American Journal of Environmental Sciences 4 (1): 22-30, 2008
ISSN 1553-345X

Dynamic Modelling of an Industrial Smelter Furnace and Converter Off-gas System

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Abstract: In smelters, metal ores or concentrates are smelted to reduce a metal oxide to a metal through a series of reactions and processes. In a smelting process, a large amount of off-gas emissions are often generated, which can cause serious environmental and plant hygiene problems if not properly treated. Off-gas systems extract and treat the off-gas emissions, and ensure that the smelter operation is in accordance with environmental and industrial hygiene regulations. In this paper, the dynamic models for an industrial smelter furnace and converter off-gas system, tackling hazardous sulfur dioxide (SO_2), carbon monoxide (CO) and carbon dioxide (CO_2), are developed using mass continuity, momentum and energy conservation laws. Based on the developed dynamic models, the effects of important variables on the system's dynamics are studied via simulations. The developed dynamic models provide a necessary basis for high performance control development of smelter off-gas systems because online measurements are limited and additional ones must be justified.

Key words: dynamic modelling, furnace off-gas system, converter off-gas system, Nickel smelter

INTRODUCTION

In industrial smelting operations, mineral concentrates, usually transported from mineral processing plants, are smelted through a series of reactions to reduce a metal oxide as well as to remove some impurity metals. The smelters provide the key operations in obtaining metal products from mineral concentrates, but the off-gases emitted from the smelters constitute a major source of atmospheric pollutions. Several decades ago, SO_2 emitted from the smelters caused severe environmental damages to the areas close to the mineral and metallurgical sites, the damages including many perished plants and trees due to the acid rain caused by SO_2 emissions[1,2]. The SO_2 abatement programs, commissioned in many smelters in the following years, resulted in a significant improvement in reducing the amount of SO_2 emission to the atmosphere[3,4]. With the increasingly stringent environmental regulations, however, many smelters will be only marginally satisfying the lower SO_2 and CO_2 emissions levels. Continued effort on process control and process modification will be necessary to further improve the operations of smelter off-gas handling systems and satisfy the tightened environmental gas emission requirements.

In the past decades, active research has been carried out on developing mathematical models for a variety of smelter operations. Most work has been focused on model development for various electric furnaces in the smelters[5-8]. The importance of the smelter off-gas systems dealing with SO_2 and CO_2 emissions has been well recognized and emphasized in some industrial conference presentations[9,10]. Academic studies on modelling smelter off-gas cleaning systems have been limited[11,12]. With the growing emphasis on environmental impacts of industrial operations, extensive studies on different aspects of the smelter off-gas systems are needed for enhanced process understanding, improved off-gas system control and potential process improvement.

Xstrata Nickel's Sudbury Smelter consists of fluidized-bed roasters for partial sulphur elimination, an electric furnace for smelting the hot calcine and converter aisles for further removal of metal impurities. A large amount of off-gas laden with sulfur dioxide is generated in the mineral roasters and the off-gas is cleaned in the roaster off-gas cleaning system and then converted to sulfuric acid in the acid plant. The off-gas generated in the electric furnace contains a significant amount of green gases such as CO, CO_2 and a small amount of SO_2. The SO_2 produced from the converter aisles, although in a much smaller amount than that

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from the roasters, may constitute a key solution in further reducing the SO_2 atmospheric emission. The off-gas generated in the converters, without passing the acid plant, is directly emitted to the stack and to the atmosphere after being cleaned in the Cottrell, and thus is the most important source of SO_2 atmospheric emissions in some smelters.

In this paper, model development is focused on the off-gas handling system of the furnace and the converters. The dynamic models for the unit operations of the system are developed using mass, momentum and energy conservation laws. The dynamic behaviour and system performance are investigated using the derived models via simulations. In industry, it is desirable to have the process and control improvement strategies justified before implementation. The developed model can be used to study potential process and control improvement. In the furnace and converter off-gas system, a significant amount of ingress air is sucked into the system due to the negative pressure and the ingress air provides cooling and other desirable effects. But the large amount of ingress air also increases the energy use of the system. The developed model can also be used for system optimization to achieve a reduced energy use.

