DYNAMIC MODELLING OF A CFB BOILER INCLUDING THE SOLIDS, GAS AND WATER-STEAM SYSTEMS

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Abstract – Due to the widespread deployment of non-flexible renewable energy sources, an increasing trend is to use coal-fired boilers as support to the base energy production. High flexibility is usually required, and consequently, it is fundamental to be able to accurately predict and study dynamic behavior of the boilers. This point is particularly crucial for Circulating Fluidized Bed (CFB) technology. Indeed, while bringing excellent fuel flexibility and emission control, different case specific boiler configurations and arrangements induce significant variations in the dynamic behavior. This calls for a computational tool capable for accurate and specific dynamic studies of the entire system. One-dimensional process modelling and dynamic simulation, including the relevant automation functionalities, offers the best solution. Modelling and simulation of CFB boiler plants includes, however, many challenges, including modelling of combined volumes of gas and solid particles, complex fluidization phenomenon inside the furnace and in the circulating loop(s), strong coupling with the heat transfer to cooling systems, and the reactions for the combustion and sulfur capture. In addition, the model build-up phase and calculation speed shall not become limiting factors for applicability in engineering projects. This paper presents the latest enhancements in the Apros simulation environment, including improved managing of the furnace solid balance, heat exchange calculation from the circulating solids, and integration of dynamic behavior of the solid material looping. These developments were evaluated in a modelling study for a 750 MWth bituminous coal-fired CFB boiler. The modelling methodology is presented and the boiler model capability is demonstrated with simulation results.

INTRODUCTION

The widespread deployment of non-flexible renewable energy sources has made it common to support the base energy production by using coal-fired boilers. High flexibility is increasingly required to comply with the network requirements. It has become fundamental to study the boiler dynamics during the engineering of the new or retrofitted boiler systems. Most of the modelling efforts in the CFB field have focused on hydrodynamic behavior inside the furnace, using computational fluid dynamics (CFD). The time-scale and modelling scope of the CFD methodology make it unpractical for system-wide studies. Instead, one-dimensional process modelling and dynamic simulation can cover the whole process system and the plant automation (main control loops at the minimum), and still run faster than real time. While providing a sufficient level of accuracy, the modelling effort remains modest if the user can take advantage of configurable model components in the model build-up phase. Accordingly, this modelling approach is agile enough to support the plant and control engineering during the plant engineering phase. It can also be updated into a training simulator, used for automation system testing, and for helping decision-making in commissioning or operating plants.

There is very limited literature on dynamic modelling of CFB where the simulation scope includes the furnace bed and return loop(s) behavior and the water-steam systems (Chen & Xiaolong 2006; Lappalainen et al. 2014; Mikkonen et al. 2016). In this paper, the latest enhancements in the Apros environment in the frame of system-wide CFB modelling are presented:

- improved managing of the solid balance in the furnace, giving realistic pressure profile and circulating solids flow
- improved integration of the furnace bed and the solid return loops
- heat exchange calculation from the circulating solids to water-steam tubes
- improved management of ash and unburnt char in the solids balance of the furnace
- updated fuel definition for better alignment with standard industrial practice.

The developments were tested and verified by modelling and simulation of a 750 MWth CFB boiler. The model capability is demonstrated with simulation results of the furnace key parameters and trends on a load change transient.

DESCRIPTION OF THE BOILER

Fig. 1 shows a generic schematic picture of the CFB boiler type that the modelled boiler represents. The thermal power of the targeted boiler is 750 MWth. The design can be characterized by a furnace with a circulating bed, where a wide range of fuel (biomass, petcoke, oil shale, various coals, etc.) can be burnt. In the targeted boiler plant the choice was bituminous coal. Coal, ballast and limestone (the latter allowing in situ sulfur capture) are injected in the bottom of the furnace, as well as air (primary air at the bottom and two levels of secondary air). To obtain a longer residence time (necessary for bad quality fuels usually burnt in CFB), the solids are separated from the flue gas in cyclones and reinjected in the furnace. The flue gases are sent through a heat recovery part where heat exchangers allow heating of steam. The heat recovery part was out of the target of this study. There are two different solid return paths (loops). At the bottom of the cyclones, ash (and other solids) are sent to seal pots. Most are sent directly back to the furnace. A small fraction is extracted via a cone valve and sent to external beds (bubbling type). These external beds allow controlling the furnace temperature and reheat steam temperature.

