Simplified Model for Steam Temperature Control in Power Plant

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Abstract

Energy balance of a model for steam generator in power plant is studied. The main components of the model steam generator are furnace, drum, evaporator, superheater, and economizer. The steam temperature exiting the superheater is assumed to be controlled by burner tilting in furnace, exhaust gas recirculation, and attemperation. A functional relationship among steam temperature and the control parameters is derived. A case study is then presented in which mutual variations of the control parameters that yield constant steam temperature obtained from the model are shown.

1. Introduction

An accurate control of superheated steam temperature is important for efficient power plant operation. The optimal temperature is usually specified during the design stage. Superheated steam temperature is then controlled to be as close as possible to the design temperature during the operation stage. A reduction in steam temperature causes loss in plant efficiency, whereas a rise in steam temperature above the design value may cause damage to superheater tubes, reheater tubes, and turbine blades.

Steam temperature is affected by many factors such as furnace temperature, mass flow rate of flue gas, steam load, feed water temperature, etc. Since interrelationships among steam temperature and these factors are not simple, textbooks on power plant engineering [1-3] treat the topic of steam temperature control only qualitatively.

In this paper, a quantitative treatment of this topic is attempted. To make the problem more manageable, a simplified model of steam generating operation is proposed, and important factors that can be used to control steam temperature are limited to heat absorption in furnace, attemperation, and flue gas recirculation. Energy balances are then performed on each component in order to find the functional dependence of steam temperature on the three factors.

2. Model of Steam Generator

Consider a steam power plant operating on the Rankine cycle with superheating, but without reheating. The schematic representation of the steam generating unit of the power plant is shown in Fig. 1. The main components of the steam generating unit are furnace, drum, evaporator, superheater, and economizer. Note that the superheater is of convective type, and a reheater is omitted from this simplified model. A more realistic model may include both reheater and radiant superheater.

The following assumptions regarding the power plant are made:

- The system is at a steady state.
- There is no heat loss.
- The mass flow rates of fuel and air are fixed.
- The amount of water (liquid + vapor) circulating in the system is constant.
- The heating value of the fuel is unchanged.
- Combustion is complete.
- Flue gas behaves like an ideal gas with constant heat capacity.

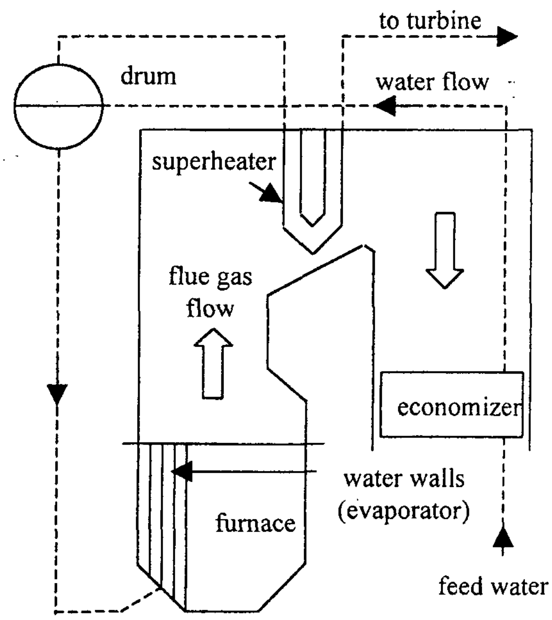

Fig. 1 Schematic representation of the steam generator in the model power plant

3. Simplified Models of Control Methods

There are several methods for controlling steam temperature. In this paper, three widely used methods are considered – (1) tilting of burners in the furnace, (2) attemperation, and (3) exhaust gas recirculation.

In the first method, vertically adjustable burners on furnace walls can be tilted to adjust heat absorption by the evaporator. If the burners are tilted upward, heat absorption by the evaporator will be reduced, and flue gas leaving the furnace will have a higher temperature. This method is considered to be a satisfactory and economical method of control.