Process Description: The operations of Xstrata Nickel's Sudbury Smelter are described in several literatures[13,14]. A schematic representation of the furnace and converter aisles off-gas system at Xstrata Nickel's Sudbury Smelter is given in Fig. 1. The mineral concentrates, produced and transported from the mineral processing plants, are roasted in the roasters to achieve a sulphur elimination of approximately 65% or higher. The hot calcines from the roasters, cyclones, gas coolers and electrostatic precipitators are collected by a system of

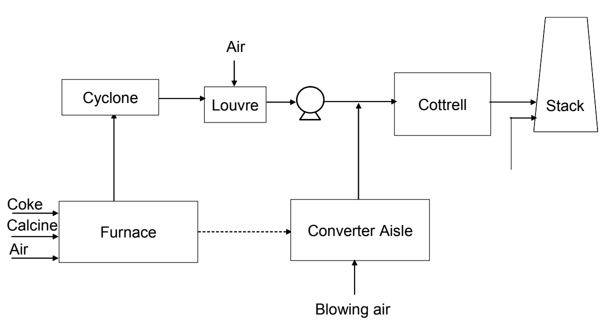

Fig.1: Schematic plot of a smelter furnace and converter off-gas system

enclosed drag conveyors which deliver them along both sides of the electric furnace. In addition to the roaster calcines, the dusts from the furnace off-gas cyclones and Cottrell plant are also fed to the furnace, and coke is fed to the electric furnace using a drag conveyor as the reductant of the furnace reactions. Air enters the furnace through the air ingress ports on the furnace walls. Each furnace is equipped with six 1.4 m diameter self-baking Soderberg electrodes projecting through the furnace roof to provide the heat required for the reactions. Complicated reactions occur in the furnace[15]. The most significant reactions involve the generation of CO. Some of these reactions can be written as:

$$Fe_2O_3 + C \rightarrow 2FeO + CO \quad (1)$$

$$Fe_3O_4 + C \rightarrow 3FeO + CO \quad (2)$$

$$FeO + C \rightarrow Fe + CO \quad (3)$$

A small amount of SO_2 can also be generated in the furnace reactions, mainly from the decomposition of sulphates:

$$FeSO_4 \rightarrow FeO + \frac{1}{2}O_2 + SO_2 \quad (4)$$

In the furnace freeboard, CO usually reacts with O_2 from the ingress area and CO_2 is generated. Therefore, the off-gas in the freeboard is mainly composed of CO, CO_2, SO_2, N_2 and O_2. It is important to maintain the furnace freeboard pressure slightly negative so that the out-leakage of the hazardous gases can be avoided. Matte and Slag, the solid products of the furnace reactions, are emptied from matte tapholes and slag tapholes, located at the lower part of the furnace wall.

The off-gas generated in the furnace is removed through the ducts, one at the matte end and the other at the slag end, in the furnace ceiling. The off-gas from the matte end and slag end of the furnace is processed separately before a Cottrell plant. At the matte end, the off-gas from the furnace freeboard enters a cyclone to remove fine calcine particles, which is recycled back to the furnace. The cleaned off-gas passes a louvre for air cooling and the louvre position is manipulated to control the amount of air ingress and, consequently, the gas temperature. The fan, on the discharge side of the louvre, draws the gases through the gas train and discharges the cooled gas into a flue connected to the Cottrell plant. The off-gas of the slag end duct from the furnace also goes through a similar but separate gas line of a cyclone, a louvre and a fan before it combines with the gas line from the matte end duct and enters the Cottrell plant, which is an electro-static precipitator (ESP) for removing the fine particles from the gas. The fans in the gas system are essential in maintaining a slightly negative pressure and suitable gas temperature in the furnace freeboards.

