Model Identification for Industrial Coal Fired Boiler Based on Linear Parameter Varying Method

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ABSTRACT: **System or process identification is a mathematical modeling of systems (processes) from test or experimental data. Process models obtained from identification process can be used for process simulation, analysis, design of safety systems and control systems for the process. This paper presents the Linear Parameter Varying (LPV) modeling of 210MW Industrial Coal Fired Boiler which is commonly used in thermal power plants. LPV model is the interpolation of linear transfer function models at different operating conditions. The LPV model is adopted by considering the fact that the Industrial Coal Fired Boiler in the thermal power plant has several operating conditions due to the fluctuations in steam flow based on demands. By assuming that at every operating condition, there are changes in parameters, the LPV model is suitable for covering all operating conditions. The Industrial Coal Fired Boiler is modeled using the mass and energy balance equation in MATLAB / SIMULINK. Data needed for identification of transfer function models is taken from first principle model of the process with sampling time of 1 second. LPV model is obtained for selected physical quantities of the process. At first, linear transfer function models are identified using the data at every operation conditions using Prediction error method and then the Linear Parameter Varying model is obtained by interpolating the linear models of different operating conditions using weighting functions. The simulation result of Linear Parameter Varying model shows reasonable fit with the First principle model response.**

Keywords- 210MW Coal Fired Boiler, modeling equations, Linear Parameter Varying Model, Model Performance.

I. INTRODUCTION

Modeling the dynamical characteristics of a process is an important step to understand the process behaviour in a better way. Most of the industrial processes are nonlinear in nature. Industrial process are modeled using Nonlinear models that can only represent a limited class of nonlinearities and their identification is complicated when compared to the Linear Time Invariant (LTI) case. Most of the existing works on process simulation is based on Linear Time Invariant (LTI) models, which is satisfactory for a number of systems. However, system identification based on LTI model appears to be of limited value when the plant operating conditions varies significantly. One of the effective methods to handle varying operating conditions in the plant is to describe such systems using LPV model. It is desired that the identified LPV model is able to represent the non-linear process behavior during the transition between the operating regions. LPV Model is the interpolation of linear models using weighing functions. The advantages of using LPV models are simple to identify, accurate tracking of process dynamics along the operating trajectory,less time consumption and suitable for both continuous and batch processes[1].

Thermal power plant is one of the power plants used for the production of electricity where Coal Fired Boiler (CFB) plays a major role in the generation of steam. A well designed control system and trained operators are essential for reliable, safe and efficient operation of the plant. Simulators play an important role in achieving these objectives. Hence simulation of boiler helps to understand its behaviour under both steady and transient operations. Astrom and Bell [2] presented a model for simulation of natural circulation boiler. Modeling is carried out for both steady state and dynamic conditions of boiler. When there are changes in boiler operating condition based on load variations, it is difficult to identify the process under different operating conditions. One of the effective methods to handle varying operating conditions in the plant is to employ LPV model.

In order to extend the validity of linear models over a wide range of operating conditions, the concept of LPV model appears to be very attractive [3]. The terminology of LPV was first introduced for the study of gain scheduling control [4]. The work on LPV model identification for stall and surge control for compressors of jet engines is discussed [5]. Linear Parameter Varying model is nothing but the interpolation of linear models, which is well explained [6,7,8]. LPV modeling based on first principle modeling is reported for SISO CSTR and MIMO polymerization [9]. The LPV modeling using subspace state space identification technique was adopted in [10, 11].

This work focuses on LPV model identification of CFB boiler using limited process parameters employed in Thermal power plant which is useful in designing a control system. In section 2, the LPV model identification method for MISO system is outlined. In section 3, development of mathematical model for CFB using mass and energy balance equations is discussed. In section 4, LPV model identification for Industrial boiler is carried out. Section 5, is the conclusion.

