Modeling of A Superheater for A Combined Cycle Power Plant

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Abstract: In this paper, we derive the time-dependent equations of a superheater of a combine cycle power plant. Simulations of the superheater are done on Matlab Simulink. We show the results of modeling the superheater based on several variations of its outputs.

Key words: combined cycle power plant, superheater, time-dependent equation, steam enthalpy, steam density, metal tube temperature, mass flow, superheated steam, simulation

I. INTRODUCTION

In a combined cycle power plant, the exhaust gas which exits the gas turbine is fed to the heat recovery steam generator (HRSG) system, to extract the heat from the exhaust gas and to produce superheated steam for running the steam turbines.

The generation of the superheated steam in the superheater involves the absorption of heat by the metal tube of the superheater and consequently, by the steam inside the superheater. The properties of steam flow from the adjacent high-pressure drum and exhaust gas exiting the gas turbine directly influence the dynamics of the steam in the superheater.

In this paper, the time-dependent equations for enthalpy of the steam in the superheater, the metal tube temperature of the superheater and the density of the steam in the superheater are derived, using the conservation of mass and energy in the superheater.

The time-dependent equations are then solved using Matlab command[1] and the solutions are then simulated using the Matlab Simulink. The input data for the simulated equations were taken from the Skegton Unit developed by Ordys *et al* [2].

I. TIME-DEPENDENT EQUATIONS

Figure 1 shows the mass flow diagram of a high pressure (HP) superheater in a combined cycle power plant. In this figure, the exhaust gas from the gas turbine is fed to the HRSG system. The superheater in the HRSG extracts the heat from the exhaust gas to produce superheated steam, which will then be used to run the high pressure (HP) and low-pressure (LP) steam turbines.

In order to heat the steam inside the superheater, the metal tube of the superheated is first heated by the hot exhaust gas flowing across the metal surface. The heat from th metal tube is then transferred to the steam inside the superheater to produce superheated steam.

The steam flow from the high-pressure (HP) drum, adjacent to the superheater into the HP superheater, depends on the pressure drop across the superheater. As the pressure drop depends on the properties of the steam inside the superheated, time-dependent equations of enthalpy of the steam inside the superheater will provide information on the dynamics of the steam.

To derive the time-dependent equation of the steam enthalpy inside the superheater, the mass and energy conservation principles are applied to the exhaust gas and steam in the superheater, as well as the metal tube temperature of the superheater.

As the steam enthalpy $T_{sh1}(t)$, also depends on the metal tube temperature $T_{sht1}(t)$, and the steam temperature inside the superheater $T_{sh1}(t)$, terms $T_{sh1}(t)$ and $T_{sht1}(t)$ will have to be solved first before solving for $T_{sh1}(t)$.

Following steps describe the derivation of the time dependent equation of the steam enthalpy in th superheater.

(i) Conservation of Mass and Energy in HP Superheater

The steam mass balance in HP superheater is given by:

$$w_{shhp1} - w_{sh1hpst} = V_{sh1} (d/dt) (\rho_{sh1}(t)) \qquad (1)$$

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where,

w_{shhp1} steam flow from HP drum to HP superheater
$w_{sh1hpst}$ steam mass flow out of HP superheater to HP steam turbine
V_{sh1} volume of HP superheater
ρ_{sh1} density of superheated steam in HP superheater

The gas-metal tube heat balance in HP superheater is given by[2]:

$$Q_{gsh1} = Q_{sh1} + M_{sh1}\, C_{sh1t}\, (d/dt)\, (T_{sh1t}) \qquad (2)$$

where

Q_{gsh1} heat supplied to the HP superheater by exhaust gas exiting from the gas turbine
Q_{sh1} heat transferred from the exhaust gas to the steam in HP superheater
M_{ssh1} mass of HP superheater tubes
C_{sh1t} heat capacitance of HP superheater tubes
T_{sh1t} metal tube temperature of HP superheater