The converters process the electric furnace matte to remove the remainder of the iron as a slag and produce a finished matte for refinery. The Peirce-Smith converters are served by two overhead cranes handling ladles and a batch operation is used. Air is blown to the converters to provide O_2 for the reactions:

$$2Fe_{matte} + O_2 \rightarrow 2FeO_{slag} \qquad (5)$$

$$FeS_{matte} + \frac{3}{2}O_2 \rightarrow FeO_{slag} + SO_2 \qquad (6)$$

The converting operation continues until only 2% of Fe is left in the final matte. The converter off-gas is transferred via common balloon flues to the Cottrell, together with the off-gases from the furnace. After dust removal in the Cottrell, the gases exit from the stack to the atmosphere.

Dynamic Model Development: Developing the first-principle dynamic models for the furnace and converter off-gas system can provide an enhanced process understanding and produce a useful foundation for process and control improvement. Some approximating assumptions are necessary for the first principle model development. These assumptions are: 1) off-gas follows the ideal gas state equation; 2) although it is recognized that the variables are not spatially uniform in most units, off-gas variables are modelled such that the spatial variations of the variables are not considered within each unit; 3) the off-gas system has relatively high temperature and the effect of kinetic energy change on temperature is negligible; 4) the potential energy due to gravity is negligible compared to other forces to which the off-gas fluid is subject; 5) the cross-sectional area of the pipes connecting the units of the system is the same, and therefore, the effect of kinetic energy due to pipe size changes is negligible. These assumptions represent a reasonable approximation for the off-gas system and some of them are used in the studies related to compressible fluids[16]. Based on the assumptions, dynamic modelling equations for the units in the furnace and converter off-gas system are developed.

Furnace Off-gas System: In the electric furnace, hot calcine from the roasters and coke are fed to the furnace continuously but the solid products matte and slag are discharged in a discontinuous way. The main gas product from the furnace reactions is CO and it reacts with O_2 to generate CO_2 in the furnace freeboard. This paper is focused on the gas handling system and the model for the solid mineral concentrate reactions is not discussed. The off-gas leaves the furnace through two openings, one at the matte end and the other at the slag end. Both off-gas lines from the furnace have almost the same type of unit operations, and thus only one gas-line, e.g., the slag end gas line, is modelled here. To model the off-gas variables in the furnace freeboard, mass continuity, First Law of Thermodynamics and the ideal gas state equation are used, leading to the following dynamic equations:

$$\frac{dP_{furnace}}{dt} = \frac{C_pR}{V_{furnace}(C_p - R)}\Big[W_{CO}(T_{CO} + \frac{H_{CO/CO2}}{C_p}) + W_{air}T_0 - W_{furnace}T_{furnace}\Big] \qquad (7)$$

$$\frac{dT_{furnace}}{dt} = \frac{RT_{furnace}}{P_{furnace}V_{furnace}(C_p - R)}\Big[W_{CO}(C_pT_{CO} + H_{CO/CO2}) + W_{air}C_pT_0 + (W_{CO} + W_{air})(R - C_p)T_{furnace} - W_{furnace}RT_{furnace}\Big] \qquad (8)$$

where P indicates pressure, T indicates temperature and W indicates mass flow-rate, C_p indicates specific heat coefficient, V indicates volume, R is the gas constant, H indicates reaction enthalpy, T_0 is the room temperature, W_{CO} and T_{CO} indicate the equivalent CO mass flow-rate and temperature entering the furnace freeboard. The first-order dynamic relation is assumed for W_{CO} from the coke (or feed) flow-rate W_{coke}:

$$\tau_w \frac{dW_{CO}}{dt} + W_{CO} = \eta_{CO}W_{coke} \qquad (9)$$

where τ_w indicates the first-order time constant of the dynamic relation and η_{CO} is the conversion coefficient from the feeding coke flow-rate to W_{CO}.

In Equation (8), W_{air} is air ingress flow-rate through the air ingress ports on the furnace walls[17], which can be calculated as:

$$W_{air} = C_dA_{fleak}\sqrt{P_{atm} - P_{furnace}} \qquad (10)$$

where C_d and A_{fleak} indicate the in-leakage coefficient and in-leakage area in the furnace, respectively. In the furnace, air in-leakage provides O_2 needed in the reaction from CO to CO_2 and cools the off-gas before the cyclone. Using the component mass balance, the model for the concentration of CO/ CO_2 can be obtained:

$$\frac{dX_{CO2\text{-}furnace}}{dt} = \frac{RT_{furnace}}{P_{furnace}V_{furnace}}\left[\frac{28}{44}W_{CO} - W_{Furnace}X_{CO2\text{-}furnace}\right] \qquad (11)$$

where X indicates concentration.