II. LINEAR PARAMETER VARYING MODEL IDENTIFICATION METHOD

The LPV modeling adopted in this work is described briefly for a multi-input single-output (MISO) process. Let y(t) represent the process output at discrete time t, , u(t) the input vector at time t and w(t), the working-point variable (scheduling variable) which determines the working point of the process operation. It is a measured variable from the process or can be calculated from measurable process variables, it can be an input, output, or independent variable. Examples of working point variables are: load of a power plant (independent variable), air feed rate of an air separation process (input variable) and product viscosity of a lubricant oil unit (output variable) where

$$w(t) \in [w_l, w_h]$$

w_l and w_h are the low and high limits of w(t) which projects the operating trajectory of the process. The identification tests are performed by adding small test signals during normal operation of the process. The test signal amplitudes are determined in such a way that they will not cause any problem in safe operation. Each linear model is identified using the data at each working point. Several linear identification methods can be used, such as prediction error method, subspace method and asymptotic method. Assume that the process has p working points and the linear models are denoted as follows:

$$\begin{aligned}
y^1(t) &= G_1^1(q)u_1(t) + \ldots\ldots\ldots\ldots\ldots + G_m^1(q)u_m(t) && w(t) = w_1 \\
y^2(t) &= G_1^2(q)u_1(t) + \ldots\ldots\ldots\ldots\ldots + G_m^2(q)u_m(t) && w(t) = w_2 \\
&. \\
&. \\
&. \\
y^p(t) &= G_1^p(q)u_1(t) + \ldots\ldots\ldots\ldots\ldots + G_m^p(q)u_m(t) && w(t) = w_p
\end{aligned} \tag{1}$$

Where G is the linear transfer function, q^{-1} is the unit delay operator, m is the number of inputs and p represents number of operating conditions along operating trajectories. Then the LPV model is obtained by interpolating the linear models using total data as follows

$$y(t) = \alpha_1(w)y^1(t) + \alpha_2(w)y^2(t) + \ldots\ldots\ldots\ldots\ldots + \alpha_p(w)y^p(t) \tag{2}$$

Where $\alpha_1(w)$, $\alpha_2(w)$ and $\alpha_p(w)$ are weights which are functions of the working point variable w(t). These weights can be determined using triangular weighing function which is pre-assigned and needs no estimation.

The LPV model using triangular weighing function for three operating regions [11] is denoted as follows

$$y(t) = \begin{cases} y^1(t) & w(t) \le w_1 \\ \dfrac{w_2 - w(t)}{w_2 - w_1} y^1(t) + \dfrac{w(t) - w_1}{w_2 - w_1} y^2(t) & w_1 < w(t) \le w_2 \\ \dfrac{w_3 - w(t)}{w_3 - w_2} y^2(t) + \dfrac{w(t) - w_2}{w_3 - w_2} y^3(t) & w_2 < w(t) < w_3 \\ y^3(t) & w_3 \le w(t) \end{cases} \tag{3}$$

III. MODELING EQUATIONS FOR INDUSTRIAL COAL FIRED BOILER

The plant data used for simulation were taken from a thermal power station whose boiler is a natural circulation, single drum with titling tangential burners. The gross output of the unit is 210MW with a steam flow rate of 690×10^{3} kg/hr and steam temperature of 540°C. The boiler process is considered as an integrated form which consists of five subsystems. They are (i) Boiler Furnace (ii) Boiler drum (iii) Primary super heater (iv)Attemperator and (v) Secondary super heater. The mathematical model for 210MW CFB is developed for each subsystem using mass balance and energy balance equations [2], as described below. Then the subsystem models are linked to obtain an integrated model. The assumptions made are:

- A lumped parameter approach is used in modeling the system
- Heat transfer coefficients are determined from steady state operating conditions.

A. Boiler Furnace

The behaviour of the boiler furnace can be captured by the following mass and energy balance equations:

The mass balance for combustion is given by

Rate of change of furnace gas flow = Fuel flow +Air flow + Recirculation gas flow - Gas flow through boiler.

This equation is represented mathematically in (4) as

$$V_{bf}\frac{d\rho_{eg}}{dt}=F_f+F_a+F_r-F_{eg} \tag{4}$$

The energy balance for combustion is given by

Rate of change of energy of hot gas =Energy from fuel input + Energy from air input + Energy from recirculation gas – Heat energy transferred to riser – Heat energy transferred to SSH – Heat energy carried by gas. And is described by the differential equation (5)

$$V_{bf}\frac{dh_{eg}\rho_{eg}}{dt}=C_f\,F_f+h_aF_a+h_rF_r-q_r-q_s-F_{eg}\varepsilon(1+\frac{e_x}{100})h_{eg} \tag{5}$$

B. Boiler Drum

The behaviour of the boiler drum can be captured by the following mass and energy balance equations:

Rate of change of mass of steam and water in the drum = Feed water flow to the system – Steam flow from the drum.

