

LUMPED PARAMETERS MODELLING OF THE FURNACE AND STEAM SYSTEMS OF A 350 MW BOILER

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ABSTRACT

The models of the combustion and steam of a boiler real time simulator are presented in this paper. The simulator reproduces the actual behaviour of a steam generator of 350 MW power plant (a dual thermal power station currently operating in Mexico). The simulator is part of an analysis tool that reproduces the response of variables such as temperature, pressure, mass flow and composition of the combustion gases in different parts the boiler under diverse operating conditions. The models were developed using a concentrated parameters approach. The simulator response was validated with extensive tests. Here, the models responses under a couple of transients are discussed.

Keywords: boiler modelling; boiler simulation; combustion model; lumped parameters

1. INTRODUCTION

The present work was developed in the Advanced Systems on Training and Simulation Department (GSACyS, after its name in Spanish) of the Institute of Electrical Research (IIE) in Mexico. This is the second part of a previous paper (Roldan-Villasana et al. 2010a) where the simulator architecture, the software platform, the simplified models, and development of the waterwalls modelling were fully explained.

The GSACyS has developed several real time simulators for operators training of power plants for the Federal Electricity Commission (CFE, the Mexican Utility Company), a complete summary of these developments have been reported elsewhere (Roldan-Villasana et al. 2010b).

Due to the high incidence of problems of broken pipes in the steam generators, caused mainly by high temperatures in the different components of the boilers, the CFE requested the development of an analysis boiler simulator in order to be able to identify and predict potential failures.

This analysis tool is called boiler simulator with distributed parameters, and allows analysis of internal

phenomena such as heat transfer, flow paths and combustion products, by using the commercial package FLUENT (Galindo-García, et al. 2010, Vázquez-Barragan et al. 2010).

The aim of this simulator is to provide a set of initial conditions from where the boiler simulator with distributed parameters, may initiate an analysis simulation.

2. LUMPED PARAMETERS SIMULATOR

The boiler simulator with lumped parameters can simulate steady state conditions, change variables values, and simulate malfunctions. The objective is to operate the boiler in any condition to reach a point where the analysis simulator may be initiated. A lumped parameter approach with both, storage and resistive modules was used (Colonna and van Putten 2007).

The lumped parameters approach simplifies the description of the behaviour of spatially distributed physical systems into a topology consisting of discrete entities that approximate the behaviour of the distributed system under certain assumptions (basically, a point has the properties of a finite volume). From a Mathematical point of view, the simplification reduces the state space of the system to a finite number, and the partial differential equations of the continuous (infinite-dimensional) time and space model of the physical system into ordinary differential equations with a finite number of parameters

The simulator session is guided through a simulation console having the main functions explained in next section.

3. SIMULATOR INTERFACES

3.1. Simulation Scenarios Interface

The user may interact with the simulator through a graphic interface (Fig. 1) where some specific functions are available. The interface is designed to guide a simulation session (the hardware/software configuration has been described in the previous part of this paper). The main available functions are:



Figure 1: Simulation Scenarios Interface

Run/Freeze. The user may start or freeze a dynamic simulation test.

Simulation Speed. Normally, the simulator is executed in real time, but user may execute the simulator up to ten times faster or ten times slower than real time.

Initial Condition. The instructor may select an initial condition to begin the simulation session. It is possible to record new initial conditions (snapshots) or to erase old initial conditions, and to specify the time interval to get the automatic snap-shooting function (up to 500 of them).

Malfunctions. It is used to introduce/remove a simulated failure of equipments.

External Parameters. They allow the instructor to modify the external conditions like atmospheric pressure and temperature (dry and wet bulb).

Distributed Parameters Simulation. Switch the program to simulate the boiler furnace with the commercial tool FLUENT.

Development Tools. The simulator has a series of implements helpful especially during the development stages: simulate just one step (1/10s), monitor and change on line the value of selected global variables, and tabulate any list of variables.

In particular, the malfunctions are a very important part of the simulator. They are defined as abnormal events associated with equipment failures. The simulator includes failures, such as trip of forced circulation pumps; trip of the fans of induced draft; malfunctions of the coal mills; rupture of the waterwalls, superheater, reheater and economizer pipelines; fouling of regenerative air heaters; trip of the soot blowers, trip of the primary air fan; and trip of the induced draft fans.

