Modeling of Gas-Particle-Flow and Heat Radiation in Steam Power Plants

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Abstract

Fired steam generators are the dominating technology of coal combustion in power plants. This paper presents a model for pulverized coal fired steam generators in Modelica. The model components are designed as an extension of SiemensPower, a Modelica library for transient simulation of power plants.

The focus is on coal combustion, gas-particle-flow and radiation heat transfer in the furnace. The dispersed flow of flue gas has to be modeled because radiation heat transfer gets considerably intensified by the contained coal and ash particles. Customized connectors for the dispersed flow of flue gas had to be developed on the base of Modelica.Fluid.

The component oriented approach supports the adaption of the model to different simulation tasks, such as stability analysis of the evaporator or influence of the coal mill on plant dynamics. Component structure, parametrization and spatial discretization were important aspects for the development of maintainable and re-usable components of the model library.

Keywords: steam power plant; coal; dispersed flow, radiation heat transfer; connectors

1 Introduction

Coal fired steam generators are widely used in commercial power plants around the world. Even in 20 years, more than one third of the world's growing electric energy demand will be produced out of coal [6]. Today's coal power plant units generate up to $1100\,\text{MW}$ of electric power and steam generators reach heights of $170\,\text{m}$.

Before combustion, the coal gets pulverized in coal mills to particle sizes of about $50\,\mu\text{m}$. Some of the combustion air is used to transport the coal dust into the furnace. In the furnace, the coal is burned while moving within the flow of combustion air and flue gas. The combustion takes about one second in most cases, but the burn-out of larger particles can take longer.

Furnaces for hard coal with dry ash removal were modeled first, as they are the dominating technology today. The model could be adapted to lignite plants by adding equations for flue gas recirculation. If necessary, slag-tap furnaces can be modeled, too.

Flexibility is the main challenge in development of coal power plants. For fired steam generators this implies more dynamic operation and usage of different coal types and biomass.

A detailed model of the steam generator is needed, in order to analyze the dynamic behavior. The heat release of the combustion is non-uniform over the height of the furnace. This non-uniform heat flow into the water wall tubes influences the flow stability and the energy storage of metal and fluid. The coal mills define the speed of fuel ramps and the distribution of coal particle sizes. The furnace model allows to study the impact of coal mill dynamics on power output.
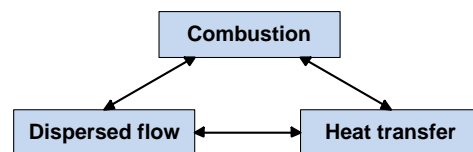

Figure 1: Dependencies of modeling domains

The focus of the presented work is on modeling of the furnace and radiation heat transfer inside of the furnace [4]. Extensive simplification has to be applied in order to achieve a model for dynamic simulation tasks on system-level. Power plant furnaces are large systems with turbulent reactive flow in three dimensions. Spatial discretization was applied in order to reduce the partial differential equations into a set of ODEs which can be solved by a Modelica tool. The guide-

line for model assumptions were proven steady-state inhouse tools. A trade-off between model accuracy and numerical speed and robustness has to be made, if the furnace model gets coupled to the water/steam-cycle.

For practical simulation tasks, the available parameter set and measurement data for calibration is very limited.

Figure 1 shows the needed models of coupled physical phenomena for the furnace model. The combustion model calculates the heat release (heat flow and burn out) and flue gas composition. This depends directly on the model of dispersed flow which fullfills the mass, energy and momentum balances. The resulting radiation heat transfer depends on the temperatures of flame and wall. Especially in transparent flame zones, flue gas composition and particle properties influence emission and absorption coefficients.

2 Modeling Framework

SiemensPower is a growing specialized model library for transient simulation of power plants in Modelica. The models are used to enhance the performance in operation and control of existing and new power plants. The components of the library are designed for many different power plant applications. One example are combined cycle gas turbine (CCGT) plants with heat recovery steam generators. The library is used as a basis for studies of multiple engineering design questions. SiemensPower is based on Modelica.Fluid connectors and Modelica.Media. Dymola [5] is used as the main tool for modeling and simulation. The model components of fired steam generators add a new field of application to the SiemensPower library.