It is described by the differential equation (6)

$$\frac{d}{dt}\left[\left(V_d-V_{dw}\right)\rho_d+V_{dw}\rho_{dw}\right]=F_{ew}-F_d \tag{6}$$

Rate of change of energy of steam and water in the drum = Total energy of steam and water mixture after leaving the water walls - Energy of drum water - Energy of drum steam and described by the differential equation (7)

$$\frac{d}{dt}\left[\left(V_d-V_{dw}\right)\rho_d h_d+V_{dw}\rho_{ew}h_{dw}\right]=F_Dh_w-\left(F_Dh_w-\left(F_D-F_{ew}\right)h_{dw}-F_Dh_d\right) \tag{7}$$

The temperature of steam and water in the drum are assumed to be equal to the saturation temperature T_d corresponding to the drum pressure P_d

The differential equations(8,9) are obtained as follows:

$$\frac{d\rho_d}{dt}=\frac{1}{q_2q_4\rho_{dw}}\left\{\rho_dF_{ew}-\rho_{dw}F_d+X_qF_D\left(\rho_{dw}-\rho_d\right)\right\} \tag{8}$$

$$\frac{dV_{dw}}{dt}=\frac{1}{q_4\rho_{dw}}\left\{\left(1+q_3\right)F_{ew}-q_3F_d-X_qF_D\right\} \tag{9}$$

Where q_1, q_2, q_3, q_4 are represented in (10,11,12,13)

$$q_1(\rho_d, V_{dw}) = \delta_{hd}\rho_d(V_d - V_{dw}) + \delta_{hdw}\rho_{dw}V_{dw} \tag{10}$$

$$q_2(V_{dw}) = V_d - (1 - \delta_{\rho dw})V_{dw} \tag{11}$$

$$q_3(\rho_d, V_{dw}) = \frac{1}{q_2}\left\{\frac{q_1}{h_d - h_{dw}} - \delta_{\rho dw}V_{dw}\right\} \tag{12}$$

$$q_4(\rho_d, V_{dw}) = 1 + q_3\left(1 - \frac{\rho_d}{\rho_{dw}}\right) \tag{13}$$

C. *Primary Superheater*

Applying the law of conservation of energy for the Primary Super Heater (PSH) steam,

Energy balance for steam change in internal energy of PSH steam = Heat transferred from metal to steam + Energy of boiler drum steam - Energy of PSH outlet steam

The energy balance equation for PSH steam is given in (14)

$$V_{sp}\gamma_{sp}\left(\frac{\partial u_{sp}}{\partial T_{sp}}\right)\frac{dT_{sp}}{dt} = a_{ip}\alpha_{msp}(T_{mp} - T_{sp}) + F_d h_d - F_{sp}h_{sp} \tag{14}$$

From thermo dynamical principles, internal energy of steam u_{sp} is a function of steam temperature T_{sp} and volume $V_{sp.}$ According to Joule's law for gases (steam), the internal energy u_{sp} is independent of volume V_{sp} and depends only on temperature T_{sp}

The heat balance equation for PSH steam is given as follows

Heat energy stored in the PSH tube = Heat energy received from hot gas – Heat energy transferred to steam.

The heat balance equation of PSH tube is given by (15)

$$M_{mp}C_{sp}\frac{dT_{mp}}{dt} = a_{op}\alpha_{gmp}(T_{gp} - T_{mp}) - a_{ip}\alpha_{msp}(T_{mp} - T_{sp}) \tag{15}$$

D. *Furnace Gas*

T_{gp} is computed using energy balance equation (16) of the furnace gas model

$$T_{gp} = T_g - \frac{\eta_{ps}}{C_{pg}F_{eg}}F_{eg}^{0.6}(T_g - T_m) \tag{16}$$

E. *Attemperator*

The mass balance equation (17) of attemperator is as follows

Steam flow through Secondary Super Heater (SSH) (F_s)= Steam flow through PSH(F_{sp})+ Attemperator spray flow(F_{spa}) (17)

