Multivariable predictive circulating fluidized bed combustor control

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Abstract

The Honeywell Advanced Combustion Control (ACC) system for the circulating fluidized bed boilers (CFB) is described. ACC is a part of Advanced Energy Solutions (UES) which is based on the predictive control technology. The CFB model is represented by a system of non-linear ordinary differential equations which capture the key CFB behavior. The model exhibits strong cross-interactions of process variables. The control based on single input single output PID loops is difficult therefore. In contrast, it is shown the CFB can be successfully controlled using the multiple-inputs multiple-outputs (MIMO) model. The bed temperature, boiler power and the oxygen concentration in the flue gas can be controlled simultaneously and independently via the primary and secondary air flows and the fuel supply rate.

Keywords: Circulating fluidized bed, control oriented model, combustion control, predictive control, Honeywell Advanced Energy Solutions.

Introduction

Fluidized bed combustors (FBC) burn solid fuels in a turbulent mixture of gases, fuel particles and inert particles suspended in an upward strong stream of primary air. They evolved from effort to achieve combustion temperatures below the threshold of nitrogen oxides forming, which is approximately at 1400ºC (Howard 1983). In FBC, the flue gases can be in effective contact with sulfur absorbents, such as limestone. The desulphurization mechanism can capture more than 95% of the SO_x formed. As a result, the FBC can be fired with low quality coals, turfs, and biomass (Basu and Frazer 1991) producing low pollutants concentration.

Quoting (Bittanti et al. 2000): `Fluidized beds are remarkably difficult to model, since the process is characterized by a series of complex thermal and mechanical interactions'. In spite of the usual practice, this text presents a successful FBC boiler control application based on the predictive control technology using the model described.

The circulating fluidized bed combustor (CFB) shown on Figure 1 represent the most sophisticated FBC type. The retention of ashes in the cyclone and its reinjection to the bed lead to lower loss of unburned fuel particles and more efficient limestone utilization. Except of improved efficiency, the principles as well as the main characteristics are similar to those of the other FBC types.

We have found the CFB dynamics contains strong cross interactions of variables. Hence the MIMO model is necessary for a successful control. Our paper is focused in the CFB MIMO model development and the predictive control strategy.

There is extreme variability in the conception of "mathematical model of the CFB boiler", either in its form, or complexity. The researchers in fluidization engineering consider usually partial differential equations based finite element method models describing the key variables like temperature, concentrations, pressure and velocity as time-varying three-dimensional fields defined in the combustion chamber (Bittanti et al. 2000) for the CFB design. On the other hand, there exists the usual transfer matrix based approach prevalent in control engineering. The transfer functions between the key manipulated and controlled variables can be readily obtained through plant step testing without actually understanding the physical laws governing them.

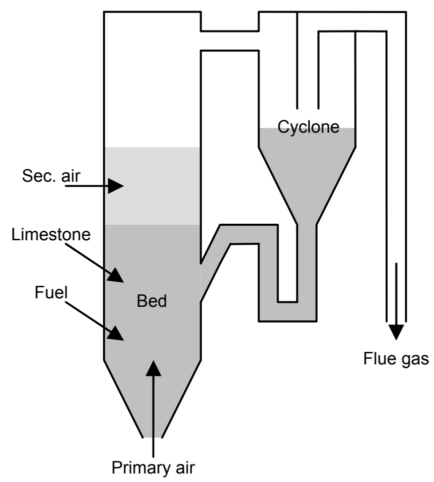

Figure 1 CFB schematics

There are a number of reasons why we have used neither of the two approaches: In the real time control with the sampling period several seconds, the accurate finite elements method based modeling is unusable due to its complexity and the computational burden implied. In contrast, the empirical transfer matrix models are appealing for their simplicity. Unfortunately, it is not possible to get a consistent set of step responses of the CFB. It has a slowly varying internal state variable, the fuel accumulation, which cannot be measured directly. This factor strongly affects the controlled variables in a simple yet non-linear manner. Hence, the input output linear relationship seemingly changes in time based on the actual mass of the fuel accumulated in the bed, (Bittanti et al. 2000) has further references to this problem.