Besides Modelica/Dymola there are several inhouse simulation tools in use at Siemens Energy which have to be maintained. If the Modelica model of the fired steam generator delivers reliable results, older inhouse tools could be potentially replaced. Other specialized inhouse tools could be coupled to the Modelica model in order to extend their application range.

The existing steady state tools were used as a guideline for component structure design, parametrization and validation of the new Modelica model.

3 Model Description

3.1 Model Structure

Figure 2 shows the layout of a steam generator model in two-pass configuration. Coal and air enter from the left into the furnace. The combustion heat gets transfered to the furnace walls. As flame temperature is about 1800 K, heat transfer is dominated by radiation, while convection is negligible in the first approach.

After combustion, the hot flue gas leaves the furnace and passes several convective heating surfaces. Radiation from the flame to the first convective heating surfaces has to be modeled, as indicated by the arrows in figure 2.
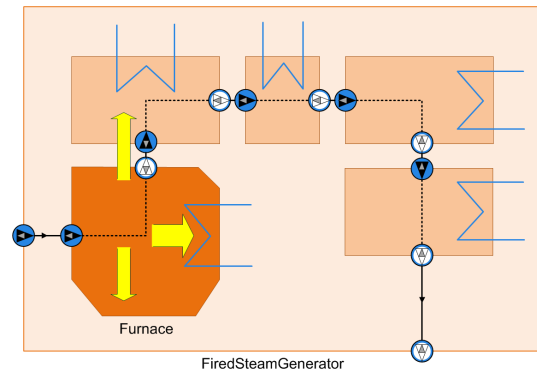

Figure 2: Model layout

Inside the furnace, the non-uniform distribution of mass and heat flows was modeled by spatial discretization in one dimension as shown in figure 3. The size of flue gas elements depends on the geometry of the specific furnace. If more spatial resolution is needed, the zones in figure 3 could be further divided into sub-segments.
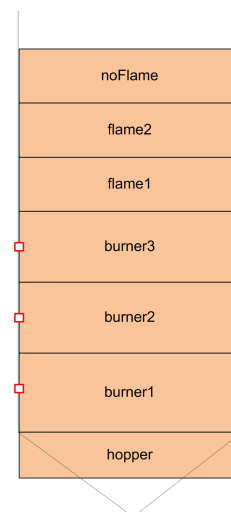

Figure 3: Furnace structure

Each furnace element consists of two components. The equations for gas-particle-flow and combustion are contained in `DispersedFlowZone`. The radiation heat exchange between all surrounding surfaces gets calculated in `RadiationHeatTransfer`.

Figure 4 shows the model diagram of the component `Furnace`. The furnace is seperated into several furnace elements according to the levels in figure 3. The left column of components consists of one `DispersedFlowZone` per furnace element, each connected to one `RadiationHeatTransfer` in the right column.
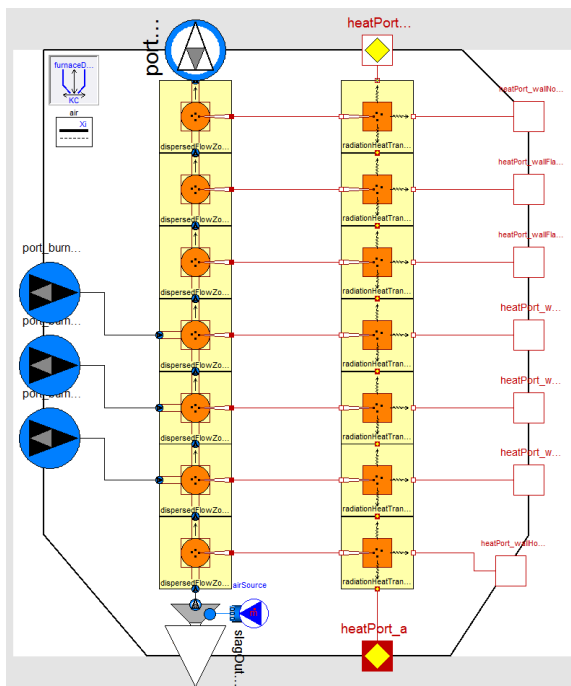

Figure 4: Furnace component diagram

Currently, the heat transfer model is a separate component, leading to a clean model structure. But, because of the strong dependancy of the equations, it will be moved into `DispersedFlowZone` as a submodel.

