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# Assessment of the Impact of Under-Fire Air Introduction on the Pulverised Coal Combustion Efficiency

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The objective of the present work was to analyse the effect of the air redistribution on the flow field, temperature profiles and combustion efficiency, in a pulverised coal-fired utility boiler. The change is due to an under-fire air (UFA) introduction through ports located at the bottom of the furnace. Computational fluid dynamics (CFD) modelling technique is used for investigation of the aerodynamic behaviour of the gas-solids mixture, combustion efficiency, temperature profiles and concentrations of gaseous combustion products in a furnace of an utility boiler of 225 MWe power plant unit. The modelling results are compared with a test matrix of measurements at different boiler operating conditions. The comparison between the numerically obtained and measured temperature profiles, as well as energy loss due to inefficient combustion, shows satisfactory compliance. The analysis of the results concerning the near-burner regions indicates the occurrence of intensified swirl and improved combustion efficiency, as under-fire air flow rate was increased.

## 1. Introduction

The tendency to increase the efficiency of the energy facilities and to reduce the amount of harmful emissions, when burning fossil fuels, is particularly relevant in cases when low grade fuels are used. Advanced modelling tools considerably facilitate the investigation of the influence of various process and design parameters of combustion plants, such as: fuel properties, air and fuel inlet redistribution, furnace geometry (furnace shape, air and fuel inlet ports, layout of air staging nozzles, recirculation holes, etc.), burner design, flame-wall interaction phenomena, heat transfer degradation, slagging propensity and other issues, to the combustion efficiency and, consequently, to the plant overall efficiency, as well as to the emission of pollutants.

There are two basic approaches to the mathematical modelling: (1) Modelling the behaviour of a system; and (2) Modelling the fundamental physics of a system to determine the behaviour (Kitto and Stultz, 2005). The computational fluid dynamics (CFD) and chemical reaction models fall into the second category. Advanced combustion models and numerical techniques have long been used and already widely accepted as efficient low-cost engineering tools for analysis and optimisation of flow, combustion and heat transfer in different industries (Ustimenko et al., 1986). Some works are directed towards development of general-purpose computer programmes for 3-D analysis of thermal processes in boilers (Fiveland and Wessel, 1988). Other works deal with development of generalised 3-D combustion models to simulate large-scale, steady-state combustion systems, including pulverised-coal systems (Hill and Smoot, 1993). The permanent progress in computers capability has enabled development and application of massive mathematical models of turbulent flows and thermal processes in combustion systems and extensive use of CFD techniques (Schnell, 2001). Numerical codes describing the processes in coal-fired boilers have been a subject of many investigations, some of them dealing with general furnace modelling (Bermudez de Castro and Ferin, 1997; Fan et al., 2001), some addressing boilers specific operational problems (Yin et al., 2002) and some integrating CFD predicted fluid flow with advanced kinetics combustion models (Pallares et al., 2007). Two-phase flow is usually accurately described by the Eulerian-Lagrangian