The metal tube-steam heat transfer in HP superheater is given by:

$$Q_{sh1} = k_{sh1}\, w_{sh1}^{0.8}\, (T_{sh1t} - T_{sh1}) \qquad (3)$$

where

k_{sh1} an experimental coefficient of HP superheater
T_{sh1} steam temperature in HP superheater
w_{sh1} steam flow in HP superheater

The heat balance for steam in HP superheater is given by:

$$Q_{sh1} + w_{shhp1}\, h_{shhp1} = w_{sh1hpst}\, h_{sh1hpst} + V_{sh1}\, (d/dt)\, (\rho_{sh1}\, h_{sh1}) \qquad (4)$$

Expanding equation (4) gives:

$$Q_{sh1} + w_{shhp1}\, h_{shhp1} = w_{sh1hpst}\, h_{sh1hpst} + V_{sh1}\, \rho_{sh1}\, (d/dt)\, (h_{sh1}) + V_{sh1}\, h_{sh1}\, (d/dt)\, (\rho_{sh1}) \qquad (5)$$

where

h_{shhp1} specific enthalpy of saturated steam from HP drum to HP superheater
$h_{sh1hpst}$ specific enthalpy of superheated steam in HP superheater

Heat transferred by convection to from exhaust gas to HP superheater is given by:

$$Q_{gsh1} = k_{gs}\, w_{EG}^{0.6}\, (T_{gsh1} - T_{sh1t}) \qquad (6)$$

where

k_{gs} an experimental coefficient of HP superheater
T_{gsh1} exhaust gas temperature at HP superheater
w_{EG} exhaust gas flow at HP superheater

(ii) Solving for steam density in superheater,ρ_{sh1}(t)

Solving equation (1) for $\rho_{vd1}(t)$ gives:

$$\rho_{sh1}(t) = (w_{shhp1} - w_{sh1hpst})\, t / V_{sh1} + \rho_{sh1}(0) \qquad (7)$$

(iii) Solving for metal tune temperature of superheater, T_{sh1t}

Substituting equations (6) and (3) in equation (2) gives:

$$k_{gs}\, w_{EG}^{0.6}\, (T_{gsh1} - T_{sh1t}) = k_{sh1}\, w_{sh1}^{0.8}\, (T_{sh1t} - T_{sh1}) + M_{sh1}\, C_{sh1t}\, (d/dt)\, (T_{sh1t})$$

or

$$- M_{sh1}\, C_{sh1t}\, (d/dt)\, (T_{sh1t}) - (k_{sh1}\, w_{sh1}^{0.8} + k_{gs}\, w_{EG}^{0.6})T_{sh1t} + k_{sh1}\, w_{sh1}^{0.8}\, T_{sh1} + k_{gs}\, w_{EG}^{0.6}\, T_{gsh1} = 0 \qquad (8)$$

The term steam density in superheater $\rho_{sh1}(t)$ in equation (7) could be converted to steam temperature in superheater T_{sh1}, using the steam table for saturated steam[2] by multiplying it with function $f(\rho_{sh1})$:

$$T_{sh1} = ((w_{shhp1} - w_{sh1hpst})\, t / V_{sh1} + \rho_{sh1}(0))\, f(\rho_{sh1}) \qquad (9)$$

Thus, equation (8) could be rewritten as:

$$- M_{sh1}\, C_{sh1t}\, (d/dt)\, (T_{sh1t}) - (k_{sh1}\, w_{sh1}^{0.8} + k_{gs}\, w_{EG}^{0.6})T_{sh1t} + k_{sh1}\, w_{sh1}^{0.8}\, ((w_{shhp1} - w_{sh1hpst})\, t / V_{sh1} + \rho_{sh1}(0))\, f(\rho_{sh1}) + k_{gs}\, w_{EG}^{0.6}\, T_{gsh1} = 0 \qquad (10)$$

Solving equation (10) for T_{sh1t} [3] gives:

$$T_{sh1t}(t) = (c_4\, t)/ b_4 - (c_4\, a_4)/ b_4^2 + d_4/b_4 + \exp(-(b_4\, t)/ a_4)\, F_4 \qquad (11)$$

