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Condition Monitoring of Power Plant Milling Process using Intelligent Optimisation and Model Based Techniques

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1. Introduction

Coal preparation is the first step in the whole process of coal-fired power generation. A typical milling process is illustrated in Figure 1. Also, coal-fired power stations nowadays are required to operate more flexibly with more varied coal specifications and regularly use coal with higher volatile contents and Biomass materials (Livingston 2004); this greatly increases the risks of explosions or fires in milling plants. The power stations are also obliged to vary their output in response to the changes of electricity demands, which results in more frequent mill start-ups and shut-downs. In many cases, coal mills are shutdown and then restarted before they have cooled adequately, which creates a potential fire hazard within the mill. Frequent start-ups and shut-downs of mills will also have an impact on power plant operation safety. Mill fires could occur if the coal stops flowing in the mill and the static deposit is heated for a period of time. Fires in out-of-service mills can cause explosions on mill starts. Fires in running mills can cause explosions on shut-downs. The result of a study indicated that as many as 300 "explosions" were occurring annually in the US pulverized coal industry (Scott, 1995). Especially, adding higher volatile Biomass materials greatly increases the chance of mill fires and explosions. The UK PF Safety Forum had recently reported an increase in the frequency of mill explosions in the UK. Operational safety and efficient combustion require better understanding to the milling process.

However, coal mills have been paid much less attention in research compared with boilers, generators, and other power generation system components. It is difficult to identify if there will be a fire in the mill. Outlet temperature and CO are established methods of detecting fires in mills, but at present they are not very effective for detecting small fires. The CO detection system becomes ineffective when the mill is in service due to dilution effects caused by primary air flow and associated oxygen content in the mill.

A wide range of literature survey shows that there are only a few reports on mathematical models of milling processes. A detailed milling process description can be found in Scott *et al.* 1995. An approximated linear transfer function model was obtained by Bollinger *et al*, in 1983. Mill modelling using system identification method was reported in 1984 (Corti *et al.* 1984). With specially designed input signals, a linear discrete time model was obtained by Cheetham, *et al* in 1990, in which system time-delay was considered. An approximated

linear time varying mill model was derived by Fan *et al.* in 1994. A polynomial matrix model was recently reported in 2000 (Hamiane *et al.* 2000). However, almost all the reported work describes the milling process by approximated linear mathematical models, which can not reflect the nonlinear features of coal mill systems. The complex nature of a milling process, together with the complex interactions between coal quality and mill conditions lead to immense difficulties for obtaining an effective mathematical model of a milling process.
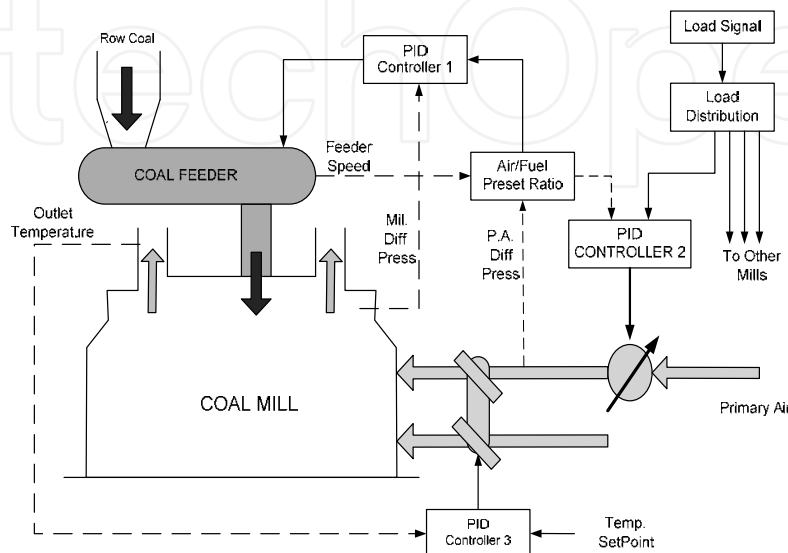

Fig. 1. A typical coal mill system

With the development of computer technology, advanced distribute control and monitoring systems enable the information data to be collected from the major plant components, e.g. mills, boilers and generators. The available measurements for coal mills include inlet/outlet temperature, PA (primary air) differential pressures, volume flow rate of coal into mills, primary airflow rate in mills *etc.* The availability of such a large volume of data offers an opportunity to identify the characteristics of mill processes and to develop a suitable coal mill model. A nonlinear coal mill model was derived based on the dynamic analysis of the coal milling process by Zhang *et al.* in 2002, which is a multi-input multi-output (MIMO) non-linear system. A machine learning method was adopted for identification of system parameters and the data employed in parameter identification covers a wide range of milling processes and also was measured on-site at power plants. Following the progress of early stage study, further studies have been carried out. It is noticed that there were no specific terms in the output temperature equation to represent the time delays caused by heat inertia in the system responses. Generally speaking, thermal processes always have big inertias, which are reflected in the system responses with obvious time delays. So the coal mill model was then improved by considering the temperature inertia terms (Wei *et al.* 2003). A multi-segment mill model was developed for the vertical spindle mills which was reported in Wei *et al.* 2007. The chapter summarises the research achievement at Birmingham in mill modelling, condition monitoring, on-line implementation, on-site test results and incident prediction.

2. Coal Mill Modelling for the Normal Grinding Process

The procedure adopted for coal mill modelling in this paper can be broken down into the following steps:

1). to derive the basic mill model dynamic equations through analysing the milling process, applying physics and engineering principles, and integrating the knowledge of experienced engineers;

2). to identify unknown parameters using evolutionary computation and system simulation techniques using the on-site measurement data;

3). to analyse the simulation results and interpret the parameters identified through the discussions between the researchers and experienced engineers;

4). to improve the mill model, that is, to go back to Step 2 if any modification is required, or to conduct further simulation to validate the model and go back to Step 3.

A nonlinear mathematical model for normal mill grinding process was developed, which were based on the following assumptions: a) The pulverizing mechanism in the mill is simplified and coal classification is not considered; b) Grinding and pneumatic transport in the milling process are separated into two stages; c) Coal size is grouped into only two categories named pulverized and un-pulverized coal. The mill model for the grading process can be described by the following equations (Zhang *et al.* 2002, Wei *et al.* 2007):

$$W_{air}(t) = 10 \cdot \sqrt{\Delta P_{pa}(t) \cdot \frac{273}{273 + T_{in}(t)} \times \frac{28.8}{22.4}} \tag{1}$$

$$W_c(t) = K_{fs}.F_s(t) \tag{2}$$

$$W_{pf}(t) = K_{16}\Delta P_{pa}(t)M_{pf}(t) \tag{3}$$

$$\dot{M}_c(t) = W_c(t) - K_{15}M_c(t) \tag{4}$$

$$\dot{M}_{pf}(t) = K_{15}M_c(t) - W_{pf}(t) \tag{5}$$

$$P(t) = K_6 M_{pf}(t) + K_7 M_c(t) + K_8 \tag{6}$$

$$\Delta P_{mill}(t) = K_9 \Delta P_{pa}(t) + \Delta P_{mpd}(t) \tag{7}$$

$$\Delta \dot{P}_{mpd}(t) = K_{11}M_{pf}(t) + K_{12}M_c(t) - K_{13}\Delta P_{mpd}(t) \tag{8}$$

$$\dot{T}_{out}(t) = [K_1 T_{in}(t) + K_2] \cdot W_{air}(t) - K_3 W_c(t) - [K_4 T_{out}(t) + K_5] \cdot [W_{air}(t) + W_c(t)] \\ + K_{14}P(t) + K_t T_{out}(t) \tag{9}$$

