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PULVERIZED COAL COMBUSTION IN SWIRL BURNER IN CO_2/O_2 ATMOSPHERE

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Abstract

The paper presents results of numerical simulations of pulverized coal combustion process in swirl burner using RANS method. Numerical simulations have been performed for the oxyfuel test facility located at the Institute of Heat and Mass Transfer at RWTH Aachen University (Toporov et al. 2008).

Key words: oxy-combustion, pulverized coal, swirl burner

INTRODUCTION

Nowadays it is important to reduce emission of greenhouse gasses to the atmosphere during the combustion process. One way to reduce the emission is to introduce the alternative energy sources such as renewable energy sources or nuclear power. However, so far renewable energy sources cannot cover all the energy consumption and therefore conventional methods using fossil fuel are used. Coal plays an important role in electricity production due to its large reserves. To reduce the emission during coal combustion one may carry out the combustion process in oxygen environment. This method is well known as an oxy-combustion (Buhre et al. 2005, Toftegaard et al. 2010). During oxy-fuel combustion, oxygen is separated from air (typically averaged of 95% purity of oxygen) and mixed with recycled flue gas (RFG). In oxy-combustion a lower emission of NOx is achieved by removing nitrogen from oxidizer. In this case as a combustion products become mostly CO_2 and water vapour. Flue gas is then purified and recirculated to the combustion chamber. Combustion process carried out in O_2/CO_2 mixture differes from air combustion. This is due to differences in CO_2 and N_2 properties such as higher density and higher heat capacity of CO_2. In order to obtain adiabatic flame temperature similar to combustion in air, the proporion of oxygen passing through the burner should be about 30% higher than for air. The required amount of recirculated flue gases is about 70%. Attempts to burn pulverized coal in oxy-combustion technology in existing installations adapted for combustion in air bring problems with flame instabilities and weak degree of fuel burnout in swirl burners. Further development of oxy-fuel combustion technology can be supported by numerical methods – Computational Fluid Dynamics (CFD).

EXPERIMENTAL SETUP

Numerical simulations have been performed for the oxyfuel test facility located at the Institute of Heat and Mass Transfer at RWTH Aachen University (Toporov et al. 2008). The test rig is a vertical, cylindrical furnace with a length of the combustion chamber of 2.1m and an inner diameter of 0.4m. Geometry of the burner and 2D CFD mesh (composed of 26,630 cells) used in the simulation are presented in figure 1.