In the presented example, there are three burner levels. Coal enters through the burner levels and gets transported upwards with the flue gas. Small ash particles leave the furnace together with the flue gas, whereas larger ash particles fall into the hopper bottom. The flame at burner levels and in the first section above the furnace is assumed to be non-transparent. Radiation heat can only be exchanged with the furnace walls and the neighboring flue gas zones. After the luminous flame, flue gas zones are partially transparent for heat radiation. Heat can be transferred from the flame to the following gas zones and heating surfaces.

The following sections describe the furnace model in more detail.

3.2 Connectors for Dispersed Flow

In steam power plants there are two major fluid systems, the two phase flow of water/steam and the flue gas. The flue gas in coal fired furnaces contains coal and ash particles which intensify the heat radiation of the flame. Coal particles can travel trough multiple flue gas elements and therefore have significant impact on the spatial distribution of heat release. Larger ash particles can move against the direction of flue gas flow because of gravitation. Therefore, new connectors were needed to describe the interaction between flue gas elements.

The `DispersedFluidPort` has been developed in order to have one connector for the flow of gas and solid phase. This minimizes wiring work and corresponds to the physical connections in reality.

The new connector is specialized for the application in the fired steam generator. Hence, the universal approach of Modelica.Fluid is not necessary [1, 2]. Well defined flow directions can be assumed and connections between more than two connectors do not have to be handled automatically. Components for splitting and mixing can be provided for the limited number of flue gas branches.

Nevertheless, the FluidPort of Modelica.Fluid should be used for the gas phase in order to be compatible with existing flue gas zones in SiemensPower. The standard components of Modelica.Fluid can be used where appropriate (e.g. boundary conditions) and connected to the FluidPort.

It was decided to add additional connectors for particles to the FluidPort and aggregate all this into the DispersedFluidPort. Figure 5 illustrates this approach.

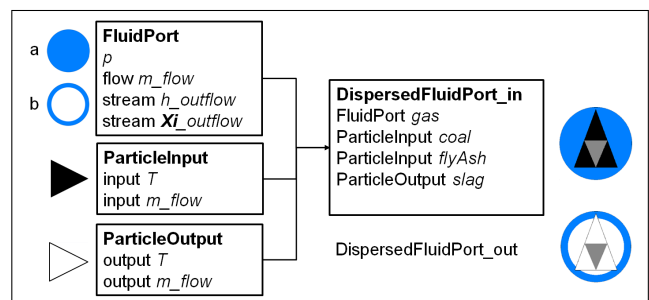Figure 5: Structure of DispersedFluidPort

The Modelica code of DispersedFluidPort:

```
connector DispersedFluidPort_in
  "DispersedFluid input connector"

  // Fluid data
  replaceable package Medium =
   SiemensPower.Media.FlueGas
   "Gas medium model";

  // Ports
  Modelica.Fluid.Interfaces.FluidPort
   gas(redeclare package Medium =
   Medium, m_flow(min=0));

  SiemensPower.Interfaces.ParticleInput coal;
  SiemensPower.Interfaces.ParticleInput flyAsh;
  SiemensPower.Interfaces.ParticleOutput slag;
end DispersedFluidPort_in;
```

`ParticleInput` and `ParticleOutput` are causal connectors containing mass flow and temperature as inputs and outputs. A standard Modelica connector with a-causal potential and flow variables was not promising because the coal and ash moves with the flue gas by convection. Therefore it is hard to define a meaningful potential variable which is the driving force of particle flow. More stream variables could have been added to FluidPort for coal and ash but it would not be possible to describe the movement of larger particles against the fluid flow direction.

The use of the aggregated connectors is quite convenient when writing equations with expressions like `port.gas.m_flow` or `port.coal.m_flow`.