Physical understanding of the CFB boiler leads to the control strategy which manages the boiler power and the bed temperature using its internal state monitored by an inferential sensor (Havlena and Pachner 2007). As a result of observations gained during our research, we have developed a simple low order ordinary differential equations based CFB boiler model. It is based on first principles, the mass and energy balance laws, and several empirical laws confirmed through the experiments to be considered reliable. Despite the simplicity, its prediction capability is sufficient. It is an example of control oriented non-linear model. The purpose is not to predict the state variables and their spatial distribution exactly, but rather to give a clue to the control system how the boiler will respond to the manipulated variables over the prediction horizon of several minutes. Such model should be simple and should have minimum number of unknown parameters.

The Honeywell UES ACC application described in this paper has been pilot-tested in Sinopec Shanghai. In the time of writing, October 2008, the solution has been tested for eight months controlling the 5A and 5B units of the Sinopec Principal Power Plant located in Jinshan. Both units are Foster Wheeler constructed 350 t/h CFB boilers. The fuel is a mixture of coal and coke. The coke is side product from the refinery which is rich in sulfur. The steam is used both for the refinery process and for the electricity generation.

The UES control solution consists of the following model based controllers and optimizers: the inter-boiler coordinated control (Economic Load Allocation for Boilers, ELA-B) Advanced Temperature Control (ATC), emissions control (Stochastic Adaptive Combustion Control, SACO), Master Pressure Control (MPC), and Advanced Combustion Control (ACC). Only the ACC is the topic of this paper. It will be explained the ACC for CFB is a gain scheduled linear model based predictive controller. The two variables used for the gain scheduling are internal process variables which cannot be measured. They are inferred by a non-linear inferential sensors.

The ACC application for the coal powder firing boilers is described in (Havlena and Findejs 2006).

The combustion process model

The fuel particles present in the bed are modeled as a population of little balls with various radii *r* [m] by the ACC. The balls are consumed from the surfaces by the combustion process at a rate which assumedly depends on the temperature and the oxygen concentration close to the surface. It means that the radius of each ball decreases in time. The rate is called the linear burning rate *b* [m/s]. It is related to the more commonly used burning rate given in [kg/s] via the total fuel surface *S* [m^2] and fuel specific mass ρ_F [kg/m^3]:

$$\text{burning rate in kg/s} = \rho_F b(t) S(t) \tag{1}$$

The linear burning rate can be controlled by the primary air flow which directly affects the oxygen availability on the surfaces of the fuel balls, which is where the combustion takes place. Whereas the instantaneous thermal power depends on the fuel surface *S*, the thermal energy, which can be released in next few minutes, depends on the mass of the accumulated fuel. This accumulated mass will be denoted as *m* [kg]. This accumulation is commonly denoted as bed fuel inventory, or bed char inventory, or bed char loading throughout the literature.

The geometric properties of the fuel particles, namely the fuel granularity, define the instantaneous energy flow and its relation to the energy accumulation. As an example, finely ground fuel accumulation produces a more intense thermal power compared to the same mass accumulated in greater lumps. It is an important observation that both the fuel surface *S* and the fuel mass *m* represent the boiler internal state. It is necessary to know both values to control the boiler power optimally. A sufficient fuel accumulation has to be present in the bed to be able to respond to the power demand changes dynamically. In contrast, the instantaneous power is controlled via the burning rate which has to be adjusted according to the fuel surface *S*.

We have used the fuel ball radii distribution function approach, i.e. the statistical viewpoint, to analyze the dynamic properties of the fuel accumulation properties $S(t)$ and $m(t)$. The important result is the following one, with assumption the linear burning rate *b* is the same for any of the balls in the population of *n* balls and the radii of the balls supplied to the bed has exponential distribution function characterized by the mean radius $\bar{r}$:

$$f(t,r) = \frac{n(t)}{\bar{r}} \exp(-r/\bar{r}) \tag{2}$$

Under these conditions the mean radius is not affected by the combustion process. By consequence, the *S/m* ratio remains constant:

$$S(t) = 8\pi n(t)\bar{r}^2, \qquad m(t) = 8\pi\rho n(t)\bar{r}^3 \tag{3}$$

This is an important result because it explains the boiler internal state can be approximately represented by only one of the two numbers *S* and *m* because their ratio is almost constant. ACC inferential sensor estimates only the mass of the accumulated fuel assuming the fuel surface is a slowly varying linear function of the mass.

