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Modelling of Effects of Process Inputs on Conditions in a BFB Furnace

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Abstract **-** The goals of the presented study are 1) a better understanding of effects of process inputs on bubbling fluidized bed combustion and 2) a simplified numerical description of furnace behaviour that can be linked to dynamic 1D power plant simulation. Ways to utilize results of computational fluid dynamic (CFD) simulations of the furnace as the basis of 1D modelling are considered. In the study, a bubbling fluidized bed furnace is simulated with a CFD model in a wide range of conditions. The main variables altered in the simulations are boiler load, fuel moisture, air ratio and air distribution. The main effects of the studied variables on the conditions inside the furnace and on heat transfer rates on evaporator and super heater surfaces are analysed. The analysis shows that load is the main factor determining temperature and concentration distributions in the furnace. Fuel moisture has also a significant effect. Air ratio and air distribution have, as expected, significant effects on concentration distributions but also effects on temperature distribution. Heat transfer rates to different heat transfer surfaces are dependent on the temperature distribution and thus the effects are similar. In the paper, the possibilities to use the generated data as basis for a simplified furnace model are discussed. Examples of correlations that can be derived based on the simulation data are presented and the general approach to link the results to 1D modelling is outlined.

Keywords**:** BFB, CFD modelling, heat transfer rate, concentration

1. Introduction

As the share of intermittent solar and wind power in energy production increases the role of combustion-based power plants such as fluidized bed (FB) boilers changes. New hybrid energy solutions emerge which combine boilers with other processes. Better process control is required to combine boilers with other process units and to allow faster ramp rates and wider load ranges. Also increased fuel flexibility is required as use of fossil fuels and peat is reducing. To change boiler load, fuel and air feeds in a FB boiler are adjusted and as a consequence, concentration and temperature distributions in the furnace and the heat transfer rates at different heat transfer surfaces change. These effects of load on process conditions are complicated and to predict them, a rigorous numerical model is required.

To develop new ways to control the process e.g. during fast ramp rates, modelling is a central tool since testing in real boilers would be risky. Hovi et al. [1] presented a dynamic simulation study of boiler operation during a load change. Computational fluid dynamic (CFD) modelling that is an efficient tool for analysis of furnace processes was used to predict furnace conditions in 3D while the steam side was modelled with the 1D dynamic simulation tool Apros. The two tools were coupled such that information was exchanged between the two models during simulation. Although load change situations could be simulated, the coupled simulation was slow. Especially CFD simulation was too slow to allow its use in testing of new control strategies. For that reason, a new goal was set to compress the information from CFD simulations in form of numerical correlations that describe the interaction between the furnace and the steam cycle and rest of the process. An alternative for using CFD modelling results as the basis for the correlations would be to use process data from the actual boiler. However, since the target of the development work is to increase ramp rates and to widen operation conditions, data that would cover all the desired conditions are not available from an existing boiler and thus an approach was selected in which a validated CFD model is used to produce data that covers effects of main control variables. The present paper presents the initial steps towards a furnace model that is based on CFD simulation results and discusses possibilities to utilize the results in 1D dynamic simulations. Main effects of process parameters on furnace condition are illustrated and as an example of derived correlations, modelling of heat transfer rate at a surface is presented.

2. Modelling Method

The CFD modeling method used in this study is the same as used in [2] where validation of the model was done against measurement data from two BFB furnaces. In the BFB freeboard, transport equations for flow, heat transfer and chemical components are solved whereas the fluidized bed and combustion processes in the bed are described by an in-house model implemented on the Ansys Fluent® platform as a user-defined function. The model describes also the exchange of heat and mass between the freeboard and the bed thus ensuring that total heat and mass balances in the furnace are satisfied. Movement of fuel particles in the freeboard and in the splash zone is modelled with the Lagrangian particle tracking method. A pre-defined maximum tracking time is set for fuel particles in the splash zone. After that time, combustible matter (char, volatiles) remaining in the fuel particle are transferred to the bed.