The second method reduces steam temperature by mixing it with low temperature water from economizer exit. For effective mixing, a spray type attemperator or a desuperheater is normally used. The spray nozzle injects water into the throat of a mixing venturi, where water spray mixes with high velocity steam in the throat, vaporizes, and cools the steam. The water used for spray must be of high purity; otherwise, deposits will be collected on superheater tubes and turbine blades.

The third method requires the recirculation of some of the flue gas exiting the economizer back to the furnace by means of fans. The recirculation system to be considered is one in which recirculated gas is admitted near the furnace exit. This is also known as gas tempering. The furnace exit temperature in this system is reduced without affecting heat absorption by the evaporator.

Models for these control methods are illustrated in Figs. 2. The effect of burner titling is represented by parameter f so that heat Q from combustion of fuel is divided into heat absorption fQ in the furnace and heat transfer $(1-f)Q$ to the flue gas. The mass flow rate $\dot{m}_g$ of flue gas exiting the economizer is divided into $g\dot{m}_g$ recirculated back to the furnace and $(1-g)\dot{m}_g$ leaving the steam generator. The attemperation is modeled by the adiabatic mixing of $x\dot{m}_s$ of water from the economizer with $(1-x)\dot{m}_s$ of steam generated by the evaporator.

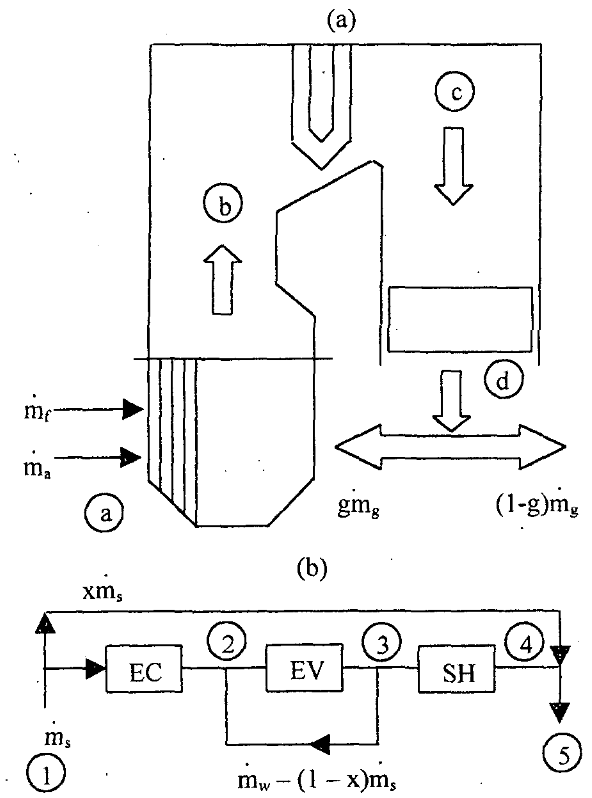

Fig. 2 Flow patterns of (a) flue gas; (b) water

Figures 2 also show state points of flue gas and water. These will be referred to the next section.

4. Mass and Energy Balances

The goal of this analysis is to find a relationship between steam temperature at state 5 and control parameters f, g, and x. To achieve this goal, equations of mass and energy balances in the system must be derived. In the following equations, quantities with numeric subscripts are associated with water, whereas quantities with subscripts a, b, c, d are associated with flue gas.

- Mass balance of flue gas in furnace

$$\dot{m}_f + \dot{m}_a = (1-g)\dot{m}_g \tag{1}$$

- Energy balance in evaporator

$$f\dot{m}_f(\mathrm{HHV}) = (1-x)\dot{m}_s\left(h_{fg} + c_{pw1}(T_3 - T_2)\right) \tag{2}$$

where c_{pw1} is the average specific heat capacity of steam between T_2 and T_3.