The variables and parameters in the above equations are defined as:

ρ :   Primary air density (kg / m^3)

M_c :   Mass of coal in mill (kg)

M_{pf} :   Mass of pulverized coal in mill (kg)

T_{out} :   Outlet temperature of coal mill (*deg C*)

ΔP_{mill} :   Mill differential pressure (*mbar*)

ΔP_{mpd} :   Mill product differential pressure (*mbar*)

W_{pf} :   Mass flow rate of pulverized coal outlet from mill (*kg/s*)

P :   Mill current (*A*)

ΔP_{pa} :   Primary air differential pressure (*mbar*)

W_c :   Mass flow rate of coal into mill (*kg/s*)

F_s :   Coal feeder speed (mm/s)

T_{in} :   Inlet temperature of coal mill (*deg C*)

W_{air} :   Primary air flow rate into coal mill (*kg/s*)

K_i :   Model unknown parameters to be identified.

A brief explanation to the coal mill model (1) ~ (9) is given below.

- Equation 1 represents that the PA (primary air) flow rate is equal to the rate of air flow delivered by the primary fans, which is proportional to the square root of the PA differential pressure and the density of air under the mill inlet temperature.

- Equation 2 represents that the flow rate of coal into coal mill is equal to the rate at which coal delivered by feeder times the feeder speed coefficient K_{fs}, which depends on the sizes of different feeders (for a small feeder, K_{fs} = 0.16 kg/mm and for a large feeder, K_{fs} = 0.24 kg/mm).

- Equation 3 represents that the flow rate of PF (pulverized fuel) out of mill is equal to the rate that PF was carried out of mill by the primary air flow, which is proportional to the mass of the pulverized coal in mill and the differential pressure produced by the primary air fan.

- Equation 4 represents that the mass change rate of the coal in mill is proportional to the difference between the coal flow into the mill the fraction of coal that is converted into pulverized fuel $K_{15} M_c(t)$.

- Equation 5 represents that the change of mass of pulverized fuel in mill is proportional to the difference between the fraction of coal converted into pulverized and the pulverized coal flow outlet from the mill.

- Equation 6 represents that the total amount of mill current consumed to run the mill motor is equal to the sum of mill current required to grind over surface area, mill current to pulverized coal, and mill current to run empty mill.

- Equation 7 represents that the mill differential pressure is resulted by the differential pressure produced by the primary air fan and the mill product differential pressure.

- Equation 8 represents that the changes in the mill product differential pressure is proportional to the pressure due to pulverised fuel in mill, proportional to the pressure due to coal in mill, and the pressure of the previous time step.

- Equation 9 represents the changes in mill outlet temperature is the results of heat transferring balance. It increases with the heat contributed by hot primary air entering mill and the heat generated by grinding and also decreases with the heat lost to coal and moisture entering mill and the heat lost to hot primary air and pulverized fuel leaving mill. Basically this equation represents the heat balance model of the coal mill system, which is demonstrated in Fig. 2.
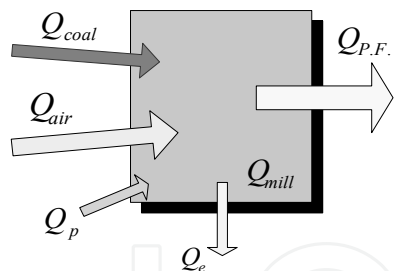
Fig. 2. Heat balance model of coal mill system

The heat of coal from inlet, Q_{coal}, is represented by the term $K_3 W_c$, the heat of primary air from inlet, Q_{air}, is represented by the term $K_1 T_{in} W_{air} + K_2 W_{air}$, the heat generated by the coal grinding process is represented by the term $K_{14} P$, and the heat of the pulverized coal outlet from the mill is represented by term: $K_4 T_{out}(t) \cdot [W_{air}(t) + W_c(t)] + K_5 \cdot [W_{air}(t) + W_c(t)]$. The heat emitted from the mill body to the environment Q_e is neglected in the model. The term $K_t T_{out}$ represents the approximation to the time delay inherent in the thermodynamics processes.

For the purpose of identifying the system parameters, the measured variables are organised into two groups - system inputs and outputs. The input variables of the model include the coal flow into the mill, primary air differential pressure and primary air inlet temperature. The output variables include mill differential pressure, outlet temperature and mil current. In order to identify the sixteen unknown coefficients of the coal mill mathematical model, the Genetic Algorithms (GAs) is adopted (Wang *et al* 2004). It has been proved that GAs is a robust optimisation method for this particular identification problem. The single-population real-value genetic algorithm was chosen and the fitness function shown in Formula (13) is employed for this purpose. The fitness function compromises the errors between the normalized coal mill measured outputs and the normalized model simulated outputs. Following the scheme of the coefficients identification shown in Fig. 3, the sixteen unknown coefficients are identified which are summarised in Table 1. More detailed information about the model coefficients identifications can be found in Wei *et al.* 2007. Define:

$$e_1(t) = {}^n T_{out}(t) - {}^n \hat{T}_{out}(t) = \frac{T_{out}(t)}{{}^{TopR} T_{out}} - \frac{\hat{T}_{out}(t)}{{}^{TopR} T_{out}} \tag{10}$$

$$e_3(t) = {}^n \Delta P_{mill}(t) - {}^n \Delta \hat{P}_{mill}(t) = \frac{\Delta P_{mill}(t)}{{}^{TopR} \Delta P_{mill}} - \frac{\Delta \hat{P}_{mill}(t)}{{}^{TopR} \Delta P_{mill}} \tag{11}$$

$$e_2(t) = {}^n P(t) - {}^n \hat{P}(t) = \frac{P(t)}{{}^{TopR} P} - \frac{\hat{P}(t)}{{}^{TopR} P} \tag{12}$$

Then the fitness function is described as follows:

$$fitness = \frac{1}{N} \sum_{t=0}^{N} \left\{ W_1 \times |e_1(t)| + W_2 \times |e_2(t)| + W_3 \times |e_3(t)| \right\} \tag{13}$$

where:

W_1, W_2, W_3 :   Weighting coefficients.