The bed temperature is set on basis of process data from the boiler. The furnace model calculates the heat of combustion that is needed to keep the bed temperature at the pre-set value and if it cannot be achieved by burning char, required additional energy is produced by burning part of the volatile gases in the bed. The flux of inert sand particles ejected from the bed to the freeboard is estimated according to the method presented in [3]. Since sand particles can either cool down or warm up in the splash zone, sand acts as either a heat sink or a source both for the gas phase and for the bed. Volatile matter is modelled as a mixture of CO, CO_2, CH_4 and H_2. The composition of pyrolysis products is calculated based on the ultimate and proximate analyses and the heating value of the considered fuel. A two-step simplified reaction scheme in which CO is an intermediate product is used to convert CH_4 in the freeboard region. A reaction is included in the mechanism for conversion of H_2 to H_2O. The rate of combustion of CH_4 and H_2 is limited by mixing rate of the reactants which is calculated by the eddy-dissipation combustion model (EDCM). Combustion rate of CO is limited either by mixing or chemical kinetics according to [4]. Turbulence is modelled with the standard k,ε-model and radiative heat transfer with the discrete ordinate (DO) method of Ansys Fluent. Formation and destruction of NOx is modelled by the combination of global kinetic schemes for NH_3 and HCN oxidation which also consider reburning. The PaSR mixing approach from [5] is employed for NOx chemistry-turbulence interaction. A more detailed description of the modeling method is given in [2] where comparisons to measurements from two commercial boilers are also presented for furnace temperature and heat fluxes. The model was shown to predict the measured distributions with sufficient accuracy. In the present work, the simulations were carried out at steady state.

3. Simulated Boiler and Process Conditions

The simulated unit is a commercial 76 MW_{fuel} BFB boiler burning biofuel. The same boiler was studied by [1]. The boiler geometry was set according to boiler drawings. Air feed in the boiler is divided into primary, tertiary and secondary air flows the amounts of which vary from load to load. In addition, part of total air is fed with fuel and through burners. Recycled flue gas is added to primary and secondary air streams. The fuel specifications were set to correspond to a typical wood burned in Finnish boilers, with 46% moisture, 80% volatile content and a heating value of 9.5 MJ/kg. Similar values were also measured for the biofuel burned in the simulated boiler although day-to-day variations in fuel composition are significant and especially fuel moisture varies.

Data from the boiler operation system was available and they were analysed to determine typical flow rates on basis of which the input values used for fuel and the primary, secondary and tertiary air flow rates were determined for normal operation at different loads. Run-time steam temperature data were used to set the boundary conditions at heat transfer surfaces. Table 1 lists the simulated cases at different loads and fuel moistures. The cases with 46% fuel moisture corresponds to typical operation in the boiler in question. To study effects of load and fuel moisture, there parameters were varied separately. Additional simulated cases in which air distribution was varied are listed in Table 2. Other air flows and flue gas circulation not listed in the table were kept the same.

Table 1: Simulations with varied load and fuel moisture marked with X.

	Fuel moisture [%]				
Load [MWt]	32	39	46	53	60
80	X	X	X	X	X
69			X		
56	X	X	X	X	X
40			X		
21	X	X	X	X	X

Table 2: Air flows given as percentage of the base case flow rates at the same load.

Load	Moisture	Case in Figures 4-6	1ry	2ry	3ry		Load	Moisture	1ry	2ry	3ry
MWt	%	a	%	%	%		MWt	%	%	%	%
80	46	b	100	100	100		32	46	100	100	100
80	46	c	69	133	100		32	46	62	137	100
80	46	d	69	120	119		32	46	62	125	125
80	46	e	100	88	117		32	46	100	88	125
80	46	f	100	112	83		32	46	100	112	75

4. Results

Modelling results were collected and analysed. The analysed data included temperature, velocity and concentration distributions inside the simulation domain and at the flow outlet and heat transfer rates at all surfaces.

4.1. Effects of process inputs

The effects of process inputs on the conditions inside the furnace were analysed by comparing the results of the simulations listed in Tables 1 and 2. Figure 1 shows the effects of load and fuel moisture on temperature distribution inside the furnace. In general, temperature increases with increased load. Especially in the bottom region there is a significant increase but also elsewhere both the average temperature and maximum temperatures significantly increase. Also temperature distribution and the locations of highest temperatures change with load.

Increased fuel moisture leads to a more uniform temperature distribution and especially in the lower part of the furnace temperature is clearly lower. This confirms that when burning very dry fuel hot spots can occur at the walls at full load, which can, in the worst case, cause damages to surface materials.

