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How can the heat transfer correlations for finned-tubes influence the numerical simulation of the dynamic behavior of a heat recovery steam generator?

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ABSTRACT

This paper presents the results of a theoretical investigation on the influence of different heat transfer correlations for finned-tubes to the dynamic behavior of a heat recovery steam generator (HRSG). The investigation was done for a vertical type natural circulation HRSG with 3 pressure stages under hot start-up and shutdown conditions. For the calculation of the flue gas-side heat transfer coefficient the well known correlations for segmented finned-tubes according to Schmidt, VDI and $ESCOA_{TM}$ (traditional and revised) as well as a new correlation, which was developed at the Institute for Energy Systems and Thermodynamics, are used. The simulation results show a good agreement in the overall behavior of the boiler between the different correlations. But there are still some important differences found in the detail analysis of the boiler behavior.

1. Introduction

In the energy and process technology most of the high power steam generators are designed as water tube boilers. Many of these boilers use the waste heat of gas turbines. In these so called combined power cycles the steam generator is arranged downstream the gas turbine (GT). Modern gas turbines for combined cycles are highly flexible in their mode of operation, i.e., concerning rates of start up, load change and shutdown. Heat Recovery Steam Generators (HRSG) arranged downstream of the GT are forced to operate in such a way, that the gas turbine operation is not restricted by them. Therefore, they should be designed for a high cycling capability with typical values in the range of approx. 250 cold starts, 1000 warm and 2500 hot starts for their typical 25 year life span.

Modern heavy duty GT are characterized by short start up times and high load change velocities. Both during a cold and warm start these GT achieve 100% of their nominal load in approx. 20 min, while 70% of the nominal GT-exhaust gas temperature and 60% of the nominal exhaust gas flow is already achieved approx. 7 min after the GT start. The downstream arranged HRSG is supposed not to hinder the operation and load change velocity of the GT. Especially for vertical type HRSG with horizontal tubes in the evaporator the requirements posed by the GT demand an accurate calculation and a detailed engineering of the dynamic behavior of the HRSG. The combined cycle power plant reaches its nominal load 120 or 190 min after the GT start, depending upon whether warm- or cold-start is performed. For a compact design of the HRSG finned-tubes are used for the bundle heating surfaces.

Careful engineering and accurate prediction and simulation tools are necessary in order to ensure an unhindered operation of the GT and take advantage of the many positive aspects of the HRSG design. In Europe many of these HRSG boilers are designed as vertical type with an natural circulation evaporator. Normally, the fluid in the natural circulation evaporator flows from the downcomer through the heated tube bank straight to the riser. The driving force of the natural circulation is generated due to the density difference of the water in the downcomer and the water/steam mixture in the tube bank and the riser tubes. The experience shows, that the most critical operation modes of HRSG's with a natural circulation evaporator are fast warm start-ups and heavy load changes. In these cases stagnation and/or reverse flow can occur due to dynamic effects (see e.g. [1–3]). In order to avoid such situations it is important to have some information about the flow distribution in the tube network of the steam generator available already in the stage of boiler design. To get some important informations it is necessary to have validated simulation tools which allow to calculate the start-up and/or shutdown behavior of boilers.

It is well known that the influence of the flue gas heat transfer coefficient to the overall heat transfer coefficient is higher compared to the heat transfer coefficient of the working medium (in case of a boiler water, steam or a water/steam mixture). For this

