

# Verification of the Mathematical Model of Pulverized Coal Combustion in Swirl Burners

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*Mathematical model of pulverized coal combustion in furnaces with swirl burners is presented. The model is based on two equation  $k-\varepsilon$  single phase turbulent flow simulation model, considering presence of the solid phase via PSI-Cell method. Disperse phase is treated by Lagrangian Stochastic Deterministic model. The radiation heat transfer is treated via Six-Flux method. Coal devolatilization, homogeneous and heterogeneous reactions are modelled together via global combustion model using own reaction kinetics data. Model was verified comparing computational and experimental results for combustion of polydisperse pulverized coal in two experimental furnaces. It is concluded that the model can be successfully used for prediction, optimization of parameters and design of swirl burners, for different burner geometries, flow and temperature boundary conditions and coals of different rank.*

**Keywords:** pulverized coal, combustion, burners, swirl, turbulence.

## 1. INTRODUCTION

Swirl burners are widely used for pulverized coal combustion due to positive influence of swirl upon flame stabilization and combustion intensification. Detailed knowledge of processes going on in furnaces utilizing this effect is of great significance. The flow field is formed in such a way that within the central zone of the swirling stream emerging from the swirl burner, recirculation of hot gases takes place, thus ensuring stable ignition and combustion of the pulverized coal particles. Therefore, a complex mathematical and numerical model of pulverized coal combustion in an axisymmetric furnace with swirl burner i.e. within turbulent particle laden swirl flow in axisymmetric geometry is developed. The model is based upon the two equation  $k-\varepsilon$  single phase turbulent flow simulation model, considering the presence of the solid phase via the additional source terms in the gas phase equations. The model was verified by comparing computational and experimental results for combustion of polydisperse pulverised coal in two experimental furnaces. First, a pulverised bituminous coal flame in International Flame Research Foundation furnace No.1 in Ijmuiden (Netherlands) with a jet burner was considered, and modelling results compared with experimental and computational results of other authors. Then, pulverised lignite combustion within a furnace with a swirl burner was modelled and results compared with data obtained in measurements performed at horizontal axisymmetric furnace in Laboratory for Thermal Engineering and Energy in Vinča (Belgrade, Serbia & Montenegro).

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## 2. MATHEMATICAL MODEL

In swirl burners, coal particles are introduced with the primary air stream. The secondary stream, through a concentric annular opening, emerges as a swirl flow and induces recirculation of hot gases, for sufficiently high value of swirl, thus ensuring conditions for stable ignition and subsequent combustion of pulverized coal. The flow is axisymmetric, turbulent and incompressible. The stationarity is assumed for the mean time averaged values of flow parameters (velocity, temperature, etc.). The gas flow in the furnace is described by elliptic partial differential equations. The model is based upon standard single phase flow two-equation  $k-\varepsilon$  model of turbulence. Set of time averaged conservation equations can be expressed as an equation for the general variable  $\phi$ , which in cylindrical coordinates takes the form:

$$\frac{\partial}{\partial x}(\rho U \phi) + \frac{1}{r} \frac{\partial}{\partial r}(r \rho V \phi) = \frac{\partial}{\partial x} \left( \Gamma_{\phi} \frac{\partial \phi}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( r \Gamma_{\phi} \frac{\partial \phi}{\partial r} \right) + S_{\phi}. \quad (1)$$

In order to define completely the turbulent gas flow field in an axisymmetric furnace, it was necessary to establish and solve the following 9 equations of type (1):

- continuity equation,
- three momentum equations (axial, radial & tangential),
- two equations of turbulence model (kinetic energy of turbulence -  $k$ , dissipation -  $\varepsilon$ ),
- energy conservation equation,
- two continuity equations for flue gas components (oxygen, combustion products).

Based upon these equations, flow field is computed (fields of axial, radial and circumferential components of the mean velocity, temperature field, fields of  $k$  and  $\varepsilon$ , fields of concentration of flue gas components etc.).

which is used as initial data for the iterative procedure of computing the gas flow, the motion of the particles, momentum, heat and mass transfer between the phases. The PSI-Cell concept considers the disperse phase through the additional source terms in the gas phase conservation equations. The disperse phase is treated through history of particles by using LSD model (Milojević, 1985). One obtains local values of velocity, temperature and mass of particles, i.e. concentration of particles and particle trajectories. Particle motion is described via the Newton equation. Energy equation for particles is considered where net change of particle enthalpy per unit time is equal to heat transfer between the phases, which is treated as - forced convection from gas to sphere, and - radiation, by using the variant of the Six-flux method (Živković, 1990).