With,

$a_4 = M_{sh1}\, C_{sh1t}$
$b_4 = (k_{sh1}\, w_{sh1}^{0.8} + k_{gs}\, w_{EG}^{0.6})$
$c_4 = k_{sh1}\, w_{sh1}^{0.8}\, (w_{shhp1} - w_{sh1hpst})\, f(\rho_{sh1})/ V_{sh1}$
$d_4 = k_{gs}\, w_{EG}^{0.6}\, T_{gsh1} + \rho_{sh1}(0))\, f(\rho_{sh1})$
$F_4 = T_{sh1t}(0) + (c_4\, a_4)/ b_4^2 - d_4/b_4$

(iv) Solving for steam enthalpy in superheater h_{sh1}

Substituting equations (1) and (3) into equation (5) gives:

$$k_{sh1}\, w_{sh1}^{0.8}\, (T_{sh1t} - T_{sh1}) + w_{shhp1}\, h_{shhp1} = w_{sh1hpst}\, h_{sh1hpst} + V_{sh1}\, \rho_{sh1}\, (d/dt)\, (h_{sh1}) + h_{sh1}\, (w_{shhp1} - w_{sh1hpst})$$

Or,

$$V_{sh1}\, \rho_{sh1}\, (d/dt)\, (h_{sh1}) + h_{sh1}\, (w_{shhp1} - w_{sh1hpst}) = k_{sh1}\, w_{sh1}^{0.8}\, (T_{sh1t} - T_{sh1}) + w_{shhp1}\, h_{shhp1} - w_{sh1hpst}\, h_{sh1hpst} \qquad (12)$$

Substituting equations (11) and (9) into (12) gives:

$$V_{sh1}\,\rho_{sh1}\,(d/dt)\,(h_{sh1}) + h_{sh1}\,(w_{shhp1} - w_{sh1hpst}) =$$
$$k_{sh1}\,w_{sh1}^{0.8}\,(((c_4\,t)/b_4 - (c_4\,a_4)/b_4^2 + d_4/b_4$$
$$+ \exp(-(b_4\,t)/a_4)\,F_4) - (((w_{shhp1} - w_{sh1hpst})\,t/V_{sh1}$$
$$+ \rho_{sh1}(0))\,f(\rho_{sh1}))) + w_{shhp1}\,h_{shhp1} - w_{sh1hpst}\,h_{sh1hpst} \qquad (13)$$

Solving for steam enthalpy $h_{sh1}(t)$ gives:

$$h_{sh1}(t) = (r\,t)/q - (p\,r)/q^2 + s\,(\exp(-(q\,t)/p$$
$$+ t\,(q - u\,p)/p))/(q - up) - (v\,t)/q + (p\,v)/q^2$$
$$+ w/q + \exp(-(q\,t)/p)\,G_1 \qquad (14)$$

with

$p = V_{sh1}\,\rho_{sh1}$
$q = w_{shhp1} - w_{sh1hpst}$
$r = (k_{sh1}\,w_{sh1}^{0.8}\,c_4)/b_4$
$s = k_{sh1}\,w_{sh1}^{0.8}\,F_4$
$u = b_4/a_4$
$v = (w_{shhp1} - w_{sh1hpst})\,f(\rho_{sh1})/V_{sh1}$
$w = k_{sh1}\,w_{sh1}^{0.8}\,(-(c_4\,a_4)/b_4^2 + d_4/b_4 - \rho_{sh1}(0)\,f(\rho_{sh1})) + w_{shhp1}\,h_{shhp1} - w_{sh1hpst}\,h_{sh1hpst}$
$G_1 = h_{sh1}(0) + (p\,r)/q^2 - s\,/(q - up) - (p\,v)/q^2 + w/q$

III. SIMULATION OF TIME-DEPENDENT EQUATIONS

The solutions for time-dependent equations (7), (11) and (14) i.e. for steam density $\rho_{sh1}(t)$, metal tube temperature $h_{sh1t}(t)$ and steam enthalpy $h_{sh1}(t)$ in superheater respectively, were simulated on Matlab Simulink.