3.2. Operation Interfaces

The user may interact with the simulated plant using the operator interface. They are graphic displays that reproduce real operation consoles in power plant control rooms. Figs. 2 and 3 present two examples of operation screens where the user interacts with the simulator by acting, for example, on pumps, valves and controls, and may verify the operative parameters.

4. GENERAL SIMULATOR MODELS

The lumped parameters approach was used for the models development. It simplifies the description of the behaviour of spatially distributed physical systems into a topology consisting of discrete entities that approximate the behaviour of the distributed system under certain assumptions (basically, a point has the

properties of a finite volume). Mathematically, the simplification reduces the state space of the system to a finite number, and the partial differential equations of the continuous (infinite-dimensional) time and space model of the physical system into ordinary differential equations with a finite number of parameters.

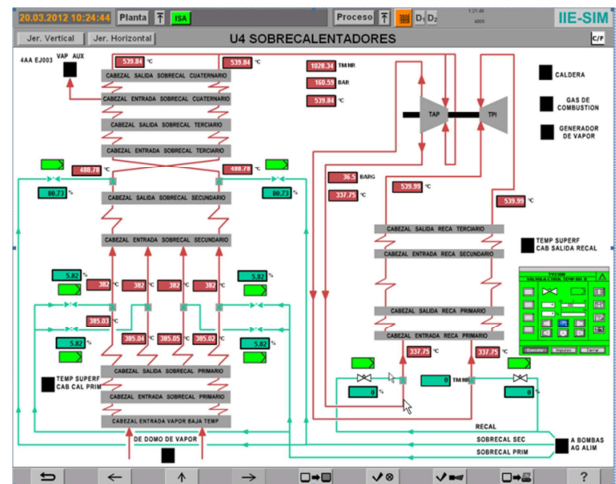


Figure 2: Superheaters

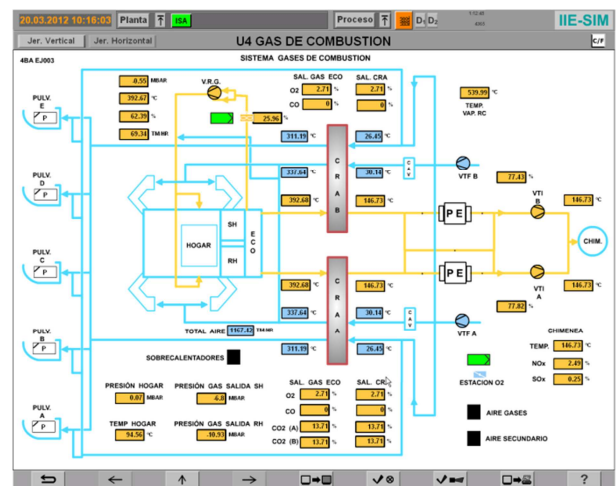


Figure 3: Gas Combustion System

The models were divided into three main parts: Simplified models; boiler part air and gases; and water and steam in the boiler.

The simplified models simulate the data required by the boiler using basic equations, but always accomplishing the first principles. These systems are: Fuel (Oil and Coal); Air and Combustion Gases; and Turbine and Auxiliary Steam.