Within the framework of the complex model of pulverized coal combustion, a global combustion model has been chosen. This means that phenomena of devolatilization, homogeneous- and heterogeneous combustion are treated together, i.e. by using the global reaction rate based upon the measurements performed at experimental furnace built in Laboratory for Thermal Engineering and Energy, Institute for Nuclear Sciences, Vinča. This is due to several reasons. First, the pulverized coal combustion model is complex itself, so one should tend to simplify each of its components but to still preserve the accuracy of the computational results. Second, although some results exist on devolatilization rate of Yugoslav lignites (Jankes, 1990) there is a significant lack of reliable data for rates of combustion of volatiles and char for our coals. And, third, available data have been used on global combustion rate of domestic coals (Saljnikov et al., 1995). For simplicity, it is assumed that the gas phase consists of inert nitrogen, unused oxygen and the final products of complete coal combustion, i.e. carbon dioxide and water vapour. Thus, it is understood that all carbon and hydrogen from the fuel oxidize with the same (global) rate - performing single step reactions with the oxygen from the fuel and from the gas phase (reaching the particle surface by diffusion). It has been assumed that a particle reacts at the outer surface and inside pores (the unreacted core combustion regime) by reducing its volume, and that the chemical reaction is controlled by both kinetics and diffusion, as well:

$$\frac{dm_p}{d\tau} = \rho_p \frac{\pi}{2} d_p^2 \frac{d(d_p)}{d\tau} = -r_p \cdot \quad (2)$$

Reaction rate for kinetically-diffusionally controlled reaction is given by expression:

$$r_p = \frac{A_p v M_p C_{mol}^{ox}}{1/k_r + 1/k_d} \cdot \quad (3)$$

The reaction rate constant  $k_r$  is assumed to depend upon temperature by the Arrhenius law. The diffusion mass transfer coefficient  $k_d$  is determined from the experimental correlation for the Sherwood number. Considering the simultaneous oxidation of carbon to  $CO_2$  and hydrogen to  $H_2O$ , the stoichiometric

coefficient is  $v = (4H + 12C) / 12(C + H)$ . Because the outlined model is elliptic, boundary conditions should be defined at all boundaries of the combustion chamber. The conditions at the gas phase inlet are defined by the nature of the problem, and at the exit by continuity. At axis, gas and particles must satisfy axial symmetry. Conditions at wall are described by "wall functions".

### 3. NUMERICAL SOLUTION

The system of elliptic partial differential equations (1) is solved by the control volume numerical method (Patankar and Spalding, 1972). Basic algorithm SIMPLE for solving elliptic flow equations incorporated in TEACH-T numerical code (Gosman and Ideriah, 1976) was modified by involving computation of particle motion, trajectories, mass and temperature, and particle source terms due to momentum, heat and mass exchange between the phases. The two-phase flow solution includes the following steps:

**a** - solution of the single phase gas equations (1) without the particle source terms  $S_\phi^p$  until a reasonably converged solution is obtained,

**b** - for such a flow field, computation of particle trajectories, heat and mass transfer to/from gas, and the particle source terms  $S_\phi^p$ ,

**c** - solution of gas flow equations (1) with the particle source terms  $S_\phi^p$  included. Iteration steps **b** and **c** are repeated until desired convergence is achieved, and the final computation of particle trajectories, heat and mass transfer and flow properties is performed. The model was verified by comparing the computational and the experimental results (this means - flow, temperature and concentration fields, as well as particle trajectories) for the combustion of a polydisperse pulverised coal in the two experimental furnaces.

### 4. COMPARISON WITH EXPERIMENTS - IFRF FURNACE

A pulverised subbituminous coal flame within the International Flame Research Foundation (IFRF) furnace No.1 in Ijmuiden (Netherlands) with a jet burner was considered, and modelling results compared with experimental and computational results of other authors. The furnace is of square cross section - 2 m x 2 m, and 5.8 m long. It was approximated with one cylindrical axisymmetric furnace with the same cross section area i.e. with a 1.09 m radius. At the furnace exit there is a back wall with a 0.414 m radius circular outlet.

