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Study of the Natural Circulation Heat Recovery Steam Generator Unsteady Behavior Using One Dimensional Model for the Evaporator Loop

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ABSTRACT: Heat recovery steam generators as a vital part of cogeneration plants play a fundamental role in energy recovery processes. According to a necessity of accurate analysis of steam generators' parameters variation rate to take a decision on steam generators processes such as start-up and shut-down, the present study aims to investigate the unsteady behavior of boilers using the dynamic simulation. In this respect, a one-dimensional model of the evaporator natural circulation loop along with boilers' drum and heat transfer models are considered for simulation. Unsteady study scenarios include changes in the input heat to tube banks due to the change in the gas turbine load, feedwater flow rate and steam demand of the downstream cycle. A computer code has been developed to solve governing equations of a one-dimensional model and to demonstrate the response of boilers' key parameters to different scenarios. Dynamic simulation results showed that a 5% increase in heat input to risers leads to an increase of 15% of the drum pressure as well as an increase of about 10 degrees of the tubes wall temperature. In addition, an increase of 20% in the heat input due to the change in the gas turbine load would increase the wall temperature of tubes by 35 degrees.

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1. Introduction

Based on the International Energy Agency (IEA) report, cogeneration systems contribute to 10% of total power generated in the countries of the world [1]. The exhaust gases of a gas turbine have a lot of energy recovery potential due to its high thermal capacity and potential [2]. Heat Recovery Steam Generator (HRSG) is one of the key components in the combined cycle and cogeneration systems and plays a fundamental role in improving the efficiency and energy recovery of the system. Changes in input heat (heat flux) to the HRSG tube bundle (the gas turbine load), increase or decrease in steam demand (generated steam flow rate) of the downstream cycle, as well as changes in the flow rate and temperature of the inlet feed water from economizer tubes, affect the different variables of HRSGs. Studying the dynamic behavior of HRSG is important due to its industrial applications and the importance of controlling HRSG parameters under the conditions of sudden changes to prevent damage to the tubes and reduction in system efficiency. This paper conducts an investigation on the HRSG response behavior using a one-dimensional natural circulation evaporator model under different conditions. A computer code used to dynamically simulate the governing equations of the one-dimensional model (nodal model) of the HRSG is developed. Dynamic response of the important operational parameters of the HRSG such as risers' wall temperature as well as drum steam pressure are extracted in accordance with applied stimulations.

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2. Methodology

The one-dimensional dynamic model of the HRSG includes sub-models such as drum, heat transfer model, and natural circulation loop evaporator model, as well as coupled equations between these three sub-models. By combining the three-steam drum, heat transfer and one-dimensional riser-downcomer tubes natural circulation loop models, a one-dimensional (nodal) model is obtained. These three sub-models are dependent on each other and the coupled equations fix this dependency. The equations governing this one-dimensional model are the conservation of mass, momentum and energy equations. Among these equations, another equation is needed according to the known variables and the goal of the problem; called the thermodynamic table state equation, which is used in accordance to the value of the existing properties to solve the system of equations.

The equations governing the drum model [3] such as the equations of conservation of mass and energy of the existing phases inside the drum, form Eqs. (1) to (3). Single-step Runge-Kutta fourth-order numerical method is used to solve its system of equations.

$$a_1 \frac{dP}{dt} + b_1 \frac{dV_L}{dt} + c_1 \frac{dV_b}{dt} = d_1 \quad (1)$$

$$a_2 \frac{dP}{dt} + b_2 \frac{dV_L}{dt} + c_2 \frac{dV_b}{dt} = d_2 \quad (2)$$

$$a_2 \frac{dP}{dt} + b_2 \frac{dV_L}{dt} + c_2 \frac{dV_b}{dt} = d_2 \quad (3)$$

The mass balance equation in the riser-downcomer tubes natural circulation loop in the unsteady form is as seen in Eq. (4) [4].

$$\frac{\partial \rho_{cl}}{\partial t} + \frac{\partial (\rho u)_{cl}}{\partial z} = 0 \quad (4)$$

The conservation equation of the forces present in the HRSG natural circulation loop is written taking the terms of friction forces, gravitational (potential), dynamic (kinetic) into account, while the conservation of momentum equation at the unsteady form is seen in Eq. (5).

$$\frac{\partial (\rho u)_{cl}}{\partial t} + \frac{\partial (\rho u^2)_{cl}}{\partial z} + \frac{\partial P_{cl}}{\partial z} + \left(C_k \rho u^2\right)_{cl} + (\rho g)_{cl} = 0 \quad (5)$$

Single-phase friction factor is used to calculate the two-phase friction factor f_{TP} in accordance to the homogenous model to obtain the friction coefficient in the frictional pressure drop term, with some corrections such as applying the two-phase multiplier [5].

The energy balance equation in the circulation loop during the dynamic form can entirely be expressed as Eq. (6).

$$\frac{\partial}{\partial t}\left[\rho\left(h + \frac{u^2}{2}\right)_{cl}\right] + \frac{\partial}{\partial z}\left[\rho u\left(h + \frac{u^2}{2}\right)_{cl}\right] - \frac{\partial P_{cl}}{\partial t} + q_w + (\rho u g)_{cl} = 0 \quad (6)$$

Forward finite difference method along the tube length and the fully implicit method along the time are used to discretize the equations governing the natural circulation loop. Mass, momentum, and energy conservation equations should be solved to calculate the four unknown variables of density, velocity, pressure, and enthalpy at every node in the loop. Another equation is needed to complement the solution process and close the system of equations. The equation of state (thermodynamic table) can calculate the density of any given node or time using known values of pressure and enthalpy. In fact, the equation of state (properties and thermodynamic table) can fix the issue of coupling between velocity and pressure as seen in Eq. (7). XSteam preset function is used to apply the state equation (thermodynamic table) and calculate the thermodynamic properties of the parameters used in the developed software. XSteam function is provided by Holmgren [6] according to the International Association for the Properties of Water and Steam (IAPWS) data.

$$\rho_{i+1}^{n+1} = f\left(h_{i+1}^{n+1}, P_{i+1}^{n+1}\right) \quad (7)$$

In every step of the unsteady solution, inlet and outlet velocity, density, and enthalpy are calculated after establishing the loop, while the mass flow rate and enthalpy of the riser and downcomer tubes connected to the drum (the start and end node of the natural circulation loop) are updated and applied to the drum model to be used in the solution of another time step.

