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NUMERICAL MODELLING OF EMISSION FORMATION IN DOMESTIC BOILER FOR COAL

MODELOVANIE TVORBY EMISIÍ MALÉHO ZDROJA TEPLA NA SPAĽOVANIE UHLIA

Abstract

The aim of the work is to develop a method of simple characterization of solid fuels combustion in fixed bed, which would be useful for CFD modelling. In this work, the measurements were performed in a test rig, where a combustion front propagates against the airflow. Concentrations of flue gas species were registered at the exit of a fixed bed reactor and the temperature of burning coal was measured in selected points of the reactor as functions of time.

Abstrakt

Cieľom práce je vyvinuť metódu charakterizujúcu spaľovanie tuhého paliva na rošte, ktorá môže byť použitá pre matematické modelovanie. Práca pozostáva zo štyroch úloh: experimentálne merania zamerané na spaľovanie uhlia v reaktore s pevným roštom, spracovanie nameraných hodnôt do formy funkcií, matematické modelovanie v CFD a verifikácia modelu pomocou meraní vykonaných na kotle o výkone 25kW.

1 INTRODUCTION

Nowadays combustion provides more than 90 % of the energy needs. Half of Europe's electricity is produced from fossil fuels and about 30 % from the total is generated from coal, in Poland is it about 90 %. Many countries use coal as a source of domestic and commercial heating requirements covering by fixed bed combustion of solid fuels. Transport of the fuel in the bed differs between boilers. Primary air passes through a fixed bed, in which drying, gasification, and charcoal combustion takes place. The aim of the work was to do series of measurements in fixed bed reactor, work out obtained results in a form of approximation function and develop a model of combustion of a fixed fuel bed on a grate and to compare the result from the model with measurements data from a test rig.

2 MEASUREMENT IN THE FIXED BED REACTOR

The measurements were performed in a fixed bed reactor, where a batch of coal is placed on a grate, which is shown in Figure 1. The reactor is made of steel and is 45 mm in internal diameter and 200 mm in length. The coal moves downward under the power of gravity in the course of the combustion process, countercurrent to the combustion air. The countercurrent process is the most common fixed bed coal combustion and gasification process.

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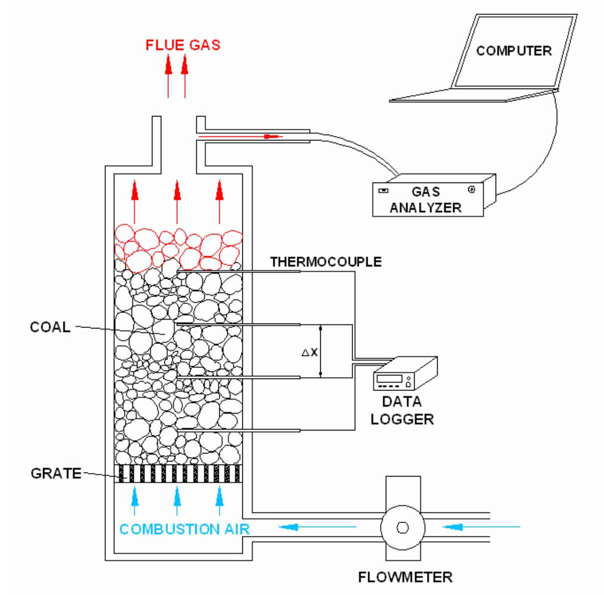

Fig. 1 The measurement setup with fixed bed reactor

Inside the reactor four thermocouples were installed in order to measure the temperature of burning coal in different heights. During the experiments the coal temperature was recorded on line in periods of 30 seconds by data logger. Thermocouples are located 50 mm apart from one to another. Concentrations of the flue gas species CO_2, CO, O_2 and NO were registered by an analyser every 30 seconds. Measurements were carried out for flow of air: 1 m^3/h, 1.5 m^3/h, 2 m^3/h, which correspond with air velocity: 0.17 m/s, 0.26 m/s and 0.35 m/s. The initial temperature of fuel and inlet air is 298 K. Each test was repeated three times. Coal with a granularity of 1-30 mm, and a lower calorific value of 28 MJ/kg was used as a fuel.