The energy balance equation (18) of attemperator is as follows

Energy of SSH inlet steam = Energy of PSH outlet steam + Energy of attemperator spray water

$$F_s h_{si} = F_{sp}h_{sp} + F_{spa}h_{spa} \tag{18}$$

Secondary Superheater

The energy balance equation of secondary superheater is as follows

Rate of change in internal energy of SSH steam = Heat transferred from SSH metal to steam + Heat obtained from the PSH steam + Heat reduction due to application of spray - Heat energy of SSH steam. It is expressed in equation (19)

$$V_s\frac{d}{dt}(\rho_s h_s) = a_i\alpha_{ms}(T_m - T_s) + F_{sp}h_{sp} + (h_{spa}h_f)F_{spa} - F_s h_s \tag{19}$$

The heat balance equation of secondary superheater is as follows

Heat energy stored in the SSH tube metal = Heat energy received from the hot gas - Heat energy transferred to steam. Mathematically it is expressed in the following equation (20)

$$M_m C_m \frac{dT_m}{dt} = a_o \alpha_{gm} \left(T_g - T_m\right) - a_i \alpha_{ms} \left(T_m - T_s\right) \tag{20}$$

F. Integrated Mathematical Model of Boiler

All the individual subsystems of boiler are formed using mass and energy balance equation. All the subsystems are connected together using MATLAB/SIMULINK. Fig 1 shows the integrated form of the Boiler system. The steady state boiler system data are collected from the Thermal power plant and the input data used for the dynamic simulation is provided in the Table1.The integrated boiler model obtained is tested for its dynamic and steady state characteristics and the results of which are described below. Table 2 shows the data received from the plant for the given boiler and those obtained from the steady state simulation. A good agreement is found between the simulation and actual parameters of the boiler.

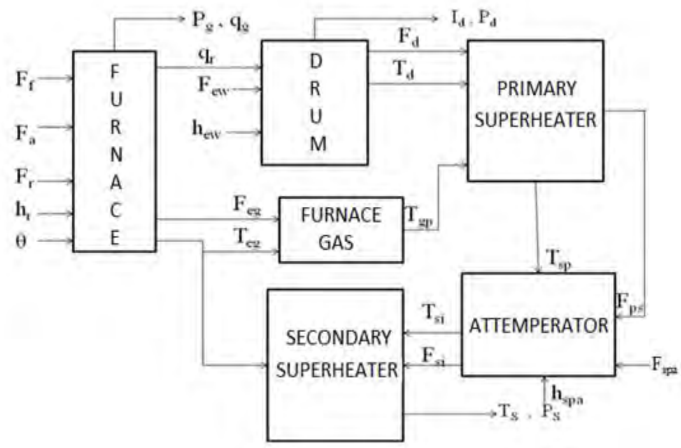

Fig. 1. Block diagram of Integrated Boiler Model

To illustrate the dynamic behaviour of the model, simulate the model to step changes in the inputs. Since there are many inputs and many interesting variables, only a few selected responses are tested. The open loop dynamic responses of furnace temperature, steam flow and steam temperature for a 5% step increase from nominal value of fuel flow of integrated boiler model are shown in Fig. 2, 3 and 4respectively. It is observed that for an increase in fuel flow, the furnace temperature, steam temperature and steam flow increases and reaches the steady state values.

