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CIRCULATING FLUIDIZED BED COMBUSTION – BUILD-UP AND VALIDATION OF A THREE-DIMENSIONAL MODEL

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ABSTRACT

This paper presents the validated simulation of a full-scale circulating fluidized bed boiler as obtained via a comprehensive three-dimensional CFB process model. The model is utilized in boiler design and scale-up as well as to study and optimize boiler performance. Feedstock characterization tests, which are also presented, are used to provide data for those parts of the process where up-to-date modeling is not fully reliable, thus enabling the model to provide accurate results.

The overall model and its sub-models have been validated against data from numerous experiments ranging from characterization tests at laboratory scale to measurements in a 550 MW_{th} CFB boiler. The paper exemplifies comparisons between model results and experimental data, showing generally good agreement.

INTRODUCTION

Circulating fluidized bed combustion (CFBC) is a technology where combustion takes place within a gas-solid suspension. CFBC offers many benefits over other combustion technologies, among these fuel flexibility and relatively low emission levels.

There is a need for comprehensive modeling of CFBC in order to support design and scale-up of boilers. Despite the availability in the literature of sub-models for specific phenomena in fluidized bed combustion, the need for an overall CFBC model has been addressed by only a few works, the most relevant being the model provided by Hyppänen et al. (1), Hannes (2), and Lücke (3).

Metso and Chalmers University of Technology have together developed a comprehensive three-dimensional CFB process model (4, 5), which is an essential part of the knowledge process for Metso CFB combustion technology (see Fig. 1). The CFB process model is utilized in the boiler design process and scale-up as well as to study and optimize boiler performance. Among the concrete applications are evaluation of circulation material behavior and flow rates, assessment of combustion characteristics, dimensioning of heat transfer surfaces, and optimization of the air and fuel feeds. The model, also widely used in planning and post-processing in experimental research campaigns, is capable of establishing the boundary conditions for other calculation tools, such as water circulation, corrosion, and emission models.

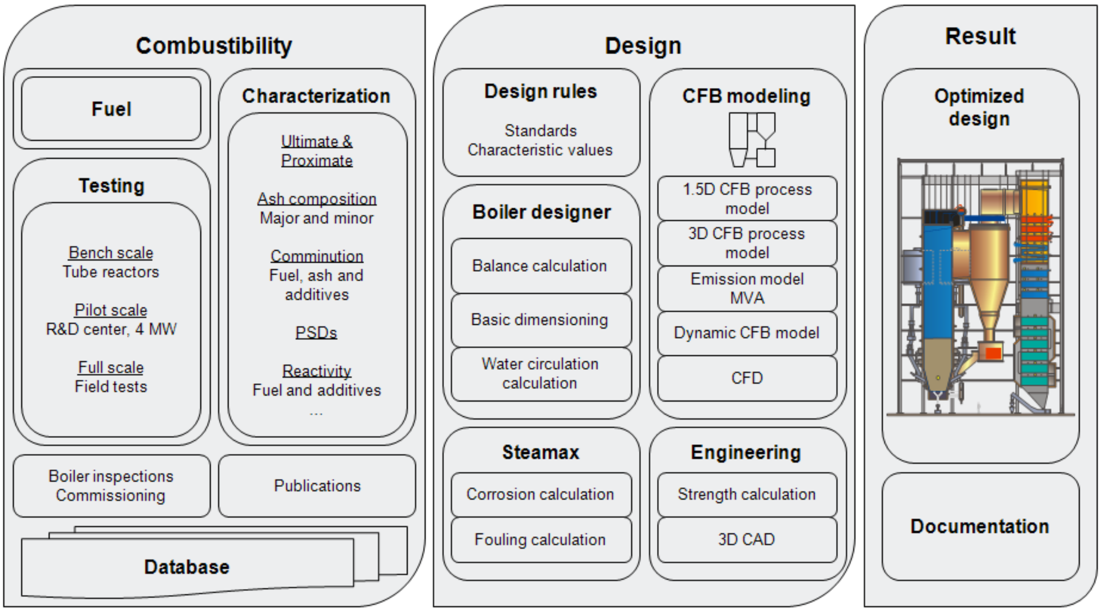


Fig. 1: Knowledge process of the Metso CFB combustion technology

Experimental data in large quantities have been used to verify the sub-models as well as the overall model. The experimental research consisted of:

- Laboratory-scale characterization tests
- Small-scale FB tube reactors
- VTT Jyväskylä 100 kW_{th} CFB
- Metso 4 MW_{th} CFB
- Chalmers 12 MW_{th} CFB
- Full-scale CFB boilers up to 550 MW_{th}

