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Modeling and Control of Coal Mill

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Abstract: The paper presents development and validation of coal mill model (including the action of classifier) to be used for improved coal mill control. The model is developed by using the mass and heat balance equations of the coal mill. Genetic Algorithm is used to estimate the unknown parameters that are used in the model validation. The advantage is that the raw data used in modeling can be obtained without any extensive mill tests. The simulation results show a satisfactory agreement between the model response and measured value. Apart from the conventional PID controller, inorder to ensure tight control with less overshoot and to handle constraints Model Predictive Controller is designed to maintain outlet temperature and pulverized coal flow at desired set point value.

1. INTRODUCTION

Coal mill is an important component of the thermal power plant. It is used to grind and dry the moisturized raw coal and transport the pulverized coal – air mixture to the boiler. Poor dynamic performance of coal mill will lead to decrease in the overall efficiency of the power plant, slow load take up rate and frequent shut down. Further, to maintain the balance between varying load and supply, and to maintain the various parameters well within their constraints improvements in the existing technology is required. Hence it is necessary to model and develop suitable control schemes to ensure tight control of the mill. The main control problem associated with the coal mill is the lack of sensors for measuring the outlet pulverized coal flow. The input raw coal flow into the mill is also difficult to be measured. Generally, the speed of the conveyor belt will be used for this purpose. Additionally, estimation of varying coal quality, type of coal, moisture content present in the inlet raw coal is difficult. Due to these problems, control algorithms lead to poor performance when load demand changes or when mills are started or shut down.

Many models have been developed in literature without including the effect of classifier in the first principle modeling equation. Outlet pulverized coal flow is measured using sensors and that information has been used in modeling of coal mill (Blankenship, 2004). The drawback is that the equipment tends to be more expensive and requires frequent calibration. Study by Dahl-Soersen and Solberg (2009) shows that the estimate of pulverized fuel flow can be obtained by means of sensor fusion using kalman filter techniques. The authors have used feeder speed and biased unreliable pulverised fuel sensors in the kalman filter design. More control oriented models have been developed in literature. Fan and Rees (2003) developed a model based on mass and heat balance equations. The model was very well able to capture the dynamics of coal mill but it required extensive parameter estimation. Piotr Niemczyk et al. (2012) developed a model including the effect of classifier, in which differential evolution algorithm based parameter estimation technique was adopted.

2. PROCESS DESCRIPTION

A simplified design schematic of a vertical spindle mill is shown in Figure 1. Raw coal is transported on a conveyor belt and dropped into the mill through the chute. The coal falls into the grinding table rotating at a constant speed. The coal then moves under centrifugal force outwards and under three passive rollers where grinding and crushing takes place. The coal output then moves towards the throat of the mill where it mixes with high speed hot primary air. The heavier coal particles are immediately returned back to the bowl for further grinding while the lighter particles are entrained in the air flow and carried into the separator section. The separator section contains a large amount of coal particles in suspension by the powerful air flow. In addition some of the heavier particles entrained in the primary air coal mix lose their velocity and fall back onto the table for further grinding, while particles that are travelling fast enough enter the classifier zone. These particles are given swirl behaviour by vanes or deflector plates. The lighter particles are drawn out of the resulting vortex as classified pulverised fuel for the burners, while the heavier particles hit the side of the classifier cone and drop back into the mill table for further processing.

3. MODELING EQUATIONS

The modelling equations proposed by Pietr Niemczyk et al. (2012) is used to develop the coal mill model. The following assumptions are made to develop the coal mill model: (1) Coal in the mill is either pulverised or unpulverised, i.e. different particle sizes are not considered. Variations of the mass of coal particles (e.g. depending on the moisture content) are not included in the model. (2) The temperature of the mill is assumed to be same as the temperature of the classifier. (3) Heat emitted from the mill to its environment is negligible. (4) The mass change of coal causes insignificant change in the total heat capacity of the mill. (5) The ambient temperature (temperature of raw coal entering the mill) T_a, coal moisture ρ_m and latent heat of vaporisation L_v are known constants.