The swirl burner introduces primary air laden with coal particles through 70.3 mm opening at 70.8 g/s and 423 K. Secondary air is introduced through 74.3/260 mm annulus at 573.3 g/s and 763 K. Mass flowrate and temperature of particles at the inlet are 58.9 g/s and 423 K. Experiments were performed with polydisperse coal Saar (Germany) of the ultimate analysis (in mass %): C(73.1), H(4.6), O(10.9), N(0.8),

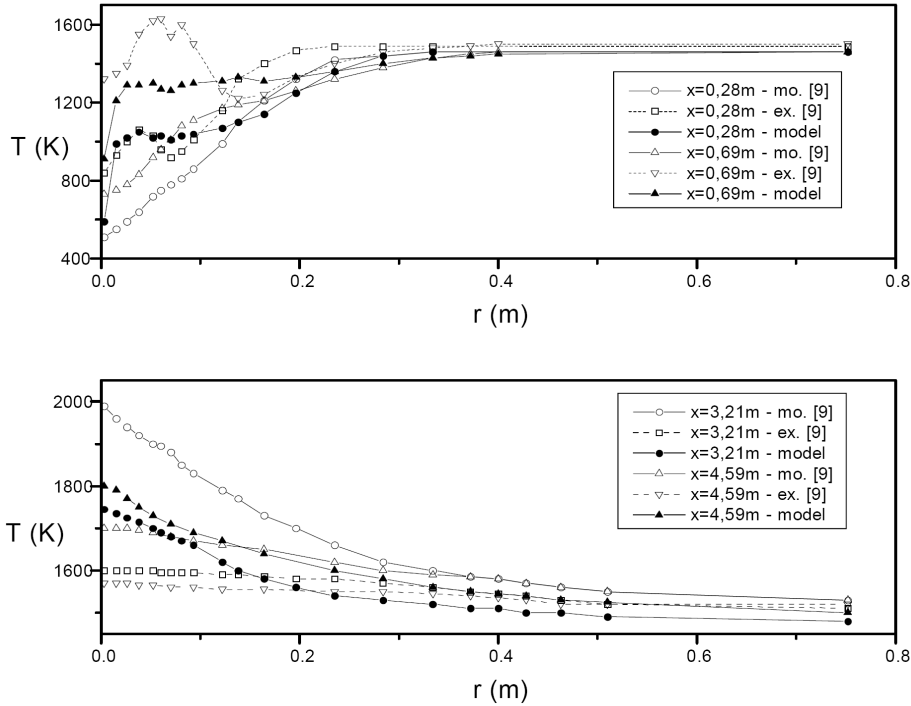


Figure 1. Radial profiles of temperature at different axial locations - results of other authors and results obtained by using the outlined model

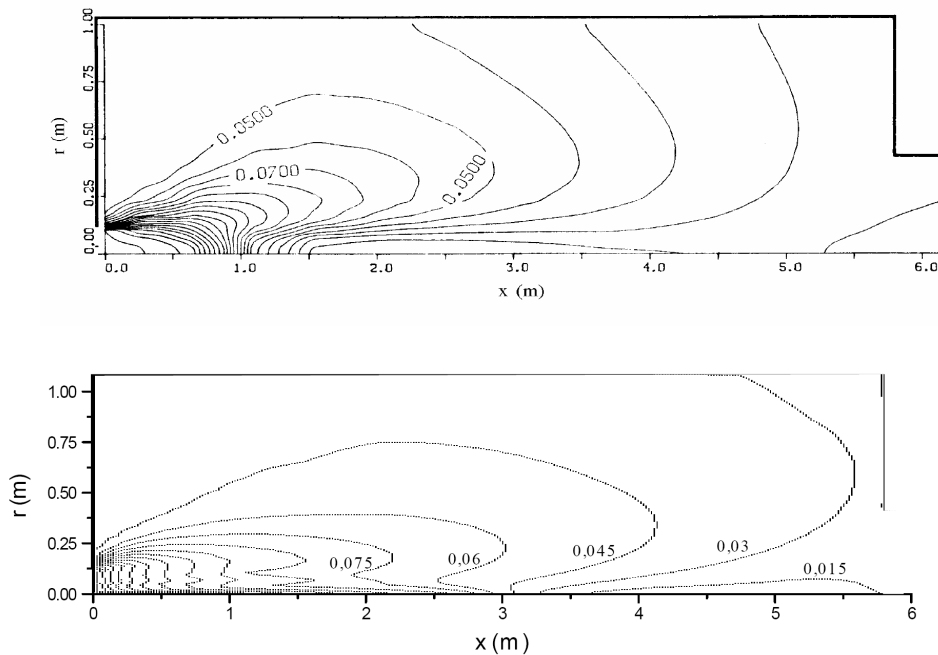


Figure 2. O<sub>2</sub> concentration field - other authors [9] (top) and the outlined model (bottom)

S (1.2), A (7.4), W (2.0) and the heating value  $H_d = 31.0 \text{ MJ/kg}$ . The pre-exponential term and the activation energy in Arrhenius expression for the reaction rate for that coal were not given. They were approximated by the values for a similar Russian subbituminous coal i.e.:  $k_0 = 7720 \text{ m/s}$  and  $E = 98200 \text{ kJ/kmol}$ . For computation purposes, the treated coal was divided into four fractions of diameter (and mass %):  $5 \mu\text{m}$  (30%),  $30 \mu\text{m}$  (25%),  $70 \mu\text{m}$

(22%),  $140 \mu\text{m}$  (23%). The wall temperature and the flue gas absorptivity were 1450 K and 0.25.