The off-gas flow-rate from the furnace freeboard is divided into two streams – the matte end gas line $W_{m\text{-}furnace}$ and the slag end gas line $W_{s\text{-}furnace}$. The differential equations for the $W_{furnace}$´s can be obtained by applying momentum conservation to the downstream cyclone units:

$$\frac{dW_{m\text{-furnace}}}{dt} = \frac{1}{L_{m\text{-cyclone}}}\Big[(P_{furnace} - P_{m\text{-cyclone}})a - \frac{1}{2}\frac{k'_{m\text{-cyclone}}}{\rho}W_{m\text{-furnace}}^{2} + \frac{1}{\rho a}(W_{m\text{-furnace}}^{2} - W_{m\text{-cyclone}}^{2})\Big] \quad (12)$$

$$\frac{dW_{s\text{-furnace}}}{dt} = \frac{1}{L_{s\text{-cyclone}}}\Big[(P_{furnace} - P_{s\text{-cyclone}})a - \frac{1}{2}\frac{k'_{s\text{-cyclone}}}{\rho}W_{s\text{-furnace}}^{2} + \frac{1}{\rho a}(W_{s\text{-furnace}}^{2} - W_{s\text{-cyclone}}^{2})\Big] \quad (13)$$

$$W_{furnace} = W_{m\text{-furnace}} + W_{s\text{-furnace}} \quad (14)$$

where a indicates cross-sectional area of the connecting pipes, ρ is off-gas density, which can be considered constant in the system when the gas pressure variation is small[18]. In the following model development for the units before the Cottrell plant, only one gas line is modelled and, for simplicity of expression, the subscripts 'm' for 'matte end' and 's' for 'slag end' are dropped in the expressions unless the distinction is necessary.

Assuming air in-leakage and heat loss for the cyclone is negligible, mass continuity, energy conservation and CO_2 component mass balance can be expressed as:

$$\frac{dP_{cyclone}}{dt} = \frac{C_pR}{V_{cyclone}(C_p - R)}\left[W_{furnace}T_{furnace} - W_{cyclone}T_{cyclone}\right] \quad (15)$$

$$\frac{dT_{cyclone}}{dt} = \frac{RT_{cyclone}}{P_{cyclone}V_{cyclone}(C_p - R)}\left[W_{furnace}C_pT_{furnace} + W_{furnace}(R - C_p)T_{cyclone} - W_{cyclone}RT_{cyclone}\right] \quad (16)$$

$$\frac{dX_{CO2\text{-Cyclone}}}{dt} = \frac{RT_{Cyclone}}{P_{Cyclone}V_{Cyclone}}\left[W_{Furnace}X_{CO2\text{-furnace}} - W_{Cyclone}X_{CO2\text{-Cyclone}}\right] \quad (17)$$

A momentum equation for the downstream louver can be obtained similar to the cyclone and can be written as:

$$\frac{dW_{cyclone}}{dt} = \frac{1}{L_{Louvre}}\left[(P_{cyclone} - P_{louvre})a - \frac{1}{2}\frac{k_{Louvre}}{\rho}W_{cyclone}^{2}\right] \quad (18)$$

where a kinetic energy term $\frac{1}{\rho a}\left(W_{cyclone}^{2} - W_{clouvre}^{2}\right)$ is dropped from the above Equation. A simple simulation indicates that its effect is negligible.