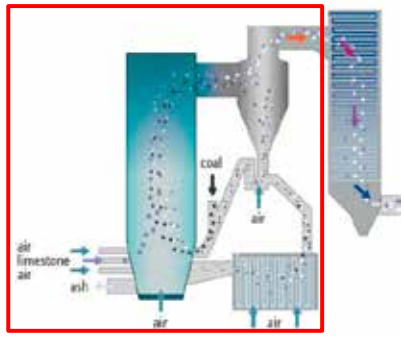

Fig. 1. Schematic picture of the boiler type (only the framed part was addressed in this study).

METHODOLOGY

General

Apros is a software product for the integrated modelling and dynamic simulation of power plants including process and piping, instrumentation, control and logics, and electrical systems. Apros features libraries of generic model components – such as pipes, pumps, valves, tanks, heat exchangers, controllers – which can be connected into a system-wide model and whose properties can be customized by adjusting parameter values, without programming. Apros is a registered trademark of Fortum and VTT (www.apros.fi). When constructing a process model in Apros, the user graphically selects suitable equipment model components, connects them and sets parameter values. Simultaneously, the system generates a calculation-level structure, which is directly used by the simulation solvers.

In respect of process flow paths, the calculation level consists of a network of nodes (control volumes) and flow branches between them. A similar network is generated for the concentration solution including reaction calculation. In respect of walls of the tubes, tanks and equipment, the calculation level includes heat structure nodes and conductive heat transfer branches between. When process fluid and the wall contact, other types of heat transfer mechanisms, convective and/or radiative, are generated between the fluid nodes and the heat structure nodes. The user selects appropriate process fluid and equipment structure materials, and determines spatial nodalisation depending on the needs in the modelling application. Fluid and material property functions calculate quantities, such as density, viscosity, heat capacity and conductivity according to the system state. Further reading for the thermohydraulic calculation principles can be found in (Hänninen 2009; Lappalainen et al. 2014). The main principles regarding the fluidized bed and the return loop calculations are introduced in the following sections. Some of the features are new developments which will be available in the Apros Combustion version 6.07.

Furnace

In this project the Apros model component FLUID_BED_ADV was used for modelling the fluidized bed furnace. It is suitable for modelling both bubbling and circulating fluidized beds; the latter features were further developed during this work. The component simplifies the furnace into a one-dimensional flow channel, where the user defines number and elevations for the vertical calculation nodes. Different cross-sectional areas can be defined for the furnace at different levels. The solids are considered as particles of equal size; each particle is handled as a separate sphere with two layers. The component offers terminals to connect input and output flows for the solids and gaseous streams, and to connect heat exchange with the water-steam systems. The component generates the calculation level structure according to the nodalisation and connections, and during the simulation it manages the solid material distribution, the gas flows, concentrations and reactions, and the interaction between the solid and gas phases. Fig. 2 illustrates the basic principles of the furnace nodalisation and connections; the actual calculation level structure is significantly more complex. The return loops for the circulating solids are configured separately, based on the needs in the targeted case.

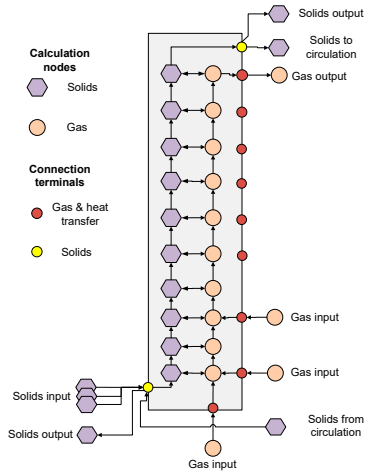

Fig. 2. Schematic picture of the furnace nodalisation and connections.

The furnace model manages two separate balance calculations: solids balance and gas balance. The gas balance is an integral part of the pressure flow network, where also the air flows, and flue gas flow paths, are included. The gas flow calculation inside the furnace takes into account available cross-sectional flow areas, and the form losses are derived from the hydraulic head of the solids. The solids balance is extended outside the furnace to model the solid return loops. The recent development has especially addressed the solids balance and vertical distribution in the furnace.