$^{n}\hat{T}_{out}(t)$, $^{n}\hat{P}(t)$, $^{n}\Delta\hat{P}_{mill}(t)$	Normalized simulated outputs of the mill model at time t.
$^{n}T_{out}(t)$, $^{n}P(t)$ $^{n}\Delta P_{mill}(t)$	Normalized measured outputs of the mill model at time t.
$T_{out}(t)$, $P(t)$ $\Delta P_{mill}(t)$	Measured outputs of the mill model at time t.
$\hat{T}_{out}(t)$, $\hat{P}(t)$ $\Delta\hat{P}_{mill}(t)$	Simulated outputs of the mill at mill model at time t.
$^{TopR}T_{out}$, ^{TopR}P $^{TopR}\Delta P_{mill}$	Top ranges of the variables.
W_1, W_2, W_3:	Weighting coefficients.
N:	Number of measured data points.
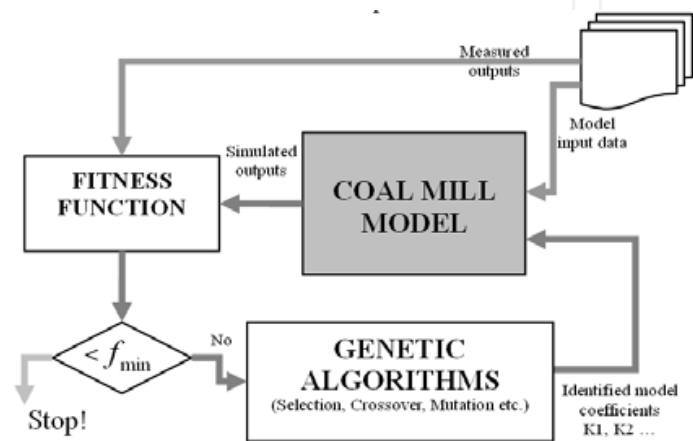
Fig. 3. Schematic diagram for the procedure of the model's coefficients identification

System parameter using the modified mill model	
$K_1 = 0.00061927802462$	$K_2 = 0.08961428118773$
$K_3 = 0.00383781469345$	$K_4 = 0.00155335789736$
$K_5 = -0.08634812\ 577403$	$K_6 = 0.01712514044766$
$K_7 = 0.00293718071483$	$K_8 = 30.17329476338669$
$K_9 = 5.54900011072344$	$K_{11} = 0.00170000000000$
$K_{12} = 0.00056524986674$	$K_{13} = 0.08677360557200$
$K_{14} = 0.03250567038921$	$K_{15} = 0.00513313270266$
$K_{16} = 0.00261803749309$	$K_t = -0.05724453482491$

Table 1. Identified coefficients for the normal running coal mill model

The simulated results using data collected from power plant are shown in Fig. 4 ~ Fig. 5, where the solid line represents the coal mill measured outputs and the dash-dot line represents the model simulated outputs.
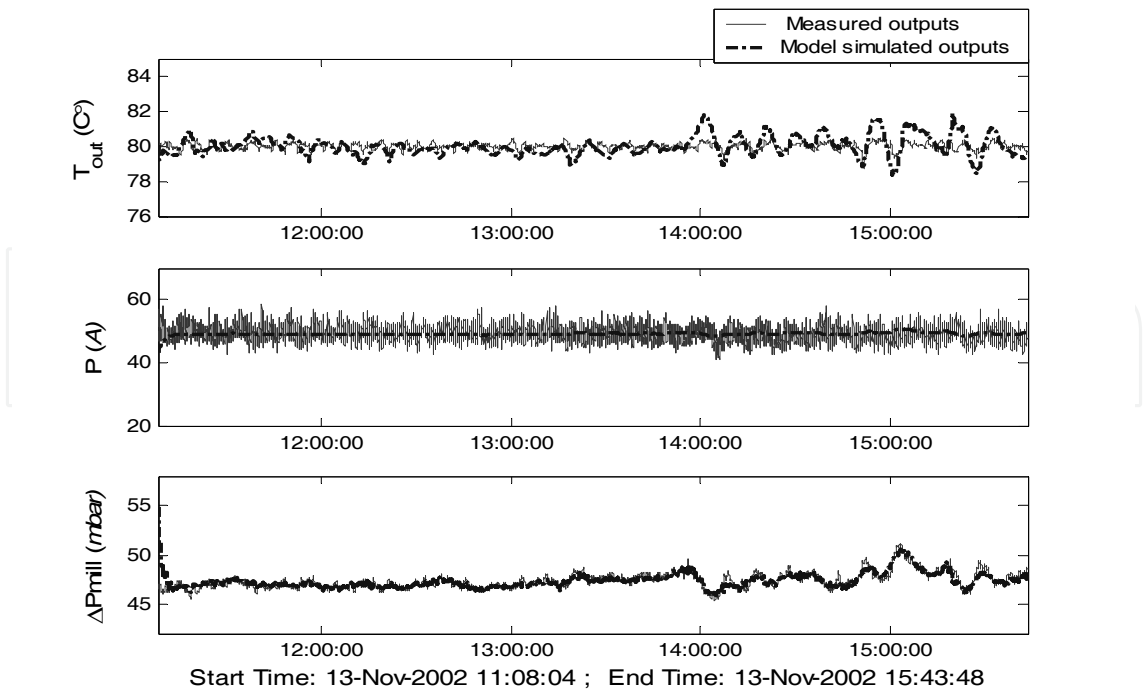
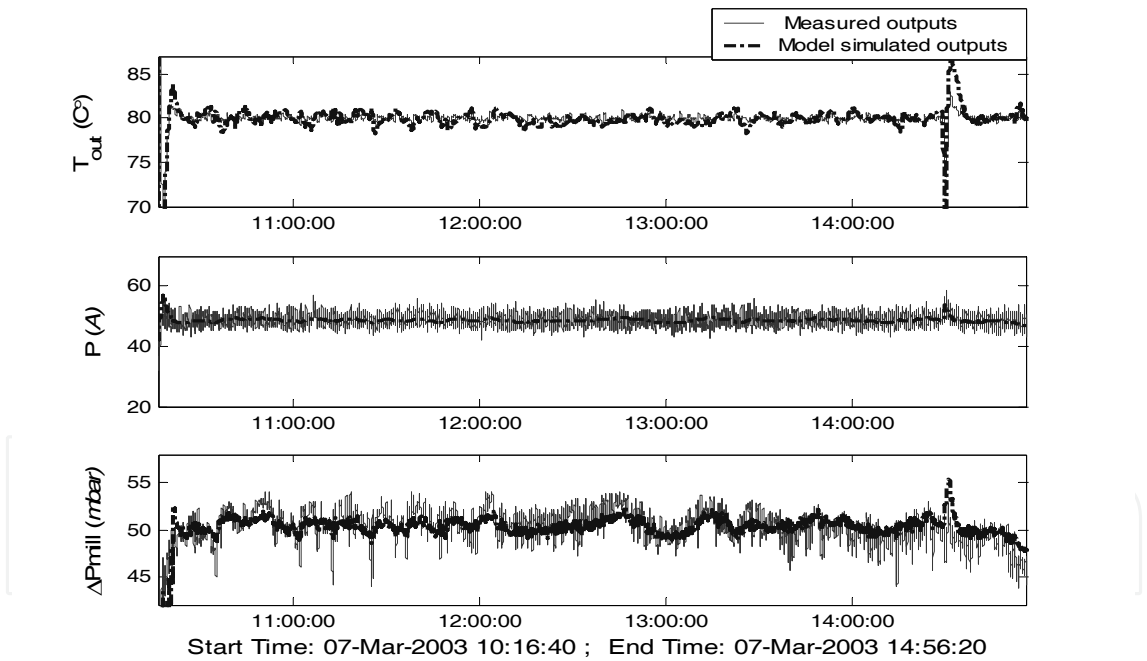Fig. 4. Coal mill model simulation results using data set 1 (normal grinding stage)

Fig. 5. Coal mill model simulation results using the data 2 (normal grinding stage)

From the simulation studies shown above, it can be seen that the model simulated outputs follow the coal mill measured outputs very well during the coal mill normal grinding period (see Figs. 4 and 5).