The louvre opening allows air in to cool the off-gas before the fan. The following relation is used for the ingress air flow-rate in the louvre:

$$W_{air\text{-}lvr} = O_{louvre}C_dA_{louvre}\sqrt{P_{atm} - P_{louvre}} \quad (19)$$

where O_{louvre} indicates the louver opening, which is used as a manipulated variable. For the manipulated variable O_{louvre}, similar to Equation (9), the first order actuator dynamics is assumed with a time constant τ_{louvre}. The mass and energy conservations can be obtained for the louvre:

$$\frac{dP_{louvre}}{dt} = \frac{C_pR}{V_{louvre}(C_p - R)}\left[W_{Cyclone}T_{Cyclone} + W_{air\text{-}lvr}T_0 - W_{louvre}T_{louvre}\right] \quad (20)$$

$$\frac{dT_{louvre}}{dt} = \frac{RT_{louvre}}{P_{louvre}V_{louvre}(C_p - R)}\left[W_{Cyclone}C_pT_{Cyclone} + W_{air\text{-}lvr}C_pT_0 + (W_{Cyclone} + W_{air\text{-}lvr})(R - C_p)T_{louvre} - W_{louvre}RT_{louvre}\right] \quad (21)$$

$$\frac{dX_{Louvre}}{dt} = \frac{RT_{Louvre}}{P_{Louvre}V_{Louvre}}\left[W_{Cyclone}X_{CO2\text{-Cyclone}} - W_{Louvre}X_{CO2\text{-Louvre}}\right] \quad (22)$$

For the fan, it is assumed that its dynamics are fast compared to other units, and thus only the steady state relations are proposed. The steady state relation for the pressure increment can be obtained from the fan law[19]:

$$P_{Fan} - P_{Louvre} = \alpha_{Fan}N_{Fan}^{2} \quad (23)$$

where N_{Fan} is the fan's speed and α_{Fan} is the constant determined by the fan's characteristics. Without considering the heat loss and the air in-leakage, the steady state relations for other variables can be described as:

$$W_{Fan} = W_{Louvre}$$
$$X_{CO2\text{-Fan}} = X_{CO2\text{-Louvre}} \quad (24)$$
$$T_{Fan} = T_{Louvre}$$

The off-gases from the fans at the matte end and the slag end of the furnace flow in a duct and combine with those from the converter aisle before entering the Cottrell plant. A detailed model for the compressible gas flow in the duct from the fan outlet to the inlet of the Cottrell plant can be expressed in a hyperbolic partial differential equation or approximately in an ordinary differential equation similar to other units discussed above:

$$\frac{dW_{s\text{-Fan}}}{dt} = \frac{1}{L_{Fan\text{-Cotrell}}}\left[(P_{s\text{-Fan}} - P_{In\text{-Cottrell}})a - \frac{1}{2}\frac{k_{Fan\text{-Cottrell}}}{\rho}W_{Fan}^{2}\right] \quad (25)$$

The off-gas from the fans of furnace gas lines combines with the gases from the converter aisles and enter the Cottrell plant for removing fine solid particles. The converter off-gas flow-rate $W_{converter}$ and the temperature $T_{converter}$ can significantly affect the mass and energy in the Cottrell. Applying energy conservation to the off-gas between the fan outlet and the Cottrell inlet gives the dynamic equation for the Cottrell inlet temperature:

$$\frac{dT_{In\text{-}Cottrell}}{dt} = \frac{RT_{In\text{-}Cottrell}}{P_{In\text{-}Cottrell}V_{fan\text{-}Cottrell}(C_p - R)}\left[W_{s\text{-}Fan}C_pT_{s\text{-}Fan} + W_{m\text{-}Fan}C_pT_{m\text{-}Fan} + W_{Converter}C_pT_{Converters} + (W_{s\text{-}Fan} + W_{Converter})(R - C_p)T_{In\text{-}Cottrell} - W_{In\text{-}Cottrell}RT_{In\text{-}Cottrell}\right] \quad (26)$$

Although $W_{converter}$ and $T_{converter}$ are the variables changing with time, they remain almost constant for the time frame, which is typically a short time period, in the dynamic simulation of the furnace off-gas system. The dynamics of the off-gas flow-rate and pressure in the Cottrell and stack are not the focus of this paper and only the steady state relations are used to complete the model for the furnace off-gas system:

$$W_{in\text{-}Cottrell} = W_{s\text{-}Fan} + W_{m\text{-}Fan} + W_{converter} \quad (27)$$

$$P_{in\text{-}Cottrell} + k_{Cottrell}W_{in\text{-}Cottrell}^{\ 2} = P_{atm} \quad (28)$$

Neglecting the dynamics of the off-gas flow-rate and pressure at the Cottrell inlet is justified by the fact that these two variables are almost constant in the time scale used in the analysis of the furnace off-gas system.

