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Modeling and Parameter Identification of Coal Mill

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ABSTRACT

The coal mill used in the coal-fired power plants is modeled in view of the controller design rather than the educational simulator. The coal mass flow and the outlet temperature are modeled by reinvestigating the mass balance and heat balance models physically. The archived data from a plant database are utilized to identify the model parameters. It can be seen that the simulated model outputs are well matched with the measured ones. It is also expected that the proposed model is useful for the controller design.

Keywords: Coal mill, Pulverizer, Modeling, Parameter identification

1. Introduction

The coal mills grind and dry the moisturized raw coal and transport the pulverized coal to the boiler burner. Their poor dynamic performance causes a slow load take-up rate and a regular plant shutdown[1], [2]. Fast response is desired to maintain power system frequency, boiler pressure, and temperature. Control performance can be improved by modeling the coal mill properly for control purpose. It is necessary to model the coal flow and the pulverized coal temperature [3], [4].

Several coal mill models have been developed in the literature. The transfer functions of coal mill are experimentally measured in [5, 6] . The authors assume that the coal mill is a linear system. Total mass air flow and outlet temperature are modeled as coupled first-order transfer functions with time delay. Since small step change in the input was used, the startup and shutdown conditions could not be modeled. Some nonlinear models with physical meaning are developed by using overall mass balance and heat balance analysis[1],[3]. Physical relationships are developed and the parameters are identified with a genetic algorithm based onsite measurements. The coal mill is modeled differently and identified according to the operating conditions like startup, shutdown, and steady states[3]. In order to consider the grinder, separator, and classifier to express the mill operation properly, a third order model for the coal mass is presented in [2]. A more complicated model is proposed, in which the internal structure of a coal mill is divided into five zones and the coal is divided into several size groups [4]. Although the model expresses a coal mill more precisely, the system has a higher order and it may be difficult to design the controller. The model outputs are not proven with the onsite measurements.

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It can be seen in the literature that modeling the pulverized coal-air mixture temperature has not been advanced. Almost all the models are based on heat balance where the coal mill body is considered as a lumped thermal mass[1]-[4], so that temperature dynamics cannot be correctly expressed for abrupt, large changes like startup and shutdown. Modeling coal mass flow has been advanced and has become a higher order system for expressing the internal status of the coal mill. If the model's order becomes higher and more complicated, the dynamics of coal mass flow can be more accurately expressed. It is, however, necessary to make a trade-off between simple and complicated models in view of controller design.

In this paper, the coal mill is modeled based on physical insight and the model parameter values are obtained by using the grey nonlinear model in Matlab System Identification Toolbox. The archived data from a plant database are used to identify the parameters and to be compared with the model outputs. The coal mass flow is modeled differently based on the mass balance model. The pulverized coal temperature is modeled by considering the coal and the pulverized coal as a lumped thermal mass. The operating conditions like startup, shutdown, and steady states can be correctly expressed with only one model, unlike the conventional model in [3]. The proposed model is verified by comparing the measured with the simulated outputs during startup and shutdown conditions.

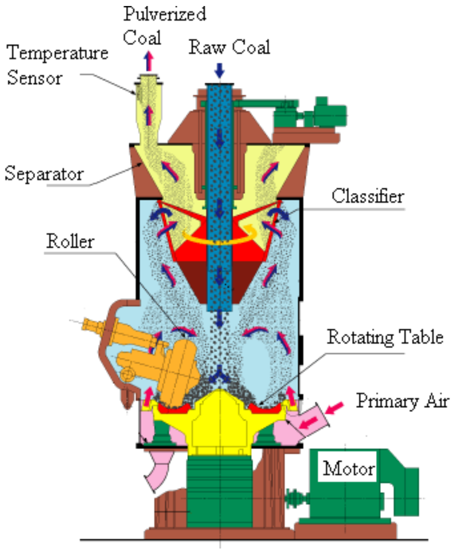


Fig. 1. Sectional view of MBF coal mill.