Figure 2 illustrates oxygen distribution in the furnace at different loads. Control algorithms determine air feeds largely as a function of the load. To reduce the amount of unburned fuel, total air ratio at low load is higher than at higher loads, which explains the high oxygen concentration in the upper furnace and in the second pass at the lowest load. The figure also shows that oxygen entering with primary air is largely consumed before secondary air inlets. Figure 2 also indicates that increased moisture leads to more efficient combustion in the bottom region. Volatiles are released more uniformly and lower in the furnace since drying of wet fuel takes longer time and fuel particles have time to penetrate deeper in the furnace before volatiles release starts.

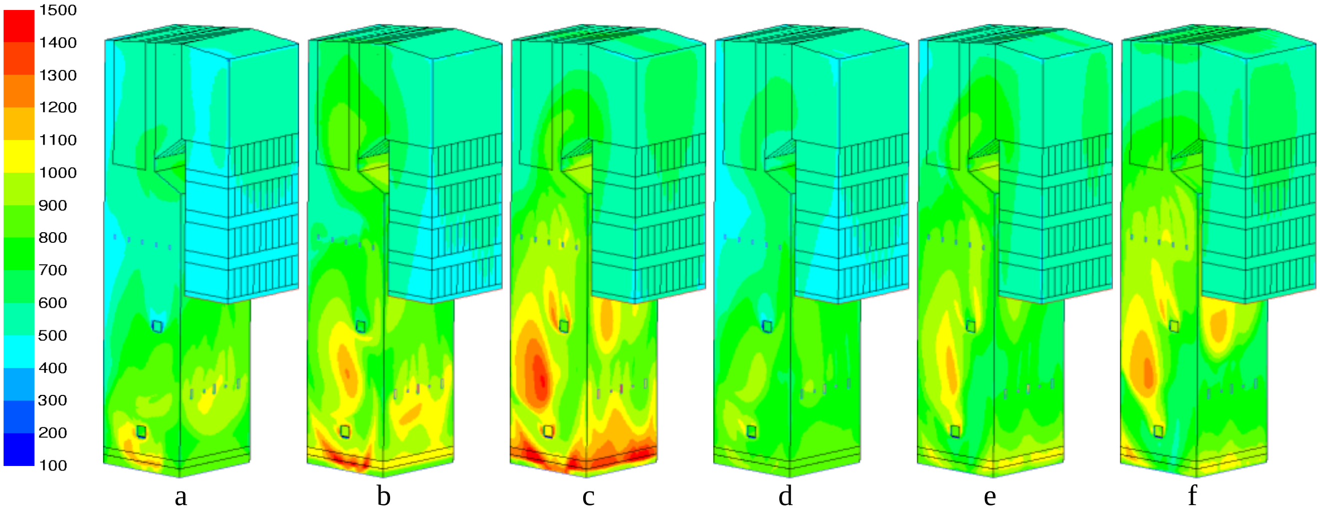

Fig. 1: Temperature in °C at furnace walls, a) 32MW, moisture 32%, b) 56MW, moisture 32%, c) 80MW, moisture 32%, d) 32MW, moisture 60%, e) 56MW, moisture 60%, f) 80MW, moisture 60%.