Other systems such as lubrication oil, control oil

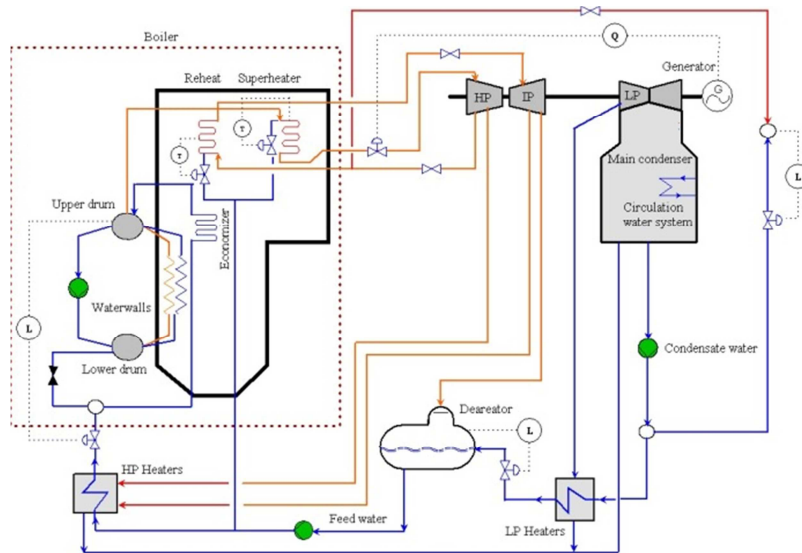


Figure 4: Simplified Diagram of the Simulated Systems

cooling water, air for instruments and electrical system are considered to always operate properly.

A basic diagram of the simulated plant is shown in Fig. 4. In this paper, the models of the boiler air and gases part and steam are presented. All others were explained by Roldan-Villasana et al. (2010a).

4.1. Causal Interaction of Models

For modelling purposes, the boiler has the boundary elements presented in Table 1. Fig. 5 is a schematic of the main interaction variables, where h is enthalpy, S is control signal, T is temperature, L is level, P is pressure, w is mass flowrate, c_i is fuel components, and q is heat.

Table 1. Interaction with other (simplified) models

Element	Frontier System
Economizer	Feed water
Deheaters (Super and Reheaters)	Feed water
Burners	Fuel System
Inlet Air Dampers	Combustion Air System
Fourth Superheater	High Pressure Turbine
Third Reheater	Intermediate Pressure Turbine
Boiler Waterwalls and Drum	Atmosphere
Boiler	Controls

5. GENERAL MODELLING

The momentum, mass and energy equations apply for all the simulated equipment and systems.

The mass balance is:

$$\frac{dm}{dt} = \sum w_i - \sum w_o \quad (1)$$

Sub-indices i and o are the properties at the inlet and output, respectively. No mass accumulation exists for incompressible flowrates (water and liquid fuel). All flowrates through a resistive element are calculated as:

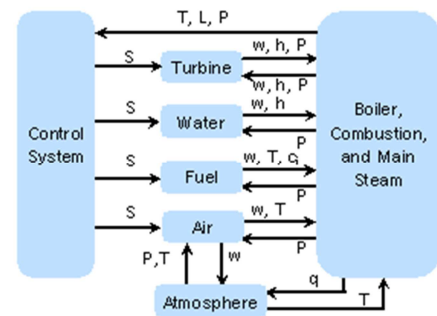


Figure 5: Boiler Main Variables Causal Diagram

$$w^2 = k A_p^\gamma \rho (\Delta P + \rho g \Delta z) \quad (2)$$

Where k is the friction coefficient, A_p the valve aperture (if this exist in the line), ρ is density, g the gravity acceleration and Δz the height difference between the inlet and the output, and γ is the valve characteristic.

For pumps and fans and any other rotate equipment, the flowrate is:

$$\Delta P = \frac{K_1 w^2}{\rho} + K_2 w \omega + K_3 \rho \omega^2 - \rho g \Delta z \quad (3)$$

There, ω is the speed and K_1 , K_2 , and K_3 are constants.

A proper energy equation is established depending of the particular equipment as summarised later.

All the model equations form a set of differential equations and a non-linear system of algebraic equations, both solved numerically. The differential equations are integrated with the Euler method with an integration step of 0.1 s. The algebraic equations are solved with a Newton-Rapson method with relaxation factor.

The thermodynamic and transport properties are calculated as a function of pressure and enthalpy. The data source was the steam tables by Arnold (1967). The functions were adjusted by least square method. The

application range of the functions is between 0.1 *psia* and 4520 *psia* for pressure, and -10 °C and 720 °C (equivalent to 0.18 *BTU/lb* and 1635 *BTU/lb* of enthalpy). The adjustment was performed to assure a maximum error of 1% respecting the reference data; to achieve this it was necessary to divide the region into 14 pressure zones. The functions are applied to three different cases: subcooled liquid saturated and superheated steam.