The basic principle for the solids profile inside the furnace originates from the steady state distribution models presented in (Hannes 1996). The vertical distribution of solids is calculated using a reference profile by (Wen & Chen 1982)

$$\bar{\varepsilon}_s = \varepsilon_{s,\infty} + \left(\varepsilon_{s,d} - \varepsilon_{s,\infty}\right) e^{-az} \tag{1}$$

The parameter values are either calculated as a function of prevailing conditions (gas flows etc., see more details in (Lappalainen et al. 2014) or given by the user. In dynamic simulation, at every simulation time step, the mass balance calculation produces actual (simulated) profile for the vertical solids distribution. In each solids balance calculation node, the difference between the actual solids mass, and the mass derived from the reference profile, determines the solids mass flow from this node upwards. Additionally, the mass flow depends on a time constant, thus giving:

$$\dot{m}_i = \frac{m_{s,i} - m_{r,i}}{\tau_i} \tag{2}$$

The time constant is either a user given single value for all vertical nodes, or it is separately calculated for each node. The latter method was used here, taking use of the theoretical particle velocity $u_{p,i}$ in the gas flow and the spatial distance Δz_i between the adjacent nodes.

$$\tau_i = \frac{\Delta z_i}{u_{p,i}} = \frac{\Delta z_i}{u_{g,i} - u_{t,i}} \tag{3}$$

In the previous CFB simulations with Apros, the furnace's solid balance was lacking one essential feature: the particles in the solids balance could not originate from the fuel. Instead, all material in the fuel was immediately moved to the gas balance, when the pyrolysis reaction took place. This deficiency was removed by introducing two solid fuel specific attributes that determine proportion of ash and char that move to the gas balance; the rest remains in the furnace's solids balance. Accordingly, part of the ash can be defined to go with the gas flow as fly ash, and the rest stays in the furnace and return loops, until extracted from the bottom of the furnace. Furthermore, the char which stays in the solids balance was given a combustion reaction of its own. Also the definition of solid fuels was renewed to better correspond with the typical input data, i.e., ultimate and proximate analyses. These improvements give significantly better means to calibrate the furnace model to match with the design values, or measured data.

Solid return loops

At the top of the furnace, most of the solids leaving the furnace are captured in cyclones, and circulated back to the furnace, either directly (short return loops) or through external fluidized bed loops. The solids recirculation plays an important role in the overall dynamics of the CFB boiler. In the external beds, heat is extracted from the moving solids by steam tubes. This heat extraction naturally has a clear impact on the furnace temperature. Besides the solids inventory in the furnace, the external beds contain significant amount of solids too. It is noteworthy that the balance between the furnace and external beds is subject to change in transients.

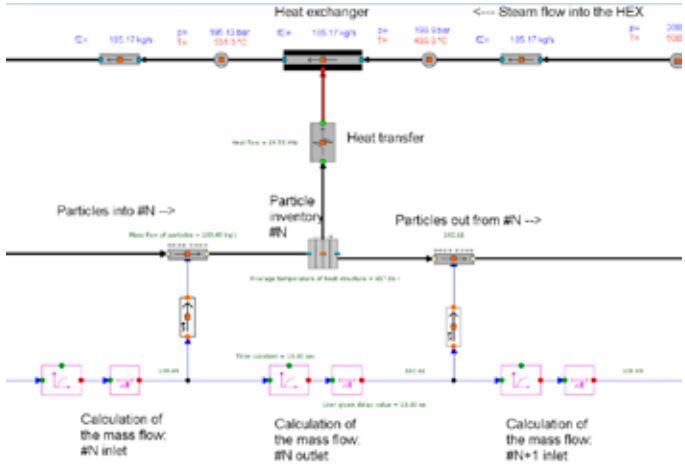

Fig. 3. Illustration of the solid return loop modelling approach (note, this is for illustration purpose only and NOT from the target boiler model). A particle inventory and transfer modules (in the middle), heat exchange to water tubes (top) and calculation of the particle mass flow rate (bottom).