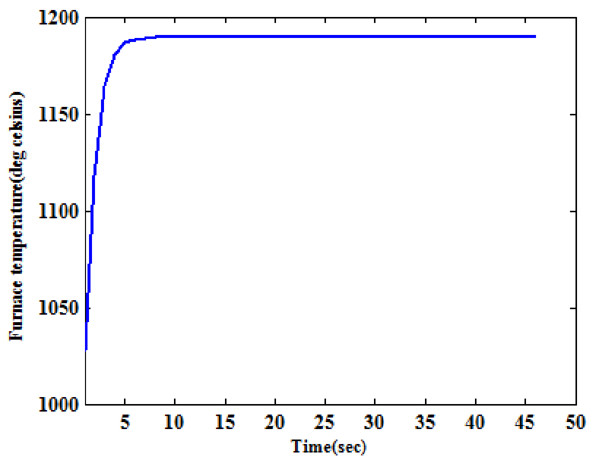

Fig. 2. Open loop response of furnace temperature

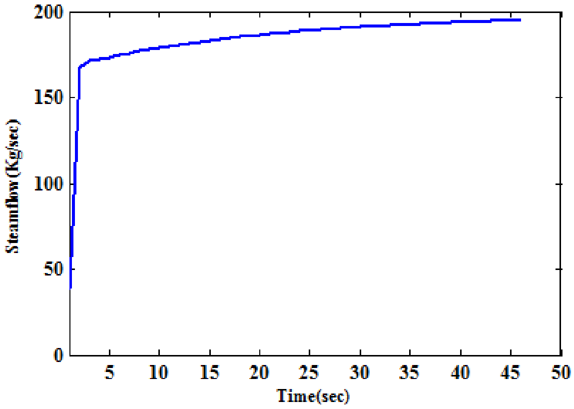

Fig. 3. Open loop response of steam flow

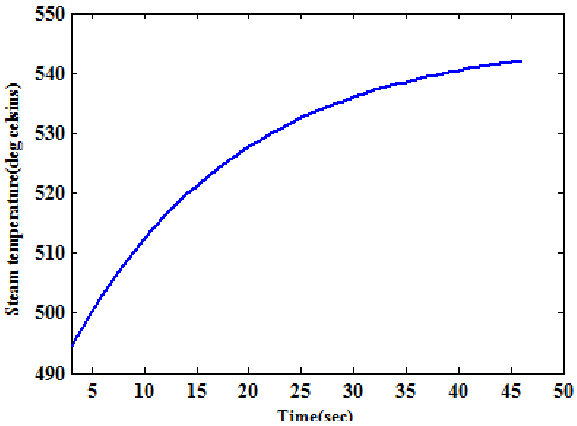

Fig. 4. Open loop response of steam temperature

TABLE I
Input data for dynamic simulation

Input parameters	Nominal values
Fuel flow(coal)	$119.3*10^3$ kg/hr
Air flow	$715.8*10^3$ kg/hr
Feed water flow	163.5023 kg/hr
Attemperator spray flow	29.984×10^3kg/hr

TABLE II
Comparison of steady state plant data and simulation

Parameter	Unit	Actual	From simulation
T_g	°C	1028	1030
T_m	°C	550	551
P_g	kg/cm^2	$1.032973*10^4$	$1.04*10^4$
F_d	Kg/ sec	175.014	175.014
T_{sp}	°C	540	540
T_{mp}	°C	430	430.03
T_s	°C	540.00	540.00
F_s	Kg/hr	$690*10^3$	$690*10^3$
q_s	Kcal/hr	$592.37*10^4$	$592.37*10^4$
T_d	°C	354	354

IV. DEVELOPMENT OF LINEAR PARAMETER VARYING MODEL FOR INTEGRATED INDUSTRIAL COAL FIRED BOILER

Linear models are used to capture the dynamics of different operating regions of the process. For identification and control, it is sufficient to have a model that can approximately represent the process behaviour in a thin envelop covering its operating trajectory. For individual regions, linear transfer function models are developed using linear model identification method. Several linear identification methods such as prediction error method, subspace method are available. Among these, an attempt was made for prediction error method. In general, linear models for three operating regions are denoted as follows

$$\begin{bmatrix} y_1^i(t) \\ y_2^i(t) \\ y_3^i(t) \\ y_4^i(t) \end{bmatrix} = \begin{bmatrix} G_{11}^i & G_{12}^i & G_{13}^i & G_{14}^i \\ G_{21}^i & G_{22}^i & G_{23}^i & G_{24}^i \\ G_{31}^i & G_{32}^i & G_{33}^i & G_{34}^i \\ G_{41}^i & G_{42}^i & G_{43}^i & G_{44}^i \end{bmatrix} \begin{bmatrix} u_1^i(t) \\ u_2^i(t) \\ u_3^i(t) \\ u_4^i(t) \end{bmatrix} \tag{18}$$

for $w(t)=w_i$

Where $y_1^i(t)$ is output in which the suffix 1 represents the first ouput and i =1,2,3 represents operating regions , $u_1^i(t)$ is input in which the suffix 1 represents the first input, w(t) is the working point variable(scheduling variable) and G_{11}^i is the linear transfer function and the suffix represents the first input and output.