3. Multi-Segment Coal Mill Model

According to different operating stages of a coal mill, a multi-segment coal mill model is developed, which covers six different segments. The structure of the six-segment model is illustrated in Fig.6, where the whole milling process is divided into six-sessions. All the different working stages of the coal mill system (e.g. the start-up, the steady-state, the shut-down and the idle stages) are considered in this model. The coal mill idle stage is modelled by the model segment 0 in the multi-segment model; coal mill start-up stage is modelled by the model segment I and II; coal mill steady state stage is modelled by the model segment III; coal mill shut-down stage is modelled by the model segment IV and V.
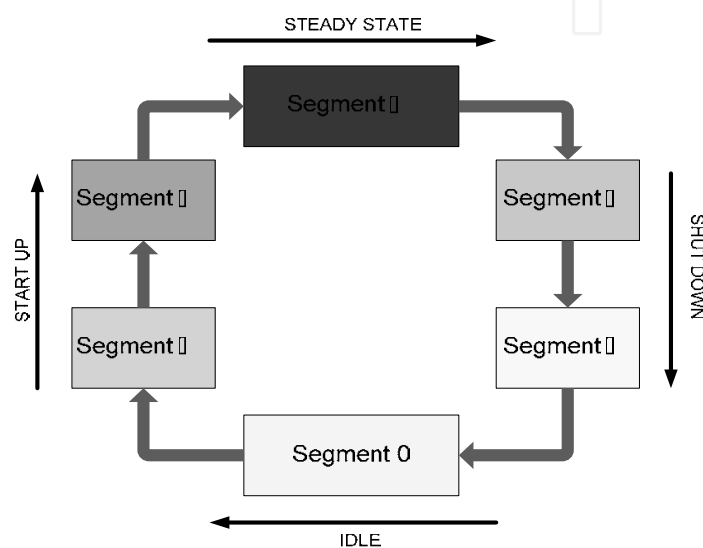

Fig. 6. Six-segment coal mill model

All the models for different segments are connected/switched by a number of operation triggers. The triggers are inherently determined by the mill operation procedures introduced in the last section of this paper. Detailed descriptions for each segment model are given in the following sections.

3.1 Coal Mill Model – Segment I

The coal mill model segment I represents the 'warm-up' process in the mill start-up procedure. During this period, the mill temperature is set to the point of the warming-up value, the PA Fan Damper is opened to the warming-up position, PA different pressure is set to a point to be higher than 4 mbar, and the mill lube oil pump starts running. The switch trigger for this segment is set to be the moment that the Primary Air Damper, the Temperature Damper are just open, which could be represented modularly by the beginning of the Step 3 as shown in Figure 7. The coal mill model segment I is described by Equation (14) ~ Equation (22).

$$W_{air}(t) = 10 \cdot \sqrt{\Delta P_{pa}(t) \cdot \frac{273}{273 + T_{in}(t)} \times \frac{28.8}{22.4}} \qquad (14)$$

$$W_c(t) = K_{fs}.F_s(t) \tag{15}$$

$$W_{pf}(t) = K_{I\_16}\Delta P_{pa}(t)M_{pf}(t) \tag{16}$$

$$M_c(t) = M_c(t_{1\_0}) \tag{17}$$

$$\dot{M}_{pf}(t) = -W_{pf}(t) \tag{18}$$

$$P(t) = 0 \tag{19}$$

$$\Delta P_{mill}(t) = K_{I\_9}\Delta P_{pa}(t) + \Delta P_{mpd}(t) \tag{20}$$

$$\Delta \dot{P}_{mpd}(t) = K_{I\_11}M_{pf}(t) + K_{I\_12}M_c(t) - K_{I\_13}\Delta P_{mpd}(t) \tag{21}$$

$$\dot{T}_{out}(t) = [K_{I\_1}T_{in}(t) + K_{I\_2}]W_{air}(t) - [K_{I\_4}T_{out}(t) + K_{I\_5}] \cdot W_{air}(t) + K_{I\_t}T_{out} \tag{22}$$

where:

$M_c(t_{1\_0})$:   The initial value of mass of coal in mill at the beginning of segment 1 (*kg*)

K_{I_i} :   Model coefficients to be identified respect to model segment I

The other notations are same as explained in Section 2.

Comparing with the normal grinding mill model shown in Section 2 of this paper, there are several significant modifications made, which are: a). The raw coal in mill M_c is set to be constant value $M_c(t_{1\_0})$ through this segment (see Equation 17) since no grinding happens during this segment; b). The changing rate of pulverized coal in mill $\dot{M}_{pf}$ is set to be negatively proportional to the mass flow rate of pulverized coal outlet from mill W_{pf} only (see Equation 18) since there is not any M_{pf} to be generated by grinding during this segment; c). The coal mill current P is set to be zero since the coal mill motor is still off during this segment, where there is no current consumed to run the mill motor; d). The mill temperate is represented by Equation 22, which is similar to Equation 9 shown in Section 2.

3.2 Coal Mill Model – Segment II

The coal mill model segment II represents the 'pre-grinding' process in the mill start-up procedure. During this period, the coal mill grinding motor is started to pre-grind the coal left in the mill, where the coal feeder is still off. The switch trigger of the segment II is set to be the moment that the mill grinding motor is commanded to start which could be represented by the modular - beginning of the Step 7 as shown in Figure 7. The segment IIcoal mill model can be described by Equation (23) ~ Equation (31)

$$W_{air}(t) = 10 \cdot \sqrt{\Delta P_{pa}(t) \cdot \frac{273}{273 + T_{in}(t)} \times \frac{28.8}{22.4}} \tag{23}$$

$$W_c(t) = K_{fs}.F_s(t) \tag{24}$$

$$W_{pf}(t) = K_{II\_16}\Delta P_{pa}(t)M_{pf}(t) \tag{25}$$

$$\dot{M}_c(t) = -K_{II\_15}M_c(t) \tag{26}$$

$$\dot{M}_{pf}(t) = K_{II\_15}M_c(t) - W_{pf}(t) \tag{27}$$

$$P(t) = K_{II\_6}M_{pf}(t) + K_{II\_7}M_c(t) + K_{II\_8} \tag{28}$$

$$\Delta P_{mill}(t) = K_{II\_9}\Delta P_{pa}(t) + \Delta P_{mpd}(t) \tag{29}$$

$$\Delta \dot{P}_{mpd}(t) = K_{II\_11}M_{pf}(t) + K_{II\_12}M_c(t) - K_{II\_13}\Delta P_{mpd}(t) \tag{30}$$

$$\dot{T}_{out}(t) = [K_{II\_1}T_{in}(t) + K_{II\_2}]W_{air}(t) - [K_{II\_4}T_{out}(t) + K_{II\_5}]W_{air}(t) + K_{II\_14}P(t) + K_{II\_t}T_{out} \tag{31}$$

where:

K_{II_i}:   Model coefficients to be identified respect to model segment II

The other notations have the same meanings as described in Section 2.

Comparing with the standard coal milling model shown in Section 2 of this paper, there are some modifications in this segment, which are shown as follows: a). The raw coal in mill M_c is self-reducing due to the pre-grinding of the coal mill system, which is represented by Equation 26; b). The mill temperate is represented by Equation 31, which is derived based on the heat balance principle of the coal mill system as described in Section 2.