Using the modelling equations derived above, the dynamic performance of the furnace off-gas system can be investigated by solving the developed ordinary differential and algebraic equations.

Converter Off-gas System: The converter is operated in a batch mode with continuous air inlet flow and gas products outlet flow. For the reaction described in Equation (5) or (6), the reaction rate can be expressed as:

$$X_{Fe} = X_{Fe}^{0}e^{-k(t-t_0)}$$
$$Rate = k\,X_{Fe} = k\,X_{Fe}^{0}e^{-k(t-t_0)} \quad (29)$$

where X_{Fe} indicates iron concentration in the matte and k is the reaction constant.

The reactions in the converters produce SO_2, a key component in environmental regulations for the smelters. Temperature in the converters is the main measured variable. Using mass and energy conservation, the dynamic modelling equation for the off-gas SO_2 concentration and temperature can be written as:

$$\frac{dX_{SO2\text{-}Converter}}{dt} = \frac{1}{\rho V_{Converter}}\left[W_{solid}k\,X_{Fe}^{0}e^{-k(t-t_0)} - W_{Converter}X_{SO2\text{-}Converter}\right] \quad (30)$$

$$\frac{dT_{Converter}}{dt} = \frac{1}{\rho V_{Converter}C_p}\left[k\,X_{Fe}^{0}e^{-k(t-t_0)}H_{converter} + W_{Converter}C_p(T_0 - T_{converter})\right] \quad (31)$$

where W_{solid} indicates the solid holdup and C_{psolid} is the specific heat coefficient for the matte in the converter. In the converters, the off-gas has slight negative pressure, usually less negative than the furnace and the roaster off-gas pressure. The converter off-gas flow-rate $W_{converter}$ mainly consists of the blowing air and the ingress air due to the slight negative pressure

The off-gas from the converters combines with those from the furnace gas lines and enters the Cottrell plant to remove the solid particles. After the Cottrell plant, the off-gas is emitted through the stack to the atmosphere.

SIMULATION AND ANALYSIS

Dynamic behaviours of the furnace and converter off-gas system can be investigated via simulation based on the models developed above. Although the furnace and converter gas units are closely inter-correlated, the two off-gas systems present significantly distinct features; the furnace off-gas system displays the feature of continuous operations while the converter off-gas system shows the characteristics of a batch operation. Simulation study is performed separately for the two parts of the off-gas system.

Furnace Off-gas System: For dynamic simulation of the furnace off-gas system, the parameters in Table 1 are used. Due to confidentiality, the parameters used in this paper may not necessarily agree with equipment and operating conditions in Xstrata Nickel Sudbury Smelter, but the parameters are selected such that the simulated industrial phenomenon reflect typical industrial operations. The initial condition is assumed to be the steady state condition corresponding to W_{CO}=2 kg/s, O_{louvre}= 10% and N_{Fan}=900 rpm.

The dynamic behaviour of the furnace off-gas system can be investigated by examining the effects of the input variables. The fans in the system are very important in controlling off-gas pressure and temperature. Fig. 2 shows the output responses to a step

Table 1: Model parameters in a furnace off-gas system

R =297 J/(Kg.K)	$H_{CO/CO2}$ = 4.04×10^6 J/Kg
C_p =1330 J/(Kg.K)	$V_{furnace}$ =30 m^3
T_0 =273.15 K	$V_{cyclone}$ =30 m^3
T_{CO} =1573.15 K	V_{louvre} =30 m^3
ρ =1 kg/m^3	$V_{fan\text{-}Cottrell}$ =30 m^3
α_{Fan} =0.001 Pa.rpm^{-2}	$L_{cyclone}$ =30 m
P_{atm} =101325 Pa	L_{louvre} =30 m
a =1 m^2	$L_{fan\text{-}Cottrell}$ =30 m
C_d =0.6	A_{fleak} =1.5 m^2
$K_{cyclone}$ =4 N/(kg/s)^2	A_{louvre} =2 m^2
K_{louvre} =2.5 N/(kg/s)^2	τ_W =1 s
$K_{fan\text{-}ctrell}$ =1 N/(kg/s)^2	τ_{louvre} =1 s
$K_{cotrell}$ =0.003 N/(kg/s)^2	