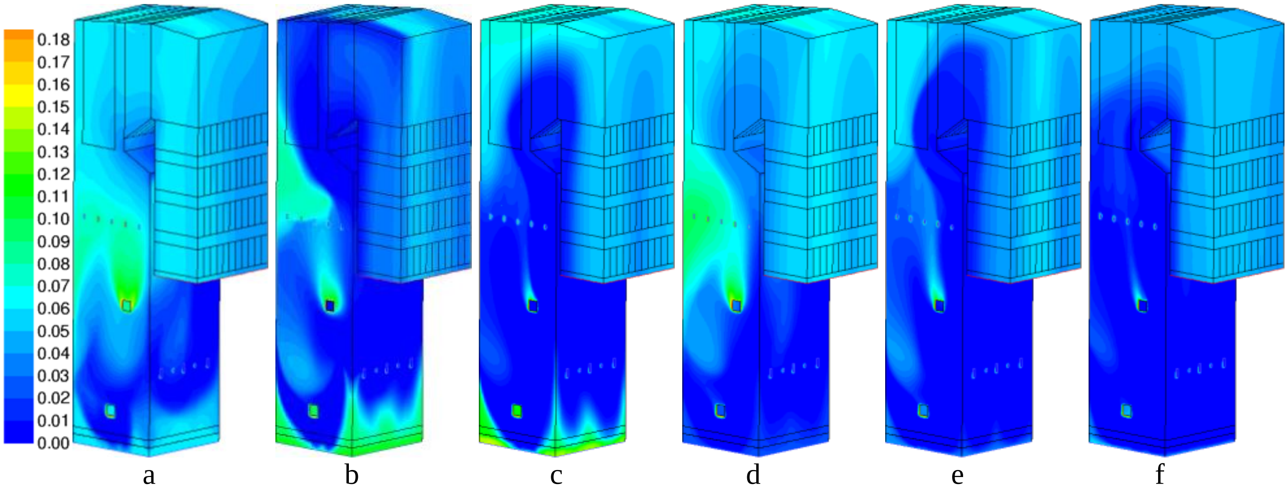

Fig. 2: O_2 mass fraction, a) 32MW, moisture 32%, b) 56MW, moisture 32%, c) 80MW, moisture 32%, d) 32MW, moisture 60%, e) 56MW, moisture 60%, f) 80MW, moisture 60%.

CO concentration distribution is shown in Figure 3 in logarithmic scale. As expected, distribution of CO is opposite to that of O_2 since in regions with high O_2 concentration combustion is fast and very little CO can remain. At low load, however, the lower temperature in the upper part of the furnace slows down reactions and CO concentration at the outlet of the simulated region remains higher than at full load although O_2 concentration at low load is higher. At all loads, the figure shows high CO concentration at the rear wall. High CO concentration can indicate an increased corrosion risk in the furnace and for that reason it is useful to analyse where the highest concentrations are found.

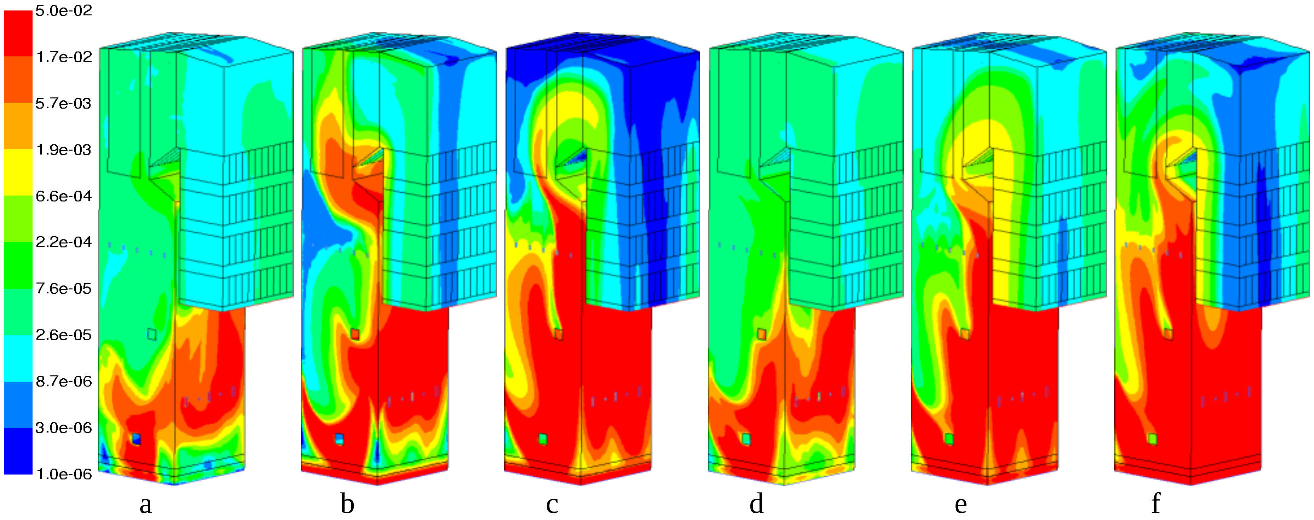

Fig. 3: Mass fraction of CO, a) 32MW, moisture 32%, b) 56MW, moisture 32%, c) 80MW, moisture 32%, d) 32MW, moisture 60%, e) 56MW, moisture 60%, f) 80MW, moisture 60%.

Effects of air distribution (see Table 2 for details) at 80 MW load on temperature, O_2 and CO distributions are shown in figures 4, 5 and 6, respectively. When primary air is reduced and moved to secondary or secondary and tertiary air feeds, temperature and O_2 concentration at furnace bottom reduce. Changes in the ratio between tertiary and secondary air have only small local effects on temperature and distribution of O_2 and CO. In general, effects of air distribution are clearly smaller than effects of load.