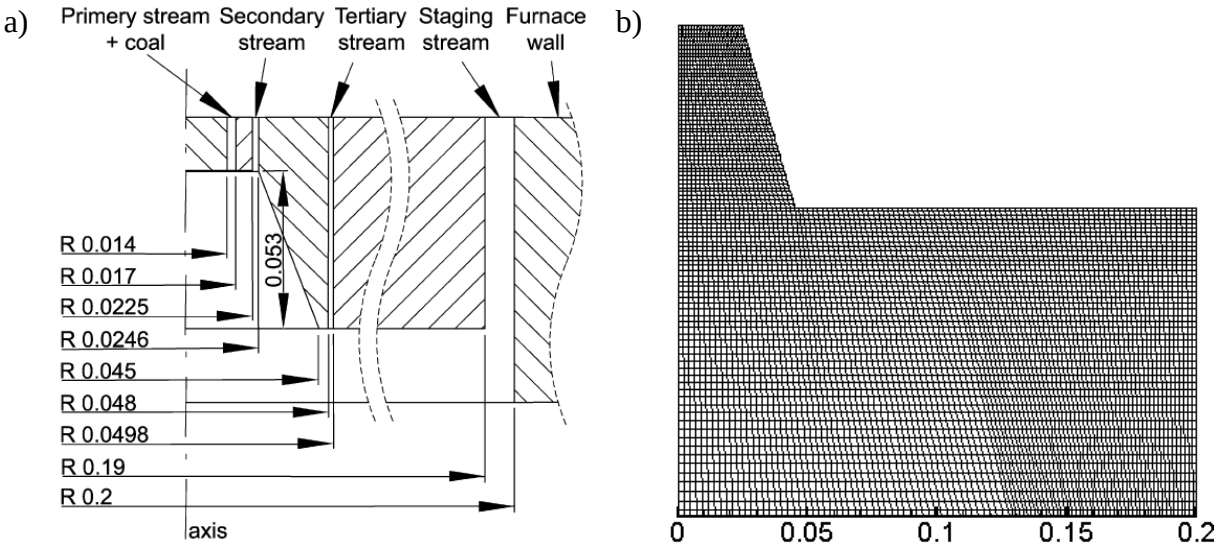

Fig. 1. View on: a) burner geometry (Toporov et al. 2008); b) CFD mesh (IMC).

Pulverized coal enters combustion chamber together with the primary air. Mass flow rate of fuel and air are 6.5 kg/h and 17.6 kg/h respectively. Secondary air mass flow rate is 26.6 kg/h and is highly swirled with the swirl number of 1.2. Flow parameters as well as proximate and ultimate analysis of the coal are summarized in tables 1 and 2. Pulverized coal is simulated as a discrete phase with particle size distribution 0.9 – 123μm with the mean diameter of 34.5μm.

Table 1. Parameters used in simulation.

	Mass flow rate (kg/h)	O_2 (%)	CO_2 (%)	Temperature (K)
Coal	6.5	-	-	313
Primary stream	17.6	0.19	0.81	313
Secondary stream	26.6	0.21	0.79	333
Tertiary stream	1.5	0.21	0.79	333
Staging stream	54.9	0.21	0.79	1173
Burner wall	-	-	-	573
Furnace wall	-	-	-	1273

Table 2. Coal proximate and ultimate analysis.

Proximate analysis				Ultimate analysis				
Fixed Carbon	Volatiles	Ash	Moisture	C	H	O	N	S
40.9	46.6	4.1	8.4	67.4	4.24	14.7	0.86	0.3

NUMERICAL MODEL

Numerical simulation of oxyfuel burner has been performed using commercial code ANSYS Fluent 13. 2D axisymmetric swirl solver has been used together with k-ε turbulence model to solve the flow field. The turbulence-chemistry interaction has been modeled using the finite-rate/eddy-dissipation model. Three homogeneous and three heterogeneous reactions have been considered with the kinetic rates of reactions taken from the work of Toporov et al. 2008 and Vascellari and Cau 2009 respectively:

Homogeneous reactions	Heterogeneous reactions
1. $C_xH_yO_zN_mS_n + (x/2 + n - z/2)\ O_2 \rightarrow x\ CO + y/2\ H_2 + n\ SO_2 + m/2\ N_2$	4. $C_{char} + ½\ O_2 \rightarrow CO$
2. $CO + ½\ O_2 \rightarrow CO_2$	5. $C_{char} + CO_2 \rightarrow 2CO$
3. $H_2 + ½\ O_2 \rightarrow H_2O$	6. $C_{char} + H_2O \rightarrow CO + H_2$

A single rate devolatilization model has been used, with the devolatilization product $C_xH_yO_zN_mS_n$ (volatile). The kinetic rates for devolatilization process has been taken from work of Khare et al. 2008, who has been investigating the ignition of flames in pulverized fuel swirl burner in air combustion retrofitted to oxy combustion. After volatile matter is released from the coal particles, heterogeneous reactions begins. The radiative heat source was calculated by the Discrete Ordinate (DO) radiation model implemented in ANSYS Fluent.

RESULTS

Numerical simulation of pulverized oxy-coal combustion are compared with experimental and numerical results obtained by group of Toporov et al. 2008 and a group of Kangwanpongpan et al. 2012, who recently has been investigating the radiation model on the same geometry. Group of Toporov et al. 2008 used CFD code Fluent 6.2 with k-ε turbulence model. Three dimensional grid, representing 1/6 of the whole furnace contained 590,800 cells. Devolatilization process was modeled using the chemical percolation devolatilization model (CPD) implemented via User Defined Function (UDF). Group of Kangwanpongpan et al. 2012 used commercial code ANSYS Fluent 12 with the Reynolds Stress Model (RSM) applied for the prediction of turbulent flow. A 1/6 of the whole furnace was used composed of approximately 100,000 cells. Similarly to Toporov et al. 2008 a CPD model was used for devolatilization process. Both authors used Finite-Rate/Eddy-Dissipation model (FR-ED) for turbulence-chemistry interaction with the homogeneous and heterogeneous reactions presented above. Additional homogeneous reverse reaction for CO_2 was modeled by the group of Kangwanpongpan et al. 2012.