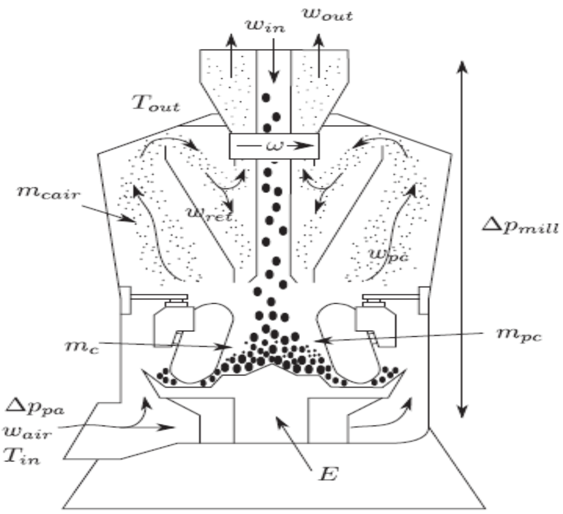

Fig. 1. Schematic diagram of coal mill

The mass of coal to be pulverised depends on the mass flow of the raw coal, w_c, the return flow of the particles rejected by the classifier, w_{ret}, and the grinding rate which is proportional to the mass of raw coal on the grinding table, m_c.

$$\frac{d}{dt}m_c(t) = w_c(t) + w_{ret}(t) - \theta_1 m_c(t) \tag{1}$$

The mass of pulverised coal on the table m_{pc}, depends on the grinding rate and the amount of coal picked up by the primary air from the table, w_{pc}.

$$\frac{d}{dt}m_{pc}(t) = \theta_1 m_c(t) - w_{pc}(t) \tag{2}$$

The mass of particles in the pneumatic transport upwards in the mill, m_{cair}, depends on the mass flow of coal particles picked up from the grinding table, the fuel flow out of the mill, w_{out}, and the return flow of rejected particles to the table.

$$\frac{d}{dt}m_{cair}(t) = w_{pc}(t) - w_{out}(t) - w_{ret}(t) \tag{3}$$

The mass flow of pulverised particles picked up by the primary air flow, w_{air}, to be transported towards the classifier is proportional to the primary air mass flow and the mass of pulverised coal on the table.

$$w_{pc}(t) = \theta_5 w_{air}(t) m_{pc}(t) \tag{4}$$

The mass flow of pulverised coal out of the mill is proportional to the mass of coal lifted from the table and depends on the classifier speed.

$$w_{out}(t) = \theta_4 m_{cair}(t)\left(1 - \frac{\omega(t)}{\theta_6}\right) \tag{5}$$

where $0 < \omega(t) < \theta_6$. θ_6 has the same unit as ω, making the term $(1 - (\omega(t)/\theta_6))$ a dimensionless factor.

The mass flow returning to the grinding table is proportional to the mass of coal in the pneumatic transport m_{cair}.

$$w_{ret} = \theta_9 m_{cair}(t) \tag{6}$$

The pressure drop, Δp_{mill}, across the mill depends on the mill differential pressure of the primary air, Δp_{pa}, and the amount of coal suspended in the air. During normal operation, the mill pressure drop is predominately proportional to the primary air differential pressure and a small change in coal mass does not affect the pressure drop significantly. Also, when the coal mass becomes zero, the pressure drop also becomes zero. These conditions are guaranteed by the term $1 - e^{-\theta_8 m_{cair}(t)} \in [0,1]$.

$$\Delta p_{mill}(t) = \theta_7\left(1 - e^{-\theta_8 m_{cair}(t)}\right)\Delta p_{pa}(t) \tag{7}$$

The power consumed for grinding is a sum of the power needed for rolling over raw and ground coal and the constant power needed for running an empty mill (E_e).

$$E(t) = \theta_2 m_{pc}(t) + \theta_3 m_c(t) + E_e \tag{8}$$

Finally, the temperature equation is based on heat balance equation of the coal mill.The significant heat contribution comes from the primary air flow , moisture of the incoming coal particles, coal flow into the mill $(C_{air}w_{air}(t)T_{in}(t),\ \rho_m C_w\ w_c(t)T_a\ ,\ C_c w_c(t)T_a)$ and from grinding$(\theta_{10}E(t))$. The heat is used to evaporate the moisture $(\rho_m w_c(t)L_v)$ and raise the temperature of the coal particles and the mill chassis to the outlet temperature $(C_{air}w_{air}(t)T_{out}(t), C_c w_{out}(t)T_{out}(t))$.