Fig. 2A shows the main block of the Matlab Simulink programme, with input data shown in Table 1 which were taken from the Skegton Unit[2]. Fig. 2B shows the three sub-blocks which calculate the steam density $\rho_{sh1}(t)$, metal tube temperature $T_{sh1t}(t)$ and steam enthalpy $h_{sh1}(t)$ respectively.

Fig. 3 shows the simulation outputs of equations (7), (11) and (14) for a period of 400s when steam outlet temperature for different value of $w_{sh1hpst}$. In Fig. 3C, the metal tube temperature of the superheater $T_{sh1t}(t)$, reaches steady-state after about 50s and depend neither on the steam density $\rho_{sh1}(t)$, steam temperature $T_{sh1}(t)$ or steam outlet flow $w_{sh1hpst}$.

In Fig. 3D, The steam enthalpy in superheater $h_{sh1}(t)$ reaches steady-state faster when steam outlet flow w_{sh1} is lower. After reaching a certain maximum, the value of steam enthalpy decreases towards negative. This is due to fact that the term $(-k_{sh1}\,w_{sh1}^{0.8}\rho_{sh1}(0)\,f(\rho_{sh1}))$ in the w of equation (14) is negative, when w_{sh1} is high.

This fact is illustrated by Fig. 4D, which shows the steam enthalpy $h_{sh1}(t)$, reaches steady state at a positive value when smaller i.e. w_{sh1}= 3kg/s.

In Fig. 4C, the metal tube temperature of the superheater $T_{sh1t}(t)$ reaches steady state at lower value when the superheater steam flow w_{sh1}, is lower .

IV. CONCLUSION

The simulation of the time-dependent equations of the superheater i.e. steam density $\rho_{sh1}(t)$, metal tube temperature $h_{sh1t}(t)$ and steam enthalpy $h_{sh1}(t)$, made the study of the dynamic of a superheater in a combined cycle power plant easier, giving a convenient tool for the design superheater.

V. REFERENCES

[1] The MathWorks Inc., Using Matlab, The MathWorks Inc, 1997
[2] A. W. Ordys, A. W. Pike, M. A. Johnson, R. Katebi, M. J. Grimble, Modeling and Simulation of Power Generation Plants
[3] John R. Lamarsh, Introduction to Nuclear Engineering, Addison-Wesley Publishing Company Inc., 1983