2. Modeling of Coal Mill

The function of a coal mill is to supply the dry and the pulverized coal to the boiler burner. Fig. 1 shows a sectional view of MBF coal mill considered in the study. Raw coal is introduced near the center of the grinding table through the coal feed pipe. The coal moves outward on the rotating table and it is ground under the roller. The primary air is generated by mixing hot and cold air, and it is introduced through an opening near the base of the coal mill. The primary air flows upward at the grinding table periphery and the air is mixed with the pulverized coal. Some of the larger particles fall back on the table and they are ground again. Finer particles of the pulverized coal pass into a classifier. In the classifier, the oversized coal particles fall back to the grinding table and the finer particles are carried through the outlet of the coal mill to the burner of the boiler.

The inputs of the coal mill model are coal flow into the mill, primary air flow, primary air inlet temperature and primary air differential pressure, which are used in practice as control inputs to improve the coal mill performance. The grinding motor power consumption can be considered as an additional input variable for a heating source. The measured output variables are mill differential pressure and outlet temperature. The coal mill model is derived from physical mass balance and heat balance relationships separately. In order to obtain the simple model for control purpose, it is assumed that the pulverized mechanism in the mill is simplified and the classification operation is not included, and the coal is grouped into pulverized and unpulverized.

The mass balance model of the coal mill is shown in Fig. 2 and it shows the dynamic process of coal flow during the mill operation. The raw coal mass flow is introduced into the mill and it generates unpulverized coal mass. Some coal mass is converted into pulverized mass through grinding and the pulverized coal mass flow is generated by the air differential pressure. The dynamic equations for coal mass can be expressed as

$$\frac{dM_c}{dt} = W_c - k_c M_c \tag{1}$$

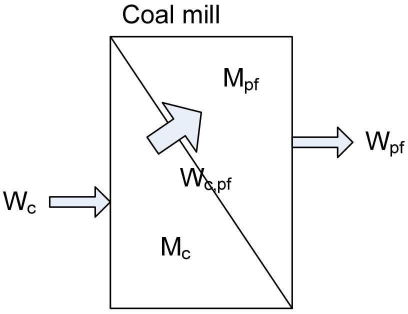


Fig. 2. Mass balance model of coal mill.

$$\frac{dM_{pf}}{dt} = k_c M_c - W_{pf} \tag{2}$$

where

M_c, M_{pf} : coal mass and pulverized mass in mill [kg];

W_c, W_{pf} : raw coal mass flow input and pulverized mass flow output [kg/s];

k_c : conversion rate factor from raw coal to pulverized coal [1/s].

The state variables are the coal and the pulverized mass in the mill, which are not measurable. The pulverized coal mass flow depends on the pulverized coal mass in the mill and the air differential pressure, such as

$$W_{pf} = k_{pf} \Delta P_{pa} M_{pf} \tag{3}$$

where ΔP_{pa} is primary air differential pressure [mmH_2O] and k_{pf} denotes a coefficient. The differential pressure between the inlet and outlet of the mill can be measured and it depends on the primary air differential pressure, coal mass and pulverized coal mass in the mill. The following equation can be derived, by considering time delay of the mill differential pressure, as

$$\frac{d\Delta P_{mil}}{dt} = -k_{mil}\Delta P_{mil} + k_{ppf} M_{pf} + k_{pc} M_c + k_{ppa}\Delta P_{pa} \tag{4}$$

where ΔP_{mil} is in [mmH_2O] and the coefficients, k_{mil}, k_{ppf}, k_{pc}, and k_{ppa}, have appropriate units.