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Nomenclature

a Discretization coefficient [kg/s]
a_{ei} SIMPLER discretization coefficient for the east neighbor of the cell i at the staggered grid [kg/s]
a_{eei} SIMPLER discretization coefficient at the east cell boundary of the east neighbor cell of the cell i [kg/s]
a_{Ei} SIMPLER discretization coefficient for the east neighbor of the cell i [kg/s]
a_{hE} SIMPLER coefficient for the east neighbor cell of the energy balance for the header [kg/s]
a_{hP} SIMPLER coefficient for the energy balance of the header [kg/s]
a_{hW} SIMPLER coefficient for the west neighbor cell of the energy balance of the header [kg/s]
a_{mEi} SIMPLER pressure correction discretization coefficient for the east neighbor cell of the cell i [m s]
a_{mhE} SIMPLER pressure correction discretization coefficient for the east neighbor cell of the header [m s]
a_{mhP} SIMPLER pressure correction discretization coefficient of the header [m s]
a_{mhW} SIMPLER pressure correction discretization coefficient for the west neighbor cell of the header [m s]
a_{mPi} SIMPLER pressure correction discretization coefficient of the cell i [m s]
a_{mWi} SIMPLER pressure correction discretization coefficient for the west neighbor cell of the cell i [m s]
a_{Pi} SIMPLER discretization coefficient for the energy balance of the cell i [kg/s]
a_{Wi} SIMPLER discretization coefficient for the west neighbor of the cell i [kg/s]
A Cross sectional area [m^2]
$A_{\min}$ Net free area of tube row [m^2]
A_{tot} Total outside surface area of the finned-tube bundle [m^2]
A_b Heating surface of the smooth bare tube [m^2]
b_{ei} Constant term in discretization equation for the cell i [N]
b_h Constant term in discretization equation for the energy balance of the header [J/s]
b_i Constant term in discretization equation for the energy balance of the cell i [J/s]
b_{mh} Constant term in discretization equation for the header [kg/s]
b_{mi} Constant term in discretization equation for the cell i [kg/s]
b_s Average segment width [m]
c General variable [var]
d_a Bare tube diameter [m]
d_{ei} East coefficient of the velocity correction of the cell i [m^{2}s/kg]
d_{wi} West coefficient of the velocity correction of the cell i [m^{2}s/kg]
D Total outside diameter [m]
g_x Component of the gravity in direction of the tube axis [m/s^2]
e Spec. internal energy [J/kg]
F Error [-]
h Spec. enthalpy [J/kg]
h_h Spec. enthalpy of the fluid inside the header [J/kg]
H Average fin height [m]
H_s Average segment height [m]
L Average tube length [m]
m_g Flue gas mass [kg]
$\dot{m}_g$ Flue gas mass flow [kg/s]
N_f Number of fins per m [1/m]
N_L Number of tubes per row [-]
N_r Number of tubes in flow-direction [-]
Nu Nusselt-number [-]
p Pressure [Pa]
Δp Pressure difference [Pa]
p_h Pressure of the fluid inside the header [Pa]
p_D Drum pressure [Pa]
p' Pressure correction [Pa]
Pr Prandtl-number [-]
$\dot{q}$ Heat flux [W/m^2]
Re Reynolds-number [-]
s Tube thickness [m]
s_f Average fin thickness [m]
S_{eci} Constant term of the linearized source term of the cell i [Pa/m]
S_{ePi} Proportional term of the linearized source term of the cell i [Pa s/m^2]
S_{ch} Constant term of the linearized source term for the energy balance of the header [W/m^3]
S_{Ph} Proportional term of the linearized source term for the energy balance of the header [kg/m^{3}s]
S_{ci} Constant term of the linearized source term for the energy balance of the cell i [W/m^3]
S_{Pi} Proportional term of the linearized source term for the energy balance of the cell i [kg/m^{2}s]
t_f Fin pitch [m]
t_l Longitudinal tube pitch [m]
t_t Transversal tube pitch [m]
T Kelvin-temperature [K]
T_f Mean fin temperature [K]
T_g Mean gas temperature [K]
U Perimeter [m]
V_h Volume of the fluid inside the header [m^3]
w Fluid velocity [m/s]
$\widehat{w}$ Pseudo-fluid velocity [m/s]
x Length [m]
α Heat transfer coefficient [W/m^{2}K]
ϱ Density [kg/m^3]
ϱ_h Density of the fluid inside the header [kg/m^3]
ϑ Celsius-temperature [°C]
η Dynamic viscosity [Pa s]
τ Time [s]
ζ Pressure loss coefficient [-]

Superscripts
0 Value at the old time step
$*$ Approximate value
$'$ Correction value
$\wedge$ Pseudo value

Subscripts
0 Characteristic length at d_a
b Bare tube
E East grid point in mass and energy balance
$ESCt$ ESCOA traditional
f Fin
$fric$ Friction
g Gas
h Header
i Counter for the heat transfer correlations