In this work, the identification of LPV model is carried out using certain inputs such as Fuel flow, air flow, feed water flow and attemperator spray flow and output variables such as steam flow, steam temperature, furnace temperature and furnace pressure. Steam flow w(t) which is the measured variable from the process is considered as the working point variable that determines the operating condition of the process. The entire operating trajectory is considered from 5% decrease to 10% increase in nominal value of input. For every 5% increase in nominal step input, operating points are estimated. For the different operating conditions the various scheduling points are

w_1= 191.3 Kg/s, w_2=197.3 Kg/s, w_3=202.8 Kg/s

At three different operating regions of steam flow, normal identification tests are performed for the collection of input data of fuel flow, air flow, feed water flow, attemperator spray flow and output data of steam flow, steam temperature, furnace temperature and furnace pressure. Using the data, first order transfer function (linear) models were developed for three operating regions using prediction error method.

General LPV model is as follows in equation (19)

$$y(t) = \alpha_1(w)y^1(t) + \alpha_2(w)y^2(t) + \alpha_3(w)y^3(t) \tag{19}$$

α_1 (w), α_2 (w), α_3 (w) are weights which are functions of scheduling point variable. These weights can be determined using triangular weighing function which is pre-assigned and needs no estimation. The weight associated with each and every operating points of scheduling variable is shown in Fig. 5.

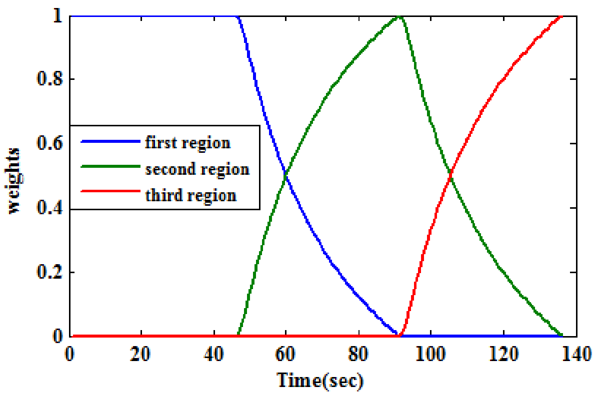

Fig. 5. Weighting Functions of LPV model, blue line-first region weights; green line-second Region weights; red line-Third Region weights.