Like the furnace, the solid return loops also offer big challenges for realistic modelling targeting real time or faster simulation. Thus the problem was simplified to achieve a robust and fast calculation method. The actual bubbling beds are not represented as such, and only solids, solid transfer with inertia, and heat transfer are represented. To do so, the fluidization air used to fluidize the bubbling beds and seal pots is neglected and an equivalent flow rate is introduced directly via the "other air" stream in the furnace. Accordingly, the modelling of the return loops only deals with the solid phase. The loops are built up using solid particle inventories or storages (HEAT_STRUCTURE_X), and particle transfer modules (PARTICLE-_TRANSMITTER). Each storage module considers its material as perfectly mixed. The transfer modules can extract particles from the furnace bed (the bottom or topmost furnace node), or from a particle storage module, and move them into another storage module, or back to the furnace bed (the bottom node). Multiple input and output transfer modules can be connected with one storage module, allowing modelling of

different types of particle collectors and dividers. In the particle transfer modules, the particle mass flow is directly given by the user, or determined by a suitable correlation. Accordingly, a solid return loop is created as a sequence of transfer modules and storages. To mimic realistic behavior of the solids flows and inventories in the loop, the user can configure his/her specific relations between the input and output mass flows. For example, in this work, the particle flow out from a storage module is typically calculated as a delayed and low-pass filtered value of the particle flow into the same storage. Fig. 3 presents the principle by showing an example section of a solid return loop, and the related calculation for managing the particle mass flows.

A storage module can also be set as a boundary condition. This is used to configure solids feeding (such as fuel, limestone or ballast) from raw material sources, and solids extraction out from the model scope into a sink (such as fly ash or bottom ash extraction).

Heat transfer

There are three basic types of heat transfer in a CFB plant model: inside the furnace, in the solid return loops, and in the flue gas channel. The latter one can be modelled with the standard Apros boiler modelling principles, but as mentioned earlier, the heat recovery part was excluded from this study. The heat transfer inside the furnace (convection and radiation) is calculated from the gas and particles to the water circulation pipes. The radiation heat transfer is introduced by a factor in a range [0…1]. The calculation of the convective heat transfer from gas/particle suspension to water-steam tubes is described in (Lappalainen et al. 2014). The user defines the connections between the furnace terminals and the water-steam tube packages. As the user has given each terminal an elevation, the connection finds the closest furnace node, where the heat is extracted from. An example view to the model of this study is given in Fig. 4.

To describe the heat transfer in the solid return loop from the recirculated particles to water-steam systems, a new heat transfer option was introduced in the HEAT_CONNECTOR component. The heat transfer calculation combines different heat transfer mechanisms into a simple form:

$$Q = h_{ext} A (T_s - T_w) \tag{4}$$

The coefficient h_{ext} can be adjusted during simulation by a user given relation, for example, to depend on the solids mass flow and temperature, like done in this study. All the water-steam flow paths were modelled using the Pipe with heat structures (HEAT_PIPE) components.

MODELLING

In this work, the process modelling focused on the process area with solid particles, where also the new developments were allocated. The surrounding process systems were included to the extent that enabled reasonable overall simulation of the boiler plant. For the selected scope, the basic control loops were included. Air pre-heating and the heat recovery part were excluded from the scope, and the turbine plant was significantly simplified. Evidently the simplifications decrease reality in the model predictions, especially in transients, because the overall dynamics builds up from the interactions of the total plant. On the other hand, the excluded parts are basic boiler plant unit operations, which modelling is considered as standard Apros modelling work, and will be carried out in the future.

Within the water-steam circulation, the Apros 6-equation thermohydraulic model was used. The gas flows and compositions, and the reactions in the furnace were simulated with the 3-equation (homogeneous) thermohydraulic model. The model dimensioning (elevations, duct and tube dimensions, etc.) was conducted using the design data of the target boiler. The furnace bed (FLUID_BED_ADV) was discretized into 16 nodes. The dense bottom part of the furnace bed was modelled using relatively more nodes than the upper part, and the last upper nodes were defined to be of equal height. Altogether seven solid materials were defined into the solids balance: SAND, FUEL, ASH_FB, CHAR_FB, LIMESTONE, GYPSUM, and quick lime. The substances ASH_FB and CHAR_FB are those that move to the solids balance from the FUEL in the pyrolysis, as described above. Specific artificial heat structure materials (HSM_MATERIAL) were defined for different steel and refractory types used in the furnace refractory and heat exchangers. Whereas real density was kept, specific material properties (heat capacity, conductivity) and thickness were artificially adjusted to compensate the difference between the model's simple geometries and the complex real configurations (tubes against single sided panels covered by refractory held in place with anchors/studs). This allowed preserving the overall thermal properties: diffusivity and thermal inertia. Some of the parallel equipment, and flow paths, were approximated using lumped models. Justification for these simplifications will be re-evaluated after comparison against real plant operation. The modelling was organized into several

diagrams, as illustrated in Fig. 4. The solid return loops were modelled using the principle demonstrated in Fig. 3.