Computational results are compared with „in-flame“ measurement results, i.e. with the results of computation by using a model (Wennerberg, 1985) for quantities lacking the corresponding experimental data. The flow fields are almost identical. Differences in recirculation zone core locations can be attributed to approximate values of turbulence intensity level at furnace inlet, not given and hence assumed. Shape of isotherms is similar

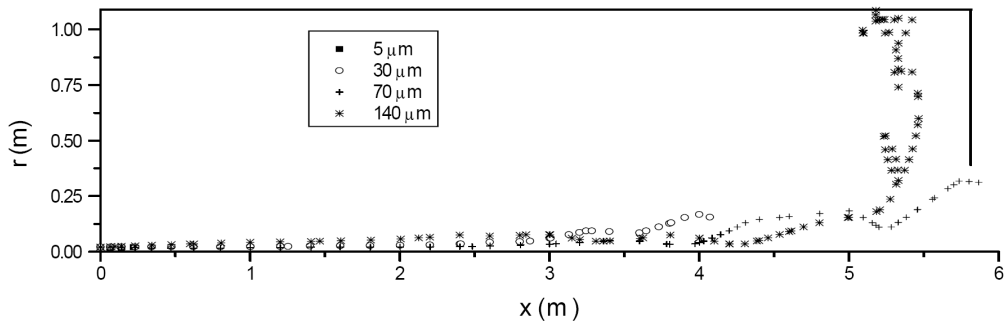


Figure 3. Trajectories of chosen particles of all fractions obtained by using the model

in the vicinity of the burner and in the rear part of the chamber. The differences in location and intensity of temperature maxima are due to differences between the two applied models of combustion, i.e. the separate modeling of coal devolatilization, diffusion and volatiles combustion, by Wennerberg, as opposed to global combustion of pulverized coal chosen in the outlined model. The same is concluded from Figure 1 where radial temperature profiles at four axial locations in the furnace are given. It is indeed important that temperature profiles obtained by using this model are quantitatively located in the region between the

computation and experimental results of Wennerberg which additionally confirms the verification.

In Figure 2 given are the corresponding oxygen concentration fields. The plots are very similar and well correlated with the temperature fields (Saljnikov, 1999). In Figure 3 shown are the trajectories of chosen particles of each fraction. The smallest particles ( $5 \mu\text{m}$ ) end their combustion at 1-1.5 m downstream from the burner. The  $30 \mu\text{m}$  particles burn out till the axial location 4-4.5 m, while practically all the  $70 \mu\text{m}$  particles exit the chamber as incompletely combusted.

