Fuel 153 (2015) 707–716

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

A comparative study of different dynamic process simulation codes for combined cycle power plants – Part B: Start-up procedure

Falah Alobaid [a,*], Ralf Starkloff [a], Stefan Pfeiffer [a], Karl Karner [a], Bernd Epple [a], Hyun-Gee Kim [b]

[a] *TU Darmstadt, Institut Energiesysteme und Energietechnik, Otto-Berndt-Straße 2, 64287 Darmstadt, Germany*
[b] *DOOSAN Heavy Industries and Construction, Boiler System Development Team, Changwon, South Korea*

HIGHLIGHTS

- First comparative study of different process codes for dynamic modelling of a HRSG.
- Good agreement between Apros and Aspen models towards measurements during start-up.
- Deviations are observed during initial start-up phase.
- Apros and Aspen models follow measurements qualitatively during post start-up phase.
- Measurements during start-up operation from an existing power plant are presented.

ARTICLE INFO

Article history:
Received 24 October 2014
Received in revised form 31 January 2015
Accepted 3 February 2015
Available online 9 March 2015

Keywords:
Combined cycle power plant
Dynamic simulation
Start-up procedure
Validation study
Aspen Plus Dynamics
Apros

ABSTRACT

The significance of dynamic simulation models for estimating the behaviour of combined cycle power plants is widely acknowledged. In part B of this study, the dynamic behaviour of a sub-critical three-pressure-stage heat recovery steam generator is numerically investigated, employing the process simulation tools Aspen Plus Dynamics and Apros. A wide set of measurement data from an existing power plant is applied to validate the generated dynamic models during warm start-up procedure. The numerical results follow qualitatively the transients during initial start-up phase and show good agreement during the post start-up phase. Furthermore, similar qualitative behaviour between both process simulation codes used is observed. The obtained results suggest that the dynamic simulation models are capable to reliably predict the system response to failure malfunctions and to modifications in design and control structures. The provided measurements are of high relevance for other researchers due to the fact that such detailed experimental data is proprietary and rarely published in scientific literature.

1. Introduction

Due to the continuous growth of population and industrial activities, the worldwide consumption of electricity and district heating has steadily increased. In order to avoid a further jump in the carbon dioxide emissions, the development of more efficient thermal power plants [1,2] in addition to the expansion of renewable energy use is of high relevance. In the short term, the optimisation of existing and planned thermal power plants that play an important role in electricity and district heat supply offers the most economical solution [3,4]. Compared to other thermal power plants, a combined cycle power plant (CCPP) is characterised by high efficiency, low emission levels and flexibility in part load, shut-down and start-up operation. The CCPP consists of two main parts, namely the gas turbine (GT) and heat recovery steam generator (HRSG). It is generally operated at its design base conditions (full load or part load), but it can also be operated on so-called off-design load condition depending on the required feed-in to the grid. This is of particular importance to compensate the intermittent power production of renewable energy sources (e.g. wind farms) [5,6]. There is typically a discrepancy between availability of renewable energy and consumer demand. For large-scale integration of renewables, at periods of low demand there may be more renewable energy available than can be consumed, while at periods of high demand there is insufficient renewable energy to cover the required load. Here, the CCPP is able to compensate the low secured capacity of renewable energy resources due to its high operating flexibility. The HRSG strongly affects the entire efficiency of the combined cycle power plant. Dynamic simulation models are therefore required to study the influence of different designs and operating parameters on the performance. These models allow an accurate prediction of the HRSG behaviour, its capability and limitation. The use of dynamic

* Corresponding author. Tel.: +49 (0) 6151/16 6691; fax: +49 (0) 6151/16 5685.
E-mail address: falah.alobaid@est.tu-darmstadt.de (F. Alobaid).