The heat balance model is shown in Fig. 3. The heat exchange is considered between the coal mill body and its contents such as coal mass and pulverized coal mass unlike [1-4]. It is assumed that the mill body includes the internal structure such as roller and rotating table, etc. It is assumed that the pulverized and the unpulverized coal mass are lumped thermal masses and their temperatures are equal to the measured outlet temperature. The heat balance can then be written as,

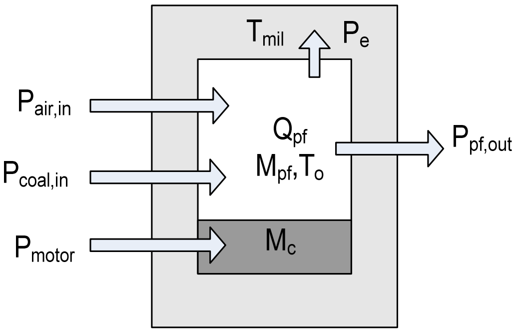


Fig. 3 Heat balance model of coal mill.

$$C_{eq}(M_c + M_{pf})\frac{dT_o}{dt} = P_{air,in} + P_{coal,in} + P_{mot} - P_e - P_{pf,out} \tag{5}$$

where

C_{eq}: equivalent specific heat constant of the lumped thermal mass [kJ/kg·°K];

T_o: outlet temperature of the mill [°C].

The input heat is carried by the primary air flow $P_{air,in}$, the coal flow $P_{coal,in}$ and the heat loss of grinding motor in the mill P_{mot}. They can be expressed as

where

$$P_{air,in} = C_a W_a T_{in} \tag{6}$$

$$P_{coal,in} = C_c W_c T_{rc} \tag{7}$$

where

C_{eq}, W_a : primary air flow [kg/s];

T_{in}: primary air temperature [°C];

C_a: air specific heat constant, usually 1.008 [kJ/kg·°K];

W_c: raw coal flow [kg/s], which contains moisture;

T_{rc}: raw coal temperature [°C];

C_c: coal specific heat constant, 1.17 (dry coal) or 1.38 (with 5 % water) [kJ/kg·°K].

The raw coal flow W_c usually contains water and the coal specific heat constant C_c varies with moisture content. The heat loss of the grinding motor in the mill can be represented as,

$$P_{mot} = C_{mot} I_{mot} \tag{8}$$

where I_{mot} means the motor current [A] and C_{mot} is heat conversion constant [kW/A].

Since the pulverized coal flow equals to the raw coal flow in steady state, the heat of air and pulverized coal can be written as

$$P_{pf,out} = C_{acm}(W_a + k_{pf}\Delta P_{pa} M_{pf})T_o \tag{9}$$

where C_{acm} denotes an equivalent specific heat constant of air and pulverized coal and the pulverized coal flow in (3) is used. The heat radiated from the equivalent mass to the mill body can be expressed by

$$P_e = k_e(T_o - T_{mil}) \tag{10}$$

where T_{mil} denotes the temperature of coal mill body and k_e is a heat transfer constant [kW/°K]. In practice, the constant k_e depends on the inner surface area of the mill and its material. Substituting equations (6) ~ (10) into (5) yields

$$\begin{aligned} C_{eq}(M_c + M_{pf})\frac{dT_o}{dt} &= C_a W_a T_{in} + C_c W_c T_{rc} + C_{mot} I_{mot} \\ &- k_e(T_o - T_{mil}) - C_{acm}(W_a + k_{pf}\Delta P_{pa} M_{pf})T_o \end{aligned} \tag{11}$$

Equations (1), (2), (4), and (11) model the coal mill. In order to identify the related parameters, these equations can be rewritten as,

$$\frac{dM_c}{dt} = -k_c M_c + W_c \tag{12}$$

$$\frac{dM_{pf}}{dt} = k_c M_c - k_{pf}\Delta P_{pa} M_{pf} \tag{13}$$

$$\frac{d\Delta P_{mil}}{dt} = k_{pc} M_c + k_{ppf} M_{pf} - k_{mil}\Delta P_{mil} + k_{ppa}\Delta P_{pa} \tag{14}$$