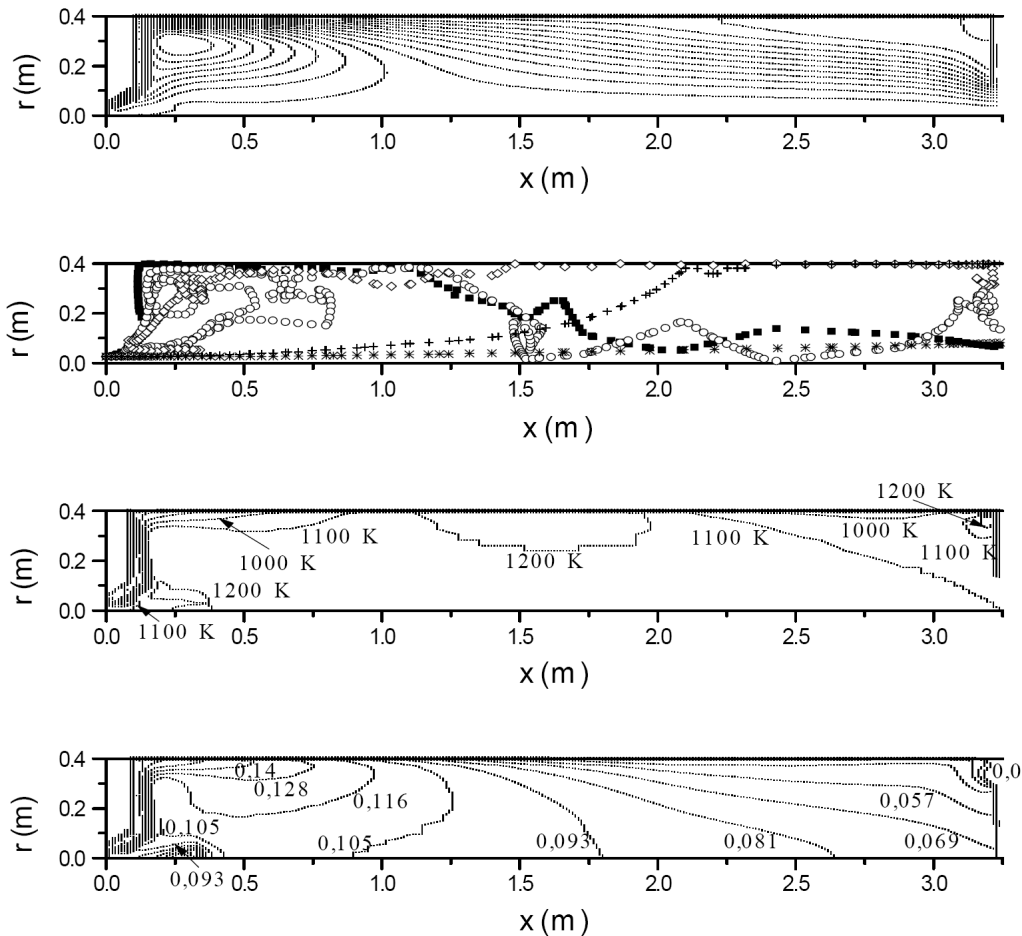


Figure 4. Computational results for the regime ( $T_{zl} = 500 \text{ K}$ ,  $tg\phi_s = 1.0$ )

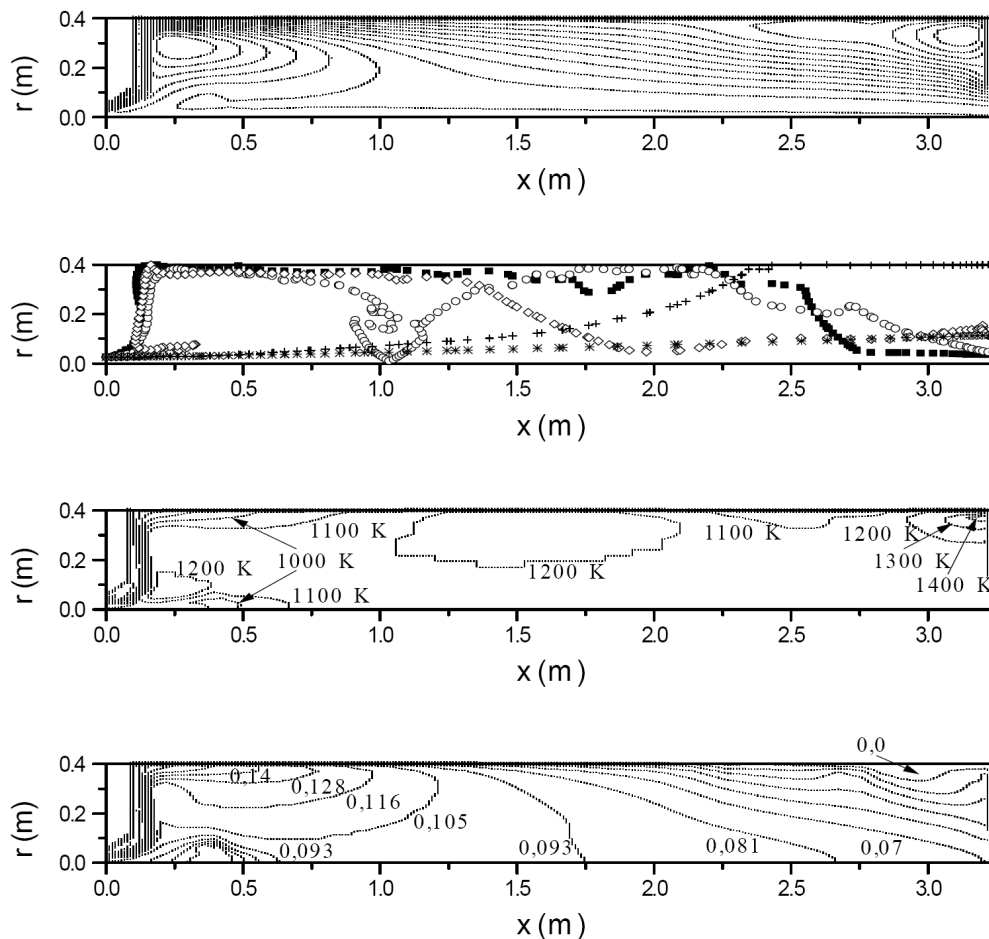


Figure 5. Computational results for the regime ( $T_{z1} = 500 \text{ K}$ ,  $\text{tg}\varphi_s = 0.75$ )

Some of the largest particles ( $140 \mu\text{m}$ ) before leaving the chamber shift to the wall where they end the combustion. This is induced by inertia of largest particles which enhances the effect of downstream spread of the central flow. Most particles flow along the axis, combust and release the heat, which complies with shape of the flow and existence of large external recirculation zone, practically free of particles.

