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Boiler model and simulation for control design and validation

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Abstract: A plant validated boiler simulator is a very useful tool for controls design, analysis and performing experiments because of the cost involved in doing experiments on a real boiler or even lab-boiler. This paper presents the dynamic model simulator of a typical power-plant boiler derived based on the first principles and a hybrid approach of suitably combining lumped and distributed modeling approach for the relevant subsystems. The developed model simulator is validated using an actual plant-data covering the dynamic plant startup scenario. The plant-data of steam flow-rate, feed-water flow-rate, feed water temperature, and heat input defines the boundary condition of the plant startup, and the model-simulated response of the drum-level and pressure are compared with the actual plant-data of boiler drum-level and pressure. The validation results are very encouraging considering the challenges posed by complex behavior and uncertainties in the actual power-plant boiler-drum, and the measurement inaccuracies in the industrial plant conditions.

Keywords. Simulation, Boilers, Steam generators.

1. INTRODUCTION

Power plant boiler is complex industrial equipment considering the nonlinear, phase-change and inverse-response (swell & shrink) behaviour and poses a significant modelling and simulation challenge. Hence, it has been of interest to academic as well as industrial researchers for a long time. A significant work on the boiler modelling is done in the past including validation with some reference plant.

One of the most-cited papers is a simple non-linear model developed by Astrom and Bell, 1988. The Astrom-Bell model is derived from the first principles, and is characterised by easily available boiler construction/ geometric data. This model uses three-states defined by pressure, water volume in drum and an average steam-quality in a riser. This model captures the dynamic swell and shrink phenomenon on the boiler with respect to the steam transients. As this model assumes only two-phase in the riser tube, the inverse behaviour on the feed water transient is not fully captured. They assume a linear curve fit for the steam-to-water distribution in the riser. The step tests on power, feed-water flow-rate and steam flow-rate are conducted. The advantage of this model is its simplicity to use and reasonable (moderate) accuracy which is suitable for the purpose of operational control study. However, this model has a significant poor performance if used to simulate dynamic operating scenario, such as, the plant start-up.

Adam and Marchetti, 1999, explored the dynamic simulation of water-in-tube boilers. The simulation results of their model are also compared with the experimental data from a 30 MW thermo-electric power plant. Their model is developed using an algorithm utilizing two non-linear models: one for the evaporation in the vertical tubes and another for the phase-separation in the steam drum. They have also incorporated a closed-loop PI controller for the feed-water flow rate. Whereas, the drum-pressure control loop is simulated as an open-loop. The results of their numerical simulation are given for the most important variables: drum-level, drum-pressure, total-mass, total-enthalpy, and feed-water flow-rate. The simulation results for these variables are compared with the plant-data for two different operational cases: *first*, a positive change in the steam-demand; and *second,* a positive change in the heat-input to evaporator vertical tubes. Their results match well with the actual 30MW plant-data for both these operational cases.

Astrom and Bell, 2000, again developed a nonlinear dynamic model for natural circulation drum-boilers. This model, derived from the first principles and physical parameters; is an extension of their previous model describing the dynamics of the drum, down-comer, and riser components. This model involves four state-variables: *two* of them accounts for the storage of energy and mass; *third* one represents the steam distribution in the risers; and the *fourth* state represents the steam distribution in the boiler-drum. The data of their simulation results are compared with the actual plant-data. The trend plots are then generated to demonstrate the correlation resulted from the model to the plant data. A strong correlation was proven for both medium and high loads while changing the fuel flow rate, feed water flow rate, and steam valve for both of the loads.

H Kim and Chori, 2005, improvised on the work of Astrom and Bell, 1999, to develop another boiler-drum model. In their work, a correlation for mass-flow from water-to-steam surface is used based on the drift-flux velocity correlation. Vijay Chatoorgoon, 1986, provides a detailed code, namely 'SPORTS' and used by Canadian Atomic Energy, that can be used for the stability studies in a natural-circulation loops of a boiler-drum. They also provide the model formulation and suitable solution method. A detailed analysis of two phase modelling and stability were compared by Nayak and Vijayan, 2008. They provide a detailed review of various instabilities in two-phase natural circulation, explain the mathematical formulization of these stability constraints, and also explain the state-of-art research space in this subject.