3.3 Coal Mill Model – Segment III

The coal mill model segment III represents the steady state milling stage. During this period, the primary air fan, coal mill grinding motor and the coal feeder *etc.* have come into the steady state milling stage. The switch trigger for model segment III is set to be the moment that the mill start-up sequence is completed, which could be represented by the modular at the beginning of the Step 11 as shown in Figure 7. The segment III coal mill model is described by Equation (32) ~ Equation (40).

$$W_{air}(t) = 10 \cdot \sqrt{\Delta P_{pa}(t) \cdot \frac{273}{273 + T_{in}(t)} \times \frac{28.8}{22.4}} \tag{32}$$

$$W_c(t) = K_{fs} \cdot F_s(t) \tag{33}$$

$$W_{pf}(t) = K_{III\_16}\Delta P_{pa}(t)M_{pf}(t) \tag{34}$$

$$\dot{M}_c(t) = W_c(t) - K_{III\_15}M_c(t) \tag{35}$$

$$\dot{M}_{pf}(t) = K_{III\_15}M_c(t) - W_{pf}(t) \tag{36}$$

$$P(t) = K_{III\_6}M_{pf}(t) + K_{III\_7}M_c(t) + K_{III\_8} \tag{37}$$

$$\Delta P_{mill}(t) = K_{III\_9}\Delta P_{pa}(t) + \Delta P_{mpd}(t) \tag{38}$$

$$\Delta \dot{P}_{mpd}(t) = K_{III\_11}M_{pf}(t) + K_{III\_12}M_c(t) - K_{III\_13}\Delta P_{mpd}(t) \tag{39}$$

$$\dot{T}_{out}(t) = [K_{III\_1}T_{in}(t) + K_{III\_2}]W_{air}(t) - K_{III\_3}W_c(t) - [K_{III\_4}T_{out}(t) + K_{III\_5}] \\ \cdot [W_{air}(t) + W_c(t)] + K_{III\_14}P(t) + K_{III\_t}T_{out} \tag{40}$$

where:

K_{III_i}:   Model coefficients to be identified respect to model segment III

The other notations have the same meanings as described in Section 2 .

The equations are same as the normal grinding mill model shown in Section 2, which represents the same stage of the coal milling process - coal milling steady state stage.

3.4 Coal Mill Model – Segment IV

The coal mill model segment IV represents the 'grinding-delay' process in the mill shut-down procedure. During this period, the coal feeder is switched off but the grinding motor is still kept on grinding the coal remained in the mill. The switch trigger of model segment IV is set to be the moment that the coal feeder is completely switched off, which could be represented by the block at the beginning of Step 19 as shown in Figure 8. The segment IV coal mill model is described by Equation (41) ~ Equation (49).

$$W_{air}(t) = 10 \cdot \sqrt{\Delta P_{pa}(t) \cdot \frac{273}{273 + T_{in}(t)} \times \frac{28.8}{22.4}} \tag{41}$$

$$W_c(t) = K_{fs}.F_s(t) \tag{42}$$

$$W_{pf}(t) = K_{IV\_16}\Delta P_{pa}(t)M_{pf}(t) \tag{43}$$

$$\dot{M}_c(t) = -K_{IV\_15}M_c(t) \tag{44}$$

$$\dot{M}_{pf}(t) = K_{IV\_15}M_c(t) - W_{pf}(t) \tag{45}$$

$$P(t) = K_{IV\_6}M_{pf}(t) + K_{IV\_7}M_c(t) + K_{IV\_8} \tag{46}$$

$$\Delta P_{mill}(t) = K_{IV\_9}\Delta P_{pa}(t) + \Delta P_{mpd}(t) \tag{47}$$

$$\Delta \dot{P}_{mpd}(t) = K_{IV\_11}M_{pf}(t) + K_{IV\_12}M_c(t) - K_{IV\_13}\Delta P_{mpd}(t) \tag{48}$$

$$\dot{T}_{out}(t) = [K_{IV\_1}T_{in}(t) + K_{IV\_2}]W_{air}(t) - [K_{IV\_4}T_{out}(t) + K_{IV\_5}]W_{air}(t) + K_{IV\_14}P(t) + K_{IV\_t}T_{out} \tag{49}$$

where:

K_{IV_i}:   Model coefficients to be identified respect to model segment IV

The other notations have the same meanings as described in Section 2.

Comparing with the standard coal milling model shown in Section 2 of this paper, there are several significant modifications made in this segment, which are: a). The raw coal in mill M_c is self-reducing due to the grinding-delay of the coal mill system, which is represented by Equation 44; b). The mill temperate is represented by Equation 49, which is similarly modelled by the heat balance model of the coal mill system same as Equation 9.

3.5 Coal Mill Model – Segment V

The coal mill model segment V represents the 'cool-down' process in the mill start-up period. During this period, the mill temperature is set to the point of the cool-down value, PA fan induction regulator is closed to 15%, and the PA fan damper is set to the mill warming position. The switch trigger for this segment is set to be the moment that the mill temperature is set point to the cool-down value, which is illustrated in the block at the beginning of the Step 21 in Figure 8. The segment V mill model is described by Equation (50) ~ Equation (59).

$$W_{air}(t) = 10 \cdot \sqrt{\Delta P_{pa}(t) \cdot \frac{273}{273 + T_{in}(t)} \times \frac{28.8}{22.4}} \tag{50}$$

$$W_c(t) = K_{fs} . F_s(t) \tag{51}$$

$$W_{pf}(t) = K_{V\_16} \Delta P_{pa}(t) M_{pf}(t) \tag{52}$$

$$\dot{M}_{cDelay}(t) = -K_{V\_15} M_{cDelay}(t) \tag{53}$$

$$M_c(t) = M_c(t_{5\_0}) - [M_{cDelay}(t_{5\_0}) - M_{cDelay}(t)] \tag{54}$$

$$\dot{M}_{pf}(t) = K_{V\_15} M_{cDelay}(t) - W_{pf}(t) \tag{55}$$

$$P(t) = 0 \tag{56}$$

$$\Delta P_{mill}(t) = K_{V\_9} \Delta P_{pa}(t) + \Delta P_{mpd}(t) \tag{57}$$

$$\Delta \dot{P}_{mpd}(t) = K_{V\_11} M_{pf}(t) + K_{V\_12} M_c(t) - K_{V\_13} \Delta P_{mpd}(t) \tag{58}$$

$$\dot{T}_{out}(t) = [K_{V\_1} T_{in}(t) + K_{V\_2}] W_{air}(t) - [K_{V\_4} T_{out}(t) + K_{V\_5}] \cdot W_{air}(t) + K_{V\_t} T_{out} \tag{59}$$

where

$M_c(t_{5\_0})$:   The initial value of mass of coal in mill at the beginning of segment V.

M_{cDelay} :   A term to indicate the grinding delay caused by the inertias of the grinding components

K_{V_i} :   Model coefficients to be identified respect to model segment V

The other notations have the same meanings as described in Section 2.