$$\begin{aligned} C_{eq}(M_c + M_{pf})\frac{dT_o}{dt} &= C_a W_a T_{in} + C_{cm} W_c + C_{mot} I_{mot} \\ &- k_e(T_o - T_{mil}) - C_{acm}(W_a + k_{pf}\Delta P_{pa} M_{pf})T_o \end{aligned} \tag{15}$$

where $C_{cm} = C_c T_{rc}$. There are four state variables, M_c, M_{pf}, ΔP_{mil}, and T_o. The mill differential pressure and outlet temperature are measurable. The model input variables are W_c, W_a, T_{in}, ΔP_{pa}, and I_{mot}. All inputs can be measured.

Compared to the conventional model in [1] and [3], the proposed coal mill model has following characteristics. In the conventional model, an intermediate differential pressure is taken as a state variable and the mill differential pressure is given by a function of intermediate pressure and primary air differential pressure. The intermediate pressure may have no physical meaning and has difficulty in choosing the initial state value. In the proposed model given in (14), the mill differential pressure is taken as a state variable. The mill differential pressure is measurable, so that it is easier to choose the initial state from the on-site data record. The thermal model in (15) has a similar structure to the conventional one. The thermal mass is considered as the pulverizer body including the contents like coal, roller etc., whose weight is approximately above 22 tons. The outlet temperature is actually much different from the pulverizer body temperature. In the proposed model, the thermal mass is taken as coal mass in the mill.

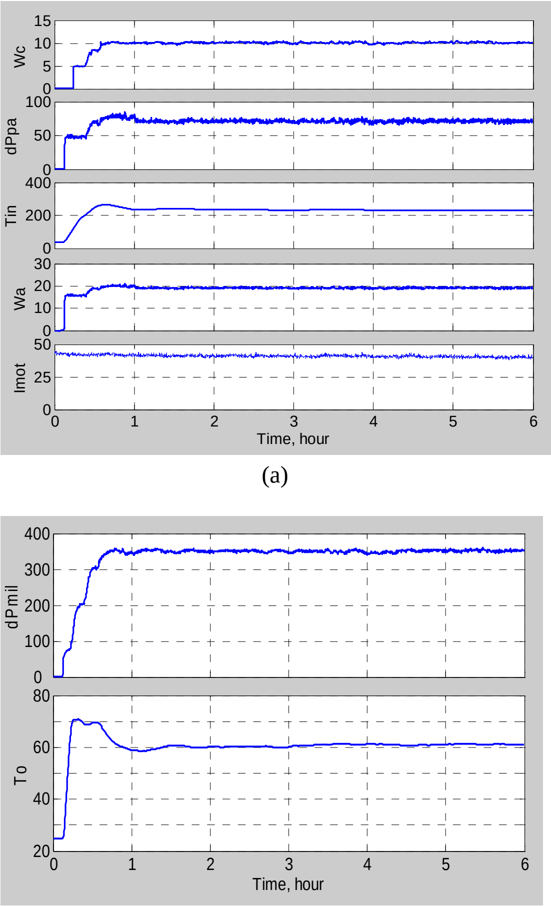
3. Parameter estimation and model verification

The parameters of the proposed coal mill model are estimated by using the Matlab System Identification tool. Based on the measured input and output waveforms, six parameters for mass model and seven parameters for temperature model are estimated with a parameter identification algorithm: k_c, k_{pf}, k_{pc}, k_{ppf}, k_{mil}, k_{ppa}, C_{eq}, C_a, C_{cm}, C_{mot}, k_e, T_{mil}, and C_{acm}. The parameters such as k_c, C_{cm}, T_{mil}, and C_{acm} depend on the operating condition like the coal moisture and temperature. Thus, their values vary slightly. Since the model is nonlinear and the structure is known, the grey nonlinear model function *idnlgrey*( ) is utilized and the parameters are estimated by using the function *pem*( ) [11]. The on-site data sets, which include the startup and shutdown waveforms, are collected from the 575 MW thermal power plants in Korean Western Power Co. Ltd. In normal condition, five pulverizers are operated and one is in rest. When the pulverizer D is shut down and the pulverizer F is started up, the related data are collected.