3. Results and Discussion

The geometric and thermodynamic properties of the studied HRSGs in this research are extracted from a simulation done by Mahdavi et al. [7]. Among its notable properties, the 7.777 m long tubes, 1064 riser tubes, 433 ^{o}C temperature input exhaust gas, and 324.10 ton/h flow rate input exhaust gas can be stated.

Fig. 1 shows changes in different parameters of the HRSG such as drum pressure and water volume, tube outlet steam quality, and tube wall temperature against time. Increasing input heat rate to the tube bundles increases pressure, system water volume and increasing the outlet steam quality of the riser tubes due to the increase in the evaporation rate. The tubes' temperature should be monitored for overheating problems. According to Fig. 1, a 5% increase in the input heat rate, results in 15% increase in HRSG pressure and about 10 degrees of tube bundle temperature.

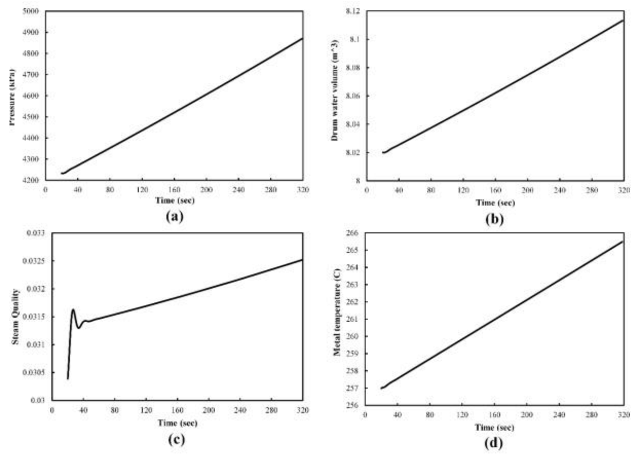

Fig. 1. HRSG dynamic response against an increase in input heat rate, (a) drum steam pressure, (b) drum water volume, (c) riser tube outlet steam quality, and (d) riser tube wall temperature

One of the important parameters of the HRSG is tube wall temperature, which due to dangers such as damage and burning as a result of increased input heat rate, the dynamic behavior of this parameter should be closely studied parametrically. Changes in tube wall temperature against time in accordance with differences in input heat rise are extracted and shown in Fig. 2. Regarding Fig. 2, a 20% increase in the input heat results in a 35% rise in tube wall temperature, showing that this parameter should be closely monitored to prevent the aforementioned dangers.

The dynamic behavior of the fluid inside HRSG tubes along the loop iw extracted in Fig. 3. Results show that 20%

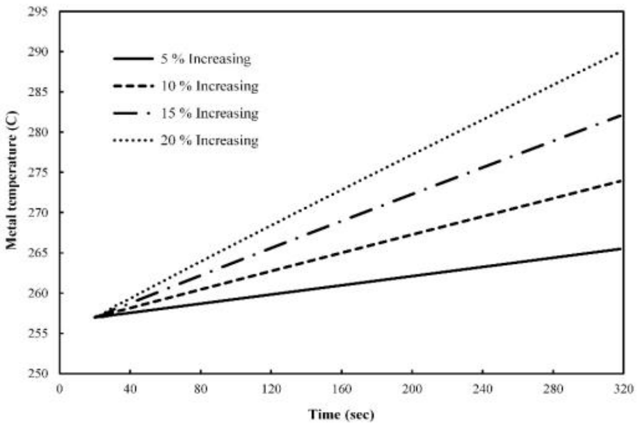

Fig. 2. Dynamic response of the tube wall temperature due to the increase in the input heat at difference percentages

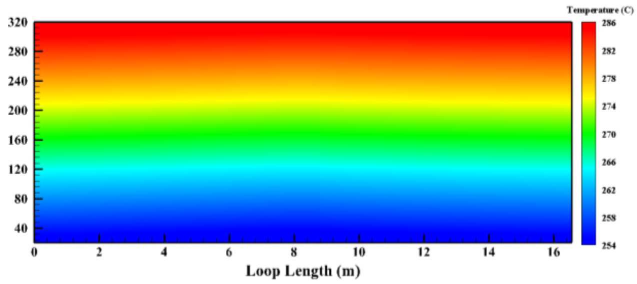

Fig. 3. Dynamic response of the fluid temperature against 20% increase in the input heat rate

increase in the input heat rate causes a 30 degree temperature rise in the fluids inside the tubes, from 255 to 285 °C.

4- Conclusions

In this paper, a computer code is developed to investigate the dynamic behavior of a one-dimensional model of the natural circulation HRSG. The governing equations of the one-dimensional HRSG model are discretized along the tube length and time. The unsteady behavior of the HRSG is studied of different conditions, such as changes in input heat to the HRSG tube bundle, feed water flow rate, and the steam demand. Controlling the temperature of the riser tubes is important due to the sudden changes induced by upstream cycle to prevent tube damage as a result of thermal stresses. The results of the dynamic simulation indicate that increasing the input heat by 20%, results in an approximate 35 degrees increase in the tube wall temperature.

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