- Energy balance in furnace

$$(1-f)\dot{m}_f(\mathrm{HHV}) = \dot{m}_g c_{pg}\left[T_b - (1-g)T_a - gT_d\right] \tag{3}$$

- Energy balance in superheater

$$\frac{T_b - T_c}{T_b - T_3} = F_{sh}\left((UA)_{sh}, \dot{m}_g, c_{pg}, (1-x)\dot{m}_s, c_{pw2}\right) \tag{4}$$

$$(1-x)\dot{m}_s c_{pw2}(T_4 - T_3) = \dot{m}_g c_{pg}(T_b - T_c) \tag{5}$$

where c_{pw2} is the average specific heat capacity of steam between T_3 and T_4, and F_{sh} is a function that depends on the type of superheater [4]. Note that the NTU-effectiveness method is used here.

- Energy balance in economizer

$$\frac{T_c - T_d}{T_c - T_1} = F_{ec}\left((UA)_{ec}, \dot{m}_g, c_{pg}, \dot{m}_s, c_{pw3}\right) \tag{6}$$

$$(1-x)\dot{m}_s c_{pw3}(T_2 - T_1) = \dot{m}_g c_{pg}(T_c - T_d) \tag{7}$$

where c_{pw3} is the average specific heat capacity of water between T_1 and T_2, and F_{ec} is a function that depends on the type of economizer [4]. The economizer considered in this model is a non-steaming one. Hence, T_2 is less than the saturation temperature of water.

- Energy balance of attemperator

$$h_5 = (1-x)h_4 + xh_1 \tag{8}$$

If $\dot{m}_f$, $\dot{m}_a$, T_a, T_1, T_3 are given, 11 variables left in Eqs. (1)-(8) are f, g, x, $\dot{m}_g$, $\dot{m}_s$, T_b, T_c, T_d, T_2, T_4, and T_5. Hence, a single relationship between T_5 and f, g, x can be obtained by solving Eqs. (1)-(8). First , let's solve Eqs. (1) for $\dot{m}_g$.

$$\dot{m}_g = \frac{\dot{m}_f + \dot{m}_a}{(1-g)} \tag{9}$$

Next, solve Eqs. (3), (4), and (6) for T_b.

$$T_b = \frac{1}{1-g(1-F_{sh})(1-F_{ec})}\left[\frac{(1-f)\dot{m}_f(\text{HHV})}{\dot{m}_g c_{pg}} - (1-g)T_a + gF_{ec}T_1 + gF_{sh}(1-F_{ec})T_3\right] \tag{10}$$

And solve Eqs. (4) and (5) for T_4.

$$T_4 = T_3 + \frac{\dot{m}_g c_{pg}}{\dot{m}_s(1-x)c_{pw2}} F_{sh}(T_b - T_3) \tag{11}$$

If c_{pw4} is the average specific heat capacity of steam between T_4, and T_5, Eq. (8) can be rewritten as

$$xh_5 + (1-x)c_{pw4}T_5 = xh_1 + (1-x)c_{pw4}T_4 \tag{12}$$

In the relevant temperature range h_5 may be approximated as follows:

$$h_5 = 2.531T_5 + 2132.7 \tag{13}$$

Combining Eqs. (7) and (12) yields

$$T_5 = \frac{x(h_1 - 2132.7) + (1-x)c_{pw4}T_4}{2.531x + (1-x)c_{pw4}} \tag{14}$$

Equation (9)-(11) and (14) form an explicit expression of T_5 in terms of known parameters, $\dot{m}_s$, and the control parameters f, g, x. Equations (2), (6) and (7) can be solved for $\dot{m}_s$ to give

$$\dot{m}_s = \frac{f\dot{m}_f(\text{HHV}) + \frac{(1-x)c_{pw1}}{c_{pw3}}\dot{m}_g c_{pg} F_{ec}(T_c - T_1)}{(1-x)(h_{fg} + c_{pw1}T_3) - (1-x)c_{pw1}T_1} \tag{15}$$

T_c can be obtained from Eq. (4).

$$T_c = (1-F_{sh})T_b + F_{sh}T_3 \tag{16}$$

Equation (15) is actually nonlinear because F_{ec} and F_{sh} are usually complicated functions of $\dot{m}_s$. So it may have to be solved iteratively.