3 RESULTS OF MEASUREMENTS

Figures 2 and 3 present an example of measured gas compositions at the outlet of the reactor. The gas compositions are given as mole fractions of the gas components. The fuel ignition is followed by propagation of a reaction front downward in the bed against the air flow. As the front passes, the fuel is heated, resulting in drying and devolatilization. Volatile gases are ignited and together with the char formed they burn as long as there is oxygen available, providing heat for propagation of the front.

It can be noticed that two phases of combustion process can be distinguished (see Figures 2 and 3). Transition of first phase to second is dedicated to the carbon concentration decline in flue gas. The char burns to carbon monoxide and carbon dioxide, in the presence of oxygen. It causes very low oxygen concentration in the first phase of combustion process, while in the second it increases. The behaviour of carbon dioxide profile is opposite to the behaviour of oxygen, meaning that most of the time the concentration of it is high and in the second period decreases. Unstable concentration of CO in the first period is caused by poor mixing of fuel with air. The profiles of carbon monoxide and carbon dioxide decline when most of the char is burnout.

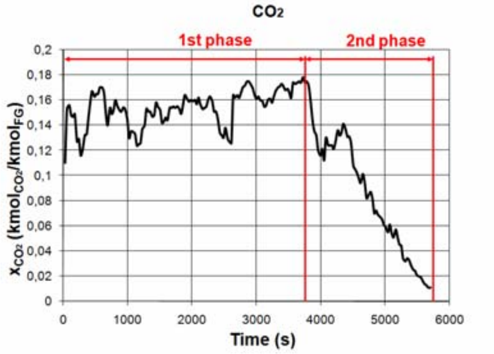

Fig. 2 Mole fraction of carbon dioxide at the exit of fixed bed reactor

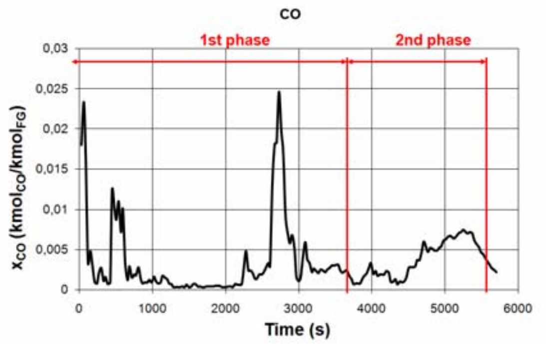

Fig. 3 Mole fraction of carbon monoxide at the exit of fixed bed reactor

4 APPROXIMATION FUNCTIONS

In this section the approximation functions for the phase A and B are presented. Approximation function is an approximation of the experimental data and is used in order to avoid random fluctuation, which occurs in experiments as well as for determination of coefficients to evaluate emissions for intermediate values of airflow. The Method of Least Squares is in our case used for specification of coefficients. This method is a procedure, requiring just some calculus and linear algebra, to determine what the 'best fit' line is to the experimental data.

The idea is to create a function with assumed linearity in the first part and in the second part assumed exponential decrease in the case of CO_2 and increase in the case of O_2 (see Figure 4).

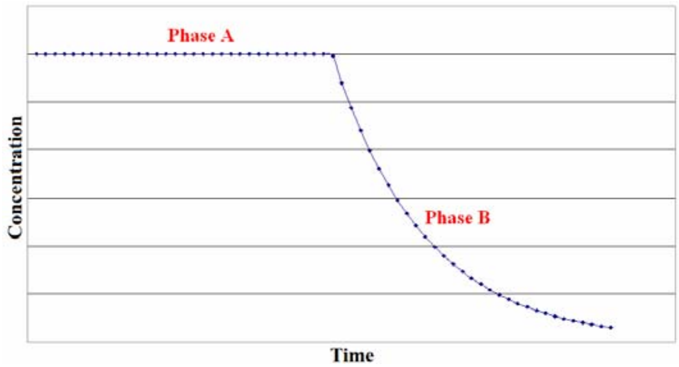

Fig. 4 Example of developed function (probable profile of CO_2 and temperature)

Developed functions will be further used for defining the boundary conditions at the interface between fixed bed and gas phase in FLUENT.

