Improvement of Coal Combustion Efficiency and Decrease of Harmful Emission Under the Influence of Plasma - Modelling

Z. Jankoski

Mechanical Engineering Department, Imperial College London, London, UK

E-mail: zlatko.jankoski@imperial.ac.uk

Abstract   A numerical study has been undertaken which simulates the process of pulverised coal preparation for combustion using plasmas. Two combustion models ('fast chemistry' based on one-step fuel transformation into final products, and 'stretched laminar flamelets' with the detailed chemical mechanism for the combustion of volatiles) are tested and validated with the experimental results. In a preliminary calculation, the spreading rate and temperature contours of the plasma jet emerging from the plasma generator nozzle were simulated, ignoring combustion. Subsequently, coal preparation calculations including the effects of combustion were performed for the plasma burner. Temperature profiles, coal particles history and species concentrations at the plasma burner exit are presented and discussed.

Introduction   This paper emphasises the modelling of the plasma-assisted combustion of pulverised coals in pulverised-fuel-fired thermo power plants (TPP). The motivation is to be found in the important role of pulverised coal as a fuel for power generation, and its significant harmful impact on the environment through gas and particulate emissions. In the present concept, a proportion of the pulverised coal and air mixture, diverted away from the bulk of the flow, is heated by an electric arc plasma within a separate plasma chamber. The highly reactive fuel fraction of unburned volatiles and partially gasified carbon residual so produced is then able to ignite the main stream of pulverised fuel/air mixture entering into the combustion chamber of the boiler. As a result, the consumption of conventional fuels (fossil oil or gas) required for boiler warm-up and flame stabilisation is eliminated, while a higher overall efficiency and early ignition result in a reduction of emissions of carbon dioxide and nitrogen oxide.

Mathematical Modelling   A computational fluid dynamics code for calculating three-dimensional turbulent reacting flows was used to predict the combustion behaviour of pulverised coal inside the plasma burner. The model, which is based on a finite volume discretisation technique, solves the mass and momentum equations using the SIMPLE

algorithm [1]. An Eulerian description is employed to formulate the gas phase time-averaged conservation equations, while for modelling of the particulate phase a Lagrangian treatment is applied [2] considering the coal particles as sources or sinks of matter, momentum and energy. Turbulence is simulated by a 'standard k-ε' turbulence model [3]. A fast chemistry multi-mixture fraction model is used for combustion modelling [4]. The model associates one mixture fraction variable for each fuel being introduced into the calculation, while the species mass fractions are calculated as state functions of the mixture fractions. Coal devolatilisation is described by a first order 'single-reaction' model [5], while the char remaining after devolatilisation is considered to be pure carbon together with ash components. Heterogeneous char reaction is governed by two competing rate limiting processes, where the reaction rate is controlled by external diffusion of oxygen to the particle surface and the chemical kinetic reaction of char at the particle surface [6]. For the radiation computation non-equilibrium diffusion is used, with the absorption coefficients being computed applying the 'two grey gas plus one clear gas' model [7]. During an initial study, the existing combustion model was revealed to be inefficient in predicting the products of coal partial combustion, mainly CO. For calculation of detailed species recombination and combustion of released volatiles, the 'stretched laminar flamelets' approach [8,9] was selected. In this approach, the single step reaction of volatiles combustion is replaced by the 'GRI-mechanism' kinematic scheme comprised of some 280 reactions and 50 species [9].

<u>Results and Discussion</u>   Measured temperature contours for a typical plasma jet are presented in Figure 1.
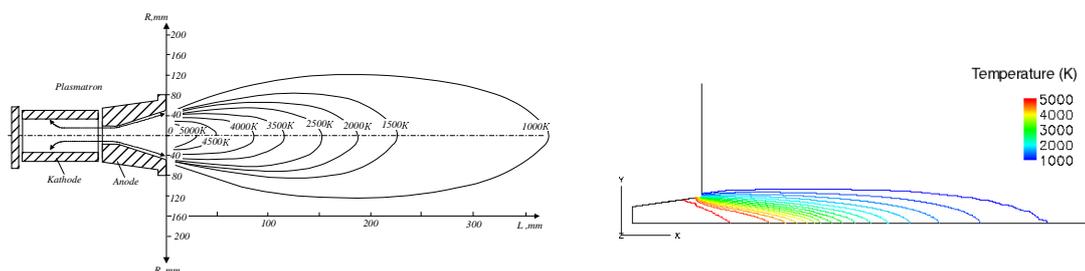

Figure 1. Measured and predicted isotherms of the air plasma flow from plasma generator

The measurements were taken for an unconfined air plasma jet flow. The mean temperature of the plasma air jet was about 5000 K while the air mass flow through the nozzle was 36 kg/h. In a preliminary calculation, the spreading rate of the plasma jet emerging from the plasma generator nozzle was simulated.