In this paper, we present our hybrid modelling approach based on – (a) the lumped-modelling for the boiler-drum sub-system, and (b) the distributed-transient-modelling for the downcomer-evaporator-riser recirculation sub-system. In fact, Adams and Marchetti, 1999, also use similar hybrid approach of combining a lumped dynamic model for the boiler-drum, and a steady-state model for the downcomer-evaporator-riser re-circulation loop. However, in our approach, the steady-state recirculation loop model of Adam and Marchetti, 1999, is modified by using the transient-two-phase-stability code approach of Vijay Chatoorgoon, 1986.

Thus, in this paper, a boiler model is derived by suitable combination of approaches used by the above referred papers. Main aim of our modelling approach is to improve the model-response mainly during the dynamic operating scenario, such as, during the plant start-up. Our proposed model is simulated in MATLAB, and this simulator is tuned to match with the plant-data for the boiler hot-start scenario, which covers significantly large dynamic operational scenario. Next, our proposed model is described in Section-2. The simulation response, plant-data and the validation results are presented in Section-3. Whereas, Section-4 covers the concluding remarks.

2. BOILER MODEL STRUCTURE

Model structure is as shown in figure 1. It consists of a one dimensional downcomer-riser circulation loop with a lumped drum model. The lumped drum-model is developed based on the concepts of Astrom and Bell, 1999 and Adams and Marchetti, 1999. The riser model uses the equations of 'SPORTS' code and the solution methods given by Chatoorgoon, 1986. Lumped drum model uses three states where as the riser model uses four states at each node. Mud drum or down header is formulated with simple algebraic equations.

2.1 Lumped Drum model

Lumped drum model is as shown in figure 2. The dynamics of macroscopic outputs like pressure and level are important from a control engineer's view point. Inputs and outputs of drum model are two phase flow from riser, single phase liquid flow to down comer , saturated steam flow from drum and single phase liquid flow to drum from feed water. Drum volume, mean area or volume versus length curves are known quantities which can be used for calculations. Lumped bubble volume represents the steam inside water. Appendix A shows the variables, inputs and states used in the equations.

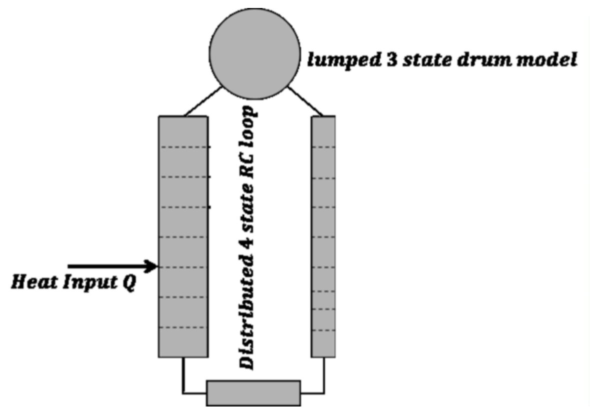

Fig. 1. Boiler model schematic

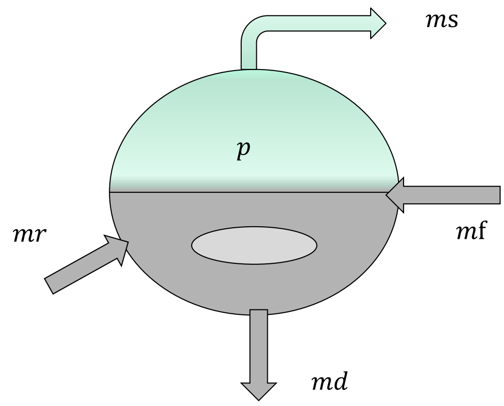

Fig.2.Lumped drum model

Applying the global mass balance, we can derive the following equations. V_s is chosen as a dependent variable.

$$V_s = V_d - V_l - V_b$$

$$\frac{d(V_l * \rho_l + V_s * \rho_s + V_b * \rho_b)}{dt} = m_f + m_r - m_s - m_d \quad (1)$$