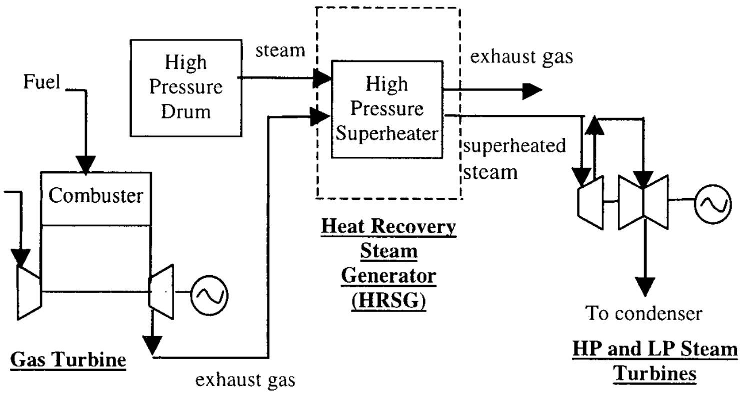
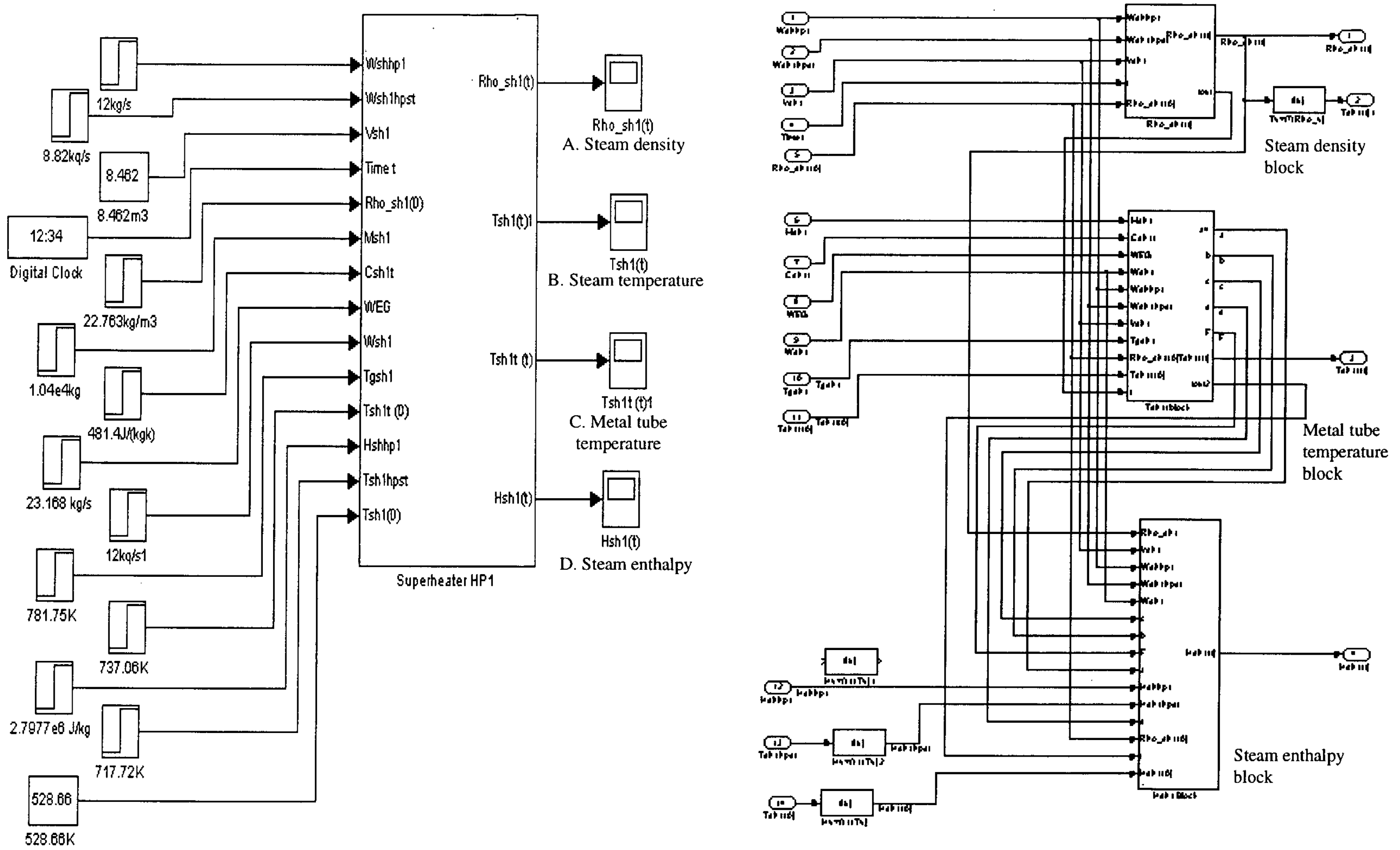


Figure 1. The mass flow diagram of steam and exhaust gas across the superheater of a combined cycle power plant.

