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Numerical and experimental study of a heat recovery steam generator during start-up procedure

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ABSTRACT

The share of renewable energies in electricity and heat supply besides the conventional energy resources gains more importance. Accordingly, the efficiency and flexibility of modern thermal power plants should be further improved. To design such a system, it is necessary to generate detailed computer models that can accurately predict the power plant behaviour during fast transients, part loads and start-up procedures. In this work, a dynamic simulation model for a subcritical three-pressure-stage HRSG (heat recovery steam generator) is built, employing the advanced processing simulation software Aspen Plus Dynamics®. The simulation results obtained from the HRSG model are validated towards the dynamic measurements during warm start-up procedure. The capability of processing simulation software used to estimate the dynamic behaviour of real HRSG is demonstrated. The HRSG model shows high accuracy at different part loads with a maximum relative error of about 5%. The good agreement suggests that the HRSG model is very reliable and is capable to predict the operational processes.

1. Introduction

The growth of world population and the steady developing of newly industrialised countries urge the international community to adopt environmentally conscious behaviour. In this context, the reduction of carbon dioxide emissions is in the focus of politics and societies, since CO_2 is regarded as the main cause of impending climate change. For energy industries, this specifically means to reduce the pollutant emissions by further expansion of wind and solar farms and increasing the number of geothermal plants. However, as the discussion around the world focuses on renewable energy, the fact must be acknowledged that an immediate change over to purely renewable energy is not economically feasible. Besides the increased employment of renewable energies, for the time being, a more efficient supply of electricity and heat in conventional thermal power plants is of major relevance.

The thermal power plants play an important role in converting chemical energy to electrical and heat energy [1,2]. A CCPP (combined cycle power plant) distinguishes itself among other thermal power plants through its high efficiency and low emissions. The combined cycle power plant, also known as CCGT (combined cycle gas turbine), merges gas turbine design with an additional HRSG (heat recovery steam generator) system. The idea behind the CCPP is relatively simple; the exhaust heat of a traditional gas-burning plant is recovered with a HRSG by converting water to steam instead of being released directly into the atmosphere to dissipate. The recovered energy in the HRSG is then reconverted to electrical energy by a steam turbine. This increases the efficiency because of a better utilization of the fuel, which reduces the overall consumption of used fuel. This results in an extension of the lifespan of resources and limits the effects of global warming. Another aspect facing the renewable energy sector is the incapability for long term energy storage. Here, the wind turbines are excellent examples. If the wind fluctuates, the produced energy will oscillate accordingly [3,4]. The dynamic quality of a CCPP is able to balance these fluctuations in the grid. In addition, the adaptability of CCPP allows the performance in high load ranges which supplements the grid as well.

Many scientific and industrial efforts have been achieved on making the heat recovery steam generator more efficient [5,6]. An essential part of the design and analysis of the associated processes over the past decade are done with the support of computational calculations. The dynamic simulation provides a useful tool for assessing the control system design, capabilities and limitations during fast transients and start-up procedures. In the literature, several dynamic simulation models were proposed to investigate the HRSG behaviour using different simulators.

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Nomenclature

A	cross-sectional area [m^2]
C_p	specific heat capacity [kJ/(kg K)]
C	molar concentration [K mol/m^3]
$\dot{C}$	molar flow rate [K mol/s]
D	diameter [m]
F	force/volume [N/m^3]
g	standard gravity [9.81 m/s^2]
h	stagnation enthalpy [kJ/kg]
K	friction factor [−]
m	mass [kg]
$\dot{m}$	mass flow rate [kg/s]
p	static pressure [Pa]
Q	heat flow/volume [kW/m^3]
T	temperature [°C]
t	time [s]
u	longitudinal fluid velocity [m/s]
Z	axial position [m]
ρ	density [kg/m^3]
θ	inclination angle with the horizontal [rad]

Subscripts

i	component index
fri	friction
gra	gravitational
ref	reference
s	steam
wal	wall

Abbreviations

APROS	advanced process simulation software
ASPEN	advanced system for process engineering
BFP	boiler feed pump
CPH	condensate preheater
CCPP	combined cycle power plant
CCGT	combined cycle gas turbine
DC	device control
Dymola	dynamic modelling laboratory
EC	economiser
EV	evaporator
EXP	experiment
FG	flue gas
FW	feedwater
GT	gas turbine
HPBCV	high pressure bypass control valve
HP	high pressure
HPMSCV	high pressure main steam control valve
HT	high temperature
HRSG	heat recovery steam generator
IP	intermediate pressure
IPBCV	intermediate pressure bypass control valve
IPMSCV	intermediate pressure main steam control valve
IT	intermediate temperature
LPBCV	low pressure bypass control valve
LP	low pressure
LPMSCV	low pressure main steam control valve
LT	low temperature
MEM	memory
MIN	minimum operators
Modelica	modelling and simulation software
MT	middle temperature
PI	proportional-integral
RH	reheater
SIM	simulation
SH	superheater
ST	steam turbine
RP	recirculation pump
VA	valve

Shirakawa et al. (2003–2005) [7,8] combined the dynamic simulation and the nonlinear programming to optimise the start-up procedures of the subcritical HRSG. The dynamic results obtained from the HRSG model are verified against the plant measurements. A model of a natural circulation heat recovery steam generator with three levels of pressure and a steam power of 130 MW_{el} was built by Casella et al. (2006) [9] using the software Modelica® [10]. The study aimed on reduction of the start-up time, while keeping the life-time consumption of critical stressed components under control. The analysis concentrates on the thermal stresses of the steam turbine, therefore the low pressure part of the HRSG was extremely simplified and the heat exchanger behaviour is not examined. Static and dynamic simulation models for subcritical and supercritical heat recovery steam generators were generated by Alobaid et al. (2008, 2009) [11,12] employing the advanced process simulation software Apros® [13]. The models show a good agreement towards the measurement in steady state at different part loads as well as during the warm start-up. A dynamic model of HRSG using the modelling and simulation software Dymola® [14] was developed by Horkeby (2012) [15]. The model is applied to study the performance of different control systems and control strategies. However in the literature, there is no study up to date regarding the capability of the advanced processing simulation software Aspen Plus Dynamics® to predict the dynamic behaviour of a heat recovery steam generator during the start-up procedure.

This work discusses the validation of a full-scale dynamic simulation model of a subcritical forced circulation heat recovery steam generator. Employing the advanced processing simulation software Aspen Plus Dynamics®, a model is generated, which contains all mechanical and electrical components of a real HRSG. Furthermore, the model includes a set of enhanced feedwater and steam bypass control circuits. The predictions of the HRSG model in steady state at different loads and during the warm start-up are compared with the measurements. The comparisons show a high agreement and confirm that the HRSG model represents the real power plant.

2. Description of real power plant

The investigated combined cycle power plant comprises of a gas turbine connected to a vertical based gas path. The heat recovery steam generator of the combined cycle is unfired, since the exhaust flue gas temperature and mass flow rate of the GT (gas turbine) are relatively high (628 °C and 587 kg/s). The water/steam circuit of the subcritical HRSG is a three-pressure-stage with a forced circulation in the HP (high pressure), IP (intermediate pressure) and LP (low pressure) evaporator paths and a reheater section after the high pressure turbine. In Fig. 1, the schematic process diagram of the