$$\frac{d}{dt}T_{out}(t) = \frac{1}{\theta_{11}}\begin{bmatrix} C_{air}w_{air}(t)T_{in}(t) + \rho_m C_w w_c(t)T_a + \\ C_c w_c(t)T_a - C_{air}w_{air}(t)T_{out}(t) - \\ C_c w_{out}(t)T_{out}(t) - \rho_m w_c(t)L_v + \theta_{10}E(t) \end{bmatrix} \tag{9}$$

m_c = Mass of unpulverised coal on the table (kg)
m_{pc} = Mass of pulverized coal on the table (kg)
m_{cair} = Mass of pulverized coal carried by primary air (kg)
w_c = Mass flow of dry raw coal out of the mill (kg/s)
w_{pc} = Mass flow of pulverized coal (kg/s)
w_{out} = Mass flow of pulverized coal out of the mill (kg/s)
w_{ret} = Mass flow of coal returning to the table (kg/s)
w_{air} = Primary air mass flow (kg/s)
Δp_{pa} = Primary air differential pressure (mbar)
T_{in} = Primary air inlet temperature ($^\circ C$)
T_{out} = Outlet temperature ($^\circ C$)
Δp_{mill} = Pressure drop across the mill (mbar)
E = Power consumed for grinding (%)
E_e = Power consumed for running empty mill (%)
ρ_m = Coal moisture (%)
L_v = Latent heat of vaporization (J/kg)
C_s = Specific heat of a substance (J/kg$^\circ$C)

4. OPTIMISATION OF COAL MILL MODEL USING GENETIC ALGORITHM

Eleven unknown parameters present in the modelling equation are to be identified using GA. From literature studies it was found that the value of θ_{11} was large. Hence, it is assumed to be constant. The initial guess was done based on the physical meaning and the rough bounds of the parameters to be estimated. The GA parameters used is given in table 1. The following fitness function is used to estimate to the parameters in GA.

$$e(t) = W_1\left(\frac{\Delta P_{mill,t} - \Delta \hat{P}_{mill,t}}{\Delta \bar{P}_{mill}}\right)^2 + W_2\left(\frac{T_{o,t} - \hat{T}_{o,t}}{\bar{T}_o}\right)^2$$

$$Fitness = \sum_{t=0}^{N} e(t)$$

$\Delta\hat{P}_{mill,t}, \Delta\hat{T}_{o,t}$: Measured data at time t

$\Delta P_{mill,t}, \Delta T_{o,t}$: Model output parameters at time

$\Delta\bar{P}_{mill}, \Delta\bar{T}_o$: Parameter high limits

W_1, W_2 : Weights of the output parameters

$e(t)$: Sum of normalised error

N : Number of measured data

5. CONTROL OF COAL MILL

In general the control systems, of mills have two components: coal air mixture temperature control and the coal feeder control. Control scheme for outlet temperature is essential since improper control may lead to chances of explosion. In the thermal power plant, the outlet temperature is maintained at $70\,°C$. This temperature is required to remove the moisture content present in the coal. Any further rise in temperature may lead to damage of the components in the mill.

Coal feeder control is essential to maintain the outlet pulverised coal-air mixture at the specified setpoint value and to prevent accumulation of raw coal inside the mill. The setpoint value is determined based on the load demand.

In this paper, both the outlet temperature and pulverised coal flow is controlled with the help of MPC controller to overcome the drawbacks of PID. The outlet temperature is controlled by manipulating the inlet primary air temperature and the pulverised coal flow is controlled by manipulating the raw coal flow rate. The PID (conventional controller) parameters are determined using ZN open loop method.

6. MODEL PREDICTIVE CONTROLLER

Model predictive controller belongs to a class of controllers which uses model to predict the future output over a extended period of time. The main parameters of the model predictive controller are predictive horizon, control horizon and model length. The basic elements of MPC are reference trajectory specification, process output prediction using model, control action sequence computation and error prediction update. The basic structure of model predictive controller is shown in Figure 2.