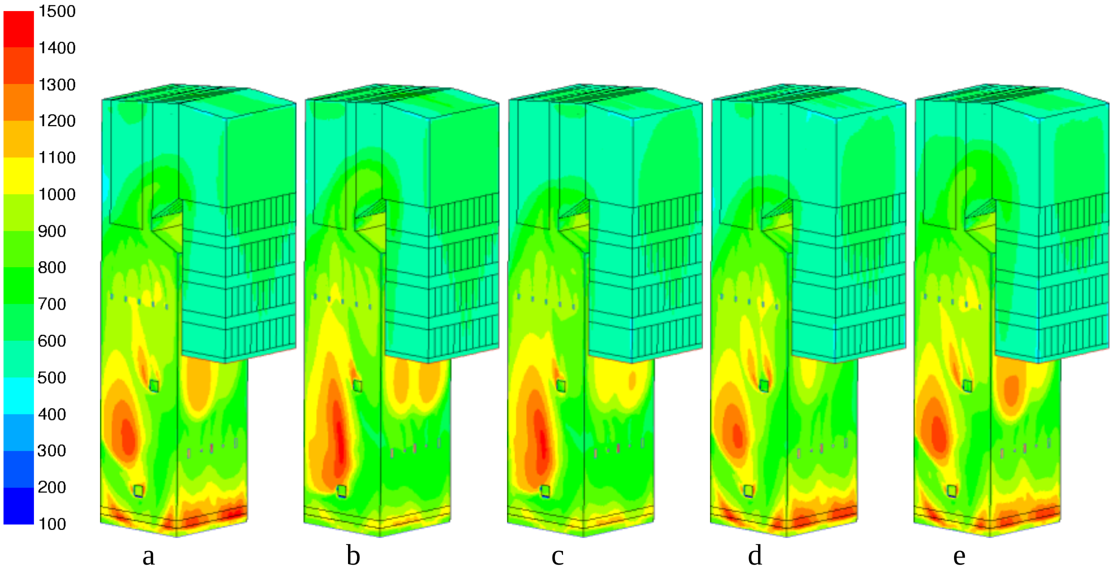

Fig. 4: Temperature in °C for load 80 MW a) base case, b) air moved from primary air to secondary air, c) air moved from primary air to secondary and tertiary air, d) air moved from secondary air to tertiary air, e) air moved from tertiary air to secondary air.

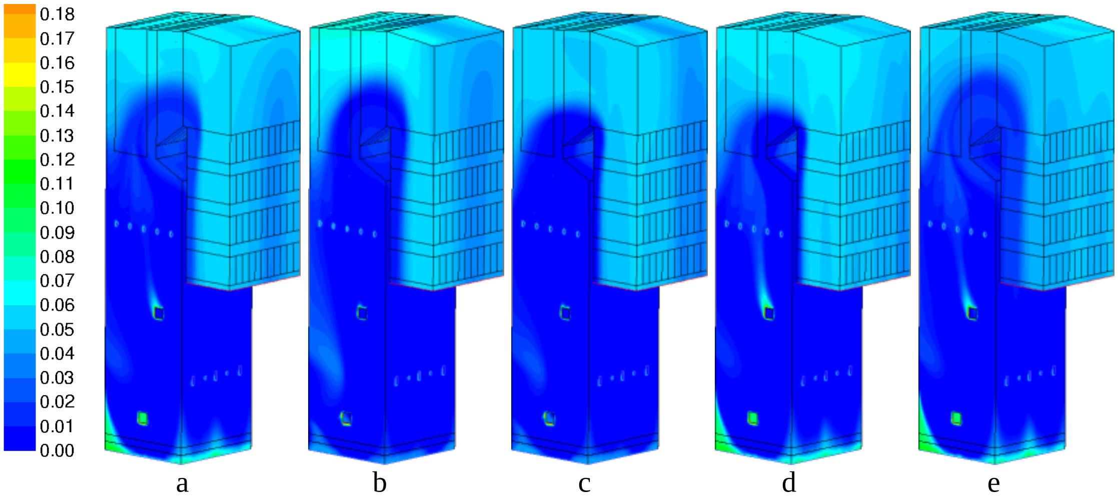

Fig. 5: Mass fraction of O_2 for load 80 MW a) base case, b) air moved from primary air to secondary air, c) air moved from primary air to secondary and tertiary air, d) air moved from secondary air to tertiary air, e) air moved from tertiary air to secondary air.