Performed analysis indicates that the computational results, obtained by using the outlined model, comply well with experimental and computational results of other authors [9]. Noted differences are attributed to the lack of relevant data such as: coal density, reaction rate constants, and especially - intake air turbulence level.

## 5. COMPARISON WITH EXPERIMENTS- IBK-ITE FURNACE

A pulverised lignite combustion within a furnace with a swirl burner was modelled and the results compared with data obtained in measurements at the horizontal axisymmetric furnace in the Laboratory for Thermal Engineering and Energy (IBK-ITE) in Vincha. The furnace represents a central part of the experimental set-up built with the purpose of both development and testing constructions of swirl burners and investigating the pulverized coal combustion. Its design and performance characteristics are given in doctoral dissertation (Repić, 1992). Geometry of the modelled combustion cases was: a  $45^\circ$  and  $43.9/107 \text{ mm}$  diffuser

conveys the flow into  $3.12 \text{ m}$  long furnace of  $0.8 \text{ m}$  inner diameter. A swirl burner introduces primary air laden with coal particles through  $21.6/27.2 \text{ mm}$  annulus at  $19.4 \text{ g/s}$  and  $288 \text{ K}$ . Secondary air is introduced through  $30.2/43.9 \text{ mm}$  annulus at  $71.9 \text{ g/s}$  and  $313 \text{ K}$ . Coal particles enter the furnace at  $15.0 \text{ g/s}$ ,  $288 \text{ K}$  and  $1500 \text{ kg/m}^3$ , respectively. Polydisperse pulverised lignite from Kolubara basin (pit Polje D), was chosen, of the ultimate analysis (in mass %): C (40.54), H (3.94), O (17.2), N (0.8), S (1.13), A (25.96), W (10.43) and heating value  $H_d = 16.188 \text{ MJ/kg}$ . Pre-exponential term and activation energy in Arrhenius expression for reaction rate for that coal are:  $k_0 = 8900 \text{ m/s}$  and  $E = 95400 \text{ kJ/kmol}$ , determined by Saljnikov et al. (1995). It is assumed that particles are distributed along 300 different trajectories. Swirl intensity was determined by  $\text{tg}\varphi_s = 1.0$  in the first experiment and  $\text{tg}\varphi_s = 0.75$  in the second, and  $\lambda = 1.05$ . Particle size of 5 fractions of polydisperse powder of investigated coal (and respective mass %) are:  $25 \mu\text{m}$  (5.02%),  $70 \mu\text{m}$  (36.58%),  $145 \mu\text{m}$  (24.17%),  $350 \mu\text{m}$  (18.14%) and  $750 \mu\text{m}$  (16.09%).

The angle between the secondary air flow velocity vector and the burner (i.e. furnace) axis ( $\varphi_s$ ) was determined by direct measurement at the burner mouth at given values of air flowrate and temperature. The computations were performed, for both swirl intensities,

for the furnace wall temperature of 500 K, that is for conditions present in furnace during these tests which lasted less than ten minutes.

The experiments were time bound because of relatively large quantities of combusted coal, about 100 kg/h. The furnace walls could not reach the temperature present under stationary conditions. The computational results for  $tg\varphi_s = 1.0$  are presented in Figure 4, & those for  $tg\varphi_s = 0.75$  in Figure 5.

It is observed that the central recirculation zone (CRZ) is longer in the case of weaker swirl, and that that the temperature maximum is higher and wider spread grace to greater freedom that particles have in their motion through the oxygen rich zones in the front section of the furnace. After entering the furnace, the particles encounter the recirculated hot gases in the CRZ and their combustion begins. First their temperature sharply rises and then they are being cooled by their surroundings. The highest gas temperatures are in the zone of reverse flow of particles, their migration towards the furnace wall and the initial part of their migration along the wall. The smallest particles (25  $\mu\text{m}$ ), after weakening of centrifugal effect that took