Table 1. Simulation data[2]

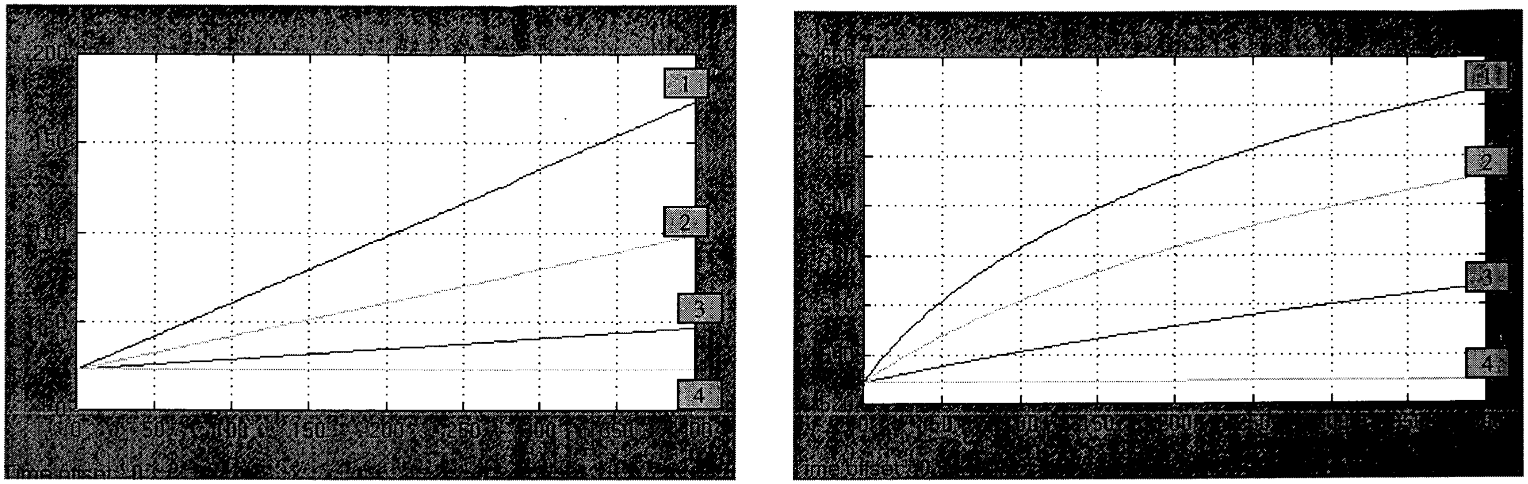
Parameter	Value
w_{shpp1}	12 kg/s
$w_{sh1hpst}$	8.82 kg/s
V_{sh1}	8.462 m^3
$\rho_{sh1}(0)$	22.763 kg/m^3
M_{sh1}	1.04e4 kg
C_{sh1t}	481.4 J/(kg°K)
w_{EG}	23.186 kg/s
w_{sh1}	12 kg/s
T_{gsh1}	781.75 °K
h_{shhp1}	2.7977e6 J/kg
$T_{sh1hpst}$	717.72 °K
$T_{sh1t}(0)$	737.06 °K
h_{shhp1}	2.7977e6 J/kg
$T_{sh1hpst}$	717.72 °K
$T_{sh1}(0)$	528.66 °K
k_{gs}	4.37e4 J/(kg°K)
k_{sh1}	4.37e4 J/(kg°K
t	1s to 400s