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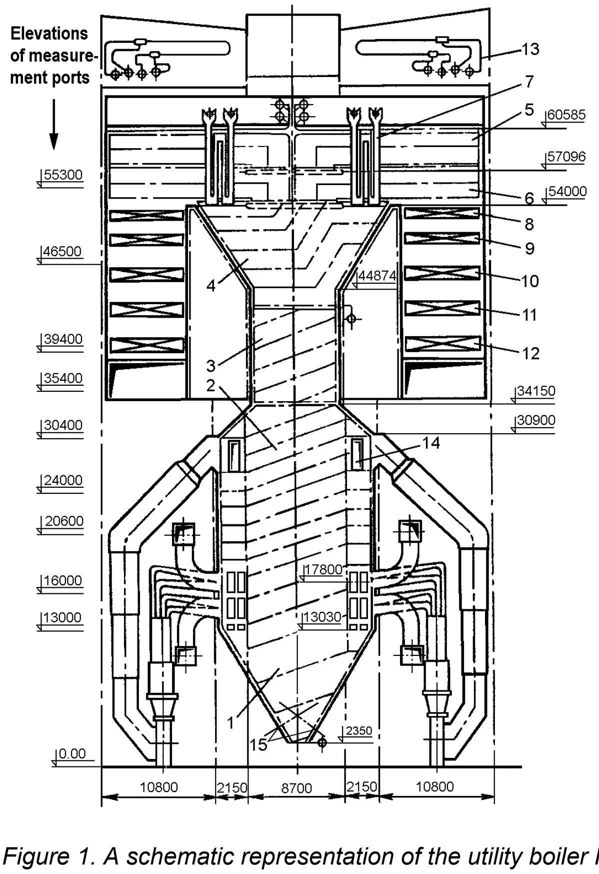
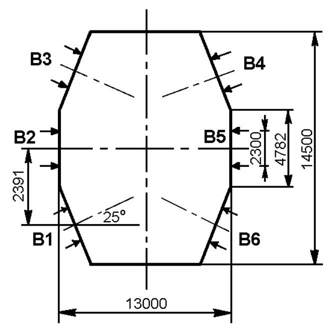
approach (Meneguz et al., 2009) and the PSI-CELL method is utilised for taking into account the influences between phases. As for the turbulence, the $k$-$\varepsilon$ model, or some derivatives, like RNG $k$-$\varepsilon$, $k$-$\varepsilon$-$k_p$, or $k$-$\omega$ model, are often used in combustion systems. Regarding the reaction modelling, the probability density function (PDF) methods provide a complete description of turbulent flow fields with chemical reactions (Kollmann W., 1990). Therefore, they are often used instead of solving gas phase conservation equations for separate chemical species. Thermal radiation is modelled by means of various approaches, some of them described in (Khalil, 1982), like discrete transfer method, variations of the P-N model (Ratzel and Howell, 1983), discrete ordinates method – for three-dimensional radiative heat transfer (Fiveland, 1988b) and for combustion processes (Yin et al., 2002), or other methods, such as the six-fluxes and the Monte Carlo.

## 2. Methodology of the research

One of the ways to improve the overall energy efficiency of the pulverised coal-fired boilers is a reduction of the heat loss due to inefficient combustion. Depending on the coal milling quality and the flow field, certain amount of coal falls down through the furnace funnel and do not participate in the combustion process. The present work was focused on an analysis of the changes of the combustion efficiency, flow and temperature fields with an implementation of under-fire air (UFA) inlet ports in the lower part of the boiler furnace (Figure 1), so that a part of the total air quantity is introduced through them. As a consequence, additional swirls are created, and part of the coarse combustible particles is entrained by the lower air flow to the upper furnace regions, enabling them to undergo complete combustion.




1 – Furnace funnel; 2 – Lower radiation part; 3, 4 - Middle radiation part; 5 – Upper radiation part I; 6 - Tube walls in the upper radiation part II; 7 – Superheater; 8, 9 – Convective superheaters; 10 – Transition zone; 11, 12 – Economisers; 13 – Heat exchanger ”steam-steam”; 14 – Recirculation openings; 15 – UFA inlet ports; B1÷B6 - Burners

*Figure 1. A schematic representation of the utility boiler Pp-670-140 GOST 3619-76 (P-65) - layout and horizontal intersection showing the burners’ disposition (Bureska, 2012)*