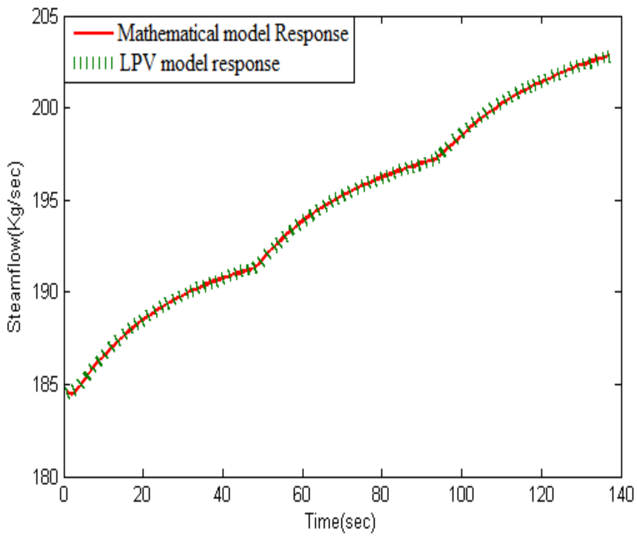

Fig. 6. Model response of steam flow

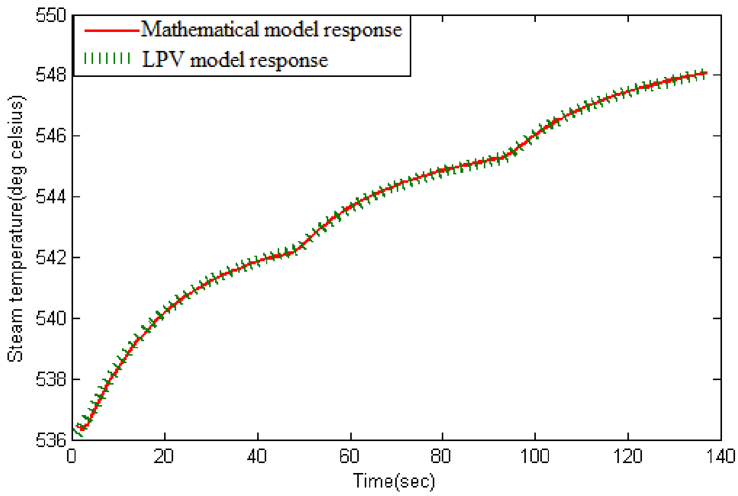

Fig. 7.Model response of steam temperature

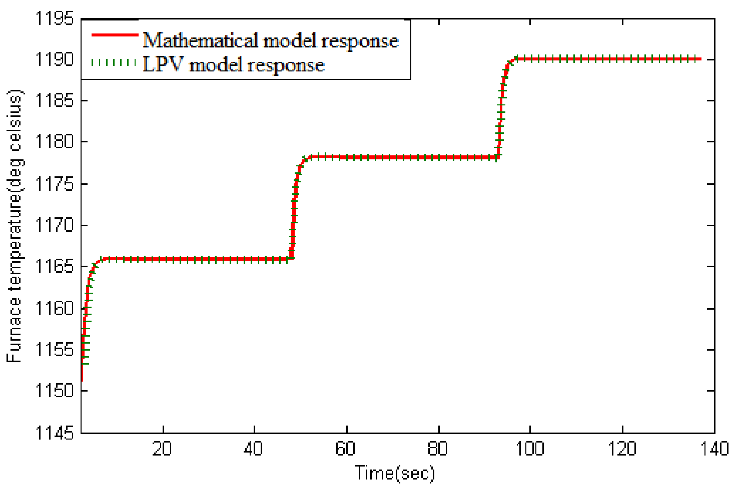

Fig. 8.Model response of furnace temperature

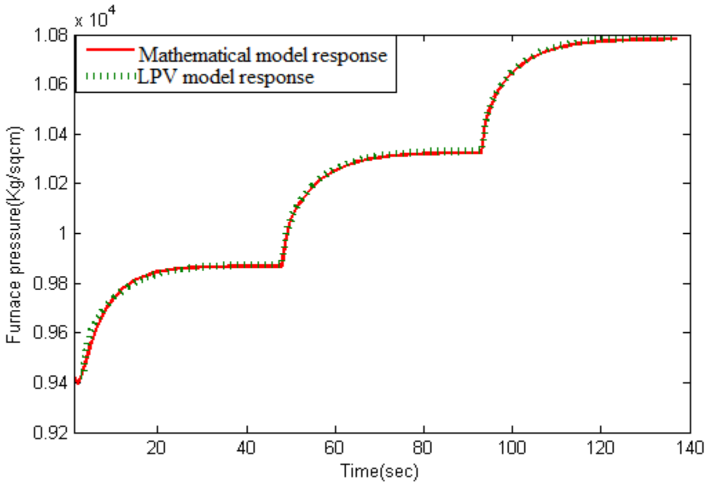

Fig. 9. Model response of furnace pressure

The LPV model is identified by interpolating the linear models developed in three operating regions using the weights which are the functions of scheduling point variable as given in the above equation. The combined simulation results of output obtained from model developed using modeling equations and LPV model outputs are illustrated in the Fig. 6, Fig. 7, Fig. 8, Fig. 9 which respectively shows the responses of mathematical and LPV model for steam flow, steam temperature, furnace temperature and furnace pressure. From the graphs below, it is inferred that the LPV model is tracking the nonlinearities of true output obtained from model developed using modeling equations in an accurate way. Any variable can be considered as scheduling variable in LPV modeling. In the proposed work, steam flow, steam temperature, furnace temperature and furnace pressure are tracked accurately using steam flow as scheduling variable. It is also possible to consider more than one variable as scheduling variable. The methodology for identification remains the same for more scheduling variables.