CFB PROCESS MODEL

The CFB process model is a combination of different validated submodels available in literature (6-11) each focusing one key phenomenon in the CFB process. These submodels contain as little empirical content as possible and are linked into an overall model by exchanging data according to the overview shown in Fig. 2. The input data need by the overall model is summarized in geometry of the unit, operational conditions (gas and solids injections, pressure drop over the furnace and waterwall temperature) and solids (including fuel) properties. As seen, some of the submodels use experimental input data from feedstock characterization tests (detailed below). Such tests are used instead of submodels where these would not be reliable enough. The model starts with a transient modeling of the fluid dynamics which accounts for the external actions taken to control the bed inventory (*i.e.* discharge of bed material and addition of makeup material) and the attrition of the solids, as detailed in (6). It is important to note that the solids inventory is modeled and monitored over the whole circulating loop including also the cyclones, downcomers and particle seals. These elements can contain significant fractions of the total solids inventory in form of finer solids than those found in the furnace. To account for the solids populating the return leg, a pressure balance over the circulating loop has to be closed, as well explained in (8). From this, the steady-state solids inventory in the unit is determined and can be used as input for the calculation of the steady-state fluid dynamics describing both the gas and solids flows as detailed in (7) and (8) respectively. For this, the solids in the furnace freeboard are divided into superimposing (ballistic) cluster and (core- annulus) disperse phases, each characterized by a decay constant, as detailed in (8). The gas flow is described according to the potential flow theory. The fluctuating nature of its mixing originates from the bubble flow in the dense bed and can be described through the formulation of a series of quasi-steady state pressure balances in the dense bed, as given in detail in (7). It is well known that fuel particles undergo varying mixing behaviors as they convert, due to the gradual decreases of size and density. Thus, a transient representation of the fuel mixing in order to account for the different mixing pattern of fresh fuel and fuel close to burn-out is needed. This is done in combination with a fuel particle conversion model, as described in (9). The conversion fate of a batch of fresh fuel is modeled on a time-resolved basis, and the solution obtained is then recalculated into a sum of continuously fed batches yielding the solution corresponding to the continuous feeding case. Finally, heat transfer is modeled by separating convection and radiation mechanisms and using individual heat transfer coefficients for convection and radiation, see (10), instead of a lumped coefficient accounting for both mechanisms (as usually is the case in works facing the modeling of the heat transfer in CFB units). This separate treatment of convection and radiation sets a basis for accurate descriptions of each mechanism (*e.g.* shadowing factors due to gas-solids suspension, internal heat exchanging surfaces such as division walls and wing walls, varying suspension emissivity and local convection peaks in furnace). A very first origin of this overall model is found in an EU-funded project (11).

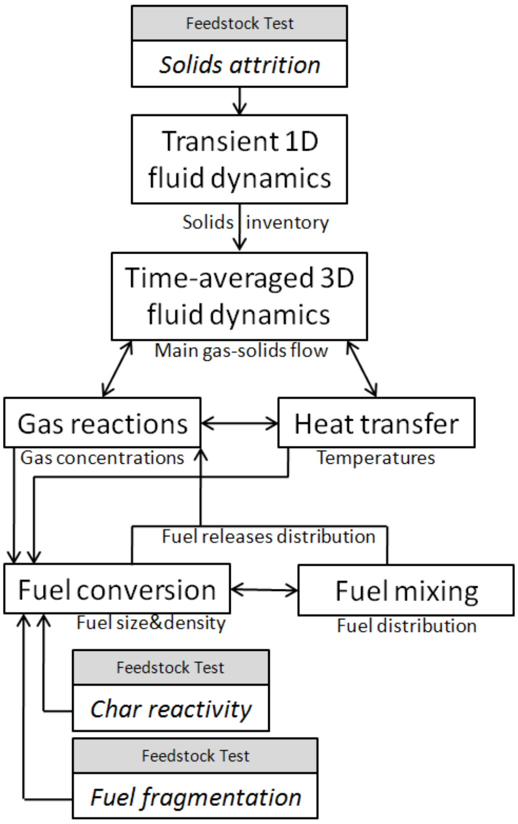


Fig. 2: Overall model structure

FEEDSTOCK CHARACTERIZATION

Conventional laboratory analyses are a starting point for basic balance calculations, but, in addition, more detailed information is needed for modeling purposes. Feed material characteristics, including the fuel fragmentation and attrition characteristics of solids generating the circulation material, must be taken into account because of their significant influence – in combination with boiler design and the operation parameters – on the CFB process.