Besides the accumulation, the linear burning rate *b* [m/s] is the key parameter of the combustion process. Analyzing the oxygen concentration in the flue gas, notably its response to a step change of the primary air supply, it is possible to understand how the burning rate is affected by the primary air supply rate.

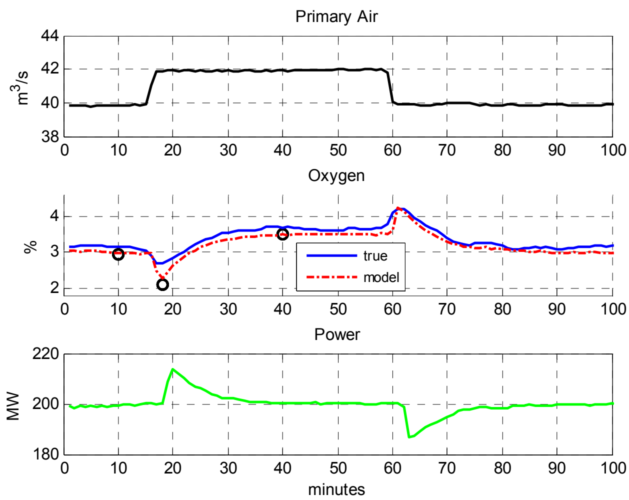

Figure 2 Oxygen concentration step response

Figure 2 shows the boiler power increases temporarily and the output oxygen concentration decreases at the same time after the primary air supply rate step up. In the steady state, the boiler power returns to the original value which is given by the fuel supply rate only; this fact is given by the energy conservation law (the mass of the fuel burned equals the fuel supply rate). The primary air rate cannot affect the boiler power in the steady state. The behavior may look paradoxical. The more air is supplied the less oxygen is left in the flue gas. This FBC behavior is different compared to the other combustor types like the powder fuel boilers.

We have found this “inverted” oxygen concentration response to a step in the air rate is caused by two effects in combination. After the step up in the air supply rate the oxygen concentration on the fuel ball surfaces increases though the oxygen concentration measured in the output flue gas decreases (i.e. there is less oxygen left in the flue gas because it is transported to the ball surfaces more effectively due to the greater gas velocity). The linear burning rate is increased by the primary air step up. The measured decreased O_2 concentration gives the information on the increased oxidization efficiency, not on the concentration on the fuel surface. After a while the increased linear burning rate decreases the fuel accumulation (fuel surface) which leads to an increased oxygen concentration in the steady state eventually.

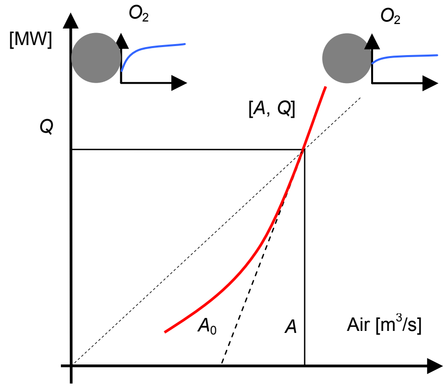

Figure 3 The linear burning rate

The mathematical condition for the inverted step oxygen concentration response is the following: the ratio of boiler powers $Q(A_2)/Q(A_1)$ for the two air rates $A_2 > A_1$ has to be greater than the ratio of the air supply rates A_2/A_1. This condition on the $Q(A)$ characteristics is visualized on Figure 3. The simplest function which satisfies the condition is an affine function with negative constant term (4). When this functional form is combined with the previously explained hypothesis the boiler power is proportional to the fuel mass accumulation we get:

$$Q(t) = Hk(A(t) - A_0)m(t), \qquad A_0 > 0\,. \tag{4}$$

Here, *H* is the fuel heating value [MJ/kg]. We suppose the fuel surface has to be scaled by *H.* We have found the equation (4) is in good agreement with the data as shown on Figure 2. The equation, despite its simplicity, is the key law which allows the accurate predictions of the CFB thermal power and the O_2 concentration in the flue gas. The two empirical parameters A_0 and k can be calculated from the O_2 concentration step response directly using three response values: before the step $A(0-)$, immediately after the step $A(0+)$, and the steady state value $A(\infty)$. Thus, they can be readily obtained on-site within half an hour. Our experiments have shown their values are remarkably stable in time: the same values have been observed over several months. Moreover, the two boilers of the same construction exhibited the same A_0 and k values (difference below the estimation errors).

The equation (4) predicts the boiler power and the oxygen concentration for a known value of the fuel accumulation *m.* Implicitly it also defines the bed temperature. If it is assumed the heat released by the combustion is used to increase the gas enthalpy, the flue gas temperature T_g would be defined as follows:

$$Q(t) = A(t)\int_{T_{g0}}^{T_g} c_p(T)dT \tag{5}$$

Here, c_p [MJ/m^3/°C] is the flue gas specific heat and T_{g0} is the air inlet temperature. Combining this with Equation (4) and considering the average c_p, the following equation holds:

$$T_g(t) = T_{g0} + \frac{Hk}{\bar{c}_p}\left(1 - \frac{A_0}{A(t)}\right)m(t) \tag{6}$$

This equation predicts inverted step response to the primary air step changes similarly to the oxygen concentration responses. After the primary air step up the combustion rate *b* increases. This leads to an increase of the flue gas temperature. After a while the fuel accumulation surface is reduced which leads to a decreased gas temperature. Though this inverted response effect is less visible than that of the oxygen, it has actually been verified. The bed temperature follows the T_g temperature assuming the heat transfer between the gas and the bed takes several minutes.

The bed temperature model accuracy can be further improved if the heat radiation is taken into account. This bed temperature model has shown a good agreement with the data, see Figure 4.

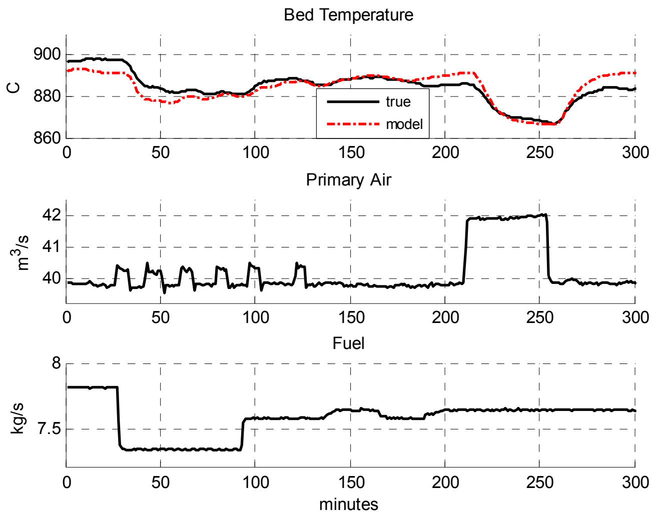

Figure 4 Bed temperature model.

The model based control strategy

The key equation (4) has to be combined with the fuel conservation equation:

$$\frac{dm}{dt}(t) = F(t) - \frac{Q(t)}{H} \tag{7}$$

Here, *F* denotes the fuel supply rate [kg/s] and *H* represents the fuel heating value [MJ/kg].

The energy conservation law for the steam/water system of the boiler yields the following equation (Åström 1998):

$$V\frac{dP}{dt}(t) = \frac{dH_s}{dt}(t) + Q_s(t) \tag{8}$$

Here, P is the main steam pressure [MPa] and V is the volume of the steam system [m^3]. The term Q_s is the thermal power transferred to the steam system and H_s represents the steam enthalpy.