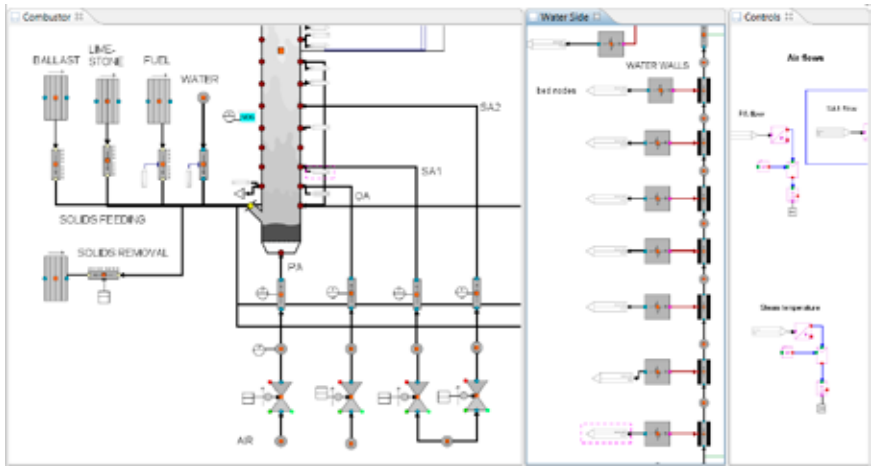

Fig. 4. Views to the model diagrams: solids and air feeding to the furnace (left), part of the water walls (middle), and control loops (right). The highlighted reference flags (see right side of the furnace, and the lowest water wall tube section) show an example, how the model continues from a diagram to another.

SIMULATION RESULTS

The simulations in the scope of this work included calibration of the model parameters to achieve an appropriate agreement with the design reference, and running of initial load change transients. Fig. 5 shows relative differences in the heat duties of the heat exchangers, which were included in the model scope. The heat exchangers include both water walls and other types in the furnace, and heat exchangers in the return loops. The 100 % load represents the initial state, and the 80 % the final state after the load change transient, which is described in the following. The results show good agreement with the design values, and proper balance between the heat exchangers inside the furnace and in the return loops. Fig. 5 also shows pressure difference profiles in the furnace bed at the same 100 % and 80 % load states.

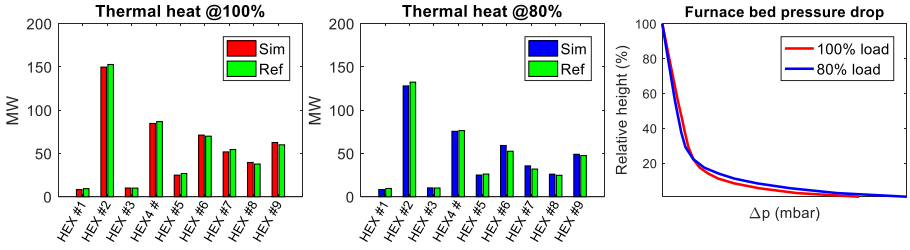

Fig. 5. Comparison of the simulated heat exchanger duties with the design references in steady state at 100 % (left) and 80 % (middle) load; Simulated furnace bed pressure difference profile at 100 % and 80 % load (right).

A load change from full load (100 %) operation to 80 % load was conducted by ramping the fuel feed down app. 20 % during a period of 20 min. Simultaneously, primary air flow was ramped down, as well as relevant boundary values and control loop set points of the water-steam system, according to the 80 % load. The control of the flue gas oxygen (O_2) content was ON during the simulation, thus manipulating the secondary air flows. The calculation speed for the model was satisfactory: more than 20 times real time with a standard laptop. Selected simulation results are shown in the following figures.

Fig. 6 shows the fuel and air feeding. The other air (OA) flow experienced only minor variations as expected since it represents air flows from equipment fluidization that do not vary with load.

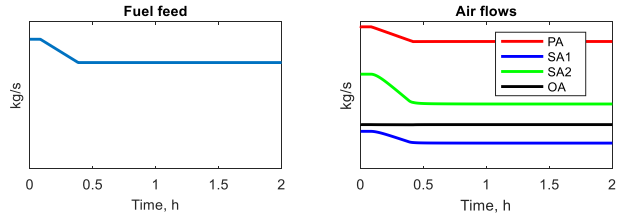

Fig. 6. Transient simulation from 100 % to 80 % load. Fuel feeding and air flows.