Attrition of Solids

As a result of the strong influence of the particulate phase in the heat and mass transfer of in-furnace processes in CFB boilers, characterization of the solids inventory is a crucial element in modeling. Attrition of different feed solid fractions and their capability to generate circulation material, along with cyclone separation efficiency, have a direct effect on the performance of a CFB boiler.

The experimental characterization of the attrition pattern for feed materials is carried out in a small bench-scale setup wherein the solids sample undergoes attrition for a set amount of time. The result for a certain fuel ash is illustrated in Fig. 3, which shows the cumulative mass size distribution of the fuel ash after different attrition times expressed as a fraction of the total test time.

The duration of the test is in the range of hours, and the test is developed to provide data used in the modeling of solids inventory as described in Reference 6. After proper processing, the test result data describes which fraction of each size range will be reduced by attrition to finer size grades in a certain time.

Production of fine material is found to be faster at the beginning of the test, which is a typical finding for experimental investigations of attrition (12). The evolution of the amount of solids having a particle size smaller than 400 μm and its fitted power law function are presented in Fig. 3.

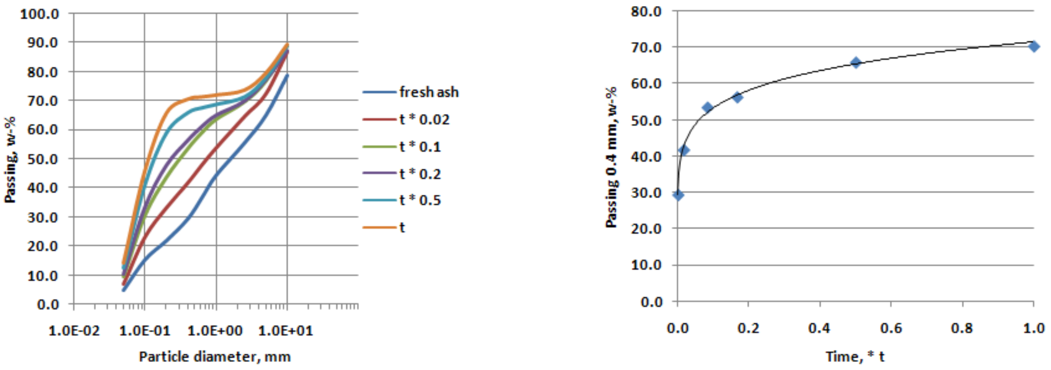


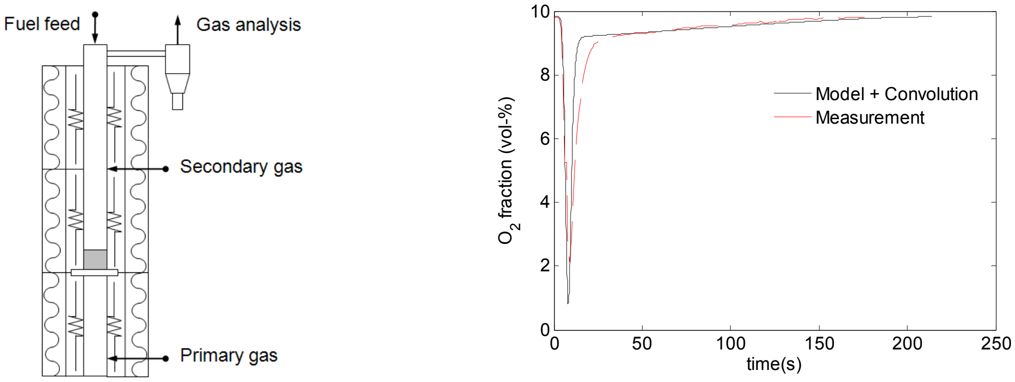
Fig. 3: Results from attrition testing for fuel ash

Rate of Fuel Conversion

The fuel conversion sub-model applied in the CFB process model is based on the formulation originally developed by Palchonok (13) and improved by Thunman (14) and Larsson (15). Fig. 4 schematizes the fluidized bed tube reactor developed to validate the fuel conversion model. Full combustion is ensured by the secondary gas, and fuel conversion is obtained from the time-resolved oxygen concentration in gases exiting the reactor (Fig. 4).