increase of the fan speed from 900 rpm to 1000 rpm. It is observed that the increase of the fan speed can quickly decrease the furnace freeboard pressure. Increasing the fan speed is also very effective in reducing the off-gas temperature with slower dynamics. The effect on the furnace freeboard temperature displays a faster dynamics than that on the louver temperature.

The louver position is an important manipulated variable in controlling off-gas temperature. Dynamic effects of increasing the louver position on furnace freeboard pressure, furnace freeboard temperature and louver temperature can be viewed from Fig. 3 for a louver opening increase from 10% to 20%. It is noted that increasing the louver opening can effectively reduce the louver temperature but it can also increase the furnace freeboard pressure and temperature. The dynamics of its effect on temperature is much slower than that on pressure. Fig. 4 presents the steady-state temperature in the furnace freeboard and louver with different louver opening. It indicates that changing louver opening has opposite effects on furnace freeboard temperature and louver temperature. As the

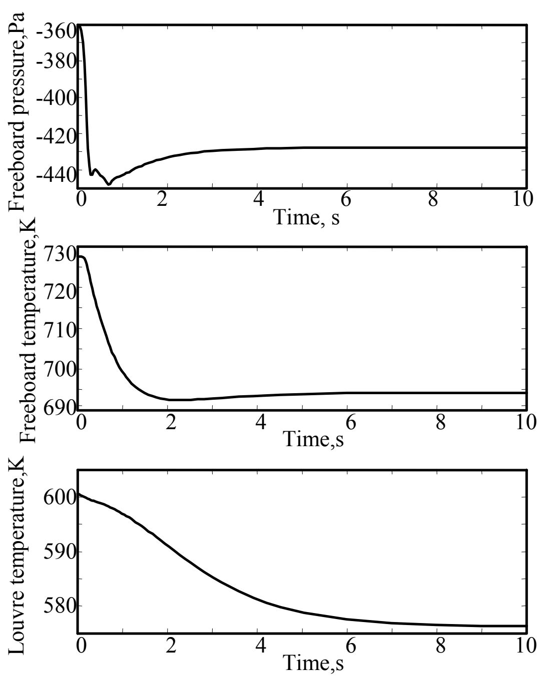

Fig. 2: Output response of a furnace off-gas system to a step increase in the fan speed

louver opening increases, the furnace freeboard temperature increases while the louver temperature decreases. Increasing louver opening is very effective in reducing louver off-gas temperature when the louver opening is small. As louver opening increases, its effect on reducing the louver temperature decreases but it can significantly increase the freeboard temperature.

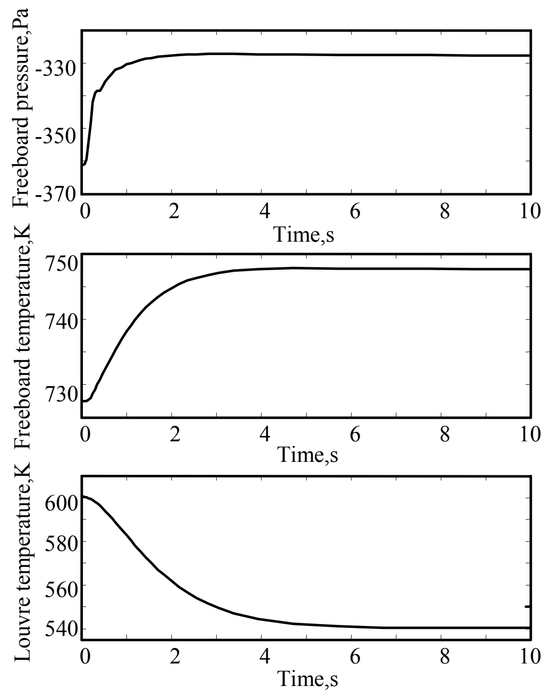

Fig. 3: Output response of a furnace off-gas system to a step increase in the louver opening