them to the furnace wall, influenced by turbulent fluctuations, move irregularly throughout the chamber. So do the 70  $\mu\text{m}$  particles, however with stronger recirculation in the CRZ. Grace to this and to their size, the particles of the two smallest fractions end their combustion within the first and second meter of the furnace, measured from the burner mouth. By their intensive combustion close to the burner, they ensure more convenient temperature conditions even for combustion of the larger particles. The majority of the smallest and the largest particles leave the furnace without travelling through the back recirculation zone (BRZ). The particles of the three medium fractions, before leaving the furnace get into the BRZ and circulate through it. There they burn and release considerable amount of heat which is observed by location and intensity of the local temperature maximum in this zone. The oxygen concentration field follows the phenomena influencing the temperature field and history of particles moving throughout the chamber. In BRZ the lack and depletion of oxygen is evident.

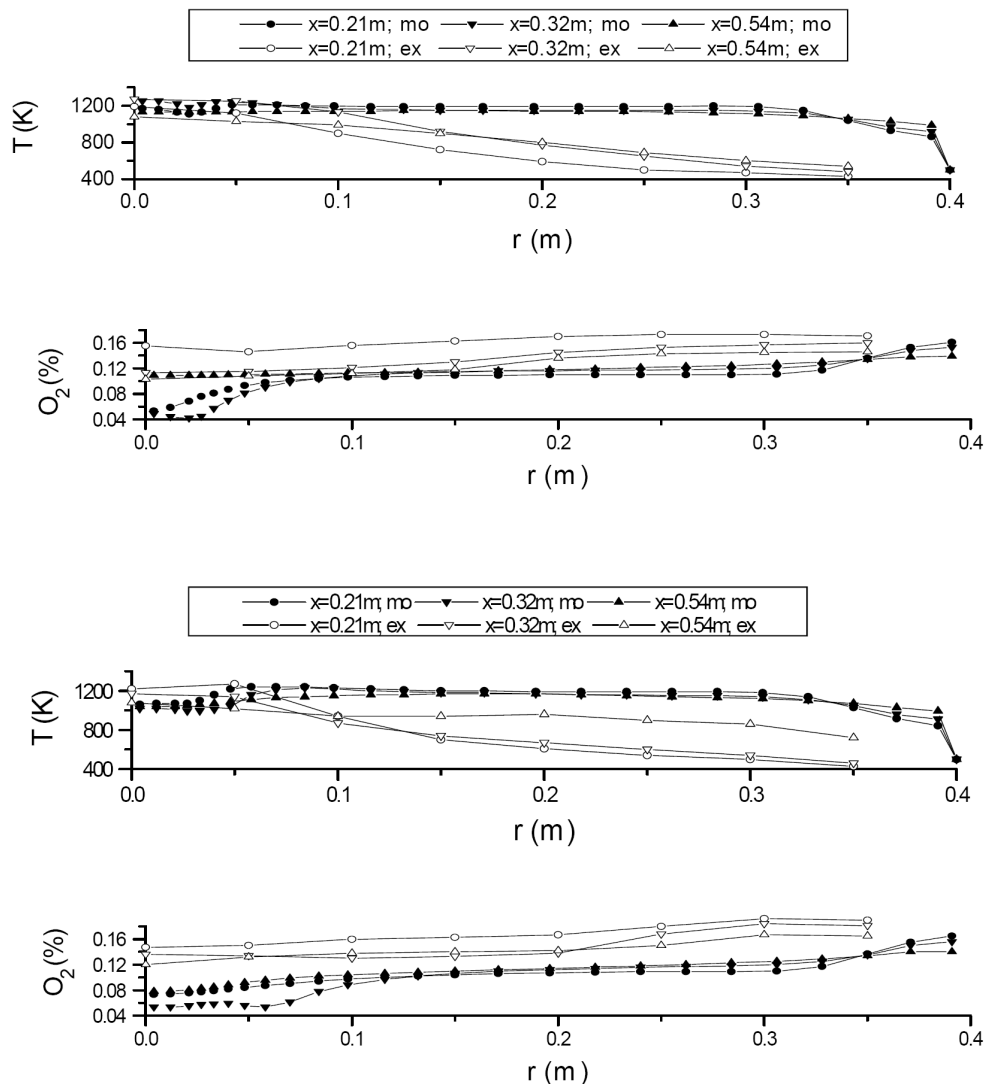


Figure 6. Comparison of experimental and computational results for regimes  
a) ( $T_{z1} = 500 \text{ K}$ ,  $tg\varphi_s = 1.0$ ) and  
b) ( $T_{z1} = 500 \text{ K}$ ,  $tg\varphi_s = 0.75$ )