In comparison of the model and measurement results, it becomes obvious that the test method's contribution to the dynamics of the oxygen measurement must be accounted for. This is done by convolving the model's output with a convolution model designed for the test reactor used. The convolution model comprises three factors affecting the result:

1) Release and combustion of volatiles
2) The duration of the gas transportation and the mixing effects along the reactor before the gas is detected by the oxygen sensor
3) The contribution of the analyzer response time, which is described by the analyzer time constant analyzer time constant



a) Schematic of the FB tube reactor

b) Dynamic O_2 concentration during test

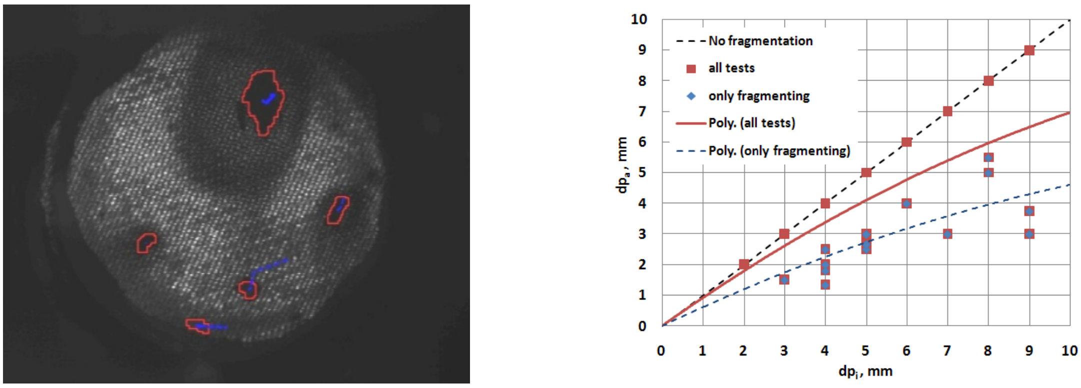
Fig. 4: Fuel reactivity test

Fuel Fragmentation

Fragmentation is the phenomenon by which fuel particles break into smaller ones during their conversion. There are several types of fuel particle comminution: primary, secondary, percolative fragmentation and attrition, which are involved in different stages of combustion. Primary fragmentation occurs in the first stages of combustion (particle heating, drying, and devolatilization) and is caused by intense thermal shock and local internal overpressures when a fuel particle is fed into a fluidized bed. Comprehensive research has been conducted on the fuel comminution phenomenon from coals and low volatile fuels (16) to waste fuels (17). However, the experimental methods used in these works are too laborious to be adopted as routine procedure in the fuel characterization process.

A fragmentation test method based on fuel particle image analysis has been developed. The fuel particle under analysis is placed in a furnace where the radiative heat transfer to the particle is adjusted to be equivalent to the total heat transfer in a fluidized bed environment. From a sequence of tests, the fragmentation probability, time of fragmentation, and number and size of fragments can be determined. This test method characterizes only primary fragmentation.

Figure 5 illustrates the particle recognition by digital image analysis of a fragmented fuel particle and exemplifies with test results the change in particle size due to fragmentation.



a) Optical image analysis of a fragmented fuel particle

b) Average particle size after the test vs. initial particle size

Fig. 5: Fuel fragmentation test results

FULL-SCALE CFB FIELD TESTS AND MODEL VALIDATION

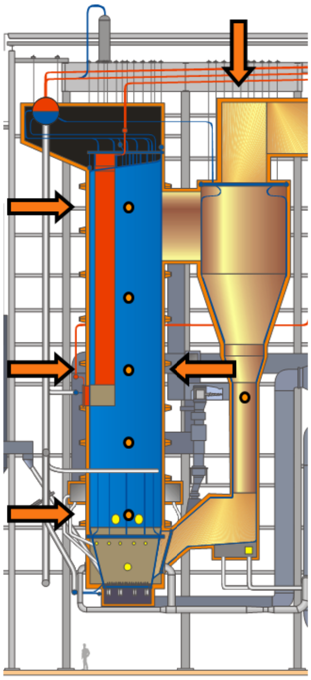
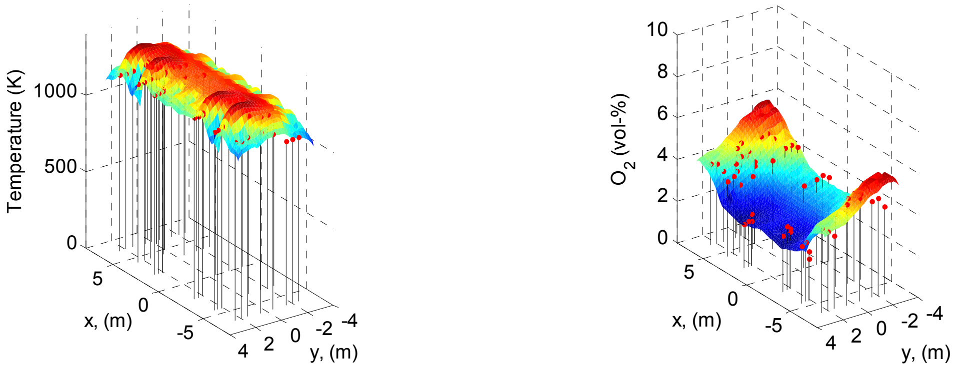