A. Superheater block with inputs from Skegton Unit[1] B. Density, metal tube temperature and steam enthalpy blocks

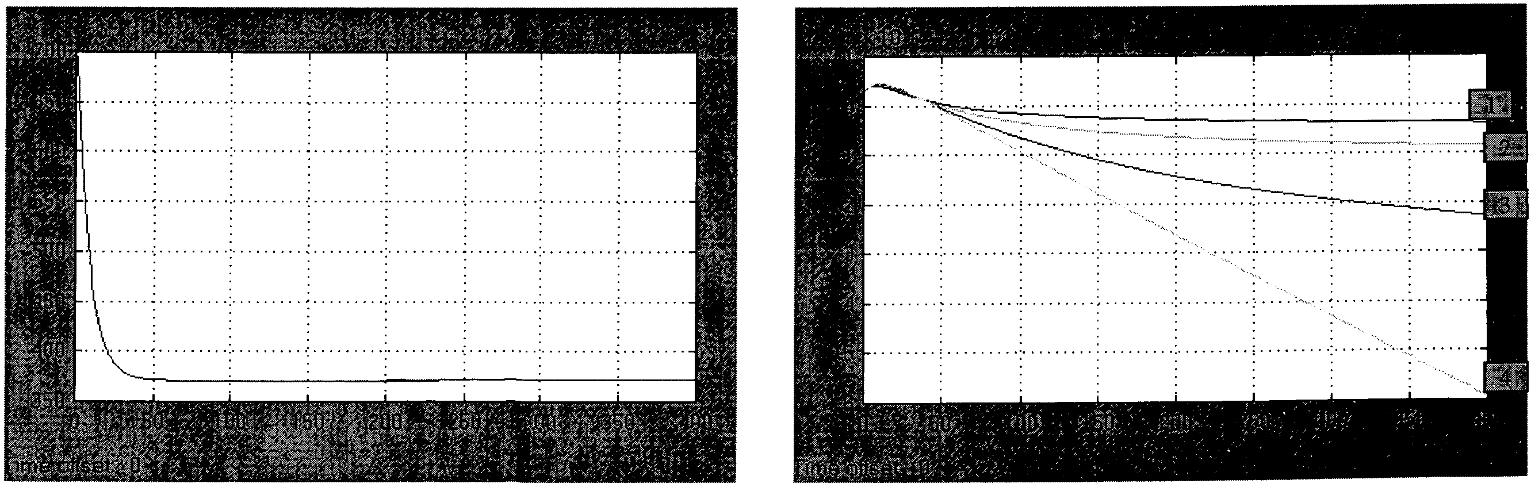
Figure 2. Dynamic Modeling of Superheater in a Combined Cycle Power Plant with MATLAB Simulink

[1] $H_{steam}(T_{steam}) = -1.8934E6 + 4.1404E4\ T_{steam} - 148.7585\ (T_{steam})^2 + 0.2471\ (T_{steam})^3 - 1.5519E\text{-}4\ (T_{steam})^4$; [2] $T_{sh1}(\rho_{sh1}) = 390.4075 + 35.5266 \log(\rho_{sh1}) + 2.7876\ (\log(\rho_{sh1}))^2$



A. Steam density $\rho_{sh1}(t)$ (kg/s) vs t (s) in superheater

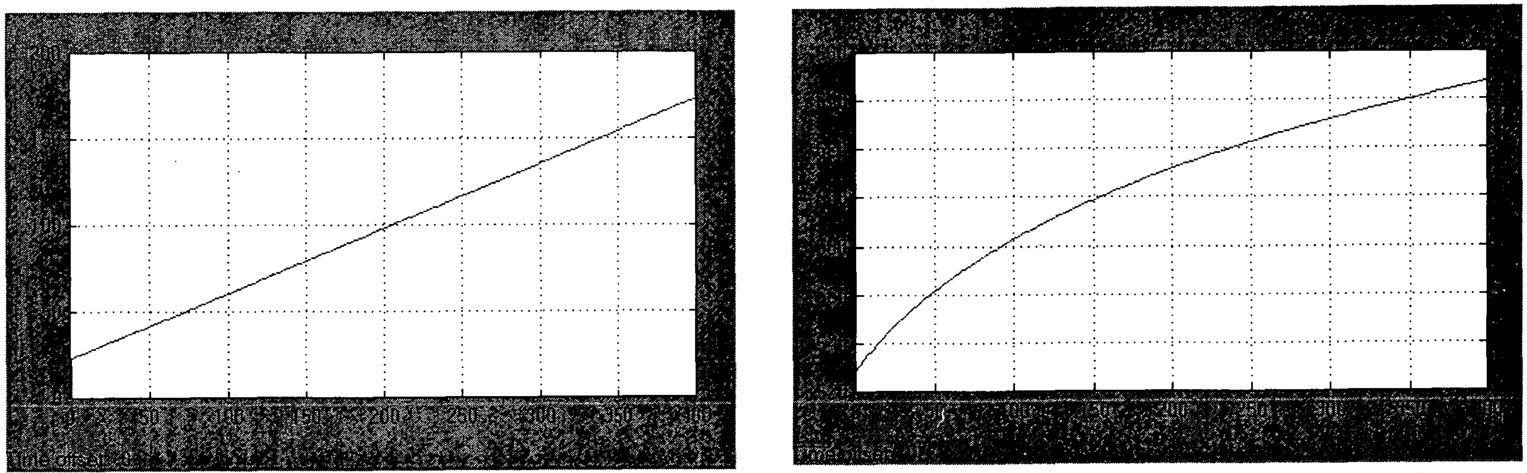
B. Steam temperature $T_{sh1}(t)$ (K) vs t (s) in superheater



