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DEVELOPMENT OF SIMPLE BOILER MODEL REQUIRED FOR ENERGY PLANNING PROCESS

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The aim of this research work was to develop a boiler model with few parameters required for energy planning. The showcase considered for this work was the boiler system of the energy center at Offenburg University of Applied Sciences. A grey box model of the boiler was developed systematically starting from model abstraction, simplification, model break-down and to the use of empirical correlations wherever necessary to describe the intermediate effects along with the use of information from manufacturer's specification in order to reduce parameters. This strategy had resulted in a boiler model with only 6 parameters, namely, nominal burner capacity, water gallery capacity, air ratio, heat capacity of wall, thermal conductance on flue gas and hot water side. Most of these parameters can be obtained through the information available in the spec sheets and thus an energy planner will be able to parameterize the model with low effort. The model was validated with the monitored data of the showcase. It was tested for the start-up, shut-down behavior and the effect of storage.

Keywords: Boiler model, generic parameterization, energy planning process.

NOMENCLATURE

Abbreviations

HWR	-	Hot water return
HWS	-	Hot water supply
NTU	-	Number of transfer units
VDI	-	Verein Deutscher Ingenieure

Latin and Greek Characters

C	-	Heat capacity	J/K
G	-	Thermal conductance	W/K
H_i	-	Lower heating value	J/kg
k	-	Overall heat transfer coefficient	W/(m^2.K)
$L_{\min}$	-	Minimum amount of air required	-
λ	-	Air ratio	-
$\dot{m}$	-	Mass flow rate	kg/s
Φ	-	Capacity percentage	% (or) -
$\dot{Q}$	-	Heat flow	kW$_{th}$
$\dot{Q}_N$	-	Nominal thermal capacity	kW$_{th}$
T	-	Temperature	K

Subscripts

ad	-	Adiabatic
Fu	-	Fuel
fg	-	Flue gas
hw	-	Hot water
hwg	-	Heating water gallery

INTRODUCTION

Background

There is a requirement for concrete energy planning of polygeneration systems due to the expansion of renewables and modern integrated energy networks. The requirement is due to the drawback of current static energy planning approaches which are insufficient to describe and consider the dynamic nature of the integrated systems. Generally, the static approaches take into consideration to find an optimal point by setting an objective function with constraints or to simply follow the guidelines or to estimate the indicators such as primary energy ratio, primary energy saving, energy utilization factor, fuel energy saving ratio, carbon dioxide emission reduction and annual total cost saving, etc. The dynamic nature of the integrated systems requires advanced planning approaches which take into consideration the topology of the system, transients at the system level, operational strategies, weather data and dynamic loads [1]. Since the issue of advanced energy planning is very broad, the first step to address it is to develop strategies for generic parameterization and models which will allow the planners to easily dimension and integrate them into the bigger network of energy systems.

State-of-the-Art

A lot of modeling and simulation was carried out on the boilers especially in areas such as detailed modeling of boiler components [2]; to address technical issues concerned with start-ups and its optimization [3], [4]; in process specific-applications [5]; to develop new control and operational algorithms to improve performance [6], [7], [8]; commercial and open libraries to analyze integrated energy systems etc. [9], [10]. Despite of the substantial amount of investigations on this subject, it seems to the authors that the question on how to achieve a suitable model during the design phase of a project was hardly answered. However, if not exactly at least few recent works have pressed about this gap. They are the works of [11], [12], [13], and [14].

[11], [12] had developed and tested three methods to model boilers, namely, the empirical delta-T approach, the effectiveness approach and detailed effectiveness-NTU approach. [11], [12] had abstracted the boiler model in the order starting from steady-state combustion chamber followed by steady-state gas to water heat exchanger and then complete boiler as a single thermal mass to describe the transient effect. The empirical delta-T approach was adapted from literature and then modified. The modification took into account the dependencies of power modulation, water mass flow rate on the outlet flue gas temperature and return water temperature. In the empirical effectiveness approach, the effectiveness was determined using an empirical equation to describe the heat transfer from flue gas to water heat exchanger and a correction factor to describe the mass flow rates of flue gas and water at part load conditions. The detailed effectiveness-NTU approach was based on the text book effectiveness-NTU method. In this approach, the thermal capacitance of the empty boiler and the water gallery were added and treated as one node. The water gallery was considered as a fully mixed body. The losses from