http://dx.doi.org/10.1016/j.fuel.2015.02.011

Nomenclature

A	cross-sectional area [m^2]
C	molar concentration [Kmol/m^3]
$\dot{C}$	molar flow rate [Kmol/s]
F	force/volume [N/m^3]
g	gravitational acceleration [9.81 m/s^2]
h	static enthalpy [kJ/kg]
h_0	stagnation enthalpy [kJ/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]
Γ	mass transfer [kg/(m^3 s)]
χ	void fraction [–]

Subscripts

g	gas phase
gra	gravitational
i	component index or interface between phases
fl	form loss
fri	friction
k	liquid or gas phase
l	liquid phase
pu	pump
s	stratified flow or steam
va	valve
wal	wall

Abbreviations

Apros	advanced process simulation software
Aspen Plus Dynamics	advanced system for process engineering
Attemp	attemperator
BFP	boiler feed pump
CCPP	combined cycle power plant
DC	device control
Dymola	modelling and simulation software
ECON	economiser
EVAP	evaporator
FG	flue gas
FW	feed-water
GT	gas turbine
HPBPCV	high pressure bypass control valve
HRSG	heat recovery steam generator
HP	high pressure
HPMSCV	high pressure main steam control valve
HT	high temperature
IP	intermediate pressure
IPBPCV	intermediate pressure bypass control valve
IPMSCV	intermediate pressure main steam control valve
IT	intermediate temperature
LPBPCV	low pressure bypass control valve
LP	low pressure
LPMSCV	low pressure main steam control valve
LT	low temperature
Modelica	modelling and simulation software
PI	proportional-integral controller
RH	reheater
SH	superheater
ST	steam turbine
Select	selector function
RP	recirculation pump
WS	water/steam

simulation models can provide an effective tool to assess new designs, improved control structures, faster load gradients and start-up procedures.

Several comprehensive steady-state process models for the combined cycle power plant can be found in the literature, while the dynamic models are far less presented. For the dynamic simulation of a CCPP, several commercial software programmes are available such as Modelica [7], Matlab Simulink [8], Apros [9] and Aspen Plus Dynamics [10]. Casella and Pretolani [11] built up an unsteady HRSG model with three pressure levels. The model was developed in Modelica using components from the thermo power library. Based on the developed model, the start-up time is reduced while the critical stressed components such as high pressure drum, superheater and reheater section are kept under control. Employing the modelling and simulation software Dymola [12] (modelling and simulation environment based on the Modelica modelling language), Horkeby [13] generated a dynamic model of a HRSG with three pressure stages. Investigation into the performance of different control systems and control strategies was carried out with developed model. Shirakawa et al. [14] combined dynamic simulation and nonlinear programming to optimise the start-up procedures of the sub-critical HRSG with three levels of pressure. Sub-critical and super-critical HRSG models were developed by Alobaid et al. [15,16] using Apros. The dynamic results obtained form the HRSG model were verified against plant measurements, showing good agreement. Recently, Alobaid et al. [17] published a study on applying the Aspen Plus Dynamics for the dynamic simulation of a HRSG. The model shows a good agreement towards the measurements at different part loads as well as during the warm start-up.

It can be concluded from the previous review that diverse process simulation codes can be applied to the dynamic simulation of the combined cycle power plant. This raises the question whether there is a major reason for selecting a specific programme. To answer this question, a full-scale sub-critical forced circulation heat recovery steam generator is built using two different dynamic software tools, namely Aspen Plus Dynamics and Apros. According to our best knowledge, there are no studies up to date that have been investigating such a comparison in the literature. In the developed simulation models, all mechanical and electrical components of the real heat recovery stream generator in addition to a set of enhanced feed-water and steam bypass control circuits are implemented. In part A of this study, the comparison between the simulation and the real plant is already presented at design base loads and during the off-design operations. Here, the numerical results obtained from both programmes are validated towards the measurements during warm start-up procedure. The results show qualitative agreements during initial start-up phase and quantitative agreements during the post start-up phase.

1.1. Objectives of work

The objectives of part B of this work are as follows:

(1) The aim of this manuscript is to compare the numerical results of two process simulation programmes (Apros and