Figure 1 shows distribution of mass source due to devolatilization process and char burnout for present simulations and results of Toporov et al. 2008. As one may observe a simple single rate devolatilization model (Fig. 2b, left hand side) gives comparable results to more advanced CPD model (Fig. 2a, left hand side).

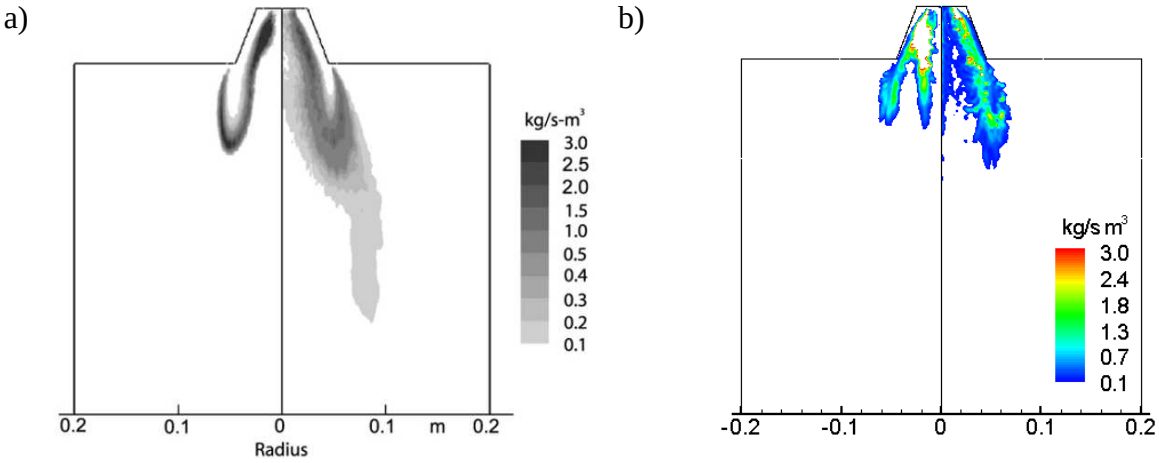

Fig. 2. Distribution of mass source due to devolatilization (left side of combustion chamber) and char burnout (right side of combustion chamber) for results of: a) Toporov et al. 2008; b) IMC.

Char burnout resulting from the heterogeneous reactions is similar for both simulated test cases. Taking into account Arrhenius coefficients for heterogeneous reactions depending on the temperature range (implemented by the group of Toporov et al. 2008) extends the char burnout process downstream. Nevertheless the mass source due to the more detailed char burnout reactions model is very small in downstream region. From both simulations one may see that the devolatilization process starts almost immediately after the coal particles enter the combustion chamber. As the coal particles are located inside the recirculation zone, both devolatilization and char burnout processes occur in this region leading to full burnout and flame stabilization.

Figures 3 and 4 show comparison of axial and tangential velocity profiles obtained in experiment and numerical simulations at two axial distances from the burner exit. Tangential velocity profiles were not available for the group of Kangwanpongpan et al. 2012. Numerical simulations of Toporov et al. 2008 and present results obtained in the Institute of Thermal Machinery (IMC) are similar for both velocities at two axial distances. As it can be seen, results for axial and tangential velocities give good agreement close to the burner exit and a small discrepancies can be seen further downstream. The reason for that could be the recirculation zone that is incorrectly predicted by the numerical model.