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combustion chamber and heat exchanger, and latent gains were also considered. This approach was also adapted and modified from several existing literature methods and for further information look into [11]. The detailed effectiveness-NTU method was validated against the measurements. The model consists of 5 parameters and 6 fitting coefficients to determine the combustion efficiency and the flue gas losses which were taken from measurements [12]. However, [11], [12] gave no information on how to parameterize the model. [13] had also adapted a similar boiler abstraction approach as [11] to compare TRYNSYS, Dymola and Excel based models of pellet boiler. [13] considered parameters from a test report but not from spec sheet and only few important design parameters were mentioned. [14] developed and validated easy-to-parameterize boiler model partly based on the existing models and added to a certain extent some dynamic aspects such as the capacitance and fluidic effects for start-up control. Similar to [11], [12] and [13], the approach of [14] consisted of a steady-state part and a dynamic part. The steady state part described the heat transfer by NTU method and the calculation of flue gas moisture. The dynamic part consisted of the flue gas capacitance, hot water capacitance and flow characteristics. The model parameters were the type of fuel, power levels, boiler mass, water content, efficiency at full load which can be easily accessed using spec sheets whereas the additional parameters such as the flue gas moisture, gas ratio, heat capacity and portion of the water content were based on the moisture content measurements and heat-up, cool-down measurements, respectively. The drawback of this model is that it was validated for small-size boilers ranging from 10 kW to 20 kW, the model development was specific to the test rig and it may or may not suit boiler of all the ranges especially the larger ones. It can be concluded from the literature survey that there is a need to expand the easy-to-parameterize approaches with adequate dynamics providing wide range of applicability. There is also lack of literature on generic parameterization methods and developing generic simple boiler models pertaining to energy planning.

Goal

In this paper, the development of a boiler model with only few parameters required for energy planning is described in detail. The boiler model was developed using Modelica language on Dymola platform. The requirements of the boiler model for energy planning are as follows:

- It must be easy-to-parameterize.
- It must allow to dimension just by varying the parameters.
- It must describe the start-up, shut-down and storage effect.
- It must inherit separately defined default fluid properties.

SHOWCASE

Fig. 1 shows the abstraction of trigeneration system (energy center) which supplies thermal and electrical energy to meet the energy demands of Offenburg University of Applied Sciences. It consists of two boilers with a nominal capacity of 1500 kW each. It also consists of micro gas turbine, internal combustion engine, absorption chiller, hot and cold water storage [15], [16]. Fig. 2 shows the cutaway side view schematic of the Viessmann boiler with input and output flows. It consists of a combustion chamber, two second hot gas passes and twenty-three third hot gas passes surrounded by water gallery. Firstly, fuel and air enter the combustion chamber or first hot gas pass where the fuel is combusted. Thereafter, the flue gas enters the second and third hot gas passes where it exchanges heat with the heating water. The heating water and the gas passes are separated by a stainless steel wall. The flue gas exits through the second and third hot gas passes. The heating water gallery has a hot water supply and return connection from and to the demand side heating circuit.

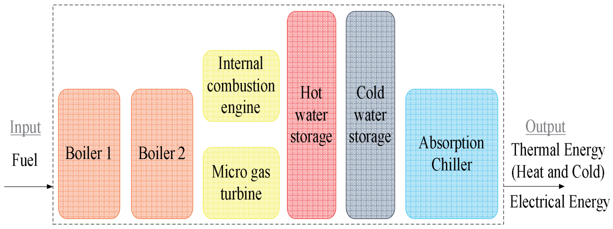

Fig. 1. Abstraction of energy center at Offenburg University.

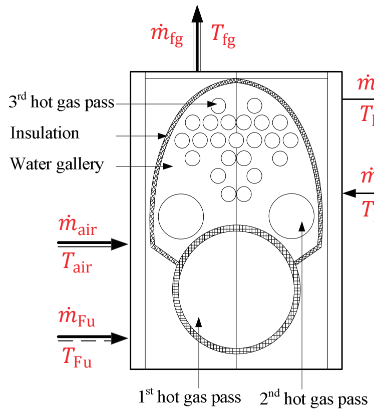

Fig. 2. Schematic showing the cross-sectional side view of the Viessmann Vitoplex 300 Type TX3 gas boiler at energy center.

MODEL ABSTRACTION

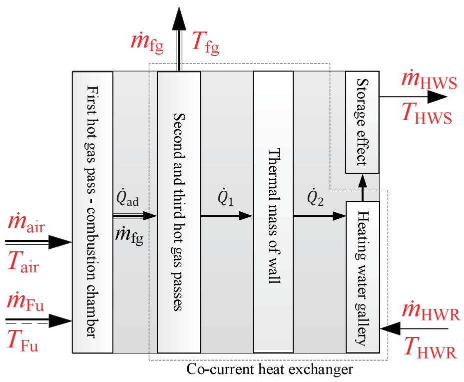

Fig. 3. Abstraction of boiler at energy center for modeling and simulation.