The modelling technique described in this paper has been validated against data acquired from the testing of Bitola Thermal Power Plant (OAO IK ZiOMAR, 2000; Schubert and Schouer, 2011). The power plant consists of three units with individual capacity of 225 MW and provides an average annual electricity generation of $4.5 \cdot 10^3$ GWh . There are three Ramzine type boiler units installed, designated as Pp-670-140 GOST 3619-76, known as P-65, each with capacity of 194.4 kg/s superhetaed steam and average gross efficiency of about 85 %, designed for a steam cycle with temperature 545 $^oC$, pressure 135 bar and feed water temperature 250 $^oC$ (Bureska, 2012). The boiler furnace intersection is octagonal, with 24 conventional burners, installed on six walls (B1 to B6, Figure 1). The boilers are designed to operate on lignite with lower calorific value in a range 6180-8100 kJ/kg (as received). The coal composition is given in Table 1 (Bureska, 2012). The simulations have been performed on a basis of commercial CFD code, adapted for pulverised coal boiler furnaces, with a similar approach to the one in (Filkoski, 2010). The numerical domain represents the boiler furnace and a part of the convective tract and the mesh is non-uniform, consisting of 1,427,987 volume cells, Figure 2. It is finer in the areas where large gradients of the variables are expected (near-burners zone, furnace funnel) and coarser in regions with relatively little expected change. A grid sensitivity check was implemented using several grids with different number of control volumes. Given the results of some previous analyses (Bureska, 2012), the present grid density is fine enough to provide grid-independent solution, satisfactory convergence and accuracy and, at the same time, to meet the restrictions in computational time.

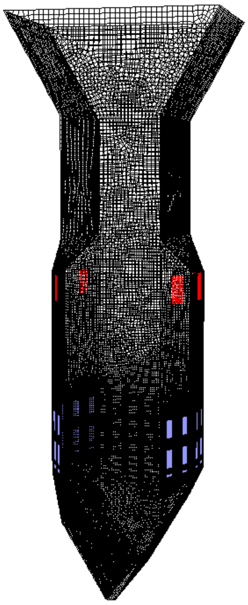


*Figure 2. Numerical mesh of the domain*

A steam boiler furnace for pulverised coal combustion is characterised with a weakly-compressible particle-laden turbulent flow, chemical reactions and specific heat transfer phenomena. For the turbulence, the standard *k-ω* model is employed as a reasonable compromise (Wilcox D. C., 1993), instead of the often used *k-ε*, which exhibits some weaknesses when applied to flows with strong streamline curvature, as in the near-burner area, or in recirculation regions. The common values of the constants are used in the *k-ω* transport equations (Fluent Inc., 2003): $\alpha_\infty^*=1$, $\alpha_\infty=0.52$, $\alpha_0=1/9$, $\beta_\infty^*=0.09$, $\beta_i=0.072$, $R_\beta=8$, $R_k=6$, $R_\omega=2.95$, $\zeta^*=1.5$, $M_{t0}=0.25$, $\sigma_k=2.0$ (turbulent Prandtl number for *k*) and $\sigma_\omega=2.0$ (turbulent Prandtl number for *ω* ). Another step of the research is going to be conducted with *k-ε* realisable as a turbulence model, which was not considered previously. The coupling of velocity and pressure is achieved by the SIMPLEC algorithm.

It is assumed that the poly-disperse coal particle size distribution fits the Rosin-Rammler equation, by 12 classes of particle size, with a mean diameter 0.12 to 0.15 mm, by setting minimal diameter at 0.020 mm and maximal at 1.5 mm, which appropriately corresponds to the sieving analysis from measurements (Schubert and Schouer, 2011). There are 24 particle stream start locations, the maximum number of steps in each particle trajectory is 1000 and the length scale of each step is 0.1 m. The coal devolatilisation and combustion parameters used in the model are given in Table 2. Due to the lack of coal characterisation data for the Bitola lignite, an extrapolation of the combustion kinetics data related to other Balkan lignites with similar composition and characteristics is used in this analysis.