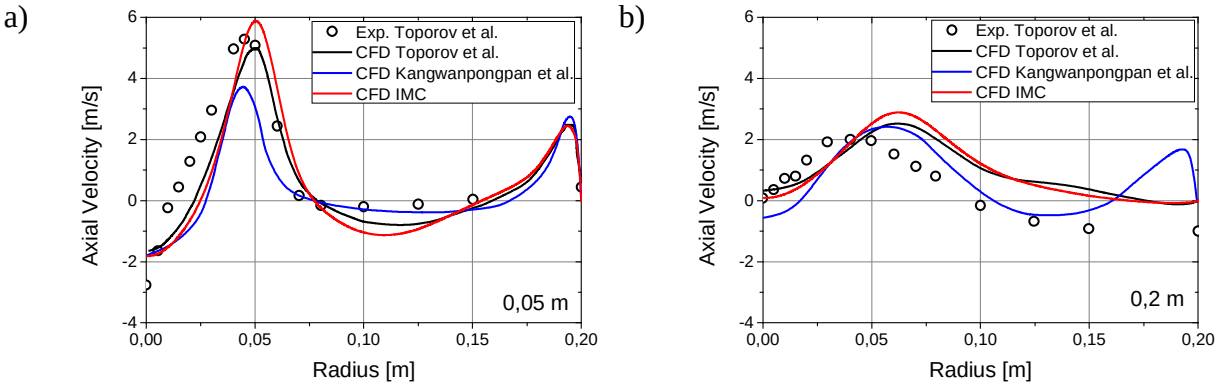

Fig. 3. Axial velocity at axial distance from the burner: a) 0.05m; b) 0.2m.

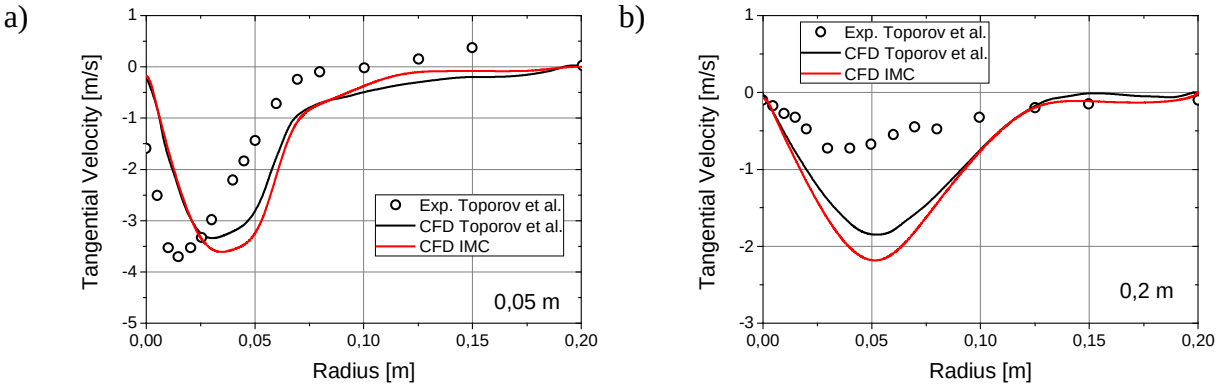

Fig. 4. Tangential velocity at axial distance from the burner: a) 0.05m; b) 0.2m.

Figure 5 presents results for temperature distribution at two axial distances from the burner exit. One may see that temperature obtained in numerical simulation differs from experimental data. First the temperature is overpredicted up to the radius R=0.024 and then is higly underpredicted in the range of radius R=0.025-0.051m. This is also the case for results of group of Toprov et al. 2008 and Kangwanpongpan et al. 2012. Although present results (IMC) give better prediction of temperature up to the radius R=0.075m, the temperature is much smaller after this radius.