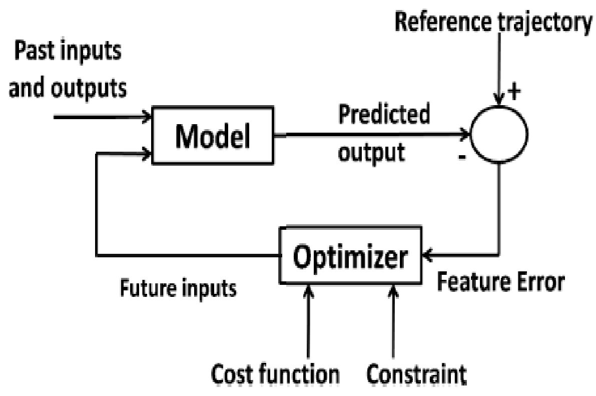

Fig. 2. Basic structure of MPC

Table 1. Genetic Algorithm Parameters

Parameter	Value
Number of variables	10
Population size	50
Cross over probability	0.95
Mutation probability	0.05

MPC is the best choice to control a process when it is difficult to control using PID controller in systems with large time delay, large time constants, and inverse response. Further, the main advantage of using MPC controller is that constraints on the input and output variables can be handled efficiently unlike conventional controllers. Future values of output variables are predicted using a dynamic model of the process and current measurements. Unlike delay compensation methods, the predictions are made for more one time delay ahead. The control action is based on both future predictions and current measurements. The manipulated variable u(k) at the k^{th} sampling instant is calculated such that it minimises the value of ISE. Constraints in the input and output variables are also considered in calculating the control outputs. The optimiser is the main part of the MPC since it determines the control action. The constraint and parameters relating to MPC used in designing MPC is given in Table 4,5 and 6 respectively.

7. RESULT AND DISCUSSION

The measurement data used in the modeling of the process are obtained from North Chennai Thermal Power Plant (NCTPS).

A. Input variables obtained from NCTPS

Figures 3 to 5 represent the input variables used in modeling. The input variables used in the model are raw coal mass flow rate, classifier speed, inlet temperature (temperature of the primary air) and primary air differential pressure. The raw data was collected during mill start-up time, under the following operating conditions: Mass flow rate of raw coal -30 tons/hr; Mill differential pressure- 160-200 mm wc; Primary air temperature- 250-280 °C; Outlet temperature- 60-70°C; Motor current- 44A; Primary air flow- 56 tons/hr. Fig 4 to 7 represents the primary data used as input. In Fig 1, at 2300 seconds, inorder to meet a sudden increase in the load demand the mass flow of raw coal was increased from 7.7 to 8.4kg/sec.

B. Response of intermediate variables

Information about the mass of raw coal, mass of pulverized coal, mass of pulverized coal carried by primary air, mass flow of pulverized coal, and mass flow of coal returning to the table can be obtained from the developed coal mill model. Fig 6 and 7 represents the variation of state variables obtained from the developed model. The variation in the raw coal flow at 2300sec leads to variation in the mass flow of pulverized coal and other intermediate variables.

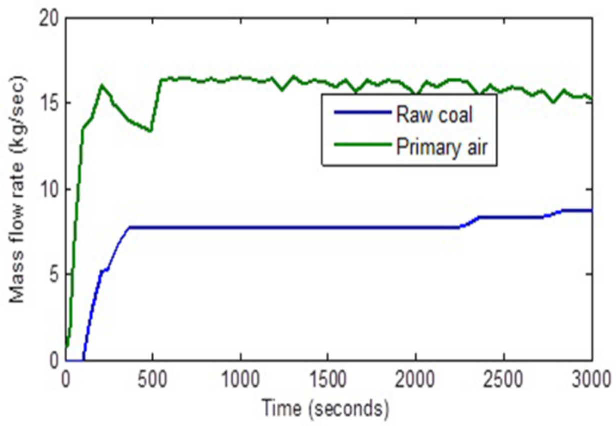

Fig. 3. Variation of mass flow of raw coal and primary air flow with time.