5. Case Study

The following operating conditions of the steam generator are assumed:

p_1	80 bar
T_1	39.5 °C
T_3	295.1 °C
HHV (fuel)	23.0 MJ/kg
η_t	90%
η_p	90%
$\dot{m}_f$	3 kg/s
$\dot{m}_a$	33 kg/s
$(UA)_{sh}$	5000 W/K
$(UA)_{ec}$	10000 W/K

The approximate values of thermal properties are given below [5].

c_{pg}	1.1 kJ/kg-K
c_{pw1}	2.8 kJ/kg-K
c_{pw2}	2.8 kJ/kg-K
c_{pw3}	4.3 kJ/kg-K
c_{pw4}	2.5 kJ/kg-K
h_{fg}	1440.5 kJ/kg

The superheater and the economizer are assumed to have the characteristics of a simple counter-flow heat exchanger so that [4]

$$F_{sh} = \frac{1-\exp\left[-\frac{(UA)_{sh}}{\dot{m}_g c_{pg}}\left(1-\frac{\dot{m}_g c_{pg}}{\dot{m}_s(1-x)c_{pw2}}\right)\right]}{1-\frac{\dot{m}_g c_{pg}}{\dot{m}_s(1-x)c_{pw2}}\exp\left[-\frac{(UA)_{sh}}{\dot{m}_g c_{pg}}\left(1-\frac{\dot{m}_g c_{pg}}{\dot{m}_s(1-x)c_{pw2}}\right)\right]} \tag{17}$$

and

$$F_{ec} = \frac{1-\exp\left[-\frac{(UA)_{ec}}{\dot{m}_g c_{pg}}\left(1-\frac{\dot{m}_g c_{pg}}{\dot{m}_s c_{pw3}}\right)\right]}{1-\frac{\dot{m}_g c_{pg}}{\dot{m}_s c_{pw3}}\exp\left[-\frac{(UA)_{ec}}{\dot{m}_g c_{pg}}\left(1-\frac{\dot{m}_g c_{pg}}{\dot{m}_s c_{pw3}}\right)\right]} \tag{18}$$

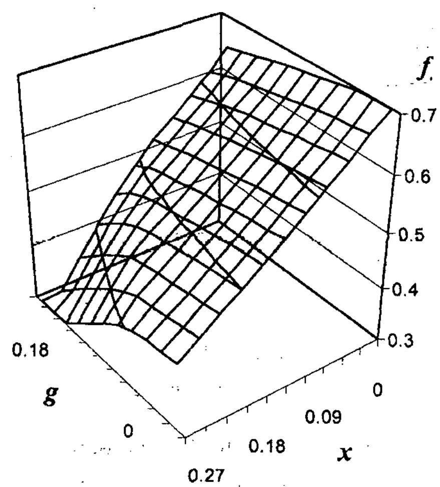

Fig. 3 Surface f-g-x that corresponds to T_5 = 400 °C

Results are now given for the case where the temperature of the superheated steam leaving the superheater is to be kept constant at 400 °C. Figure 3 shows the three dimensional plot of f-g-x surface that yields T_5 = 400 °C. Figure 4 shows the two-dimensional plots of this surface.