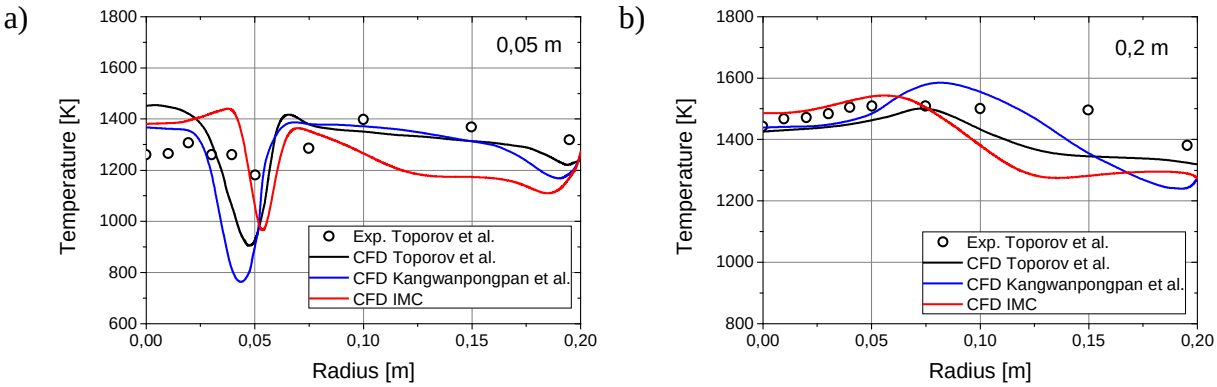

Fig. 5. Gas temperature at axial distance from the burner: a) 0.05m; b) 0.2m.

Figure 6 show results of oxygen concentration at two axial distances from the burner. Results of oxygen concentration for axial distance of 0.05m from the burner were not available for the group of Kangwanpongpan et al. 2012. As it can be seen, a low oxygen concentration in the region close to axis of the combustion chamber is predicted by all numerical simulations. In the close to wall region all numerical simulation highly overpredict the oxygen concentration.

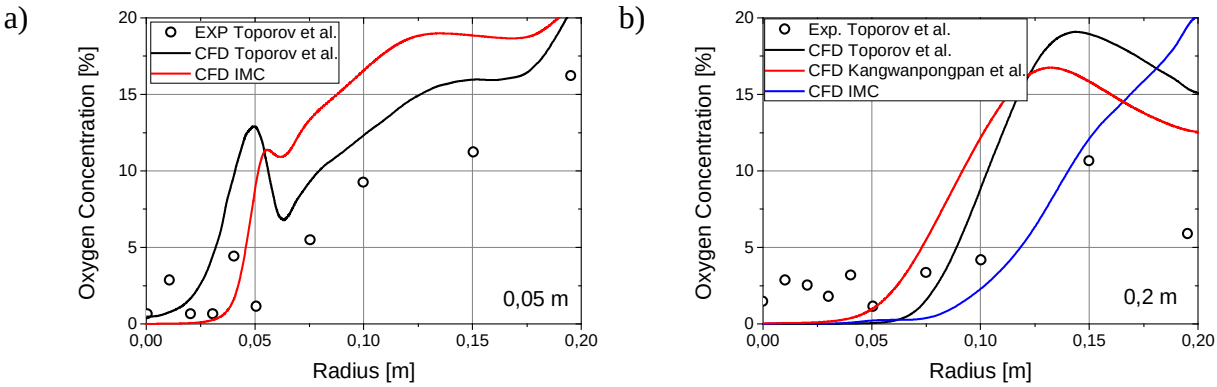

Fig. 6. Oxygen concentration at axial distance from the burner: a) 0.05m; b) 0.2m.

CONCLUSIONS

In the present paper the results of an oxy-combustion process of pulverized coal were shown for swirl burner located at the Institute of Heat and Mass Transfer at RWTH Aachen University. Comparison between experimental data and numerical simulations obtained by the researchers were presented. Present 2D axisymmetric swirl simulation shows similar results to 3D simulations representing 1/6 of the whole combustion chamber performed by the groups of Toporov et al. 2008 and Kangwanpongpan et al. 2012. Numerical results obtained by all the researchers show some discrepancies to the experimental data. The reason for that could be turbulence model or combustion mechanism used in all simulations. More work need to be done in this topic in order to correctly predict the recirculation zone which could give better overall results, using Large Eddy Simulation.

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