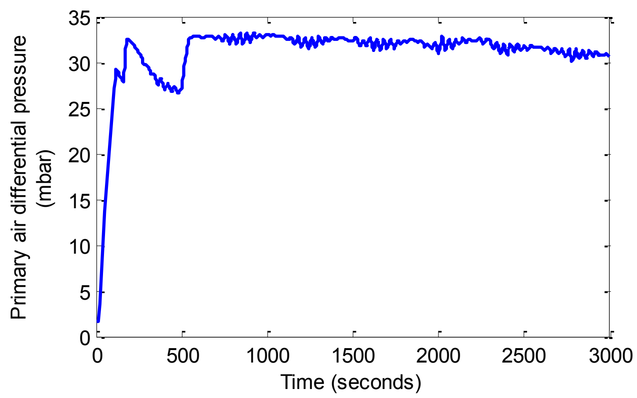

Fig. 4. Variation of primary air differential pressure with time

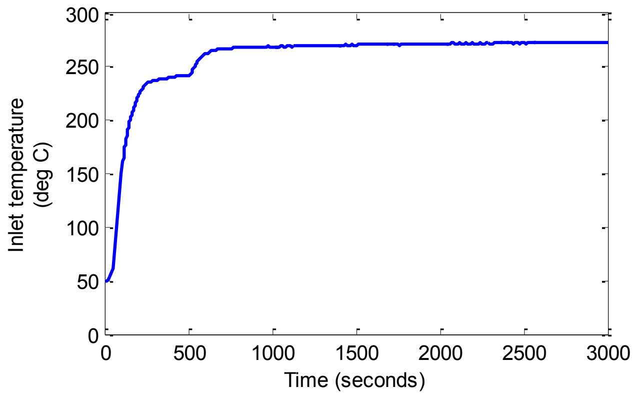

Fig. 5. Variation of inlet temperature with time

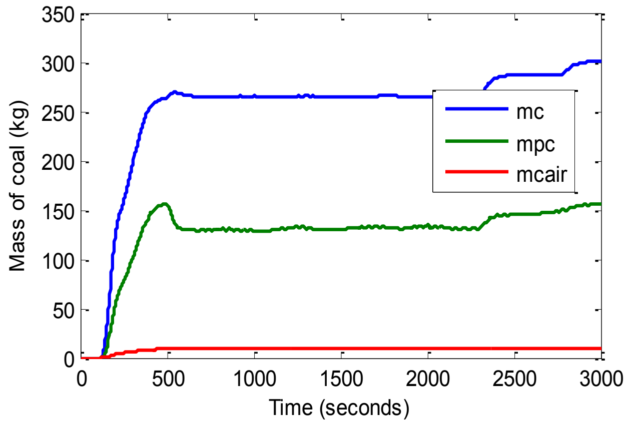

Fig. 6. Predicted variation of mass of coal of different categories.

C. Response of output variables

The output variables obtained from the model are mass flow of pulverized coal out of the mill, pressure drop across the mill, power consumed for grinding, and classifier temperature (outlet temperature) of the mill. Fig 8 to 11 represents the output obtained from the model. The variables such as mass flow of pulverized coal flow out of the mill, mass of coal rejected by classifier etc. which is not measurable in the power plant can be obtained from the model.

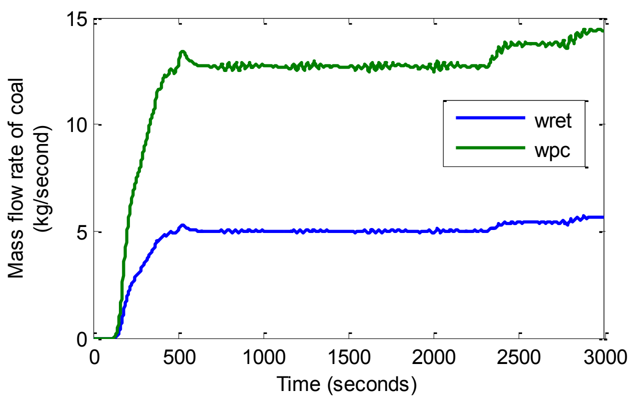

Fig. 7. Variation of mass flow rate of pulverized coal and coal rejected from classifier with time