It was decided to use functions to describe the simplified profile of emissions formation, as well as velocities and temperatures of the flue gas.

5 NUMERICAL MODEL

Modelling of coal combustion in a domestic boiler improves the understanding of the combustion process and can support the design of furnaces and the investigation of problems related to the fuel bed.

Boiler geometry is one of the critical stages in CFD simulation; proper definition of the geometry provides a more realistic scenario for the simulation. In the domain just half of the combustion chamber has been modelled, taking advantage of the symmetry. For the grid sensitivity analysis, two grids were constructed and run in FLUENT to determine a grid density and quality that was fine enough to obtain a solution of acceptable accuracy. The two meshes whose results are presented in this thesis are as follows: Mesh-I: An unstructured tetrahedral mesh with about 330,000 cells. Mesh-II: A hybrid hexahedral mesh created by dividing the boiler geometry into several small, individual sections or volumes and meshing them separately. It is a high-quality mesh consisting of 400,000 cells.

The most important part of the work was the determination of the detailed boundary conditions. At the inlet of retort following boundary conditions were set: profiles of calculated concentrations (CO, O_2, CO_2 and H_2O), temperature and velocity of flue gases. Boiler walls and pipes were set at temperature 343 K and symmetric plane as symmetry.

6 MEASUREMENTS IN THE BOILER

The verification of a self-developed empirical model was carried out by means of measured gas temperatures and the measured gas species concentrations for O_2, CO_2 and CO inside the combustion chamber.

The investigated boiler is designed for operation in domestic heating system. It has heat power equal to 25 kW. The boiler is 1060 mm high, 1020 mm length and 540 mm in width. The ecological fine coal fired boiler is designed for operation in heating systems, firing coal in a smokeless way.

The boiler construction was equipped with measurement slots, so the probe could be easily inserted inside the combustion chamber during the tests. The composition and temperature of emitted flue gas was measured at certain points of the combustion chamber (see Figure 5-left) as well as in the outlet of the boiler. The flue gas temperatures were registered by a data logger and species concentrations were recorded by an analyser, both in periods of 30 seconds. First series of tests were carried out in the centre of chamber (Figure 5-right) and second series were done in the 100 mm far field region from the centre. Temperature of water was measured during the test in the inlet and outlet of water pipes.

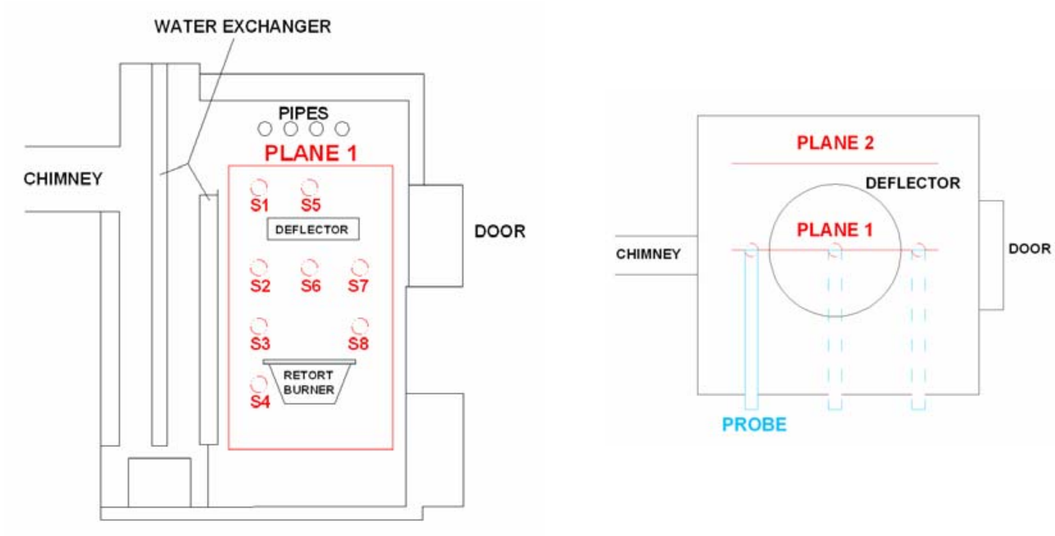

Fig. 5 Positions of measurements performed in the chamber- slots 1 to 8 (left) and the top view of boiler (right)

In order to improve the reliability of the experimental data and ensure the steadiness of the system, experimental configuration is maintained for at least 30 min before the start of sampling.