6. SIMPLIFIED MODELS AND CONTROLS

6.1. Simplified Models (Boundaries)

These are models that simulate the input data required by the boiler. The approach is to state simple equations, but following first principles.

The fuel (oil and coal) system supplies any type of fuel. It is ready to go into operation when required. The fuel flow is calculated depending on the demand of the control. The boiler has four burner elevations for both, fuel and carbon, and the flowrate depends on the number of elevations in operation. The fuel properties are considered constant.

The air system serves to provide air for the combustion in the furnace. No heaters are modelled, thus, the air temperature is a function of the main steam flowrate with an empirical equation.

Turbine is driven by the steam generated in the boiler and it is directly connected to the electrical generator for power generation. The high pressure and low pressure turbines were simulated in a simplified way. The output conditions of the turbines are obtained by calculating the enthalpy at isentropic conditions and correcting it considering a constant efficiency.

The auxiliary steam is a system that provides steam to the turbine seals to prevent entry of air or steam leak in the cylinder of the turbine.

6.2. Controls

A full distributed control system is not necessary for this simulator. All control models are simplified in both parts analogical and logical.

PI controls were considered. They include the derivations of superheater and reheater steam, superheater and reheater temperatures (deheat water), fuel demand, excess air for combustion, and gas recirculation. The signal control is, where K_p is proportional constant, ε error, and τ integral time constant:

$$S = K_p \varepsilon + \frac{1}{\tau} \int d\varepsilon \quad (4)$$

As a simplification, the fuel and excess air set points were considered to be a function of the generated electric power.

The logical control was simplified, the start/stop sequence of burners, for example, does not check for the pilot ignition or if the fuel valve is open. A perfect behaviour was assumed for the simplified systems.

7. BOILER STEAM MODEL

The steam produced by the waterwalls flows through the superheater, the high pressure turbine, and then to the reheater and the intermediate and low pressure turbines to be discharged into the condenser.

Both, the superheater and the reheater are finned tubes taking heat from the combustion gases to be transformed in mechanical energy in the turbines to produce electricity.

Small nodes (for example, nodes where the feed-water deheat flow discharges) are considered resistive and their pressure is calculated with the equations set produced by (1) to (3). Their energy balance is:

$$\frac{dh}{dt} = \frac{\sum w_i (h_i - h) + q_m}{m} \quad (5)$$

Where the mass m is considered constant in these cases and just represents the inertia of the node. Heat q_m is transferred from the pipeline metal (subindex m) that depends on physical and operative conditions and metal temperature:

$$\frac{dT_m}{dt} = \frac{\sum q}{(m_m C_{p_m})} \quad (6)$$

Being C_p the heat capacity and the heat sum the difference between the heat flow from the furnace and to the fluid.

For big nodes (like headers) two state equations are established for the enthalpy and pressure. Different equations apply according the state of the fluid (Roldan-Villasana, E and Verduzco Bravo, A, 2009).

For saturated conditions, the equations applied on a volume V are:

$$\frac{dh}{dt} = \frac{I}{\left(\frac{\partial \rho}{\partial P}\right)_h \rho + \left(\frac{\partial \rho}{\partial h}\right)_p} \left\{ \frac{\left(\frac{\partial \rho}{\partial P}\right)_h \left[\sum (wh)_i - \sum (wh)_o - \sum q \right]}{V} + \left[1 - \left(\frac{\partial \rho}{\partial P}\right)_h h \right] \frac{d\rho}{dt} \right\} \quad (7)$$

$$\frac{dP}{dt} = \frac{I}{\left[\frac{\partial \rho}{\partial P}\right]_h} \left(\frac{d\rho}{dt} \left[\frac{\partial \rho}{\partial h} \right]_p \frac{dh}{dt} \right) \quad (8)$$