C. Metal tube temperature $T_{sh1t}(t)$ (K) vs t (s) in superheater

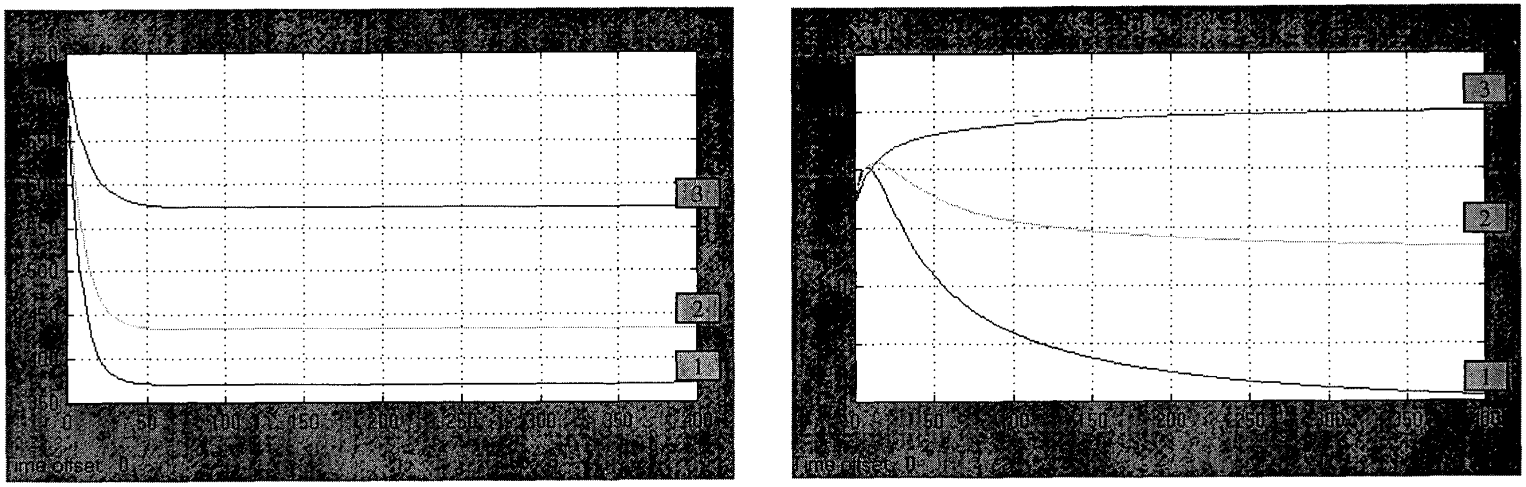
D. Steam enthalpy $h_{sh1}(t)$ (J/kg K) vs t (s) in superheater H

Figure 3. Simulation outputs when outlet steam flow $w_{sh1hpst}$ is varied: (1) 8.82kg/s (2) 10.4kg/s (3) 11.4kg/s (4) 11.99kg/s



A. Steam density $\rho_{sh1}(t)$ (kg/s) vs t (s) in superheater

B. Steam temperature $T_{sh1}(t)$ (K) vs t (s) in superheater



C. Metal tube temperature $T_{sh1t}(t)$ (K) vs t (s) in superheater

D. Steam enthalpy $h_{sh1}(t)$ (J/kg K) vs t (s) in superheater H

Figure 4. Simulation outputs when steam flow in superheater w_{sh1} is varied: (1) 12kg/s (2) 8kg/s (3) 3kg/s