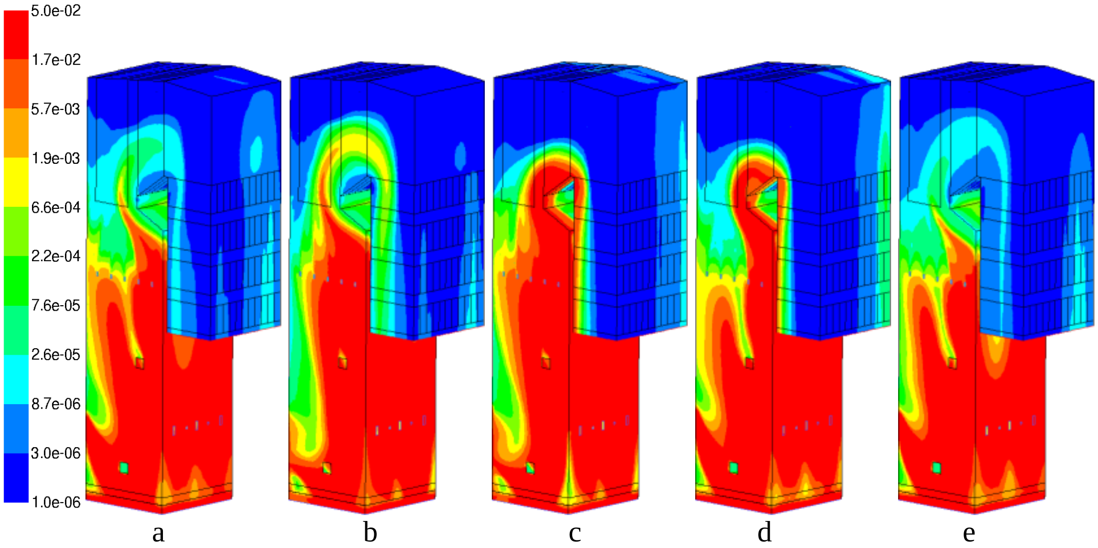

Fig. 6: Mass fraction of CO for load 80 MW a) base case, b) air moved from primary air to secondary air, c) air moved from primary air to secondary and tertiary air, d) air moved from secondary air to tertiary air, e) air moved from tertiary air to secondary air

4.2. Effects on heat transfer rates

Correlations were derived for heat fluxes to different surfaces of which in Fig. 7 correlations for evaporator walls are shown as an example. The heat flux is expressed as a function load and fuel moisture content by means of a second order polynomial. To account for air distribution, the result of the polynomial is multiplied by a correction coefficient that is a second order function of the shares of total air flow injected through primary, secondary and tertiary air inlets. Figure 7 shows that simple polynomial expressions describe well the effects of load, fuel moisture, and air distribution. Similar correlations were derived for heat transfer rates at superheater surfaces.