Table 1. Comparison of measured and predicted length of isotherms for an air plasma flow from the plasma generator nozzle

Temperature (K)	5000	4500	4000	3500	2500	2000	1500	1000
Experiment (m)	0.030	0.050	0.086	0.116	0.153	0.188	0.227	0.375
Numerical (m)	0.030	0.086	0.109	0.123	0.167	0.202	0.255	0.370

The nozzle was defined with inner and outer diameters of 40 and 60 mm respectively, while the length of the nozzle was 80 mm. Predicted isotherms profiles are shown in Figure 1, while comparisons between the isotherms lengths are presented in Table 1. These initial predictions were achieved ignoring combustion. Such a plasma generator has been attached on a direct flow burner to provide the necessary ignition source for the partial combustion of coal. The burner is a cylinder of 0.25 m in diameter and 2.35 m in length (Figure 2).
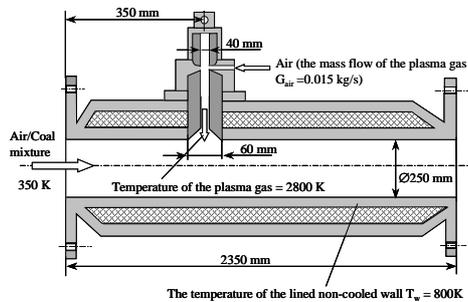

Figure 2. Schematic view of the full-scale industrial plasma burner
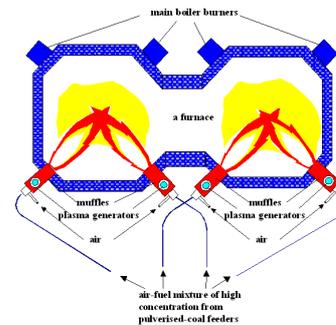

Figure 3. Principle scheme of direct flow plasma burners (BKZ 640 boiler)

The industrial application of plasma burner in TPP Gusinoozersk (Russia) is presented in Figure 3, where the plasma burners have replaced a half of the conventional pulverised coal burners. For a power consumption by the plasma generator of 100 kW, the plasmatron efficiency of 85% and the plasma gas mass flow rate of 54 kg/h, the plasmatron generates a low-temperature plasma with the mean temperature of 2800 K. The coal and air mass flow rates through the muffle were 1.75 t/h and 3.5 t/h respectively; while the coal-air mixture inlet temperature was 350 K. The coal dust concentration was around 0.5 kg of coal per kg of air. Such a concentration provides very fuel-rich conditions within the plasma chamber, with the fuel/air equivalence factor being around 4.0. The numerical simulations of plasma burner operation include the effects of combustion. For modelling purposes, the plasma flame is assumed to be a heat source having an exit temperature of 2800 K and a mass flow of about 54 kg/h. The predicted radial temperature and species concentrations at the chamber exit are presented in Figure 4. The predictions obtained from the 'fast-chemistry' calculations show very high temperature levels. The simple chemical reacting system (fast

chemistry model) takes into account only the global nature of the combustion process resulting in CO_2, H_2O and SO_2 as final products, while the intermediate reactions and species are ignored. The more detailed chemical mechanism, using the 'laminar flamelets' approach, improved the predictions. The zero oxygen concentration at the burner exit suggests complete consumption of the oxygen, while particles history analysis showed that about 57% of the carbon is released from the particles. However, the prediction of carbon monoxide has proved more difficult. This is perhaps explained by the predicted lower carbon release 57%, compared with the experimental value of around 75%. This suggests that the plasma promotes a substantial increase in the char reactivity. Further study on the effect of electric plasmas flame on the activation properties of the chemical reactions is required.
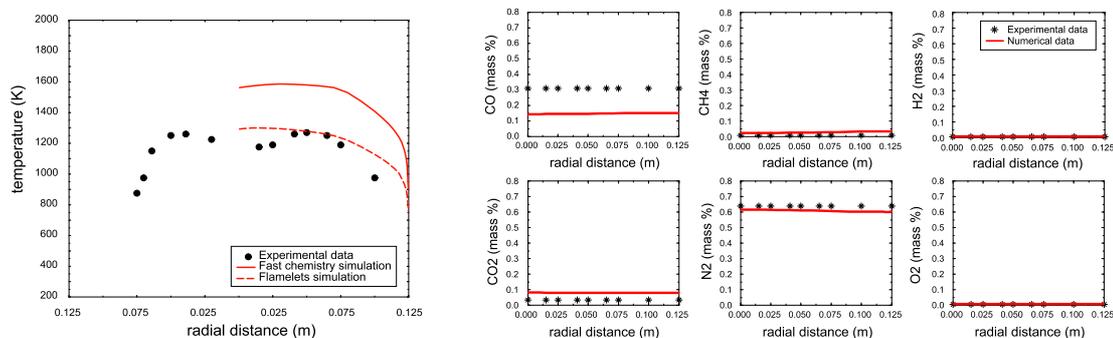

Figure 4. Predicted radial temperature profile and species concentrations using the 'laminar flamelets' model

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