Comparing with the standard coal milling model shown in Section 2 of this paper, some modifications have been made in the model segment V, which is shown as follows: a) At the beginning of the cool down process, the raw coal in mill M_c is self-reducing for a short period of time due to the grinding-delay caused by the grinding inertias. Afterward it stays at a constant value through the segment as the grinding stops completely. Over the segment V, the raw coal in mill, M_c, is calculated by Equations 53 ~ 54, in which M_{cDelay} indicates the grinding delays caused by the inertias of the grinding components; b) The changing rate of pulverized coal in mill, $\dot{M}_{pf}$, is set to be negatively proportional to the mass flow rate of pulverized coal outlet from mill, W_{pf}, and proportional to the pulverized coal generated by the grinding delays due to the inertias of the grinding motor M_{cDelay}, which is modelled by Equation 55; c) The coal mill current P is set to be zero since the coal mill motor is switched off during this segment; d). The mill temperate is modelled by Equation 59, which is derived based on the heat balance principle.

3.6 Coal Mill Model – Segment 0

The coal mill model segment 0 represents the 'idle' stage of the milling process. During this period, the mill grinding motor, the coal feeder, the lube oil pump *etc.* are switched off. This segment model represents the natural cool down process of the coal mill system. The switch trigger for this segment is set to be the moment that the coal mill shut-down sequence completed, which is illustrated in Figure 7 (Step 0). The segment coal mill model is described by Equation (60) ~ Equation (67).

$$W_{air}(t) = 10 \cdot \sqrt{\Delta P_{pa}(t) \cdot \frac{273}{273 + T_{in}(t)} \times \frac{28.8}{22.4}} \tag{60}$$

$$W_c(t) = K_{fs}.F_s(t) \tag{61}$$

$$W_{pf}(t) = 0 \tag{62}$$

$$M_c(t) = M_c(t_{0\_0}) \tag{63}$$

$$M_{pf}(t) = M_{pf}(t_{0\_0}) \tag{64}$$

$$P(t) = 0 \tag{65}$$

$$\Delta \dot{P}_{mill}(t) = K_{0\_9} \Delta P_{pa}(t) + K_{0\_p} \Delta P_{mill}(t) \tag{66}$$

$$\dot{T}_{out}(t) = [K_{0\_1}T_{in}(t) + K_{0\_2}]W_{air}(t) - [K_{0\_4}T_{out}(t) + K_{0\_5}] \cdot W_{air}(t) - K_{0\_e}(T_{out} - T_e) + \frac{K_{0\_t}}{M_c(t) + M_{pf}(t)}T_{out} \tag{67}$$

where

$M_c(t_{0\_0})$:   The initial value of mass of coal in mill at the beginning of segment 0 (*kg*)

$M_{pf}(t_{0\_0})$:   The initial value of pulverized mass of coal in mill at the beginning of segment 0 (*kg*)

T_e: Temperature of the environment (℃)

K_{0_i}:   Model coefficients to be identified respect to model segment 0

The other notations have the same meanings as described in Section 2.

In this segment, all the components of the coal mill system are off, there is no grinding and blowing happens, so that M_c, M_{pf} etc. should be constants through this segment. Further more, the coal mill temperature and the pressure are gradually dropping as described in Equations 66 and 67.

Comparing with the normal grinding coal milling model shown in Section 2, some modifications are made which are: a) In segment 0, all the components of the coal mill system is idle, so that M_c, M_{pf}, and P are set to be constants or zero, which are described by Equations 61 ~ 64; b) PA fan damper and coal mill valves are closed solidly during the idle stage, so coal mill pressure is naturally dropping, which is indicated in Equation 66. c) Equation 67 represents the naturally self-cooling process of the coal mill system through this segment. It is developed corresponding to the heat balance of the coal mill system as well, where the term $K_{0\_e}(T_{out} - T_e)$ represents the heat lost to the environment from the mill system via the mill body and valves *etc*.

4. Parameter identification and model validation

After the multi-segment coal mill model has been structured, the next task is to identify the unknown parameters associated with the six segment model. Then it is necessary to conduct the simulation to compare the performance of the new multi segment mill model. The validation of the new multi-segment model should be conducted as well. This section covers system parameter identification, simulation studies, and model validation.

4.1 Parameter identification and simulation study

A number of on-site data sets that cover the whole processes are chosen for parameter identification and simulations studies. An example using the data collected from a power plant is given as follows. The results obtained have been compared with the previous single grinding model, especially, the periods of start-up, normal grinding operation, shut-down and idle periods. The system parameters identified using this set of data are summarised in Table 3 ~ Table 8.

Identified coefficients of model Segment I		
$K_{I\_1} = 0.00072541\,773658$	$K_{I\_2} = 0.04000000\,000000$	$K_{I\_4} = 0.00057219\,041327$
$K_{I\_5} = -0.0167545\,8545105$	$K_{I\_9} = 5.60489077\,201246$	$K_{I\_11} = 0.00012470\,913837$
$K_{I\_12} = 0.00002265\,487671$	$K_{I\_13} = 0.07943094\,801093$	$K_{I\_16} = 0.00010750\,292422$
$K_{I\_t} = -0.01329789\,102972$		

Table 3. Identified coefficient for model segment I

Identified coefficients of model Segment II		
$K_{II\_1} = 0.00080694\,873686$	$K_{II\_2} = 0.03085438\,464572$	$K_{II\_4} = 0.00056967\,623620$
$K_{II\_5} = -0.01389776\,245975$	$K_{II\_6} = 0.00658219\,296696$	$K_{II\_7} = 0.00500000\,000000$
$K_{II\_8} = 29.46408084\,086195$	$K_{II\_9} = 6.32278529\,817438$	$K_{II\_11} = 0.00008854\,456902$
$K_{II\_12} = 0.00036159\,145893$	$K_{II\_13} = 0.02000000\,000000$	$K_{II\_14} = 0.09036443\,542765$
$K_{II\_15} = 0.00068284\,301758$	$K_{II\_16} = 0.00144872\,777708$	$K_{II\_t} = -0.0566973\,9327072$

Table 4. Identified coefficient for model segment II

Identified coefficients of model Segment III		
$K_{III\_1} = 0.00061927\,802462$	$K_{III\_2} = 0.08961428\,118773$	$K_{III\_3} = 0.00383781\,469345$
$K_{III\_4} = 0.00155335\,789736$	$K_{III\_5} = -0.08634812\,577403$	$K_{III\_6} = 0.01712514\,044766$
$K_{III\_7} = 0.00293718\,07148$	$K_{III\_8} = 30.17329476\,338669$	$K_{III\_9} = 5.54900011\,072344$
$K_{III\_11} = 0.00170000\,000000$	$K_{III\_12} = 0.00056524\,986674$	$K_{III\_13} = 0.08677360\,557200$
$K_{III\_14} = 0.03250567\,038921$	$K_{III\_15} = 0.00513313\,270266$	$K_{III\_16} = 0.00261803\,749309$
$K_{III\_t} = -0.0572445\,3482491$		

Table 5. Identified coefficient for model segment III

Identified coefficients of model Segment IV		
$K_{IV\_1} = 0.00100000\,000000$	$K_{IV\_2} = 0.03814538\,663991$	$K_{IV\_4} = 0.00110256\,287195$
$K_{IV\_5} = -0.0127384\,9970596$	$K_{IV\_6} = 0.00502786\,796442$	$K_{IV\_7} = 0.01271951\,516693$
$K_{IV\_8} = 26.1933187\,675971$	$K_{IV\_9} = 6.02804165\,980328$	$K_{IV\_11} = 0.00001000\,000000$
$K_{IV\_12} = 0.00021827\,836644$	$K_{IV\_13} = 0.00594054\,009917$	$K_{IV\_14} = 0.06082368\,997338$
$K_{IV\_15} = 0.00500000\,000000$	$K_{IV\_16} = 0.00284411\,656238$	$K_{IV\_t} = -0.0495682\,7263247$