3.3 Furnace Element

The furnace element is one element of plug flow of flue gas. The flue gas is modeled as a mixture of ideal gases from Modelica.Media. The following figure shows the mass and energy flows:

Figure 6: Mass and energy balance of one furnace element

The energy balance of one furnace element:

$$
\begin{aligned}
\frac{dU}{dt} =& + \dot{H}_{a,\text{flueGas}} + \dot{H}_{a,\text{coal}} + \dot{H}_{a,\text{flyAsh}} + \dot{H}_{\text{burner,air}} \\
& + \dot{H}_{\text{burner,coal}} + \dot{H}_{\text{burner,addOnFuel}} + \dot{H}_{b,\text{slag}} \\
& + \dot{H}_{a,\text{slag}} + \dot{H}_{b,\text{flueGas}} + \dot{H}_{b,\text{coal}} + \dot{H}_{b,\text{flyAsh}} \\
& + \dot{Q}_{\text{combustion}} \\
& + \dot{Q}_{a,\text{radiation}} + \dot{Q}_{\text{wall}} + \dot{Q}_{b,\text{radiation}}
\end{aligned} \tag{1}
$$

U is the internal energy of the flue gas element. $\dot{H}$ are enthalpy flows, $\dot{Q}$ are energy flows. $\dot{Q}_{\text{combustion}}$ is calculated from the lower heating value and the burned mass flow of coal. The balance of radiation heat transfer and the energy balance result into the correct temperature of the flue gas element.

Radiation heat transfer is calculated according to [3], chapter K. For radiation heat exchange between flame and wall the following equation is used:

$$
\dot{Q}_{\text{flame,wall}} = A\,\sigma \cdot \frac{\varepsilon_{\text{wall}}}{\alpha_{\text{flame}} + \varepsilon_{\text{wall}} - \alpha_{\text{flame}}\,\varepsilon_{\text{wall}}} \\
\cdot (\alpha_{\text{flame}}\,T_{\text{wall}}^4 - \varepsilon_{\text{flame}}\,T_{\text{flame}}^4) \tag{2}
$$

$Q_{\text{flame,wall}}$ is the heat flow from the flame to the wall, A is the wall area, σ is the Stefan-Boltzmann constant, ε_i are emissivities and α_i are absorbances.

Radiation properties and corresponding surface areas play a key role for correct simulation results. The emissivity of the *wall* is set to an empirical value for each furnace element. The emissivity of the *flame* can be calculated by the model, which uses functions depending on flue gas temperature, gas composition and zone geometry [3].

The standard Modelica heat port was extended by information on emissivity and surface area in order to calculate the net radiation heat flow. The known functions for view factor calculation are implemented in Modelica.

The mass balance is written for every chemical contained in the flue gas and for the three types of particles (coal, fly ash and slag). Momentum balance is reduced to a hydraulic resistance of the gas phase until more data is available.

3.4 Usability Aspects

When using and maintaining the described model, three aspects could be improved. Handling of 3D ge-

ometry parameters is not intuitive in 2D model diagrams. All geometry data is stored centralized in a record `FurnaceData`, but the user has to make sure the correct parametrization of the furnace elements. Some 3D-support for the parametrization of 1D-models would simplify this task.

It is not easy to implement the radiation heat balance in component oriented model where data exchange between objects should be transparent for the user. Unfortunately, there is no simple solution for 3D radiation exchange.

There is no language or tool support for 1D spatial discretization of partial differential equations in Modelica. For-loops of equations or connects are written, without graphical representation. The model user mostly has to look into the equations in order to follow the details of discretization. Possibly annotations could be generated to visualize the discretization.