*Table 1. Coal composition (OAO IK ZiOMAR, 2000)*

| Component | With total moisture | With analytical moisture | Dry basis |
|---|---|---|---|
| Proximate analysis (in %) | | | |
| Char | 28.97 | 51.99 | 57.72 |
| Fixed carbon | 14.76 | 26.48 | 29.40 |
| Volatiles | 21.22 | 38.08 | 42.28 |
| Ash | 14.21 | 25.51 | 28.32 |
| Moisture | 49.81 | 9.93 | - |
| Sulphure | 0.56 | 1.00 | 1.11 |
| Combustibles | 35.98 | 64.56 | 71.68 |
| Ultimate analysis (in %) | | | |
| C | 23.33 | 41.86 | 46.48 |
| H | 2.15 | 3.85 | 4.28 |
| S (combust.) | 0.13 | 0.23 | 0.26 |
| O+N | 10.37 | 18.62 | 20.66 |

*Table 2. Coal combustion parameters (Bureska, 2012 )*

| a) Coal devolatilisation data | | |
|---|---|---|
| Devolatilisation model – two competing rates | | |
| Parameter | 1st rate | 2nd rate |
| - pre-exponential factor | $2.0 \cdot 10^5$ s$^{-1}$ | $1.3 \cdot 10^7$ s$^{-1}$ |
| - activation energy, J/kmol | $7.50 \cdot 10^7$ | $1.45 \cdot 10^8$ |
| - weighting factor | 0.3 | 1.0 |
| b) Combusting particles properties | | |
| Density | 1250 kg/m$^3$ | |
| Specific heat capacity – polynomial profile | | |
| Thermal conductivity | 0.045 W/mK | |
| Mass diffusion limited rate constant | $4.5 \cdot 10^{-12}$ | |
| Kinetic rate pre-exponential factor | 0.002 | |
| Activation energy | $7.5 \cdot 10^7$ J/kmol | |

A pulverised coal combustion simulation involves modelling of a continuous gas phase interaction with a discrete phase of coal particles. In this work, species and chemical reactions are modelled using the mixture fraction/probability density function (MF/PDF) approach and the full equilibrium chemistry – the book by Kuo (1986) and the advanced model by Kollmann (1990), assuming that the two-streams PDF mixture consists of 20 species. The turbulence-chemistry interaction is modelled using a double-delta PDF. An algorithm, based on the minimization of the Gibbs free energy is used to compute species mole fractions (Kuo, 1986).

The furnace of a pulverised coal-fired boiler is an example of a space with a two-phase emitting-absorbing and scattering medium. In this case, the Discrete Ordinates (DO) model is utilised as the most appropriate thermal radiation model, since it effectively comprises the influence of the discrete phase and the presence of localised heat sources in the boiler furnace (Fluent, 2003). The so-called S6 approximation was applied in the framework of the DO model, corresponding to 48 flux approximations (Fiveland, 1988b), which yields sufficiently reasonable results for the amount of the numerical work. The utilised values of the particles emissivity, reflectivity and anisotropic scattering are derived as approximations of data from various sources – e.g. from (Blokh et al., 1991) for radiative heat transfer and from (Rusas, 1998) for pulverized coal combustion. The variable absorption coefficient is defined as composition-dependent, using the weighted-sum-of-gray-gases model (WSGGM) (Modest, 1991), as a compromise between the over-simplified gray gas model and a complete model that takes into account particular absorption bands. The path length is calculated according to the mean-beam-length approach, based on an average dimension of the domain. The effect of the soot concentration on the radiation absorption coefficient is included in the simulations.

## 3. Results and discussion

In order to obtain accurate information on the flame position and shape, a complex set of temperature measurements was conducted on the TPP Bitola boiler units. The temperature was measured with optical infrared pyrometer Minolta-Land Cyclops 52, designed for temperature range 600 to 3000 C. Twelve test cases were used for validation of the CFD methodology applied in this work, covering operating modes between 70 and 100 % of the boiler full load (OAO IK ZiOMAR, 2000; Schubert and Schouer, 2011).