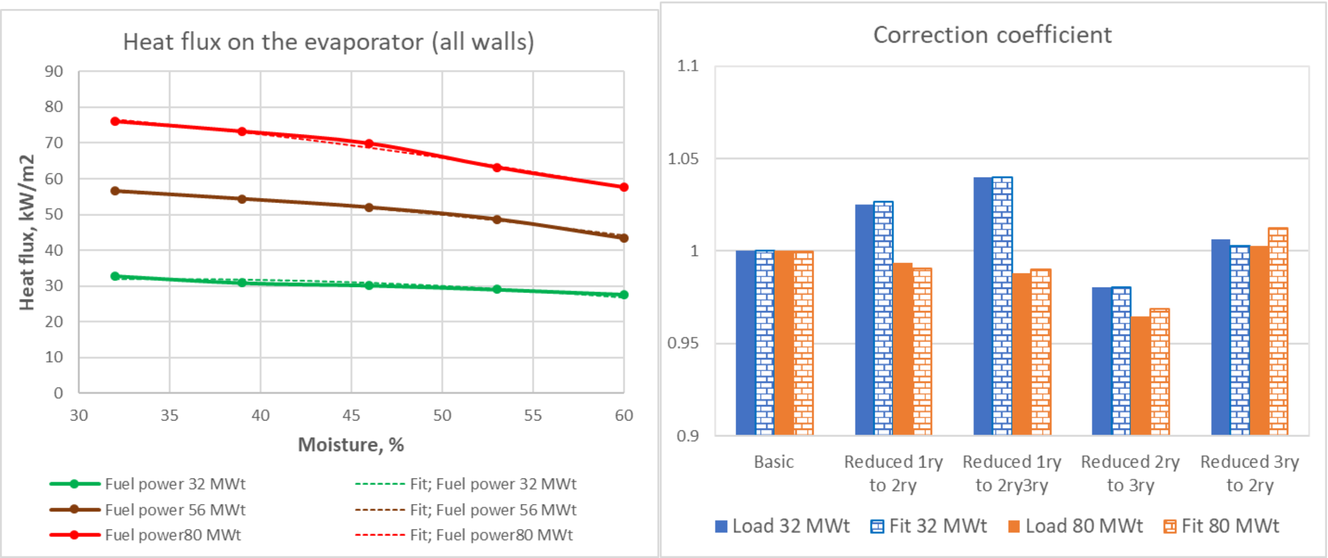

Fig. 7: Left: Heat flux to evaporator walls determined from the simulations as a function of load and results from a polynomial function fitted to the data. Right: Effect of air distribution on the heat flux to evaporator walls determined from the simulations as a function of load and results from a second order function that is fitted to the data.

5. Discussion on Use of the Results in 1D Dynamic Modelling

One of the goals of the work was to develop correlations that can be used to describe furnace behaviour in dynamic 1D process modelling where a full CFD model is too heavy to use to describe effects of process inputs. The simulations produced clear trends as functions of the main process inputs, i.e. fuel load, fuel moisture and air distribution. On basis of the CFD modelling results, correlations for heat transfer rates were derived. The simulations were carried out at steady state and thus the results represent the conditions toward which the process is heading at given process inputs. To apply the results in dynamic simulations, information on dynamic response of the process is required and separate CFD simulations need to be carried out for analysis of the dynamics. Alternatively, the dynamics can be identified from the actual boiler furnace if suitable dynamic experiments are allowed.

In addition to heat transfer rates, correlations could be derived based on the simulation results for local temperatures and CO concentrations near surfaces. To support process control, such correlations would be useful if a limit is required for maximum temperature at a specific wall or CO concentration which both are related to materials risks and corrosion.

6. Conclusion

In this paper, a bubbling fluidized bed furnace was simulated with a computational fluid dynamic model in a wide range of conditions. The main variables altered in the simulations were furnace load, fuel moisture, air ratio and air distribution. The main effects of the studied variables on the conditions inside the furnace and on heat transfer rates on the super heaters were analysed. The analysis shows that load is the main factor affecting temperature and concentration distributions in the furnace. Fuel moisture has also a significant effect. Air ratio and air distribution have, as expected, significant effects on oxygen distribution but also effects on temperature distribution. Heat transfer rates to different heat transfer surfaces are dependent on the temperature distribution and thus the effects are similar. In the paper, the possibilities to use the generated simulation data as bases for a simplified description of furnace behaviour are discussed. As an example of correlations that can be derived based on the simulation data, correlations for heat transfer rate at evaporator walls are presented.

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References

[1] V. Hovi, M. Huttunen, I. Karppinen, T. Pättikangas, H. Niemistö, L. Karvonen, S. Kallio, S. Tuuri and V. Ylä-Outinen, "Integrated transient simulation of a BFB boiler with CFD models for the BFB furnace and dynamic system models for the steam cycle and boiler operation", *Energy Procedia*, vol. 120, no. August, pp. 508-515, 2017.

[2] M. Huttunen, P. Jukola, L. Karvonen, T. Leino and J. Kauppinen, "Comparison of model predictions to available measurements in two BFB boiler furnaces", in *Proceedings of the 22nd Int. Conf. on Fluidized Bed Conversion*, Turku, Finland, 2015

[3] S.T. Pemberton and F.J. Davidson, "Elutriation from fluidized beds -1 Particle Ejection from the Dense Phase into the Freeboard", *Chem. Eng. Sci.*, vol. 41, no. 2, pp. 243-251, 1986

[4] J.B. Howard, G.C.Williams and F.H. Fine, "Kinetics of Carbon Monoxide Oxidation in Post Flame Gases", Pittsburg, in *Proceedings of The Combustion Institute, 14th Symp. Int. on Combustion*, 1973

[5] V.I. Golovitchev and N. Nordin, "Detailed Chemistry Spray Combustion Model for the KIVA Code", in *Proceedings of User's Group Meeting at the SAE Congress*, Detroit, 2001