac{\partial \rho_{oa} u_g}{\partial t} + \frac{\partial \rho_{oa} (v_g + p_g)}{\partial x} + \frac{\partial \rho_{oa} v_g}{\partial r} = -r \left[ u_k \tau_s + v_k \tau_s + w_k \tau_b + n_k \alpha_k S_k \left(T_k - T_k^0\right)\right] + 0.5G \left(u_k^2 + v_k^2 + w_k^2\right),$$ \hfill (6)

$$\frac{\partial \rho_{oa} v_g}{\partial t} + \frac{\partial \rho_{oa} \left(u_g + p_g\right)}{\partial x} + \frac{\partial \rho_{oa} u_g}{\partial r} = r \tau_s - rG u_k,$$ \hfill (7)

$$\frac{\partial \rho_{oa} v_g}{\partial t} + \frac{\partial \rho_{oa} v_g}{\partial x} + \frac{\partial \rho_{oa} u_g}{\partial r} = r \tau_s - rG v_k + \rho w_k^2,$$ \hfill (8)

$$\frac{\partial \rho_{oa} w_g}{\partial t} + \frac{\partial \rho_{oa} w_g}{\partial x} + \frac{\partial \rho_{oa} u_g}{\partial r} = r \tau_s - rG w_k - \rho_s w_k v_k,$$ \hfill (9)

$$\frac{\partial \rho_{oa}}{\partial t} + \frac{\partial \rho_{oa} (e_g + p_g)}{\partial x} + \frac{\partial \rho_{oa} e_g}{\partial r} = r QG + \rho G \left[u_k \tau_s + v_k \tau_s + w_k \tau_b + n_k \alpha_k S_k \left(T_k^0 - T_k\right) - G \left(u_k^2 + v_k^2 + w_k^2\right)\right],$$ \hfill (10)

and the initial conditions:

$$u_g(x,r,0)=v_g(x,r,0)=w_g(x,r,0)=u_k(x,r,0)=v_k(x,r,0)=w_k(x,r,0)=0,$$

$$n_k(x,r,0)=p_k(x,r,0)=T_k(x,r,0)=0, T_g(x,r,0)=T_g^0, p_g(x,r,0)=0, p_{oa}(x,r,0)=a_{oa} \rho_{oa}. \hfill (13)$$

The boundary conditions at the axis $r = 0$ are:
\[
\begin{align*}
\frac{\partial u_y(x,0,t)}{\partial r} &= \frac{\partial u_y(x,0,t)}{\partial r} = \frac{\partial v_y(x,0,t)}{\partial r} = \frac{\partial v_y(x,0,t)}{\partial r} = \frac{\partial w_y(x,0,t)}{\partial r} = 0, \\
\frac{\partial n_k(x,0,t)}{\partial r} &= \frac{\partial n_k(x,0,t)}{\partial r} = \frac{\partial T_y(x,0,t)}{\partial r} = \frac{\partial T_y(x,0,t)}{\partial r} = \frac{\partial \rho_y(x,0,t)}{\partial r} = \frac{\partial \rho_y(x,0,t)}{\partial r} = 0. 
\end{align*}
\]

The following initial values are set at the inlet \((x = 0)\): the enthalpy, the gas flow rate, the gas and particle velocity along the radial and tangential directions, the oxidizer mass concentration in the gas, particle mass flow rate and the number of particles.

\[
H_y(0,r,t) = c_i T_y + \frac{u_y^2}{2} + \frac{w_y^2(0,r,t)}{2}, \quad H_y(0,r,t) = c_p T_y + \frac{u_y^2}{2} + \frac{w_y^2(0,r,t)}{2},
\]
\[
G_y(0,r,t) = u_y \rho_{gb}, \quad G_y(0,r,t) = \Delta u_y \rho_{gb}, \quad v_y(0,r,t) = v_y(0,r,t) = 0, \quad w_y(0,r,t) = w_y(0,r,t) = A_k (r/R), \quad n_k = V_y \rho_{gb} / (\Delta u_y \rho_{gb}), \quad a_{o2}(0,r,t) = a_{o2b}.
\]

The boundary condition at the outlet of the pipe \((x = L_o)\) is the atmospheric pressure.

