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Modeling and Simulation of an Industrial Steam Boiler

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ABSTRACT

A steam boiler is a complex system consist of numerous components. The pressure variation phenomena inside a furnace of a steam boiler affect the steam boiler's efficiency and safety. In this paper a simple mathematical model describing the thermodynamic processes, which take place inside the furnace, is presented. The simulation model is applied to a boiler furnace. Each component of boiler has been modeled individually in such a way that when they are fitted together, the complete boiler can be simulated. A real industrial boiler has been taken as a reference to build the model.

Keywords: *Boiler, Steam Boiler, Boiler Efficiency, Industrial Boiler.*

1. INTRODUCTION

A steam boiler plays an important role in all types of industries. In industry steam boiler is generally required for the following reasons:[1]

- Steam as a means of direct or indirect heating.
- Steam as a raw material.
- Steam as a means of generating electrical power.

A boiler is an enclosed vessel that provides a means for converting water into steam. The steam under pressure is then used for transferring the heat to a process. Water is a useful and cheap medium for transferring heat to a process. When water is boiled its volume increases by about 1600 times, producing a force that is almost as explosive as gunpowder. This causes the boiler to be extremely dangerous and must be treated with a lot of care.

The boiler's operating conditions is very necessary to control because the high pressures and temperatures are the main hazard problems and it has the risk of explosion. Also steam boiler has very high manufacturing cost, operating cost and maintenance cost.

The operating conditions of steam boiler are very complex to control because all the variables (pressure, temperature, flow, level) are interrelated. Taking measurement directly on boiler is very difficult due to dangers from the operating conditions and not economical.

So in this paper an alternative method is presented to know the different operating condition which is Simulation. Simulation is a way to represent the behavior of a real process through the resolution of a mathematical model.

The advantages of using mathematical models can be summarized as follows:[2]

- A process can be analyzed in depth, determining which variables or parameters are critical and have a significant effect on overall system behavior.
- They can be used for operator training purposes.
- They are of great help to determine best possible Operating conditions.

2. MATHEMATICAL MODEL OF THE BOILER

To develop the mathematical model fuel mass flow rate $d/dt\,(m_f)$ is considered as input variables and the pressure P_f inside the boiler as output variables.

Figure 1 shows the model of boiler. In this model following parameters are balanced.[3]

- Mass
- Energy
- Momentum

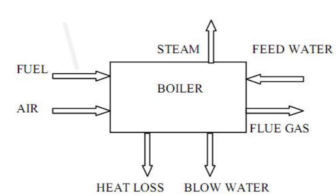

Fig 1. Boiler Model

Mass Balance[4, 5]

The density for homogeneous fluid is:

$$\rho = \frac{m}{V}$$

Taking the time derivative for constant volume:

$$\frac{d\rho}{dt} = \frac{dm/dt}{V} \qquad (a)$$

For a constant volume conservation of mass gives:

$$\frac{dm}{dt} = \sum_{in}(\dot{m}_{in}) - \sum_{out}\dot{m}_{out} \qquad (b)$$

Putting equation (b) in (a)

$$\frac{d\rho}{dt} = \frac{\sum_{in}(\dot{m}_{in}) - \sum_{out}\dot{m}_{out}}{V}$$

$$V * \frac{d\rho}{dt} = \sum_{in}(\dot{m}_{in}) - \sum_{out}\dot{m}_{out}$$

$$V_f * \frac{d(\rho_g)}{dt} = \frac{d}{dt}m_{fb} + \frac{d}{dt}m_a - \frac{d}{dt}m_g$$

Energy Balance[5-7]

For energy balance two quantities are considered to be conserved:

- Conservation of Mass
- Conservation of energy

Conservation of mass

Mass is a conserved property, it cannot be created or destroyed. The conservation of mass can be stated as:

$$\sum m_{in} - \sum m_{out} = \Delta m$$

The conservation of mass can be expressed in rate form as:

$$\sum \dot{m}_{in} - \sum \dot{m}_{out} = \frac{a}{dt}m$$

Conservation of Energy

The conservation of energy can be stated as:

$$Q - W + \sum E_{in,mass} - \sum E_{out,mass} = \Delta E$$

The conservation of energy can be expressed in rate form as:

$$\dot{Q} - \dot{W} + \sum \dot{E}_{in,mass} - \sum \dot{E}_{out,mass} = \frac{a}{dt}E$$

Work Flow[8]

It is the energy that is required to push fluid into or out of a control volume.

$$F = PA$$

$$W = PA$$

$$W = PV$$

$$W_{flow} = \frac{W_{flow}}{m}$$

$$W_{flow} = PV$$

$$\theta = PV + e$$

$$\theta = PV + (u + Ke + Pe)$$

$$h = u + PV$$

$$\theta = h + Ke + Pe$$

$$\theta = h + \frac{V^2}{2} + gz$$

$$\frac{dE}{dt} = \dot{Q} - \dot{W} + \sum_{in}\dot{m}_{in}\left(h_{in} + \frac{V^2{}_{in}}{2} + gz_{in}\right)$$

$$- \sum_{in}\dot{m}_{out}\left(h_{out} + \frac{V^2{}_{out}}{2} + gz_{in}\right)$$

$$\frac{dE}{dt} = Q + \sum_{in}\dot{m}_{in}\, h_{in} - \sum_{out}\dot{m}_{out}\, h_{out}$$

$$E = V(\rho U)_{ave}$$

$$V\frac{d[(\rho V)_{ave}]}{dt} = Q + \sum_{in}\dot{m}_{in}h_{in} - \sum_{out}\dot{m}_{out}h_{out}$$

$$\sum \dot{m}_{in}h_{in} - \sum \dot{m}_{out}h_{out} + \dot{Q} = V\frac{d(\rho_{ave}U_{ave})}{dt}$$