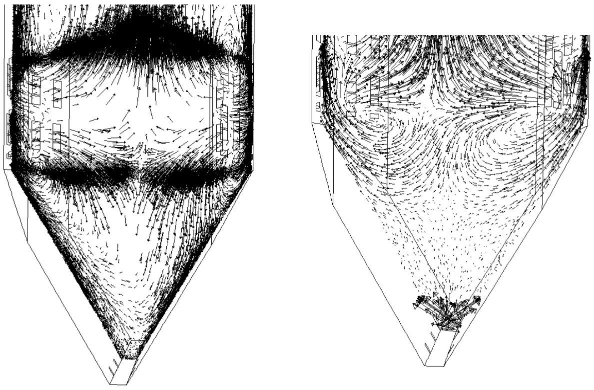
*Table 3. Operating conditions of the boiler (OAO IK ZiOMAR, 2000)*

| Variable, unit | T1 | T5 | T6 | T10 |
|---|---|---|---|---|
| Unit electrical output, MWe | 218 | 215 | 200 | 219 |
| Feed water flow, kg/s | 195.3 | 194.2 | 178 | 195 |
| Feed water temperature, $^{o}$C | 250 | 250 | 245 | 250 |
| Primary steam flow, kg/s | 193.6 | 193.9 | 175 | 193.3 |
| Primary steam temperature, $^{o}$C | 539 | 540 | 537 | 537 |
| Primary steam pressure, bar | 134 | 133 | 133 | 135 |
| Fuel LCV (as rec.), kJ/kg | 7528 | 6557 | 6490 | 7227 |
| Fuel consumption, t/h | 304.5 | 352.7 | 327.4 | 318 |
| Fuel loss through the furnace funnel (measured), % | 0.70 | 1.29 | 1.00 | 0.96 |
| Boiler gross efficiency, % | 85.3 | 83.0 | 83.4 | 84.6 |
| Total air flow, $m_n^3$/s | 230 | 268 | 270 | 260 |
| Under-fire air velocity, m/s | 39 | 17 | 33 | 29 |
| Ratio: lower air to total air flow | 0.15 | 0.06 | 0.11 | 0.12 |

The operating conditions of four typical cases are summarised in Table 3 (OAO IK ZiOMAR, 2000). Velocity vectors in the central vertical intersection of the lower part of the furnace, in cases without and with under-fire air (UFA) introduction, are shown in Figure 3. Examples of traces of groups of coal particles, released from the burners system assigned as B1 (see Figure 1), depict obvious difference of the number of particles that fall through the funnel in the cases without and with UFA introduction, Figure 4, a) and b).

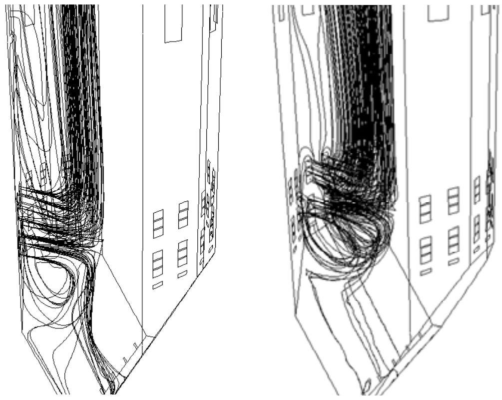
Calculated temperature profiles along the furnace height at four operating modes, together with the average measurement values at elevations of 13.0, 16.1, 20.6, 24.0, 30.4, 35.4 and 39.4 m (Bureska, 2012), are displayed in Figure 5, demonstrating the general similarity between the measurement data and the predicted temperature trend-line. It must be noted that the results obtained with the other sets of parameters, which are not presented here, show similar agreement with the respecting tests measurements (Bureska, 2012).