Fig. 3 illustrates the abstraction of the boiler shown in Fig. 2. The break-down of boiler consist of three important sections, namely, combustion chamber followed by a co-current heat exchanger and then thermal water storage. The heat exchanger consists of a hot gas pass and heating water gallery separated by a wall. Fundamentally, any type of boiler from different manufacturers consists of these three sections with varying dimensions. Therefore, the abstraction had allowed formulating a generic model with an option to change fluids.

MODEL FORMULATION AND VALIDATION

Combustion chamber

Equation (1), (2) and (3) describe the chemical energy of the fuel, mass balance and air-ratio, respectively. As shown in Equation (1) and Fig. 4, a linear correlation was derived to describe the adiabatic temperature of the combustion chamber exit using engineering equation solver subroutine. It was based on the energy balance of CH_4 combustion with excess air.

$$\dot{Q}_{\mathrm{Fu}} = \dot{m}_{\mathrm{Fu}} \cdot H_{\mathrm{i,Fu}} \quad (1)$$

$$\dot{m}_{\mathrm{fg}} = \dot{m}_{\mathrm{Fu}} + \dot{m}_{\mathrm{air}} \quad (2)$$

$$\lambda = \frac{\dot{m}_{air}}{\dot{m}_{Fu} \cdot L_{min}} \quad (3)$$

$$T_{\mathrm{ad}} = a + b \cdot \lambda \quad (4)$$

where, a=2992.58, and b=-868.29.

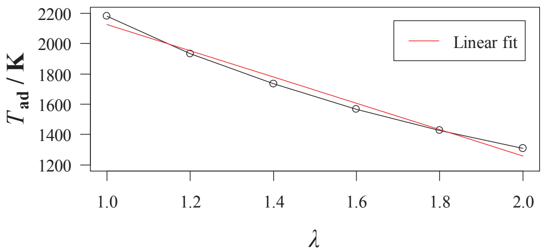

Fig. 4. Linear dependency of T_{ad} on λ for CH_4 combustion.

Heat exchanger

It is assumed to be a simple co-current heat exchanger. Equations (5) and (6) express the heat transfer from hot gases pass side through wall to heating water side. It was derived using effectiveness-NTU method. For this specific example, the geometry of the heat exchanger active surface was calculated by dismantling the complete boiler unit.

$$T_{\mathrm{fg,out}} - T_{\mathrm{wall}} = (T_{\mathrm{fg,in}} - T_{\mathrm{wall}}) \cdot e^{\left(-\frac{G_{\mathrm{fg}}}{\dot{m}_{\mathrm{fg}} \cdot c_{p,\mathrm{fg}}}\right)} \quad (5)$$

$$T_{\mathrm{HWS}} - T_{\mathrm{wall}} = (T_{\mathrm{HWR}} - T_{\mathrm{wall}}) \cdot e^{\left(-\frac{G_{\mathrm{hw}}}{\dot{m}_{\mathrm{hw}} \cdot c_{p,\mathrm{hw}}}\right)} \quad (6)$$

The thermal mass of the wall represents the heat capacity of the material and it is assumed to be lumped thermal element storing heat. The boiler body weight excluding water was considered as the mass of the wall. Mathematically, it is represented by Equation (7) and (8).

$$\dot{Q}_{\mathrm{wall}} = C_{\mathrm{wall}} \cdot \frac{dT_{\mathrm{wall}}}{dt} \quad (7)$$

$$C_{\mathrm{wall}} = m_{\mathrm{wall}} \cdot c_{p,\mathrm{wall}} \quad (8)$$

Thermal storage

Large boilers have high thermal mass on the water side and act as a storage unit when it is not in operation. Therefore, the effect of the storage was considered using Equation (9) in this model in order to include start-up or shut down effect on the supply water temperature without any lags. As the boiler is well insulated, the losses to the surroundings were neglected due to its minimal effect.

$$m_{\mathrm{hwg}} \cdot c_{p,\mathrm{hw}} \cdot \frac{dT_{\mathrm{HWS}}}{dt} = \dot{Q}_{\mathrm{HWR}} - \dot{Q}_{\mathrm{HWS}} \quad (9)$$