Results of measurements are compared and evaluated for CFD simulations in the following section.

7 COMPARISON OF MEASURED AND NUMERICAL RESULTS

In this section, the results of the numerical simulations are presented and compared to measured values from boiler.

For all simulations presented in this paper were applied results of airflow 1.5 m^3/h. The measured data of this airflow were the most related to the condition in the test boiler. In the graphs below there are indicated ranges of concentrations and temperatures by minimal and maximal measured values. Figure 6 gives the comparison of calculated carbon dioxide and results from measurements. It is important to note that calculated concentrations in the region of the deflector (slots 2, 6 and 7) are in the range of the experimental results. The predicted values are in very good agreement with measured data.

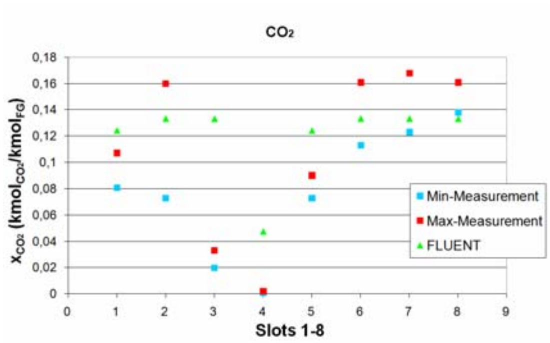

Fig. 6 Comparison of carbon dioxide in certain points of the combustion chamber

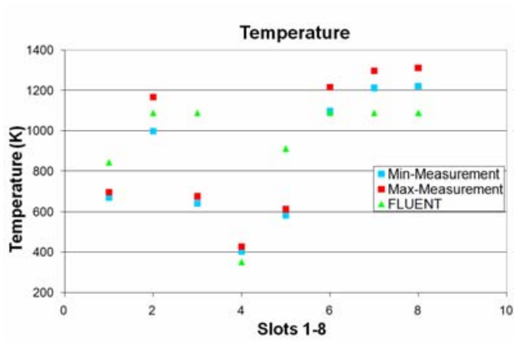

Fig. 7 Comparison of predicted and measured temperatures

Computed temperatures from selected positions are shown in Figure 7. No major difference between simulations and the experiments can be noticed, with the exception of slot 5 (above the deflector), where the temperature is over-predicted by the model. The numerical predictions of temperatures agree very well with the measured values. In all above presented graphs a significant deviation of calculated results to the measurements is observed in slot 3. The reason of the deviation can be caused by an error occurring during the experiments in the boiler.

8 CONCLUSIONS

The aim of this thesis was to develop a method of simple characterization of solid fuels combustion in fixed bed with emphasis placed on CO_2, CO and O_2 formation. The development of the method was based on experiments in a fixed bed reactor, approximation of obtained results, mathematical modelling and verification of the model by measurements collected in a domestic boiler. The goal was to examine whether the self-developed empirical model could predict the characteristics of coal combustion.

Considering all uncertainties of measurements in a fixed bed reactor which underlie fluctuations in operation conditions, the qualitative agreement with the calculations is satisfactory.

A significant effort, in both modelling and experimentation, has been made toward a reliable CFD model for the 25 kW domestic boiler. Gas temperature and composition were measured with a probe in order to evaluate the accuracy of predicted results by the model.

From a modelling perspective, the main aim of simplifications, algorithms of solution, numerical models and methodology employed seem to be correct as the prediction of the main behaviour of the system has been made with an acceptable level of accuracy. The numerical results indicate that the predicted generation of CO_2 is consistent with the data measured in the centre plane. No major difference in the comparison of O_2 concentrations was found and predictions agree reasonably well with the experiments. The simulations indicated that the probable reason for low CO prediction is that most of the carbon monoxide is converted to carbon dioxide. More tests and comparisons with measurements are necessary in order to improve the model. Furthermore, the different CFD settings could lead to an improvement in pollutant formation and temperature distribution in the furnace.

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