For saturated steam:

$$\frac{dh}{dt} = \frac{dP}{dt} \left\{ \left[x \left(\frac{dh_g}{dP} \right) + (1-x) \left(\frac{dh_f}{dP} \right) \right] + \left[\frac{(h_g - h_f)}{(v_g - v_f)} \left[\frac{x}{\rho_g^2} \left(\frac{d\rho_g}{dP} \right) + \frac{(1-x)}{\rho_f^2} \frac{d\rho_f}{dP} \right] \right] \right\} + \frac{(h_g - h_f)}{(v_g - v_f)} \left[\frac{1}{\rho} \left(\frac{\sum w_i - \sum w_o}{V} \right) \right] \quad (9)$$

$$\frac{dP}{dt} = \rho \frac{dh}{dt} + \left[\frac{\sum w_i (\sum h_o - \sum h_i) - \sum q}{V} \right] \quad (10)$$

Here, the subindexes f and g represent condition of saturated gas and saturated liquid, respectively and x is the vapour quality.

8. FURNACE

The model simulates the combustion in the furnace and calculates the heat transfer from the flue gas to the economizer, superheater, reheater, waterwalls, regenerative air heaters and electrostatic precipitators. The preheated air from the air/steam heater and the Ljunström regenerative heater is mixed with the fuel and recycled gas in the furnace. After the combustion, a fan located at the exit of the boiler, induce the flow of gases to the chimney.

In summary, the model is based on the solution of the combustion stoichiometric equation considering as reactive agents C, H₂, O₂, H₂O, S, N₂, CO₂, CO, and SO₂. The products depend on the molar flow of air and fuel and the composition of the fuel. Molar flow for each combustion agent considers the contribution flow of fuel or carbon, air to burners, air to pilots, atomization air, steam on breakage of tubes from waterfalls, steam soot blowers, and recirculated gas.

There is not taken into account the kinetics of combustion; it is considered a perfect mixing in the furnace, and it is stated that the combustion gases follow the ideal gases law. A chemical balance is obtained to calculate the excess air in the furnace.

The emission of carbon monoxide in the combustion depends on excess air: more excess air, lower amount of CO and vice versa. CO emissions also depend on the flow regime, i.e. less turbulence decreases efficiency of mixing and CO emissions increase due inefficient combustion.

The flame temperature, as a function of the formation enthalpies, is used as the basis for calculating the heat transfer in each area of the gas path, from the furnace up to the exhaust.

The furnace (fu) conditions are obtained with two equations for the derivatives of the state variables (pressure P and temperature T):

$$\frac{dP_{fu}}{dt} = RT_{fu} \frac{d\rho_{fu}}{dt} + R\rho_{fu} \frac{dT_{fu}}{dt} \quad (11)$$

$$\Sigma(w h)_i - \Sigma(w h)_o + \Sigma q = V_{fu} \left(\rho_{fu} C_{p_{fu}} \frac{dT_{fu}}{dt} + h_{fu} \frac{d\rho_{fu}}{dt} - \frac{dP_{fu}}{dt} \right) \quad (12)$$

Where R is the gas ideal constant, V is the volume, C_p is the heat capacity, and q is the heat flow.

Note that density is not a state variable and its derivative is used only as a value for the solution of (11) and (12). The sum of the heat flow refers to heat transferred by radiation and convection to the waterwalls.

After the furnace, the combustion gases heat other fluids and metals in the steam generator: upper sections of the waterwalls, superheater, reheater, economizer, regenerative air heaters and electrostatic precipitators.

If along the path of the gases a series of control volumes are established (each occupied by a specific heat transfer equipment), assuming that there is not accumulation of gases at any point in his path, with a balance of energy may be calculated the outlet temperature of each control volume. In all cases, heat transfer coefficients were calculated with the help of correlations found in the literature.

The heat transfer along the circuit water/steam considers the thermal resistance of the metals.

9. TESTS AND RESULTS

9.1. Proposed Test

One test was proposed to be presented in this paper in order to the general scope of the models. However, during the acceptance tests, the simulator was probed in all the normal operation range, from 25% to full charge, including the response under malfunctions and abnormal operation procedures. The simulator variables were compared with the plant data at every steady state (25%, 50%, 75%, and 100% of load). In all cases the response satisfied the existing ISA S77.20 (1993).