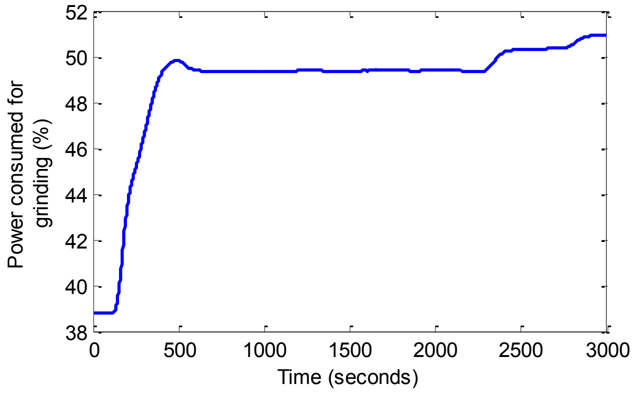

Fig. 8.Predicted variation of power consumed for grinding

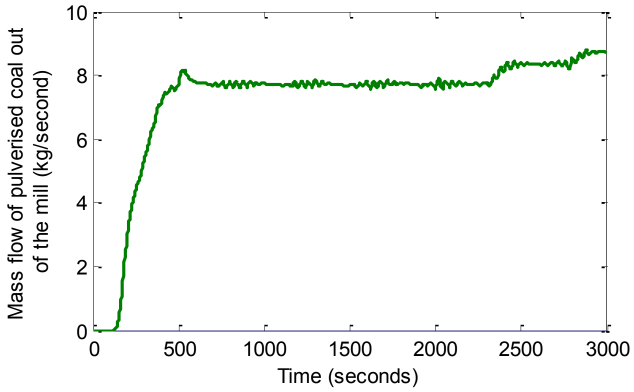

Fig. 9. Variation of mass flow rate of pulverized coal out of the mill with respect to time

From the results obtained, it can be inferred that any change in the mass flow rate of raw coal causes corresponding change in the mass flow rate of pulverized coal entering the boiler. The mass flow rate of pulverized coal without classifier action has the maximum value and it is equal to the sum of mass flow rate of pulverized coal entering the boiler and the mass flow rate of pulverized coal rejected by the classifier at steady state. Further, the response obtained for the mill differential pressure and outlet temperature show that there is a satisfactory agreement between the model response and measured value.

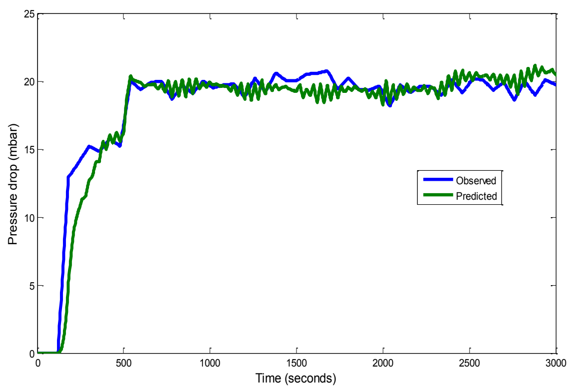

Fig. 10. Comparison between measured and simulated output of pressure drop across the mill

Table 2. Values of estimated parameters

Parameter	Value
θ_1	0.03 $second^{-1}$
θ_2	0.02 kg^{-1}
θ_3	0.04 kg^{-1}
θ_4	0.9 $second^{-1}$
θ_5	0.002 kg^{-1}
θ_6	2.5 $^{rad}/_{second}$
θ_7	3.7
θ_8	0.2 kg^{-1}
θ_9	0.4 $second^{-1}$
θ_{10}	8.0 $J\ second^{-1}$
θ_{11}	4x 10^6 $^{°C}/_{J}$

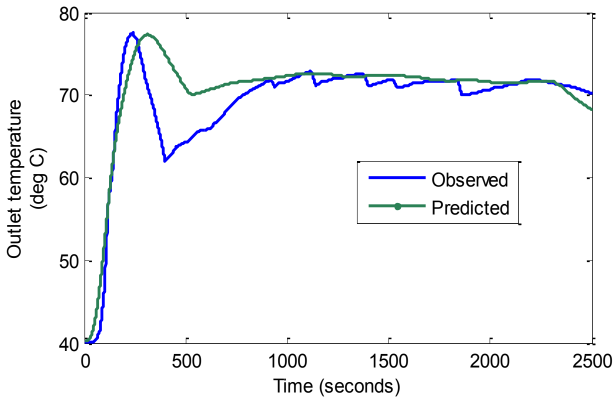

Fig. 11. Comparison between simulated and measured output of outlet temperature of the mill.