Fig. 6: Boiler unit and main measurement locations

Tests were carried out in a 350 MW_{th} CFB boiler with two cyclones combusting petroleum coke. Both a side view of the boiler and the main measurement locations are shown in Fig. 6. In total, 32 measurement ports in the furnace were used for measurement of the main gas components, temperatures, and pressures. Intensive sampling of feed materials, circulation material, and ashes was conducted during the campaign.
After setting of the input data (geometry, operation conditions, and solids properties – including results from characterization tests), the case can be properly modeled. The calculation mesh normally consists of 50,000–300,000 hexahedral cells for modeling of full-scale CFB units.

Even though the model contains the least possible empirical content, some sub-models are based on experimental correlations. For example, parameters affecting heat transfer, air and fuel feed penetration, dispersion, and mixing of gases and fuel have been adjusted to achieve satisfactory agreement with the measured data. These parameters have been validated against several experiments, with different boiler sizes, fuel mixtures, and load levels.

Temperature and main gas concentration profiles were measured simultaneously from 10 locations with specially designed probes and a multi-channel gas analyzer. Measured and modeled horizontal temperature and O_2 profiles above secondary air level are shown in Fig. 7 (where results from wall layers are omitted). As seen, agreement is satisfactory for both comparisons, although the model overestimates O_2 concentration in location close to the wall layers. This is a consequence of the (non-accounted in the model) diffusion of volatile matter and char from the wall layers to the core region.



a) Modeled and measured temperature

b) Modeled and measured O_2 concentration

Fig. 7: Furnace horizontal profiles above secondary air level

The vertical pressure profile in the furnace was measured by differential pressure transmitters and is presented in Fig. 8 together with corresponding modeled data, showing a very good agreement. Fig. 9 presents the modeled and measured cumulative mass size distribution of furnace bottom ash. As observed, the model predicts the presence of a significant mass fraction of particles finer than 100 µm in the bottom ash. The reasons for this disagreement are most likely 1) the perfect vertical mixing in the dense bed assumed in the modeling and 2) not accounting in the model for the size segregation effect in the bottom ash cooler (where a significant part of the finest particles are entrained back to the riser).

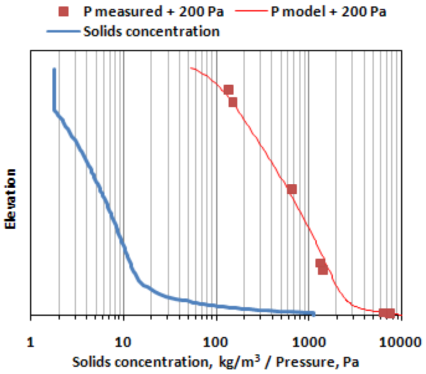


Fig. 8: Modeled and measured vertical pressure profile and solids density profile

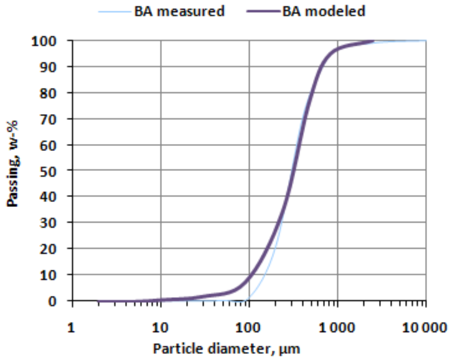


Fig. 9: Modeled and measured bottom ash particle size distribution

CONCLUSIONS

Key features and validation of a new comprehensive model of CFB combustion are presented. The model is formed by a combination of semi-empirical models describing key phenomena in the CFB combustion process. The validated overall model aims at being a tool for boiler design and scale-up as well as to study and optimize boiler performance.

Accurate characterization of feed materials plays a critical role in the modeling. The main feedstock characterization tests used in combination with the model are described and examples are given.

NOTATION

d_p particle diameter

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