Assuming two heat transfer time constants: τ_Q for bed to steam transfer and τ_B for gas to bed transfer, the final CFB equations can formally be expressed as the following transfer matrix between the inputs $F(s)$ (fuel), $A(s)$ (primary air) with two disturbance inputs $H(s)$ (heating value) and $1/s$ and the three outputs $Q(s)$ (power), $T_B(s)$ (bed temperature), $m(s)$ (fuel mass accumulation):

$$\begin{array}{c|cccc} & F(s) & A(s) & H(s) & 1/s \\ \hline Q_s(s) & 0 & \dfrac{kmH}{\tau_Q s+1} & -\dfrac{kmA_0}{\tau_Q s+1} & 0 \\ T_B(s) & \dfrac{Hc_2}{s(\tau_B s+1)} & -\dfrac{c_2kmH}{s(\tau_B s+1)} & \dfrac{c_2kmA_0}{s(\tau_B s+1)} & c_1 \\ m(s) & \dfrac{1}{s} & -\dfrac{kmH}{s} & \dfrac{kmA_0}{s} & 0 \end{array} \qquad (9)$$

The CFB predictive controller is based on the above linear time varying transfer matrix. The gains of the transfer functions in matrix are scaled by the fuel heating value and the fuel accumulation. Nonlinear estimators of these variables are necessary to provide the gain scheduling. As both fuel heating value and the fuel accumulation are slowly varying, the gains can be considered constant on the control horizon which is fifteen minutes long. This is supported by the fact the control system stabilizes the fuel accumulation actively. Therefore, a time invariant model with the gains scheduled appropriately is used to make the predictions.

The boiler power is controlled via the primary air supply rate which defines the fuel linear burning rate. Because the primary air supply rate directly affects the linear burning rate of the fuel already accumulated in the bed, the speed of the boiler power control is limited by the heat transfer time constant only. The achievable time constant is somewhat shorter than this heat transfer time constant, three minutes approximately. Thus, the boiler response time to a power demand change is less than three minutes. The fuel supply rate is then used to stabilize the fuel accumulation. The control system can decrease the fuel accumulation temporarily in favor of the faster boiler power response. Thus, the boiler can increase the power faster compared to its natural response to the increased fuel supply rate. This is actually the existing practice in the CFB power control. The control described decreased the boiler response time significantly.

The fuel accumulation is related to the bed temperature. The control system finds the optimal accumulation adaptively to meet the bed temperature set point. For the boiler described the accumulation was 3 - 4t.To allow the control system to decrease the accumulation temporarily during an abrupt power demand step up, the bed temperature is not controlled on a target set point but to a set range. The respective penalty function is zero as long as the predicted bed temperature trajectory is within prescribed limits, see the range control description in (Havlena and Findejs 2005). The range chosen by the operator is usually 5 or 10ºC wide. In the steady state the bed temperature fluctuations are ±2ºC.

The oxygen concentration is affected by the fuel accumulation and the total air flow. Basically, the oxygen concentration in the flue gas is an affine function of the boiler power [MW] to the total air flow ratio [m^3/s]. As the primary air is used for the power control primarily, the oxygen concentration is controlled by the secondary air flow. During the ACC operation the O_2 set point is tracked ±0.1%.

Conclusion

The control strategy based on the simple non-linear model described in this text can control the CFB thermal power, excess oxygen level, and the bed temperature independently. This would not be possible with the classic PID loops. The model described predicts inverted responses for the oxygen concentration and the bed temperature. This represents another difficulty for the classic PID loops. There is no manipulated variable which could control the bed temperature directly. The bed temperature control can be achieved via the simultaneous coordination of all the manipulated variables only. Tighter bed temperature control affects the desulfurization efficiency. Thus, the ACC ability to control this temperature can be used to decrease SO_x emissions. Lower excess air levels increased the boiler thermal efficiency. Finally, the accumulated fuel can be used to improve the boiler responsiveness significantly.

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