The starting point for this test was the full load condition (350 MW). The oil fuel consumption is 21.3 kg seg⁻¹ and the produced steam is 285 kg seg⁻¹. The user made no actions on the simulator during the test. In Figs. 6 and 7 the response of some variables is presented.

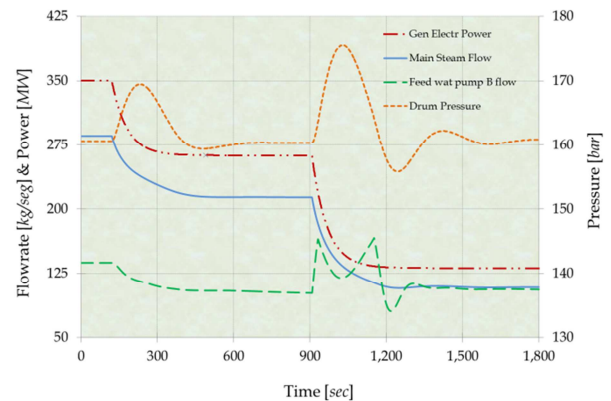


Figure 6: Flowrates, Electrical Power and Pressure

After 120 s of steady state, the user, by means of the proper control, ask to download the load to 75%. The system is stabilised by the control approximately at 500 s and then at 900 s, a feedwater pump is trip.

9.2. Graph Results

During the first part of the test, the electrical power (Fig. 6) is gradually changed from 100 % to 75% during 260 s approximately. As a response of the turbine admission valves, the main steam flow descends continuously.

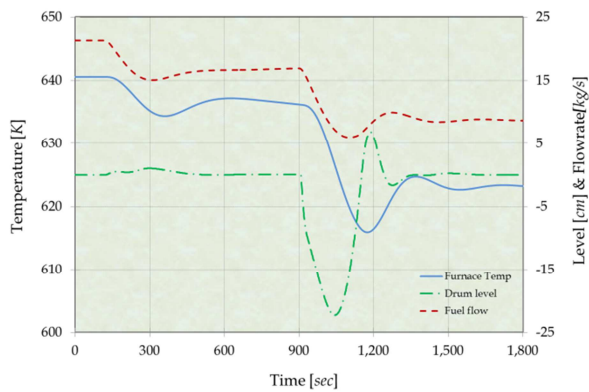


Figure 7: Temperature, Level and Flowrate

The feedwater flow also descends following the drum level control (the level remains practically stable).

The change in the electrical load origins a notorious response in the drum pressure caused by reduction in the consumption of steam.

The fuel flowrate goes down trying to control the changing electrical power. Due the control parameters, when the charge finally stabilises, the fuel flowrate presents a small oscillation. The furnace temperature, as expected, moves practically with the same tendency that the fuel flowrate.

Once the transient is controlled, the pressure returns to its initial value. At 600 s the plant is stable at 75% of electrical load.

For the second part, at 900 s, one of the feedwater pumps is trip. This action is detected by the control and a runback is activated (the charge demand is automatically set at 50%). The electrical power descends smoothly.

The main steam flow declines its value gradually following the aperture of the turbine valves that partially close due the runback.

Initially, the feedwater pump B flow increases its flow when the pump A is trip (they are connected in parallel). Then, the flowrate changes according the control valve aperture trying to stabilize the drum level that presents, as expected, the stronger response (note that the total feedwater flow decreases during the transient).

The drum pressure initially increases its value due the diminution of the main steam flowrate and then it is affected by the changes in the feedwater flowrate and the temperature in the furnace.

Again, the fuel flow is adjusted according the value of the electrical load, and a mild oscillation is presented. The furnace temperature follows the fuel flowrate but a delay may be appreciated mainly due to the thermal inertia of the boiler.

At 1500 s approximately, the plant is stable again in its new state (50%).

10. CONCLUSION

The presented boiler simulator is a replica, high-fidelity, plant specific simulator. Realism is provided by the use of detailed modelling. The lumped parameter approach is adequate for the purposes of the simulation that was tested and validated by the client according plant data and international norms. The tests that were followed to validate the modes were performed in the defined operation range of the plant and were successful. This makes the simulator a reliable tool for analysis purposes.

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