In (1)–(15) the following notations are used: \(\varepsilon_g = p_g / (\gamma - 1) + 0.5 \rho_g (u_g^2 + v_t^2 + w_t^2)\) is the total energy of the gas, \(\varepsilon_k = c_i T_k \rho_k + 0.5 \rho_k (u_k^2 + v_t^2 + w_t^2)\) is the total energy of the particles, \(\alpha_k = N u \lambda_k / (2 r_k)\) is the gas-particle heat exchange coefficient, \(\gamma = c_p / c_v\) is the heat capacity ratio, \(\tau_{x,\gamma,\phi}\) is the friction force along axial, radial and tangential directions, \(\rho\) is the density, \(u, v, w\) are the axial, radial and tangential velocity components, \(t\) is the time, \(r\) is the coordinate, \(P\) is the pressure, \(T\) is the temperature, \(A_k\) is the maximum tangential velocity, \(A_k\) is the particle volume fraction in the whole mixture, \(r_k = \sqrt[3]{3 \rho_k / (4\pi n_k \rho_{gb})}\) is the particle radius, \(Q\) is the heat of the reaction; \(k_0\) is the chemical rate constant, \(a_y = \mu_{o2} \rho_{o2} / (r_y \sqrt{\gamma} \sqrt{\rho_g})\) is the oxygen discharge ratio in the reaction with the coal dust particles, \(\mu_{o2}\) are the molar masses of oxygen and carbon; \(v_{o2}, v_c\) are the stoichiometric coefficients of the reactions; \(a_{o2}\) is the mass fraction of the oxidizer in the gas phase, \(H_{yo}\) is the enthalpy of the gas and particles, \(G_{yo}\) is the gas and particle flow rate. The following subscripts are used: \(b\) for the initial parameters, \(k\) for the particles parameters, \(g\) for the gas parameters, \(st\) for parameters at the inlet, \(O2\) for oxygen.

The mass change rate of the particles during combustion is calculated from the expression:

\[
G = n_k S_m \rho_{o2} b_{o2} k_0 e^{-E_o/RT} \left[ \beta_m + k_0 e^{-E_o/RT} \right], \quad \text{where} \quad \beta_m = \lambda_y (T_y) N u \rho_{gb} / (c_y \rho_g r_k) \quad \text{is the mass-transfer coefficient.}
\]

The friction force along the axial direction is equal to \(\tau_{x,\gamma,\phi} = n_k F_{w,x} [7]\), where

\[
F_{w,x} = C_{w} S_m \rho \left( u_g - u_k \right) \left[ u_g - u_k \right] / 2 \quad \text{is the interaction force of a single particle with gas, is the friction coefficient,} \quad \text{Re}_{x} = 2 \rho_g r_k \left[ u_g - u_k \right] / \eta \quad \text{is the Reynolds number,} \quad S_m \quad \text{is the mid-sectional area,} \quad \eta \quad \text{is the dynamic viscosity of the gas. The components of the friction force along the radial and tangential directions were determined in a similar way.}
\]

The solution method of the problem is the same as in the study [7] and is based on the algorithms described in [8, 9]. The spatial grid steps along the axial and radial directions were set equal to \(10^{-3}\) m, the time step was calculated from the Courant–Friedrichs–Lewy condition [8].

3. Results

We have carried out the numerical investigation on the features of the combustion front motion. We have varied the size and mass concentration of the particles and the constant \(A_k\), which characterizes the flow swirl at the inlet. The aim of the parametric calculations is to determine the influence of the swirl on the combustion front motion in the coal dust suspension in the air and on the degree of
particle burn-out. The thermo-physical and kinetic parameters used in the calculations has been taken from [7]. The calculation results are presented in Figures 1 - 6.