There are six coal mills in a unit of coal-fired power plant. Among them, five coal mills operate in normal condition. For maintenance, one mill is in rest for a period. The startup and shutdown transient periods occur during the mill exchange so that they are usually negligible when compared with the normal operation of one coal mill and the steady state performance period is more important than the transient periods.

Fig. 4 shows the measured input and output waveforms while the pulverizer F is being started up. The model parameters are estimated by using Matlab function and they are given in Table 1. The initial values are properly chosen and searched in the range [0, ∞). Fig. 5 compares the simulated and measured output waveforms. The simulated mill differential pressure is well matched with the measured one. The temperature dynamics is much sensitive to the coal mass in the mill as seen in (15). The coal mass in the mill cannot be measured and the value is unknown before the operation. It is difficult to choose the initial states in (12), (13), and (15). Hence, there exists a slight discrepancy between measured and simulated outlet temperatures, which may be reduced if the initial values are chosen as the final state values of the coal mass during the shutdown period. Fig. 6 shows the measured input and output waveforms while the pulverizer D is shut down. The estimated model parameters are shown in Table 1. The initial values are properly chosen and searched in the range [0, ∞). Fig. 7 compares the simulated and the measured output waveforms. The model outputs are well matched with the measured ones during both steady state and shutdown periods. It can also be seen that we can obtain the immeasurable states and output like coal mass, pulverized coal mass in the mill and the pulverized coal flow. Compared with the results of the conventional model in [1] and [3], the proposed model can express the coal mill more accurately.

The estimated parameter values given in Table 1 can be considered to be well matched with the actual ones. For



(a)

(b)

Fig. 4. Measured waveforms during startup period, (a) inputs (W_c: kg/s, dP_{pa}: mmH$_2$O, T_{in}: °C, W_a: kg/s, I_{mot}: A), (b) outputs (dP_{mil}: mmH$_2$O, T_o: °C).

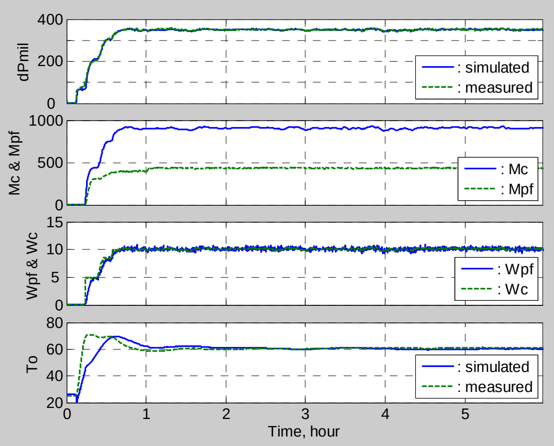
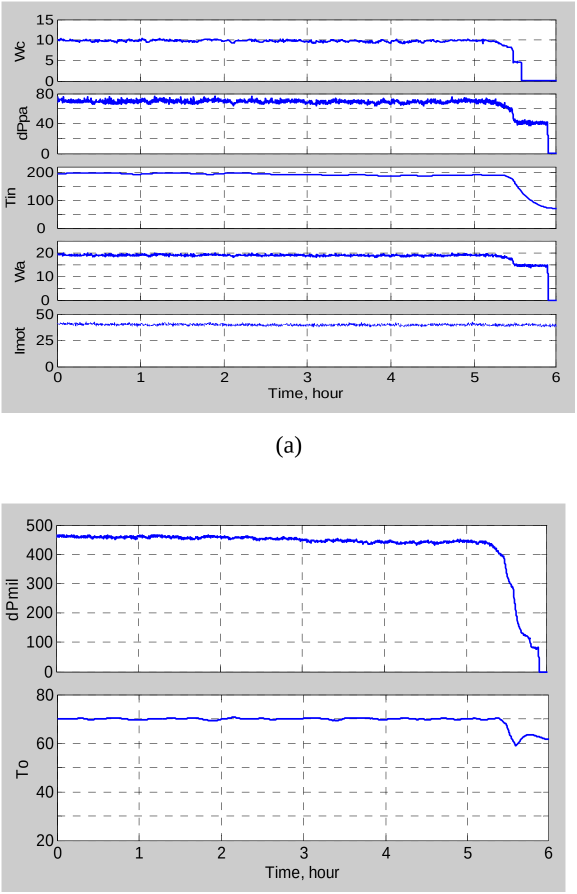