Substituting V_s in terms of V_d, V_l and V_b and rewriting all steam property time-derivatives to the product of pressure time-derivative and steam- property pressure-derivative. We can simplify above equation and re write as shown below. Another assumption is that the density of bubble and density of steam are same.

$$\frac{dp}{dt}(V_l \frac{d\rho_l}{dp} + V_d \frac{d\rho_s}{dp} + V_l \frac{d\rho_s}{dp}) + \frac{dV_l}{dt}(\rho_l - \rho_s) + \frac{dVb}{dt}\rho_l$$

$$= m_f + m_r - m_s - m_d \quad (2)$$

Applying local mass balance on liquid phase following equation can be written.

$$\frac{d(V_l*\rho_l+V_b*\rho_b)}{dt}=m_f+m_r-m_d-m_b \tag{3}$$

Simplifying,

$$\frac{dp}{dt}(V_l\frac{d\rho_l}{dp}+V_b\frac{d\rho_s}{dp})+\frac{dV_l}{dt}\rho_s+\frac{dV_b}{dt}\rho_b$$
$$=m_f+m_r-m_d-m_b \tag{4}$$

Where, 'm_b' is the net mass transfer between liquid and vapour phase. We can use correlation to compute vapour velocities inside liquid and thereby calculate m_b. But, for this work we computed a mass balance on steam vapour side and computed one step behind value.

Applying global energy balance on drum, we can derive the following equation,

$$\frac{d(V_l*\rho_l*h_l+V_b*\rho_b*h_b+V_s*\rho_s*h_s)}{dt}$$

$$=m_fh_f+m_rh_r-m_sh_s-m_dh_d-M_d*C_p*\frac{dT}{dt} \tag{5}$$

Simplifying we can re write as below,

$$\frac{dp}{dt}(V_lh_l\frac{d\rho_l}{dp}+V_l\rho_l\frac{d\rho_s}{dp}+V_dh_s\frac{d\rho_s}{dp}-V_dh_s\frac{d\rho_s}{dp}$$
$$-V_l\rho_s\frac{d\rho_s}{dp})+\frac{dV_l}{dt}(\rho_lh_l-\rho_sh_s)$$
$$=m_fh_f+m_rh_r-m_sh_s-m_dh_d-M_d*C_p*\frac{dT}{dt} \tag{6}$$

For drum, we have three states (p, V_b, V_l) and three equations. The drum-level can be derived as a function of liquid volume and a bubble volume.

2.2 Distributed recirculation loop model

'SPORTS' code developed by Chatoorgoon, 1986, for the study of thermo hydraulic flow stability was used to solve the natural circulation loop consisting of downcomer and riser. The formulation of the 'SPORTS' code captures complex physics of two-phase fluid-flow with a simplified solution algorithm. The equations can be classified as 4-equation homogenous thermal equilibrium class. Basic governing equations – mass-balance, energy-balance and momentum balance are given by

$$\frac{d\rho}{dt}=-\frac{d(\rho*u)}{dz} \tag{7}$$

$$\hat{q}+\frac{d\rho}{dt}=\frac{d(\rho*h)}{dz}+\frac{d(\rho*h)}{dz}+\rho*u*g$$
$$+\rho mCp\frac{dT}{dt} \tag{8}$$

$$\frac{d\rho u}{dt}=-(\frac{d(\rho*u^2)}{dz}+\frac{d(p)}{dz}+\rho*g+C_k\rho u^2) \tag{9}$$

There are four unknowns and three equations. Hence, the steam-table is used to find the fourth state. This method uses four-equation approach to solve two-phase problems. Above equations can be discretized and solved by using simple backward-differentiation method. A detailed approach with an example is given in his paper to solve thermo-syphoning loop with a definition for stability with discretization. Appendix-A shows the variables and some details.

2.3 Solution method

For a evaporator-downcomer model, the step model solves a boundary value problem every time. The steady-state solutions of the model can be achieved using a large time step in the equations. First, the drum-model is initialized using the initial conditions. Then the steady-state solution is obtained using the initialized pressure and initial heat-input. These act as the initial conditions for each node, and thereby complete the model initialization. Once initial conditions are obtained, transients are solved as follows:

- Solve drum model
- Solve recirculation model to match current boundary values

The solution for the recirculation-loop is iterative in nature. It converges till the boundary conditions are satisfied. The flow-chart of this iterative algorithm used to simulate the recirculation-loop model is shown in Figure 3.