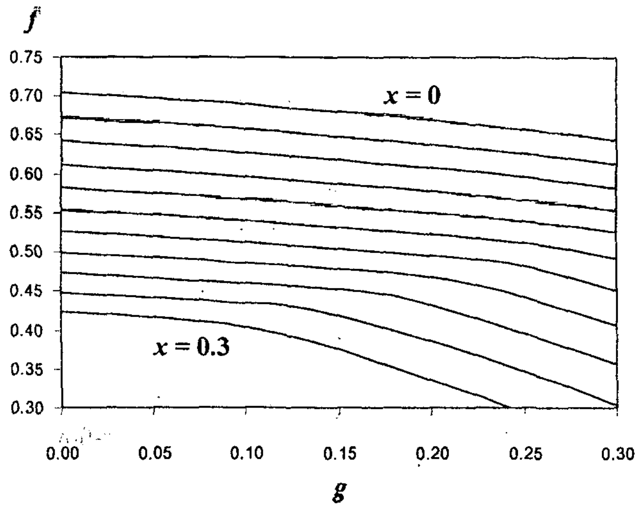

Fig. 4 Two-dimensional plots of Fig. 3

It can be seen that at constant x, f decreases with increasing g. This means that controlling T_5 can be done by tilting burners upward and increasing exhaust gas recirculation without changing attemperation. Another result that can be deduced from both figures is that T_5 can be made smaller by tilting burners downward, increasing exhaust gas recirculation, and extracting more feed water from economizer outlet for attemperation.

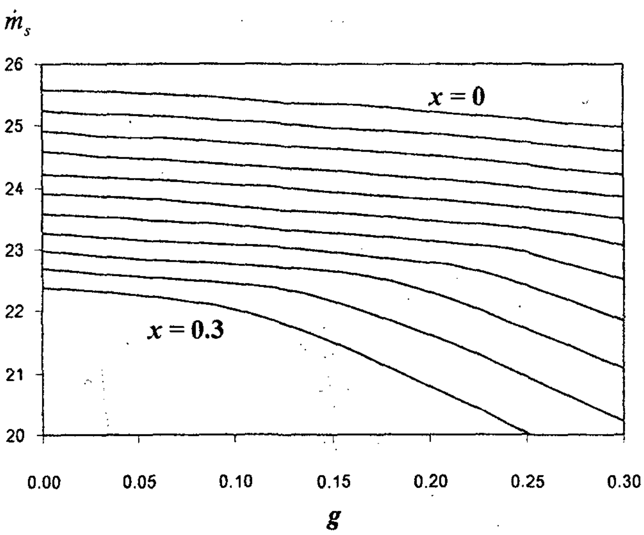

Fig. 5 Variations of steam flow rate with x and g that keep T_5 at 400 °C

It is interesting to note that the dependence of $\dot{m}_s$ on the control parameters (f, g, x) is not the same as the dependence of T_5. Therefore, by keeping T_5 constant, $\dot{m}_s$ may change. Figure 5 shows how $\dot{m}_s$ varies with the control parameters that yield constant T_5 (400 °C). To achieve the maximum flow rate, there should be no exhaust gas recirculation and attemperation, and burners should be tilted to the downward position that causes T_5 to be the desired temperature.

6. Conclusion

A simplified model of steam generator has been successfully employed to obtain a function relating steam temperature exiting superheater to parameters representing three methods that are used to control temperature, which are burner tilting, exhaust gas recirculation, and attemperation. The function appears to give correct effects of the control parameters on steam temperature. Therefore, it should be useful for teaching the topic of steam temperature control in power plant engineering course. However, this model needs further improvement before it can be used in actual steam control in power plant. Among the features of actual power plants that are omitted in the model but should be considered in a more realistic model are reheater, radiative superheater, and other control methods.

References

[1] K. W. Li and A. P. Priddy, Power Plant System Design, Wiley, New York, 1985, pp. 163-164

[2] P. K. Nag, Power Plant Engineering, Tata McGraw-Hill, New Dehli, 1998, pp. 360-367.

[3] B. W. Jackson, "Steam Generator" in Power Plant Engineering, ed. L. F. Drbal, Chapman & Hall, New York, 1996, pp. 192-194.

[4] J. P. Holman, Heat Transfer, McGraw-Hill, New York, 1986.

[5] W. C. Reynolds, Thermodynamic Properties in SI, Department of Mechanical Engineering, 1979.