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Research paper

Development and validation of a dynamic simulation model for a large coal-fired power plant

Ralf Starkloff [a, *], Falah Alobaid [a], Karl Karner [a], Bernd Epple [a], Martin Schmitz [b], Felix Boehm [b]

[a] TU Darmstadt, Institut für Energiesysteme und Energietechnik, Otto-Berndt-Str. 2, 64287 Darmstadt, Germany
[b] Alstom Power GmbH, Boveristr. 22, 68309 Mannheim, Germany

HIGHLIGHTS

- Detailed modelling of large coal fired power plant with minimal boundary conditions.
- Validated against operational data showing a very good agreement.
- Maximum relative errors of less than 5% regarding the mass flow rate, temperature and pressure.
- The model will be ideal for research regarding innovative flexibility measures.

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ABSTRACT

The rapid expansion of renewables due massive use of subsidies in the last years changes the operation of fossil fired power plants in Germany dramatically. Since the large-scale storage of electricity is still difficult and forecasts for wind and solar energy have unavoidable uncertainties, the conventional power plants have to compensate the demand in the grid. Several new measures are introduced by power plants operators in order to respond to these new market conditions like the reduction of the low load operation of the nominal load and the continuous operation at an off-design operation point. In this work, a full-scale dynamic model of large scale coal-fired power plant has been developed to investigate the operation flexibility. The dynamic model, developed in the process simulation program APROS, includes all power plant components and its associated control schemas. The only boundary conditions are the coal composition, the ambient temperature and the temperature and amount of cooling water in condensers. The developed model is validated against operational data from the real power plant during part load transients, showing a very good agreement. The validated model is of high relevance for further investigations regarding flexibility increase in conventional large coal-fired power plants.

1. Introduction

Coal-fired power plants are of high importance for the secure electrical power generation in the next decades. However, the massive growth of renewable energy in some countries changes the market conditions [1]. In 2014, the installed capacity of wind and photovoltaic energy has reached an amount electrical capacity of 40.4 GW and 38.2 GW, respectively [2]. Especially the fluctuating wind energy production can lead to extreme situations, like a sudden increase of more than 10 GW wind energy production within a couple of hours, resulting in negative prices for the spot market [3]. Traditionally large coal-fired units were designed for an operation of 6000–8000 full load hours per year. Due to the new requirements of the market, the economic operation must be secured at 1500–3000 full load hours per year [4]. It is also expected that the flexibility for conventional power plants will increase even more in the near future. As a result, the power plant operators are forced to develop new technical solutions.

The new challenges of coal-fired power plant operation can be split in three parts. Firstly, faster positive and negative load transients between operational points are necessary due the volatile power generation from renewable sources. Furthermore, the

* Corresponding author. Tel.: +49 6151 16 76197; fax: +49 6151 16 5685.
E-mail address: ralf.starkloff@est.tu-darmstadt.de (R. Starkloff).

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Nomenclature

F	force/volume in N/m^3
f	friction factor
h	static enthalpy in kJ/kg
h_0	stagnation enthalpy in kJ/kg
K	correction factor
Nu	Nusselt number
p	pressure in MPa
Pr	Prandlt number
$\dot{Q}$	heat flow/volume in kW/m^3
Re	Reynolds number
T	temperature in K
t	time in s
u	longitudinal fluid velocity in m/s
z	longitudinal distance in m
α	heat transfer coefficient in $W/(m^2K)$
Γ	mass transfer in $kg/(m^3\ s)$
ρ	density in kg/m^3
σ	Stefan–Boltzmann constant in $W/(m^2\ K^4)$
χ	void fraction

Subscripts

con	convection
fl	form loss
g	gas phase
grav	gravitation
HE	heat exchanger
i	interface between phases
k	phase (either liquid or gas)
l	liquid phase
pu	pump
rad	radiation
va	valve
w	wall

Abbreviations

APH	air pre-heater
APROS	advanced process simulation software
BC	boundary condition
CP	circulation pump
CCV	circulation control valve
CRH	cold reheat
E	extraction
ECO	economizer
ESP	electrostatic precipitator
EVAP	evaporator
FDF	forced draft fan
FWP	feed water pump
FWPT	feed water pump turbine
FWT	feed water tank
G	generator
HPT	high pressure turbine
HRH	hot reheat
IDF	induced draft fan
IPT	intermediate pressure turbine
LPT	low pressure turbine
PAF	primary air fan
PH	pre-heater
RH	re-heater
SCAPH	steam coil air pre-heater
SCR	selective catalytic reduction
SG	steam generator
SH	super heater

dynamic of start-up processes (cold, warm and hot) has to be increased in response to a sudden loss of energy generation from wind turbines in the grid. Secondly a broader operational range is necessary. The technical minimal load limit has to be re-evaluated. Lower load limits save fuel and reduce the number of shut-offs and start-ups. For combined heat and power plants a total shut-down is often not an option since the heat demand is de-coupled from the fluctuations in the grid. For coal-fired power plants the technical low load limit is defined by the firing concept, burners, fuel, steam generator design and the corresponding water–steam cycle. Thirdly a thermo-economical optimization of the plant within the complete operational range, especially in the part load, is necessary since the time running at full load is reduced. A coal-fired power plant with lower efficiency losses at part loads may have a better position in a liberated market.

With increasing pressure on the electricity price investment decisions have to be chosen carefully [5]. A promising method is the use of computer aided process simulation tools. In the past, steady state process simulation programs, which are limited to time independent operational points, were the preferred choice for process optimization. For the above-mentioned fluctuating respond requirements of coal-fired power plants a steady state approach is no longer sufficient and a dynamic process simulation approach becomes necessary. These dynamic models enable the researchers to test new control concepts, to modify load transients characteristics and to optimize the plant behavior in off-design operation conditions.

The first developed dynamic models contained only plant sections for a specific application. The danger of boiler implosions, in case of a fuel or a fan trip, led to the development of mathematical models for the air/gas dynamics of the power plants [6,7]. Whereas other models investigated the behavior of steam generators [8,9], turbines [10] or both [11,12]. Recently, a study has been carried out to couple a process simulation model with a computational fluid dynamic model in order to evaluate the effects of the three dimensional firing system to the water steam cycle in generic coal power plant [13]. Also, a large model of a conventional drum-based coal-fired power plant was proposed in Ref. [14]. It is validated against four steady state operational points, which leaves the question open how well the model performs at transients at all. Apart from this the focus of dynamic simulation of coal-fired power plants shifted towards carbon capture and storage and especially to oxyfuel combustion. Here dynamic simulation tools are mostly used to evaluate the switch over from air to oxygen combustion or load changes. Since no large scale oxyfuel fired plants exist, measured data is not available either. Several researchers have published work, with strong focus on the steam-generator gas-side. Some of them used advanced process simulation software APROS for model development [15,16], while some used other software [17,18].

The objective of this study was the development of a full scale dynamic model of an existing German power plant, including all plant components and all required automation processes with minimum boundary conditions, based on the real design specifications, construction drawings and control schemes. On the water–steam side, the only boundary conditions are inlet temperatures and mass flow rates of the cooling water into the