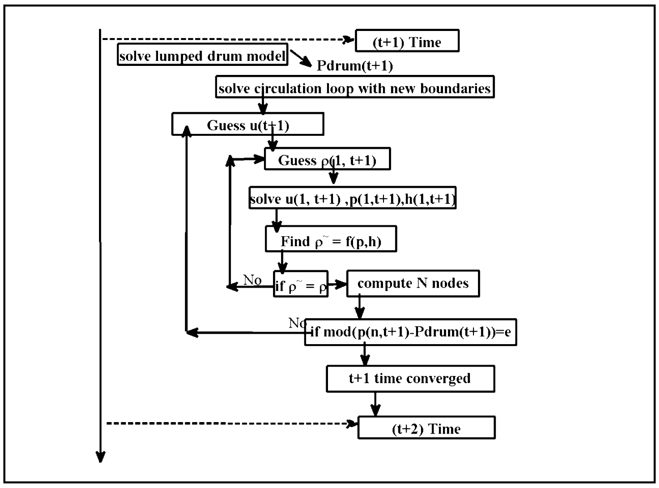

Fig.3 Simulation Execution flow diagram

3. SIMULATION AND VALIDATION

The boiler simulation is performed to validate the response of the macroscopic variables like pressure and level, which are of specific interests for controls and operability study. The hot start-up data of a heat-recovery boiler from the actual combined-cycle power plant is used to tune and validate our model. The boiler-model parameters are first characterized and sized with the actual HRSG boiler, whereas the actual plant-data is used as an input to provide time-varying boundary-data for the model. The simulation results for the drum-pressure and drum-level are then validated by comparing the same variables obtained in the plant-data.

3.1 Field data and model parameterization

The main geometric parameters of our boiler-model simulator are configuration to match with the actual power-plant boiler by calculating drum-volume, down-comer volume, riser-volume and metal-mass of both drum and riser from the equipment drawings. The non-linear look-up table characterizing the drum-volume to drum-level is incorporated using the equipment drawing and is incorporated in our drum-model simulator to calculate drum-level from the total liquid volume (V_l + V_b). The model is matched with the steady-state heat and material balance at the base-load (i.e. 100% load) operating point by appropriately tuning certain parameters in our model-simulator e.g. heat-transfer coefficient and the friction-factor to match recirculation ratio.

The hot start-up data of boiler from an actual, large combined cycle power plant is used to validate the model. Input variables like heat input, steam flow-rate, feed-water flow-rate and feed-water temperature are collected with respect to time at a sampling rate of 1-second. Since steam flow-rate measurement is usually accurate after 30-40% of the rated steam flow-rate value, the plant-data corresponding to the steam flow-rate from 50% to 100% of the rated steam flow-rate are used for the validation. Figure 4 shows one hour of start-up plant-data collected and used as a time-series boundary in our model simulation study. Figure 5 shows the drum-level and drum-pressure response obtained in the plant-data, which was used to compare and validate the model simulation results. The data showed in this paper is normalized with the maximum continuous rating (MCR) of the equipment and the plant.