V. CONCLUSION

LPV model is proposed for its merit of tracking both static and dynamic non linearities along the operating trajectory. Modeling of industrial boiler with multiple operating conditions was considered. Using MATLAB/SIMULINK, mathematical model of industrial boiler has been developed with the help of mass and energy balance equations. LPV model was identified for industrial boiler using limited inputs and outputs with steam flow as scheduling variable. Using the linear polynomial curve fitting method, it is proved that LPV model response fits the model developed using modeling equations response with 99.9% accuracy. The LPV model for Industrial boiler thus obtained can be used for design of controller which can operate the plant at varying operating conditions. It can be applicable for both continuous and batch processes.

Appendix.
Nomenclature

ρ_{eg}	Density of boiler furnace gas(Kg/m^3)
h_{eg}	Specific enthalpy of furnace gas(Kcal/Kg)
F_f	Fuel flow(coal)(Kg/hr)
F_a	Air flow(Kg/hr)
F_r	Recirculation gas flow(Kg/hr)
F_{eg}	Mass flow of furnace gas through the boiler(Kg/hr)
Θ	Burner tilt angle(Radians)
q_s	Heat transferred to Secondary Super Heater(SSH)(Kcal/hr)
V_{bf}	Furnace combustion chamber volume(m^3)
E	Stoichiometric air/fuel ratio
h_r	Specific enthalpy of recirculation gas(Kcal/Kg)

e_x Percentage excess air level(**%)**

C_f Calorific value of coal (Kcal/Kg)

q_r Heat transferred by radiation to riser(Kcal/hr)

E Stefan-Boltzmann constant(Kcal/(hr.m$^{2\cdot}$0K^4))

h_a Specific enthalpy of air (Kcal/Kg)

Tg Temperature of furnace gas(°C)

Tm SSH Metal Temperature(°C)

Pg Furnace gas pressure(kg/cm^2)

V_d Volume of drum(cm^3)

V_{dw} Drum water volume(cm^3)

ρ_d Density of drum steam(Kg/ cm^3)

ρ_{dw} Density of water in drum(Kg/ cm^3)

F_{ew} Feed water flow(Kg/ sec)

F_d Steam flow from drum(Kg/ sec)

p_d Drum steam pressure(Kg/ cm^2)

T_d Saturated steam temperature(°C)

h_{dw} Enthalpy of feed water(Kcal/Kg)

V_{sp} Volume of Primary Super Heater(PSH)(m^3)

γ_{sp} Specific weight of steam in PSH(kg/m^3)

u_{sp} Internal energy of steam in PSH(Kcal/Kg)

T_{sp} Temperature of PSH steam(°C)

T_{mp} PSH metal temperature(°C)

F_{sp} Mass flow rate of steam in PSH(Kcal/hr)

a_{ip} Inside heat transfer area(m^2)

α_{msp} Metal to steam heat transfer coefficient(Kcal/hr.m^2.°C)

a_{op} Outside heat transfer area(m^2)

α_{gmp} Gas to metal heat transfer coefficient(Kcal/hr.m^2.°C)

M_{mp} Mass of PSH section(Kg)

C_{mp} Specific heat of PSH metal(Kcal/Kg.°C)

C_{vp} Specific heat of PSH steam at constant volume(Kcal/Kg.°C)

T_{gp} Gas temperature at PSH(°C)

η_{ps} Experimental coefficient

C_{pg} Specific heat of exhaust gases(Kcal/Kg.°C)

F_s Mass flow rate of steam in SSH(Kg/hr)

F_{spa} Attemperator spray flow(Kg/hr)

h_{si} Enthalpy of SSH inlet steam(Kcal/Kg)

h_{sp} Enthalpy of PSH steam(Kcal/Kg)

h_{spa} Enthalpy of spray water(Kcal/Kg)

V_s Control volume of SSH(m^3)

T_s Main steam temperature(°C)

T_m SSH inlet temperature(°C)

α_i Inside heat transfer area of SSH(m^2)

α_{ms} Metal to steam heat transfer coefficient(Kcal/hr.m^2.°C)

M_m Mass of SSH metal(Kg)

C_m Specific heat of SSH metal(Kcal/Kg.°C)

α_0 Outside heat transfer surface area(m^2)

α_{gm} Gas to metal heat transfer coefficient(Kcal/hr.m^2.°C)

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