D. Closed loop studies

Open loop response to design controllers is obtained by giving a step change in primary air temperature (for outlet temperature control) and raw coal flow rate (pulverised coal flow). From the transfer function obtained, using ZN open loop tuning method the PID parameters are obtained. The PID parameters for outlet temperature and pulverised coal flow are shown in table 3. The results show that the PID controller is able to track the set point but the overshoot is high. Inorder to improve the response and to handle constraints MPC controller is designed. The MPC parameters is shown in table 4.The comparison of closed loop response of both MPC and PID controllers is shown in figure 12 and 13. From the response it can be inferred that MPC controller has less overshoot than PID. Further, MPC can handle constraints and from the performance indices it can be concluded that MPC provides better control action when compared to PID controller.

Table 3. PID Parameters

PID Parameter	Outlet Temperature Control	Pulverised Coal Flow
k_c	4.169	5.336
τ_i	26.58 seconds	9.018 seconds
τ_d	6.645 seconds	2.245 seconds

Table 4. MPC Parameters

MPC Parameter	Outlet Temperature Control	Pulverised Coal Flow
Sampling Time	1	1
Prediction Horizon	100	100
Control Horizon	50	25

Table 5. Input and Output constraints of MPC for outlet temperature control

Parameter	Minimum	Maximum
Input- Primary air temperature	$0\,°C$	$700\,°C$
Output- Outlet temperature	$40\,°C$	$100\,°C$

Table 6. Input and Output constraints of MPC for pulverised coal flow control

Parameter	Minimum	Maximum
Input- Raw coal flow	0 kg/sec	10 kg/sec
Output- Pulverised coal flow	0 kg/sec	8 kg/sec

Table 5. Performance Indices

Controller	Pulverised Coal Flow			Outlet Temperature Control		
	ITAE	IAE	ISE	ITAE	IAE	ISE
PID	2*10^6	3952	1.6* 10^4	1.9* 10^6	6829	1.03* 10^5
MPC	1.29* 10^4	263.4	795.6	6.8* 10^5	3808	6.2* 10^4

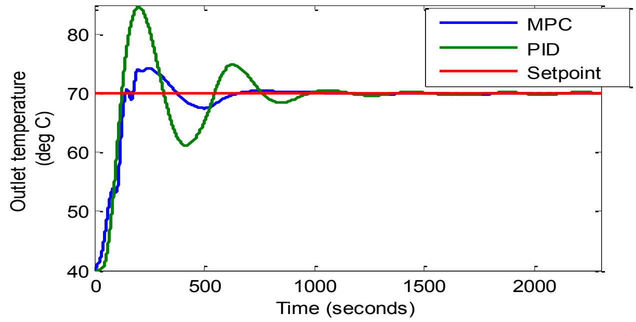

Fig. 12. Comparison of response of outlet temperature for a setpoint of 70 °C in the presence of PID and MPC

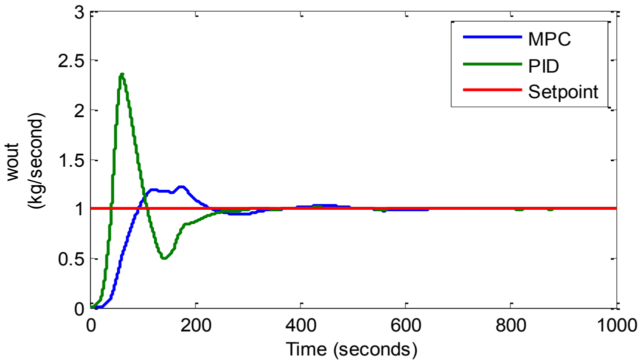

Fig. 13. Comparison of response of pulverized coal flow for a setpoint of 1 kg/sec in the presence of PID and MPC

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