Fig. 5. Comparison between measured and simulated waveforms during startup period (dP_{mil}: mmH$_2$O, M_c & M_{pf}: kg, W_c & W_{pf}: kg/s, T_o: °C).



(a)

(b)

Fig. 6. Measured waveforms during shutdown period, (a) inputs (W_c: kg/s, dP_{pa}: mmH$_2$O, T_{in}: °C, W_a: kg/s, I_{mot}: A), (b) outputs (dP_{mil}: mmH$_2$O, T_o: °C).

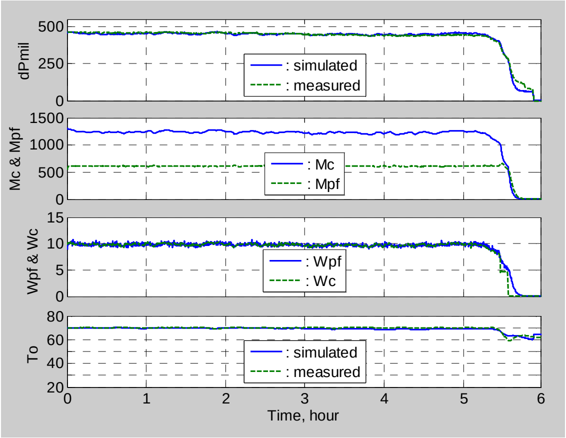


Fig. 7. Comparison between measured and simulated waveforms during shutdown period (dP_{mil}: mmH$_2$O, M_c & M_{pf}: kg, W_c & W_{pf}: kg/s, T_o: °C).

example, the value of air specific heat constant C_a is about 1.008 kJ/kg·°K, which is near the estimated values at startup and shutdown conditions. Before the coal mill begins to operate, the temperature of mill body T_e is near the ambient temperature. Its estimated value is about 26 °C. While the mill operates, the actual body temperature is about 50 °C and the estimated value is about 54.5 °C.

Table 1. Estimated parameter values.

Parameter	Unit	Value at startup	Value at shutdown
k_c	1/s	0.0111481	0.00793269
k_{pf}	1/s·mmH$_2$O	0.000326882	0.000231083
k_{pc}	mmH$_2$O/s·kg	0.0141358	0.0212569
k_{ppf}	mmH$_2$O/s·kg	0.0207428	0.0213403
k_{mil}	1/s	0.0855736	0.112551
k_{ppa}	1/s	0.114809	0.165189
C_a	kJ/kg·°K	1.01372	1.10102
C_{cm}	kJ/kg	23.3922	17.3807
k_e	kW/°K	16.247	37.883
C_{acm}	kJ/kg·°K	2.36429	1.80868
T_e	°C	26.1872	54.5876
C_{mot}	kW/A	0.494407	0.526108

4. Conclusions

The coal mill used in the coal-fired power plants is modeled for the controller design. The coal mass flow and the outlet temperature are modeled by physically reinvestigating the mass balance and heat balance models. The model parameters are identified by using the archived data from a plant database. The simulated model outputs are well matched with the actual ones. The proposed model can accurately express the mill operations, even though the conventional model has different structures according to the operating conditions like startup, shutdown, and normal states. It can be expected that the proposed model is useful for the controller design.

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