Some results in that direction are depicted in Figure 6, showing that the fuel loss through the ash funnel becomes smaller than 1 % at velocities over 20 m/s, and theoretically approaches to zero at velocities of 30-35 m/s (Bureska, 2012). This indicates that the optimal ratio of lower air to total air flow is between 0.10 and 0.15, which corresponds to air velocities between 27 and 35 m/s. Further increase in under-fire air velocity does not result in significant reduction of energy loss due to unburned fuel, and even on the contrary, certain negative consequences that result with higher energy losses may become dominant.



a) b)

*Figure 3. Velocity vectors in the central vertical cross-section without (a) and with (b) UFA introduction*



a) b)

*Figure 4. Traces of particles released from the burners B1 without (a) and with UFA (b)*

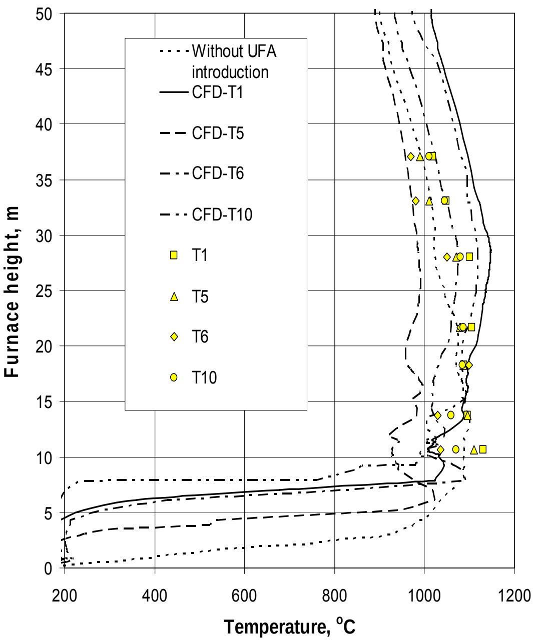



*Figure 5. Temperature along the central axis: CFD-T1, T5, T6, T10 – simulations (Bureska, 2012; Filkoski et al., 2012); Test 1, 5, 6, 10 – measurements (OAO IK ZiOMAR, 2000)*

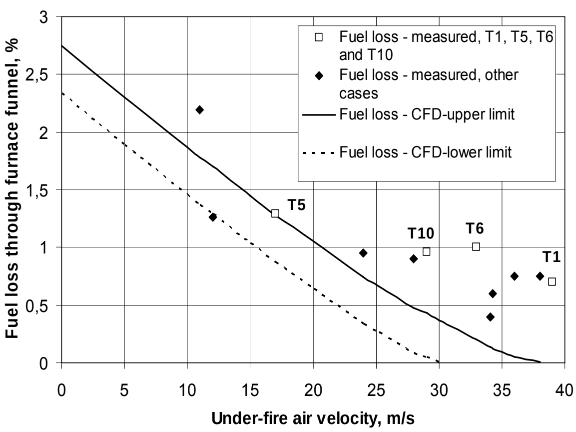



*Figure 6. Dependence between the under-fire air (UFA) velocity and fuel loss through the furnace funnel - measurements (OAO IK ZiOMAR, 2000) and CFD results (Bureska, 2012)*

The obtained results are in the expected limits and the comparison with the measurements shows quite satisfactory agreement. In that sense, the research is a good basis for further investigation and evaluation of optimisation opportunities of the analysed facility and other similar cases.

## 4. Conclusion

The described CFD based methodology gives a possibility for investigation of the operation of fossil fuel boilers in various modes, with different load and with redistribution of fuel and air mass flow rates. On a basis of the comparisons with plant tests, a conclusion can be drawn that the model produces realistic insight into the furnace processes. The analysis for optimisation of the under-fire air velocity introduction, with regards to the reduction of fuel loss due to decay through the furnace funnel, indicates that the optimal velocity values are in the range 27-35 m/s, which corresponds to the ratio of lower air to total air flow between 0.10 and 0.15. A general conclusion from the present work is that the obtained flow field with the UFA introduction enables decrease of the heat loss due to incomplete combustion, higher boiler efficiency and higher overall power plant efficiency.

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