Momentum Balance[9-11]

Four terms are conserved in momentum balance:

- Friction
- Hydrostatic head
- Inertia
- Acceleration

The change in pressure due to friction is given by:

To determine the pressure drop , it is convenient to work with the "Moody" or "Darcy" friction Δfactor, which is dimension less parameter defined as:

$$f = -\left(\frac{dp}{dx}\right)D/\rho\mu^2/2$$

The pressure drop = P_1-P_2 associated with fully developed flow from the position x_1 to x_2 may then be expressed as:

$$\Delta P = -\int_{P1}^{P2} dx$$

$$\Delta P = f\rho\mu^2/2D \int_{X1}^{X2} dx$$

$$\Delta P = \frac{f\rho\mu^2}{2D(x2-x1)}$$

The final friction loss pressure term is

$$\Delta P = \frac{fLm^2{}_{ave}}{2DA^2\rho_{ave}} \qquad (1)$$

2) The pressure loss due to hydrostatic head is given by:

Hydrostatic head loss:
The heat produced by coulomb friction due to fluid particles.

$$\Delta P = \rho_{ave}gL \qquad (2)$$

3)The inertial term for the pressure loss is given by:

Using Newton's 2nd law:

$$F = \frac{P}{A}$$

$$\Delta PA = F = \frac{d}{dt}(mv)$$

$$\Delta P = \frac{L}{A}\frac{d}{dt}(\dot{m}_{ave}) \qquad (3)$$

4) The acceleration term for the pressure loss is given by:

Using Newton's 2nd law:

$$\Delta PA = F = d/dt(mv) = d/dt(\rho V v)$$

$$\Delta PA = d/dt(\rho_{out} V_{out} v_{out} - \rho_{in} V_{in} v_{in})$$

$$\Delta PA = \rho_{out} v_{out} \frac{d}{dt} V_{out} - \rho_{in} v_{in} \frac{d}{dt} V_{in}$$

$$\Delta P = m^{2_{out}}/\rho_{out} - \rho^{2_{in}}/\rho_{in} A^2 \qquad (4)$$

Combining equation (1),(2),(3) and (4) gives the total conservation of momentum equation

$$\Delta P = fLd/dt(m_{ave^2})/2DA^2\ \rho_{ave^2} + \rho_{ave} gL + L/A[\frac{d}{dt}(\dot{m}_{ave})] + (d/dt(m^{2_{out}})/\rho_{out}A^2 - d/dt(m^{2_{in}})/\rho_{in}A^2)$$

3. SIMULATION OF BOILER DYNAMICS

The developed mathematical model is then transferred to Simulink. To do this, a number of simple components is needed to create which will show each of the process units that represent the boiler. Then they can be fitted together to simulate the behavior of the complete boiler.

Figure 2 shows the Boiler block diagram representation in Simulink.When the inputs of the model of the boiler in Simulink is the temperature (heat) 241 º C and for supplying water (feed water flow) 100 m³ then exits (heat disturbance, drum pressure, steam flow, steam vol) taking values shown in the figure 3, figure 4.

4. CONCLUTION

In this paper a model for simulating a boiler has been given. The model consists of a number of sub models for the different components being present in the boiler. Each of the sub-models is build up as a set of Differential-Algebraic Equations (DAE's). Subsequently the models are merged into a global model for the system.

MatLab/SimuLink has been applied for integrating the model.

From the simulation results it is concluded that:

- The pressure inside the furnace increases linearly and then reaches to a steady state, caused by variations of the fuel flow inside the boiler and due to the low resistance of the boiler, the phenomenon occurs very fast.

Such a system is not part of daily life for people due to the complex mode of difficulty to understand the problem which leads to the design of the controller.

The control system of the system may be developed on the basis of these characteristics. This system requires that the gas pressure at the end of furnace should be measured to develop a regulating system.

For a good working of the regulating system it is required that the measurement of the pressure should be done in all four sides of the furnace and all four values should be calculated together to find out their mean value, which will be used further on by the regulating system.

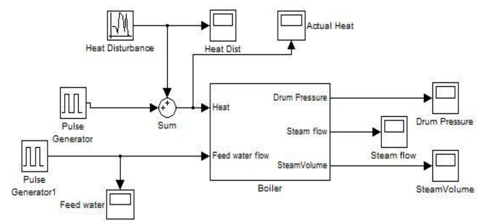

Fig. 2. Boiler Model

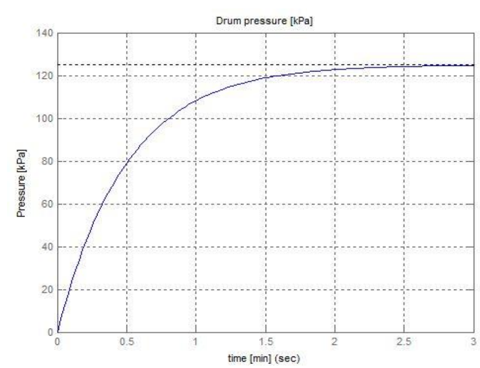

Fig. 3. Drum Pressure

Fig. 4. Steam Flow

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NOMENCLATURE

In this appendix the applied symbols are explained.

A	Area [m2]
H	Heating value[kJ/kg]
L	Length[m]
U	Energy content[kJ]
V	Volume[m3]
E	Energy[kJ]
W	Work[Nm]
Ke	Kinitic Energy[kJ]
Pe	Potential Energy[kJ]
mfb	burning fuel mass[kg]
ma	air mass[kg]
mg	gas mass[kg]
θ	Methalpy[kJ/kg]
ρ	Density[kg/m3]
x	Distance[m]
h	Enthalpy[kJ/kg]
p	Pressure[bara]