In the Figure 6 presented are the radial profiles of temperature and the oxygen concentration of the gas at different axial locations in the furnace for both swirl intensities. The values of temperature almost coincide near the burner, i.e. in CRZ. However, they differ farther from axis as well as downstream ( $x = 1.2$  m and  $2.2$  m) which is not shown here. This difference is attributed to the influence of the so-called "false" air and increased heat losses for heating the cold walls. The surrounding cold air, sucked-in through several openings within the furnace brick walls due to relative vacuum induced by the flue gases exhaust fan, exerts strong influence at the reduction of temperature and the increase of oxygen concentration near the laboratory furnace wall. Oxygen concentration values comply less than the temperature profiles, even inside the CRZ. The measurement results show abundance of oxygen near the walls and in the region of developed flame. This certainly indicates that the pulverized coal combusted under conditions of high oxygen availability, i.e. at the larger excess air. The majority of the so created heat was consumed for heating the cold walls so the temperatures in CRZ and throughout the furnace are lower. In such circumstances, a part of coal particles, the coarser ones, was not able to get ignited and fell unburnt onto the furnace bottom, as visually observed. Since a part of fuel hasn't participated in combustion, oxygen is increasingly available for the remainder of the fuel, as measurements have shown.

It has been concluded that computational results obtained by using the outlined model comply well with the experimental measurements. Noted differences are attributed to effects present in experiments which couldn't be fully included in the model. Analysis of both cases (IFRF and IBK-ITE furnaces) indicates that the model can be readily applied for computing the complex process of pulverized coal combustion for cases different in furnace geometry, flow and temperature boundary conditions, origin of coal etc.

## 6. CONCLUSION

A complex mathematical model of pulverized coal combustion in axisymmetric furnace with swirl burner is presented. The model is based upon the  $k$ - $\epsilon$  single phase turbulent flow simulation model, considering the solid phase through additional source terms in gas phase equations. Disperse phase is treated via history of mass, temperature, velocity and location of particles by using the Lagrangian Stochastic Deterministic model. Coal devolatilization, and homogeneous- and heterogeneous chemical reactions are modelled together by a global combustion model using own reaction kinetics data. The model was verified by comparing computation and experiment for combustion of pulverised coal in two experimental furnaces. First, a pulverised bituminous coal flame within the International Flame Research Foundation furnace No.1 in Ijmuiden (Netherlands) with a jet burner was considered, and modelling results compared with experiments and computations of other authors. Then, pulverised lignite combustion within a furnace with a swirl burner was modelled and the results compared with performed measurements at a horizontal

axisymmetric furnace within the Laboratory for Thermal Engineering and Energy in Vincha. It is concluded that the developed model can be successfully used for prediction, optimization of parameters and design of swirl burners, for different geometries, flow and temperature conditions and coals of different rank.

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## NOMENCLATURE

$A_p$	- particle area, $m^2$
$d_p$	- particle diameter, m
$k$	- turbulence kinetic energy, J/kg
$k_d$	- diffusion coefficient, $kg/m^2s$
$k_r$	- reaction rate constant, m/s
$m_p$	- particle mass, kg
$r_p$	- reaction rate, kg/s
$S_\phi$	- source term
$U, V$	- gas velocity - axial, radial, m/s
$x, r$	- axial, radial coordinate, m

$\Gamma_\phi$  - diffusion coefficient

$\varepsilon$  - dissipation of  $k$ ,  $m^2/s^3$

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## ВЕРИФИКАЦИЈА МАТЕМАТИЧКОГ МОДЕЛА САГОРЕВАЊА СПРАШЕНОГ УГЉА У ВРТЛОЖНИМ ГОРИОНИЦИМА

Александар Саљников, Мирко Коматина,  
Дарко Горичанец

Приказан је математички модел сагоревања угљеног праха у ложишту са вртложним горионцима. Модел се заснива на двоједначинском  $k$ - $\varepsilon$  симулационом моделу једнофазног турбулентног струјања, а који узима у обзир присуство чврсте фазе путем PSI-Cell методе. Дисперзна фаза се

третира Лагранжевским стохастичко – детерминистичким моделом. Пренос топлоте зрачењем се третира помоћу методе Шест флуксева. Деволатилизација угља, као и хомогене и хетерогене реакције су моделиране скупа користећи модел глобалног сагоревања уз употребу сопствених података о кинетици реакције. Модел се верификује поређењем рачунских и експерименталних резултата при сагоревању полидисперзног угљеног праха у два експериментална ложишта. Закључено је да се овај модел може са успехом искористити за предвиђање, оптимизацију и пројектовање вртложних горионика за различите геометријске, струјне и температурске граничне услове као и угљеве различитог квалитета.