4 Results

In order to test the furnace model, a test environment with ideal components for heat controller, coal feeder, coal pulverizer, coal distributor and precipitator has been developed (figure 7). Temperature boundary conditions are connected to the furnace instead of water tubes. The components of this test environment can be configured and improved according to the specific simulation task.
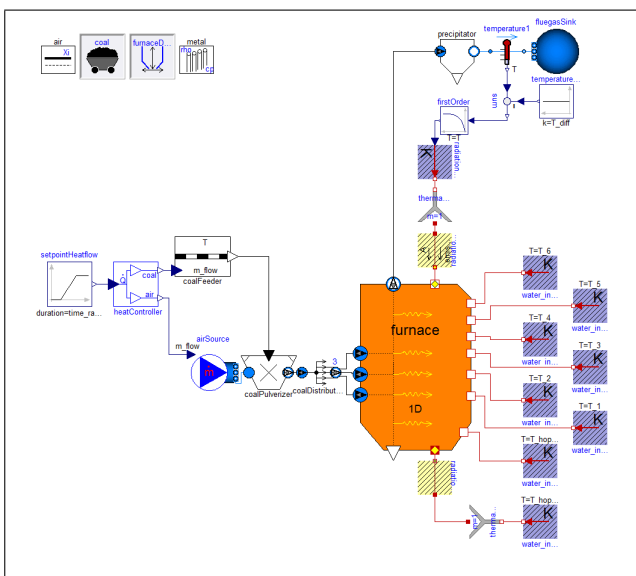
The practicality of the model concept was tested by calculations on an existing large scale power plant. A model of this plant was available in an in-house steady state tool. Parameters and boundary conditions of the Modelica model were obtained from construction data of the plant and the existing model. The results of the existing model were compared to steady state results of the new Modelica model. Figure 8 and figure 9 show these results. The rectangles on the height coordinate indicate the three burner levels. The solid line shows the Dymola result which agrees with the dashed reference line in the lower segments. At the furnace exit, the fit is not that good because of the imprecise test environment without convective heating surfaces.
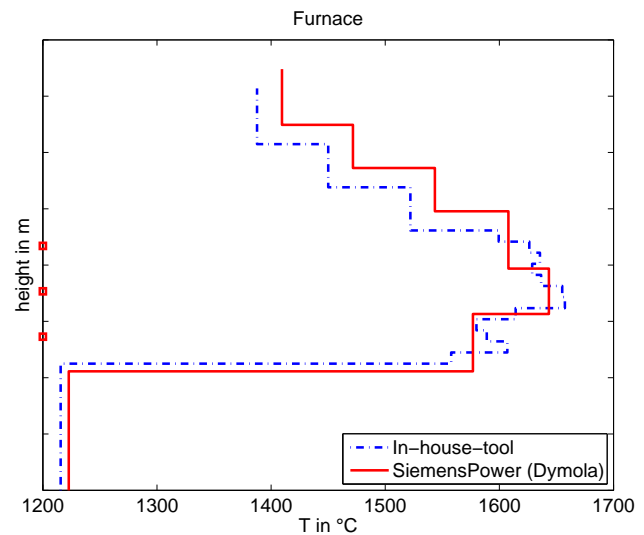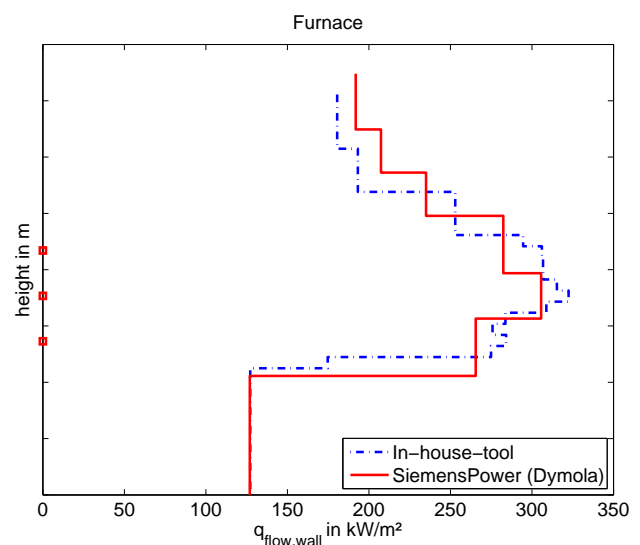

Figure 8: Temperature versus furnace height

Figure 7: Test environment of furnace model

Figure 9: Heat flux versus furnace height

5   Conclusion and Outlook

A modeling framework for coal fired furnaces was described which can be used for dynamic simulations of steam power plants. The new Modelica components serve as an extension to the existing SiemensPower library.

Further validation is needed for transient operation. The next step would be to attach evaporator tubes and super-heaters in order to compare the model to dynamic simulation results and measurements.

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