Altogether, the model consists of two states, i.e., T_{wall} and T_{HWS}. A fluid properties package was developed using VDI Heat Atlas and was included in the model. The developed boiler model was validated using monitored data with one-minute time interval from the energy center. The input signals to the model were capacity percentage, hot water return temperature and mass flow rate of return water. Equation (10) and Fig. 5 describe the capacity percentage signal which was modulating during this time period. Fig. 6 and Fig. 7 show the validated results of the hot water supply temperature and the flue gas temperature. The dynamic behavior of the simulated and the measured hot water supply temperature was in good agreement with a maximum discrepancy of 1%. The maximum discrepancy for the flue gas simulated temperature was about 8%. In Fig. 7, the delays in the start-up and shut-down path, shortened peaks and troughs of the simulated result can be attributed to the thermal mass of the wall and storage effect.

$$\Phi_{\mathrm{Burner}} = \frac{\dot{Q}_{\mathrm{Fu}}}{\dot{Q}_{\mathrm{N,Burner}}} \cdot 100 \quad (10)$$

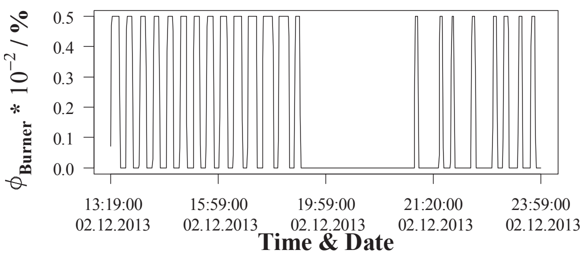

Fig. 5. Capacity percentage of boiler from measurements.

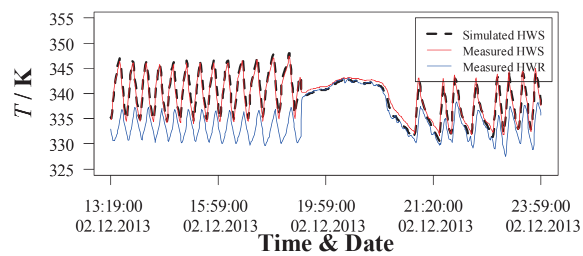

Fig. 6. Validation of hot water supply temperature.

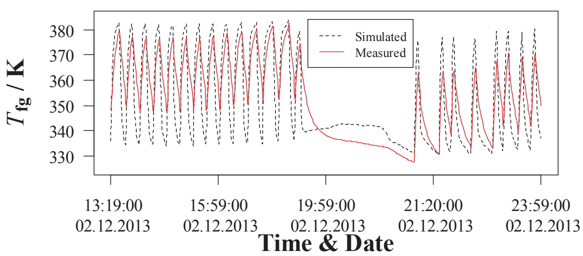

Fig. 7. Validation of flue gas temperature.

RESULTS AND DISCUSSION

Table 1 shows the list of parameters for the boiler model. The model consists of 6 parameters out of which nominal capacity of burner, heating water gallery capacity and heat capacity can be found directly in the spec sheet. The thermal conductance on flue gas side and the hot water side can be estimated based on the information available in the spec sheets such as flow rates and dimensions. Air ratio for most of the boiler is in the typical range of 1.0 to 1.3. Additionally, 2 fittings coefficients are required to describe the adiabatic temperature of combustion chamber as shown in Equation (1). It can be derived using combustion calculation of fuel and it is a part of the default database. These parameters are generic to any boiler model to describe their dynamics and the model can be easily transferred to other examples. There are also more ideas on the parameter reduction such as finding a mathematical relationship between the nominal capacity of burner and the heating water gallery capacity based on the sizing pattern of different manufacturers. Therefore, these simple parameters can be adequately used to dimension the boiler model at the concept phase of energy planning to arrive at a quick decision.

From the experience of developing the above boiler model and also based on literature [14], it can be concluded that it is a challenge to develop simple models with few parameter and still keep all the dynamics intact. It involves trade-off, for example, as the model dynamics increases the complexity increases which will in turn increase the number of parameters or vice-versa.

Table 1. Parameter set of boiler model.

Parameter	Description	Source
$\dot{Q}_{\mathrm{N,Burner}}$	Nominal capacity of burner	Spec sheet
m_{hwg}	Heating water gallery capacity	Spec sheet
C_{wall}	Heat capacity	Spec sheet
G_{fg}	Thermal conductance on flue gas side	Estimation possible
G_{hw}	Thermal conductance on hot water side	Estimation possible
λ	Air ratio	Typical range

OUTLOOK

One idea can be on studying and developing strategies to deal with various thermal masses (boiler body with and without water) and their effects on the simulation results of this model to further improve dynamics and still keep the parameters low.

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