Table 6. Identified coefficient for model segment IV

Identified coefficients of model Segment V		
$K_{V\_1} = 0.00093729\,490970$	$K_{V\_2} = 0.03715004\,727992$	$K_{V\_4} = 0.00109096\,339731$
$K_{V\_5} = -0.0174981\,6468507$	$K_{V\_9} = 5.97603398\,05287$	$K_{V\_11} = 0.00001000\,000000$
$K_{V\_12} = 0.00001000\,000000$	$K_{V\_13} = 0.12948317\,846770$	$K_{V\_15} = 0.15002431869507$
$K_{V\_16} = 0.00031424\,102569$	$K_{V\_t} = -0.0084228\,3447028$	

Table 7. Identified coefficient for model segment V

Identified coefficients of model Segment 0		
$K_{0\_1} = 0.00153223\,119637$	$K_{0\_2} = 0.05315223\,812253$	$K_{0\_4} = 0.00239019\,497476$
$K_{0\_5} = -0.0135178\,0190605$	$K_{0\_9} = 0.35000000\,00000$	$K_{0\_p} = -0.0586331\,9829717$
$K_{0\_t} = -0.0974950\,6071560$	$K_{0\_e} = 0.00027743\,032875$	

Table 8. Identified coefficient for model segment 0

The simulation results using the data collected from a power plant are shown at Fig.7 ~ Fig.8, which covers all the start-up, normal running, shut-down, idle periods.
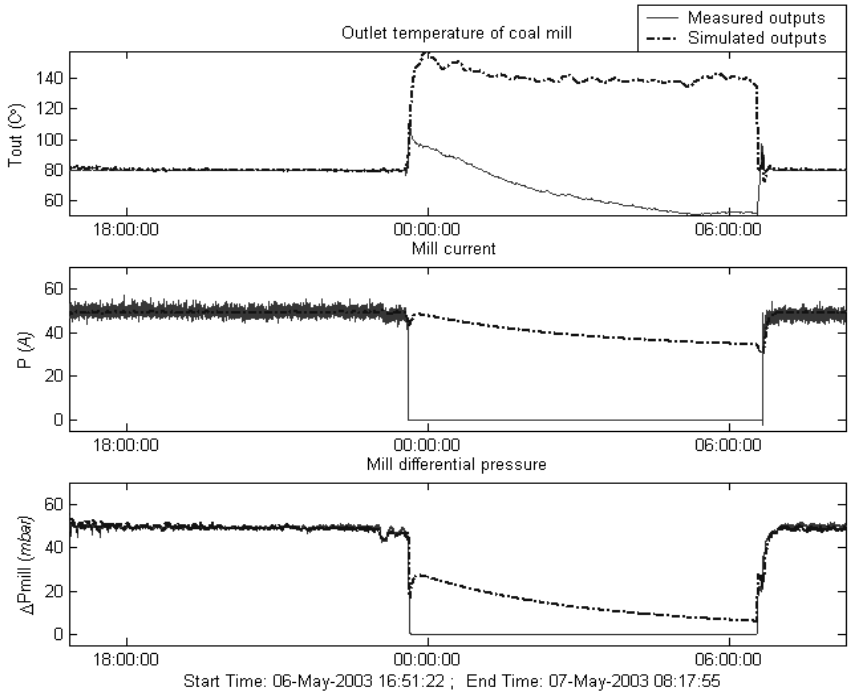
Fig. 7. Simulation results for the overall processes using coal mill single model
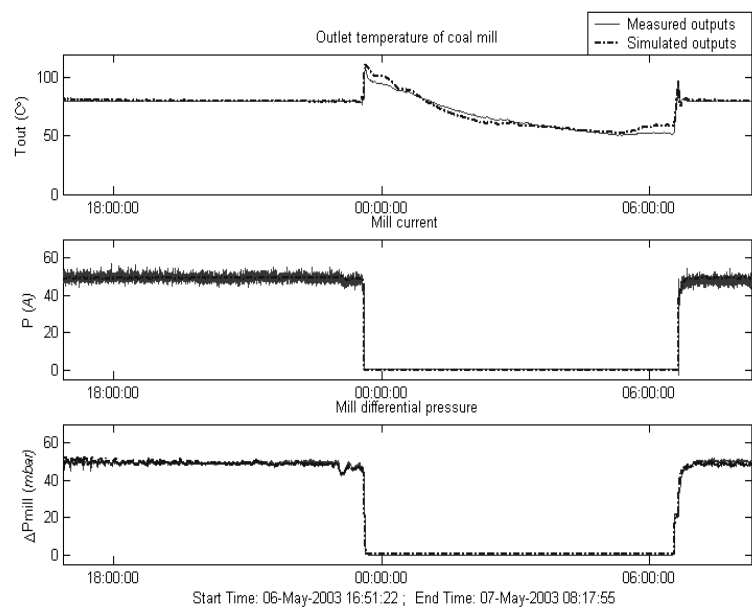
Fig. 8. Simulation results for the overall processes using multi-segment model

From the simulation results shown in Fig.7 and Fig.8, it is clearly that the six segment model gives the predicted system output more close to the measured system output comparing with the the single grinding mill model. Especially, during the periods of starting-up and shutting-down, the multi-segment model gives the accurate results while the single grinding model fails to predict the system outputs.

4.2 Model validation
The coal mill multi-segment model's validations have been carried out based on a number of on-site data sets that include start-up/shut-down dynamic processes. The validation results are shown in Fig. 9 and Fig. 10. The results are convincing.
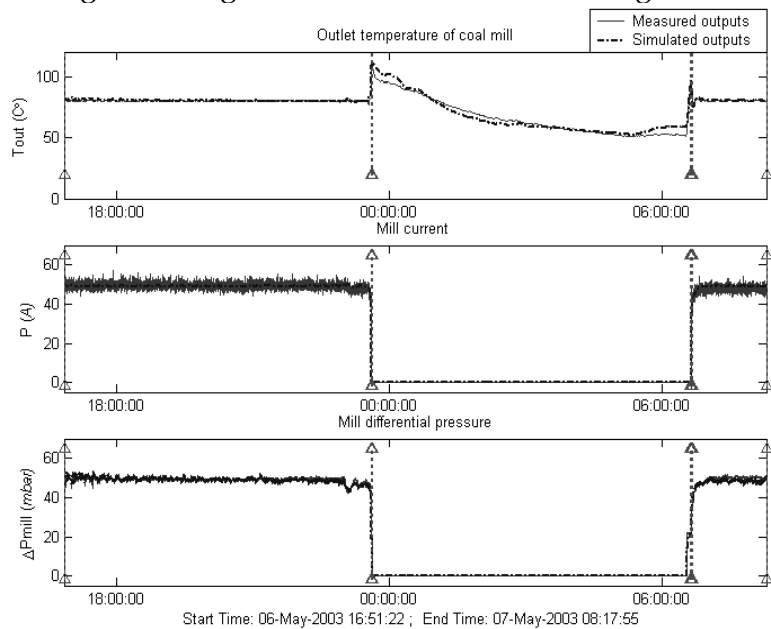
Fig. 9. Model validation uing a different data set