Fig. 7 shows trends for the average temperature of the furnace, the flue gas O_2 content, and total pressure difference over the furnace bed. The O_2 content controller was tuned tightly, so only small deviation from the set point took place during the ramping. The furnace bed total pressure drop, together with the pressure drop profiles in Fig. 5 reveal, how the furnace bed inventory and solids distribution change during the transient.

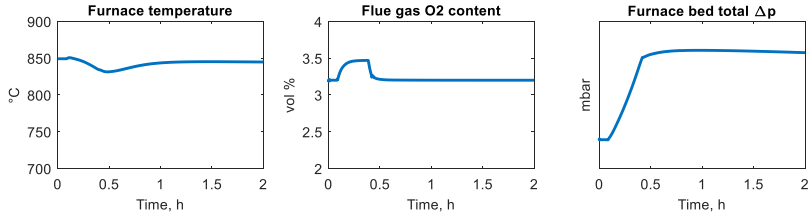

Fig. 7. Transient simulation from 100 % to 80 % load. Furnace average temperature, flue gas O_2 content, and total pressure drop over the furnace bed.

Fig. 8 illustrates variables in the water-steam side: drum pressure and level, steam flow, and thermal heat transferred to water. The last one represents the sum of the heat exchangers, which were included in the model scope.

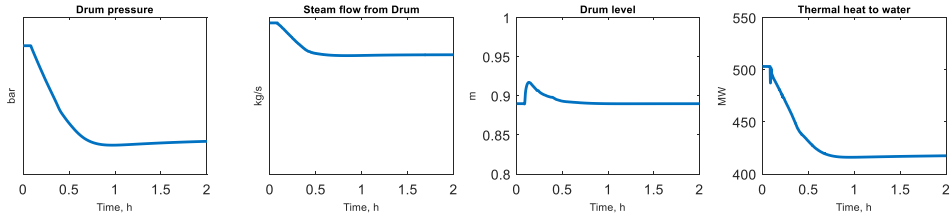

Fig. 8. Transient simulation from 100 % to 80 % load. Drum pressure and level, steam flow and thermal heat to water.

DISCUSSION AND CONCLUSIONS

In this work, using the Apros simulation platform, was modelled a combination of furnace bed and solid return loops, gaseous streams in/out and inside the furnace, and heat transfer from the furnace and circulating solids to the water-steam paths. New features were developed in Apros and used in a modelling and simulation study of 750 MWth CFB power plant. The modelling method and simulation results were evaluated in two ways: i) the steady state results were compared with design data of the target plant, and ii) the results from the transient experiments were qualitatively evaluated with domain experts. The steady state results were well aligned with the design values, and the load change results showed dynamic behavior as expected. The calculation managed the gas flows, reactions, system temperatures, solids inventories in the furnace and external beds, as well as the heat extracted into water-steam paths in a reasonable way.

A short term future goal is to extend the modelling from the current scope, and to evaluate it with new transient tests and against experimental data. An ultimate goal to pursue in respect of modelling and simulation, is to integrate the modelling in engineering projects' work flow, and to continuously reflect the knowledge of the real plant and the virtual plant. A dynamic simulation model, when accurate enough and flexible to configure and use, provides an invaluable tool for supporting engineering tasks during a plant

design project. The current demand, and even higher potential in future, motivates to apply and further develop the presented approach in new projects.

NOTATION

a	coefficient, -	T_w	temperature of tube outer wall, °C
A	heat transfer area, m^2	$u_{g,i}$	gas superficial velocity in node i, m/s
$\bar{\varepsilon}_s$	volume fraction of solids, -	$u_{p,i}$	particle velocity, m/s
$\varepsilon_{s,\infty}$	volume fraction of solids at top, -	$u_{t,i}$	particle terminal velocity, m/s
$\varepsilon_{s,d}$	volume fraction of solids in dense bed, -	Q	heat flow, W
h_{ext}	heat transfer coefficient, $W/m^2/K$	z	vertical coordinate, m
$\dot{m}_i$	mass flow, kg/s	Δz_i	distance between adjacent nodes, m
$m_{s,i}$	simulated mass in node i, kg	OA	other air
$m_{r,i}$	reference mass in node i, kg	PA	primary air
τ_i	time constant for node i, s	SA1	first secondary air
T_s	temperature of solid particles, °C	SA2	second secondary air

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