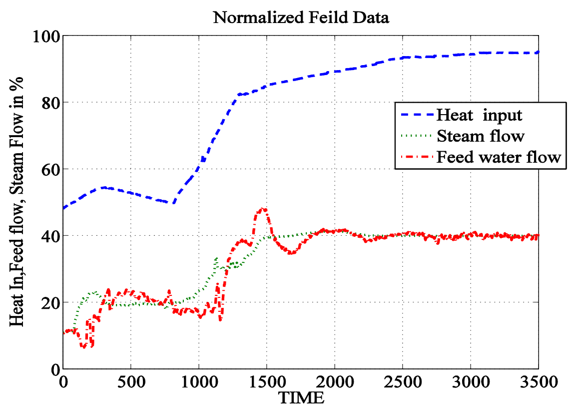

Fig 4 Input boundaries for model from field data

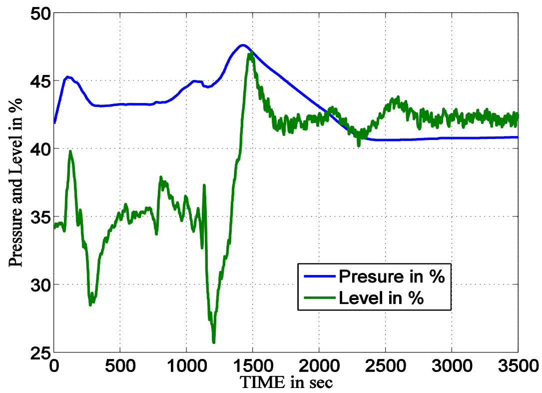

Fig 5. Pressure and level from actual plant- data.

3.3 Simulation results

Figure 6 below shows the comparison between our model-simulation results and the actual plant-data for drum-level and drum-pressure.

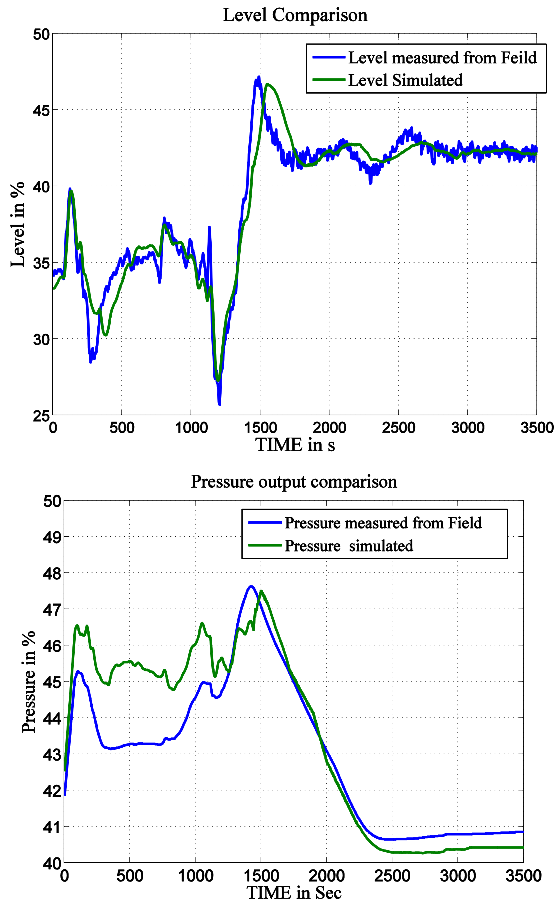

Fig 6 Level and Pressure comparison – simulated versus plant-data

4. CONCLUSIONS

This paper presents our preliminary work on development of a new boiler drum model that can work well across a wide dynamic operation regime, development of model-simulator and validation of simulation results with the actual plant-data. The results are found promising. The boiler-model is developed using a hybrid approach of logically combining different modelling approaches available in published literature. A MATLAB based boiler-model simulator is developed which is configured for a specific real-life combined cycle power plant boiler. Diligent efforts are made to collect the actual plant-data, carry out appropriate pre-processing to screen suitable data. The simulation results are then validated with the actual plant-data covering a wide range dynamic operation i.e. hot start-up. In future, we plan to extend this model by modifying underlying heat-transfer model, leveraging distributed evaporator model. The aim is to obtain even better match with the actual plant-data, and to enable it to cater to even wider-range dynamic operation e.g. cold-start-up.

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Appendix A. List of Variables

Variable	Description
V_d	Drum volume
V_s	Steam volume
V_b	Bubble volume
V_l	Liquid Volume
m_s	Steam flow
m_f	Feed water flow
m_d	Downcomer flow
m_r	Riser flow
p	Drum Pressure
u	Velocity
ρ_l	Liquid density
ρ_s	Steam density
ρ_b	Bubble density
h_l	Liquid Enthalpy
h_s	Steam Enthalpy
h_r	Riser Enthalpy (two phase)
dz	Discrete node length
g	Acceleration due to gravity
M_d	Drum metal mass
C_p	Specific heat capacity
C_k	Friction factor
M_r	Riser metal mass