5. Mill diagnostic and fault detection

The model developed has been on-line implemented to give a real-time mill predicted outputs. The on-line model can be used for mill condition monitoring in the following ways: 1) to compare the mill measured and predicted outputs. If there are unusual differences between these two variables, the fault may occure and alarm should be raised. 2) to monitor the intermideat variable – coal in mills. If the coal inside the mill increases to an unusual high level, that indicates that too much coal inside the mill, which may cause problems and they should be monitoed closely. 3) to identify any unusual changes of model parameters. From the simulation study shown in the above section, it is noticed that the model parameter may need to be updated more frequently which is due to coal quality changes or biomass material mixture. This inspired a new idea for identification of the key model parameters related to the key variables in a short parameter updating period. This idea has been applied to Tube-ball mill based on a modified mathematical model.
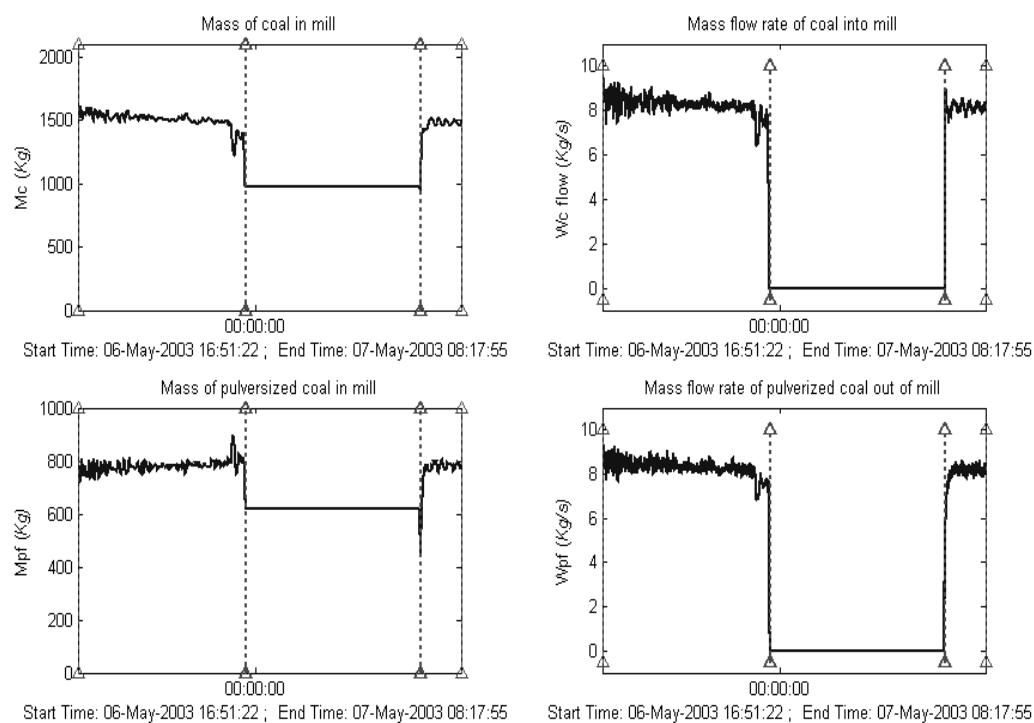

Fig. 10. Model validation using a different data set, intermidiate variables

Further study has been carried out to investigate if this parameter updating scheme can be adapted for condition monitoring. The parameter K_t in (9) is chosen to be updated in every 5 minutes as shown. The idea underline for this adaptation is to see any rough change or large deviation from the base value can indicate the mill condition changes. From the simulation, it is noticed for a particular data set, the parameter K_t has an extreme sharp change during a period of time. Also, the mill performance during this period of time varied violently. The measured and predicted responses are shown in Fig. 11. To identify what has happened at the power plant, we have had a discussion with the

plant engineers. It is confirmed that the abnormal variation is caused by the big chunk of bio-mass fuel coming into the mill and melted later on. This is confirmed from other cases as well. So the potential uneven distribution of biomass mixing could be possibly identified and the potential fire incident can be picked up early to avoid mill broken down.

6. Conclusion

A complete multi-segment coal mill model was presented in this chapter. The model considered heat, mass, power balances involved in the milling process. The mill model can represent the whole milling process including the start-up and shut-down periods. Then the model is validated using on-line measurement. By adopting this multi-segment coal mill model in power plants, the power plant engineers will be offered a non-stop model for monitoring the coal mill system The model can estimate the inmeasurable intermediate variables which is very valuable for condition monitoring and fault detection. So the model will contribute for better mill control actions and prediction of system faults. The multi-segment model is implemented on-line usiing C++ language. Based on the mathematical model and its on-line implementation, a new diagnose method is introduced to diagnose the mill operation condition. From the current results, the model could predict the uneven mixture of biomass material with coal inside the mill from the variation trend of the key parameters, which can then predict potential fire incidents.
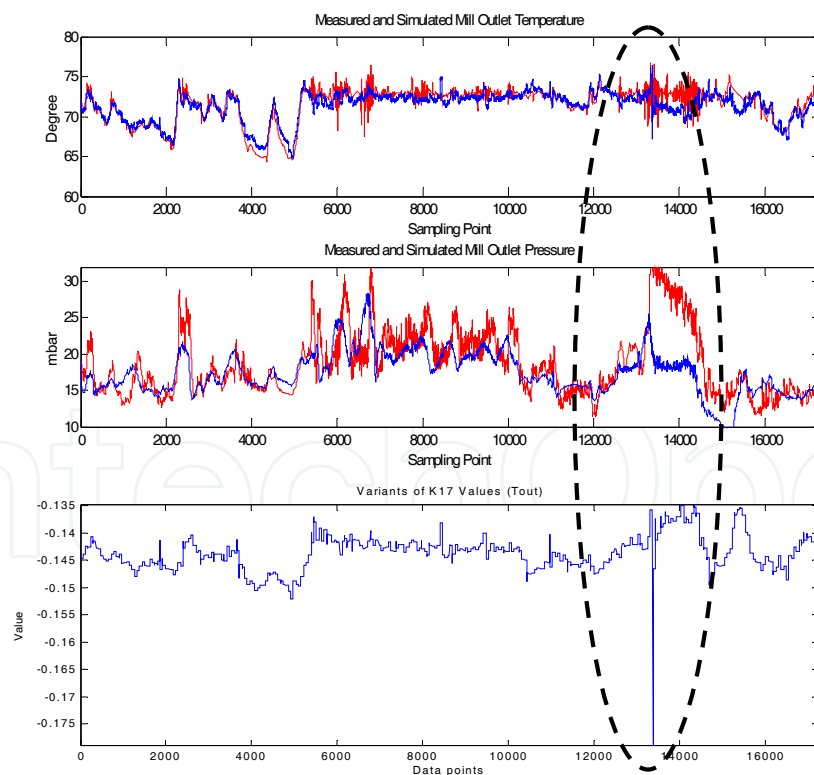

Fig. 11. Model simulated outputs, with K_t re-identified in very 5 minutes

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