Fuel 167 (2016) 135–148

Contents lists available at ScienceDirect

Fuel

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

Dynamic simulation of a triple-pressure combined-cycle plant: Hot start-up and shutdown

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HIGHLIGHTS

- First numerical study of hot start-up and shutdown based on measurement data.
- The calculated steam mass flows, pressures and temperatures show good agreement.
- Thermal inertia of the plant is underestimated due to neglected auxiliary systems.
- Complete set of start-up measurements obtained from a real power plant is presented.
- Shutdown response of most relevant parameters is shown.

ARTICLE INFO

Article history:
Received 14 August 2015
Received in revised form 12 November 2015
Accepted 14 November 2015
Available online 21 November 2015

Keywords:
Combined cycle
Start-up
Shutdown
Dynamic simulation
Measurement validation
Apros

ABSTRACT

The operation of combined-cycle power plants is increasingly determined by frequent start-ups and shutdowns for grid balancing. This study investigates the capability of a comprehensive process simulation model to predict the transient response of a triple-pressure heat recovery steam generator (HRSG) with reheater to the start-up and shutdown procedures of a heavy-duty gas turbine. The model is based on geometry data, system descriptions and heat transfer calculations established in the original HRSG design. The numerical solution approach and the practical development of a suitable model structure, including the required control circuits, are explained. Detailed simulation results are presented, using initial conditions that correspond to a previous overnight shutdown. Calculations are performed for a complete operating cycle of the plant, where the following main phases are distinguished: start-up procedure, load-following operation, design operation and shutdown procedure. The numerical model is validated with measurement data of the commercial power plant for each pressure stage, yielding good agreement. Deviation from the transient behaviour of the real plant is discussed with regard to modelling assumptions and incomplete information on components outside the HRSG system boundaries.

1. Introduction

Combined cycle power plants (CCPPs) have received much recognition in the last decades for high efficiency, fast load response and comparatively small environmental impact [1]. In the combined-cycle process, the waste heat of a gas turbine (GT) unit is absorbed by a heat recovery steam generator (HRSG) installed downstream in the flue gas path. The steam is used in a Rankine bottoming cycle, which generates additional power in the steam turbine (ST). While early configurations only used simple HRSGs with a single pressure stage, additional pressure stages were introduced over time in order to mitigate temperature mismatch and increase second law efficiency of the bottoming cycle. A triple-pressure subcritical HRSG system with reheater, where GT and ST units are combined in a 1 + 1 configuration, is considered state of the art. Nominal efficiency of modern CCPPs amounts to more than 60% with gas turbine inlet temperatures between 1500 °C and 1600 °C [2]. Current research focuses on higher turbine inlet temperature enabled by new cooling concepts for blades and combustion chamber and innovative thermal barrier coatings, potentially increasing the process efficiency up to 65% [3]. Part of this efficiency gain will be contributed by the bottoming cycle by reason of higher steam parameters [4], where even supercritical steam pressure is considered [5]. Integration of a gasification unit in the highly efficient combined cycle (IGCC) is a promising concept as coal-based power generation is still expected to account for a major part of the electricity mix in the foreseeable

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http://dx.doi.org/10.1016/j.fuel.2015.11.055
0016-2361/

Nomenclature

A	cross-section area (m^2)
c_k	two-phase friction multiplier (–)
D_H	hydraulic diameter (m)
E	rate of entrainment (–) or modulus of elasticity (MPa)
F	force/volume (N/m^3)
f	friction coefficient (–)
g_z	gravitational component in z-direction (m/s^2)
H	height (m)
h	static enthalpy (kJ/kg)
h_0	total enthalpy (kJ/kg)
k	interfacial heat transfer coefficient (kg/s)
$\dot{m}$	mass flow rate (kg/s)
L	level (m) or length (m)
P	power (MW)
p	static pressure (bar)
$\dot{Q}$	heat flow/volume (kW/m^3)
R	rate of stratification (–)
T	temperature (K)
t	time (s)
u	fluid velocity (m/s)
z	spatial coordinate (m)
α	void fraction (–) or stress concentration factor (–)
β	thermal expansion coefficient (1/K)
Γ	mass exchange rate ($kg/(m^3\,s)$)
δ	wall thickness (mm)
ν	Poisson's ratio (approx. 0.3 for steel)
ρ	density (kg/m^3)
σ	stress (MPa)

Subscripts

a	annular flow
av	average
b	bubbly flow
d	droplet flow
el	electric
fl	form loss
g	gas phase
i	component index or interface between phases
ig	interaction between phase interface and gas phase
ik	interaction between phase interface and liquid/gas phase
il	interaction between phase interface and liquid phase
in	inner wall
k	liquid or gas phase
l	liquid phase
lin	linear
max	maximum
ns	non-stratified flow
pu	pump
s	stratified flow
sat	saturation
sp	single phase
t	tangential
th	thermal
T	with respect to temperature
va	valve
w	wall
wk	interaction between wall and liquid/gas phase

Abbreviations

BC	boundary condition
BFP	boiler feed pump
CCPP	combined cycle power plant
DC	device control
ECO	economiser
EV	evaporator
FEM	finite-element method
FG	flue gas
GT	gas turbine
HRSG	heat recovery steam generator
HP	high pressure
IGV	inlet guide vanes
IP	intermediate pressure
LP	low pressure
PI	proportional–integral controller
RH	reheater
SH	superheater
ST	steam turbine

future. However, further research and optimisation are required in order to improve current availability from 80% [6] to the standard of a pulverized coal plant and make the technology economically viable.

In view of increasing renewable feed-into the electricity grid, plant operators have gradually shifted their attention from high efficiency at design loads to operating flexibility and fast response. Typical start-up procedures are divided according to initial material temperature: hot, warm and cold start-up for up to eight hours standstill, 48 h standstill and 120 h standstill, respectively. Start-up ramps of the steam turbine and the HRSG are limited by thermal stress in thick-walled components and therefore depend on the initial temperature. In contrast, the GT start-up is practically independent: 70% of the design temperature and 60% of the design mass flow at GT exhaust are available after seven minutes already [7]. Heavy-duty gas turbines may reach full load 30 min after ignition, roughly accounting for two thirds of the total combined-cycle power. Following grid requirements, the operator may choose to accelerate combined-cycle start-up at the cost of ST and HRSG lifetime consumption [4]. Standard HRSG design is essentially based on steady-state heat transfer calculations for different load cases. In order to consider fast response capability, accurate modelling of the physical components and control circuits and dynamic simulation are required.

Since plant flexibility is a decisive competitive advantage in a liberalised market where residual load is subject to rapid fluctuations, dynamic simulation is a practical approach with significant potential both for innovative plant design and optimisation of existing power plants. Many researchers have conducted theoretical investigations on the transient behaviour of different HRSG systems. For a single-pressure HRSG modelled with simple bulk heat exchangers, Kim et al. [8] performed quasi-steady start-up analyses. The authors used an exhaust gas bypass to keep the thermal stress in the drum within allowable limits, despite the additional heat loss. Wippel [9] and Shin et al. [10] calculated the system responses of different HRSGs to flue gas parameter steps as well as to sinusoidal and step variations of the gas turbine load. Several numerical works focused on developing optimisation procedures to reduce the required time for combined-cycle start-up, where thermal stress in the HP drum and steam turbine rotor were considered as constraints [11–14]. Bertini et al. [15] applied evolutionary algorithms to extend the optimisation problem towards multiple conflicting objectives, such as maximising power output while minimising pollutant emissions. Walter and Hofmann [7]