Figure 1 shows the initial stage of the combustion in case of unswirled flow, whilst Figures 2-3 presents a swirling flow according to the law $u_0(0, r, t) = A_r(r/R)$, where $R$ is the radius of the pipe and $A_r$ is the maximum velocity along the angular component. The calculations have been performed for the suspension with the particle radius $r_p = 10^{-6} m$; the mass concentration of the particles supplied to the tube was equal to 5% of the supplied gas mass $\rho_{gb} = 0.05 \rho_g$; the axial feed rate was $u_{fb} = 2 m/s$. The particles are assumed to move together with the gas, the velocity lag of the particles is slight.

![Figure 1](image1.png)

**Figure 1.** Particle temperatures at time $t = 0.005 s$ (a), 0.015 s (b); $r_p = 10^{-6} m$, $A_r = 0 m/s$, $u_{fb} = 2 m/s$, $\rho_{fb} = 0.05 \rho_{gb}$.

![Figure 2](image2.png)

**Figure 2.** Particle temperatures at time $t = 0.005 s$ (a), 0.015 s (b); $r_p = 10^{-6} m$, $A_r = 1 m/s$, $u_{fb} = 2 m/s$, $\rho_{fb} = 0.05 \rho_{gb}$.

The effect of the combustion front inhomogeneity, arising due to the angular component of the flow velocity, can lead to the significant changes in the nature of the combustion wave propagation through the pipe. This effect can influence the combustion completeness of the suspension.

For the cases shown in Figures 3-4, the contours of the mass concentration of particles along the channel at the time $t = 0.015 s$ have the form shown in Figure 4. According to Figure 4, there is a region of unburned particles, located around the inlet and near the wall.

In the case of the unswirled flow, the combustion front motion can be described by the one-dimensional formulation. Whilst a swirled flow provides the inhomogeneous temperature distribution along the radius of the pipe (Figures 2, 3). In Figures 2-3, the maximum swirl velocities at the inlet are 1 and 10 m/s, respectively. The presence of a swirl leads to a bending of the combustion front, with a subsequent increase in the angular component of the gas velocity at the inlet, which shifts the combustion front to the side surface of the tube. Therefore, there is a significant heterogeneity of the temperature field.
The conducted calculations show that the swirling affects the temperature distribution in the pipe, therefore the temperature heterogeneity occurs during the steady state combustion. The steady-state temperature distribution is almost uniform along the pipe at the relatively low swirl speed ($A_z <= 0.5$ m/s). At high speeds, after the establishing the steady combustion regime, the fields of the gas temperature and particle mass concentration have the form shown in Figures 5-6.

According to Figures 5-6, a region of the unburned particles occurs near the pipe wall and there are no particles on the axis of symmetry. The maximum gas temperature is observed at a distance from the inlet and pipe wall. There are no unburned particles at the outlet of the pipe. Thus, the final combustion of the particles takes place at the outlet region of the pipe.

We also have conducted the calculations with large particles, which have a major velocity lag, due to greater inertia. In this case, the effect of the swirling is weaker, since large particles are less carried...
away by the swirled flow. Thus, swirling is of great importance in the case of a finely-divided coal dust combustion suspended in the air.

![Figure 6. Particles mass concentration at time $t = 0.1$ s; $r_k = 10^{-6}$ m, $A_z = 10$ m/s, $u_{xb} = 2$ m/s, $\rho_{kb} = 0.05 \rho_g$.](image)

4. Conclusion

We have developed a physical-mathematical model of coal dust combustion in the swirled airflow in a pipe. The model is axisymmetric and the swirling is taken into account by the tangential component of the velocity vector. Using the model, we have conducted a numerical study on the influence of the swirling speed on the gas temperature field inside the pipe and on the completeness of coal dust combustion. The obtained data shows that for the small particles, which is carried away by a swirling flow due to the low inertia, the presence of the swirling leads to the formation of a region with unburned particles at the inlet of the pipe and near the wall. The indicated features of the coal dust combustion during flow swirling can effect significantly on the flame propagation regimes in the suspension.

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