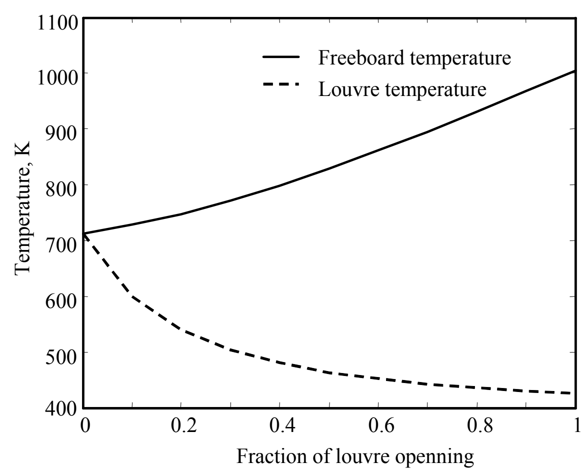

Fig. 4: Furnace freeboard and louver temperature at different louver openings

Therefore, a special caution is needed in using louver tempering air to cool the off-gas.

Calcine and coke are the main feeds to the furnace and the feed flow-rate is an important source of process disturbances. Coke and calcine are often fed to the furnace at a specified ratio. The effect of feed-flow-rate can be studied through examining the output responses of a step increase in W_{CO} generated in furnace, as in Fig. 5, which corresponds to a 10% step increase in Wco. Fig. 5 indicates that the coke (feed) flow-rate can disturb the off-gas pressure initially but cause only a slight variation in the steady-state furnace freeboard pressure. The small off-gas pressure change from the feed flow-rate is because the major portion of the off-gas mass is not from the furnace reactions but from the air ingress. In contrast to the relatively small off-gas pressure change, the increase in feed (coke) flow-rate can significantly increase the off-gas temperature and CO/ CO_2 concentration.

Converter Off-gas System: In the converters, the converting reactions occur in a batch mode while the air flow enters the system and gas products (composed of SO_2 and air) leave the converter continuously. The temperature is the main measured variable in the converter operation. In each batch run, the converter would experience temperature rise and temperature decrease periods. A typical operating converter flue temperature measurement can be viewed in Fig. 6. The

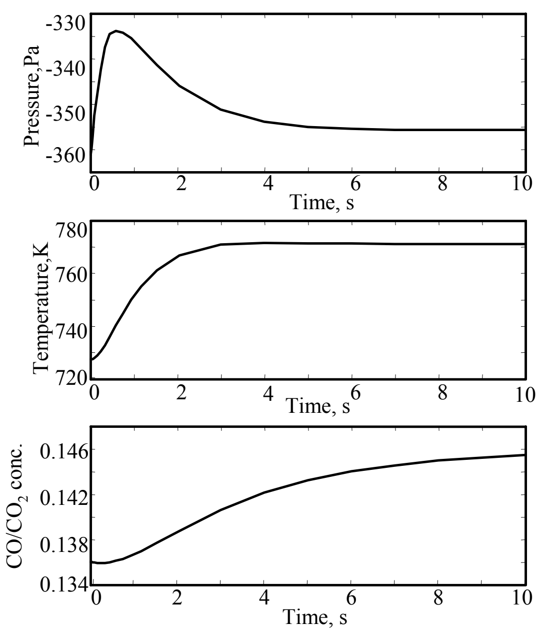

Fig. 5: Output response of a furnace off-gas system to a step increase in coke (feed) flowrate

focus of the simulation and analysis in this section will be on the temperature decrease period, described by Equation (31). In Fig. 6, it is reasonable to assume that $\frac{dT_{converter}}{dt} = 0$ at the peak points. From Equation (31), the corresponding iron concentration X_{Fe}^0 at these peak points can be determined, given the constant parameters. With the obtained X_{Fe}^0, the temperature $T_{converter}$ and X_{Fe} can be simulated using Equation (30) and (31) for each separate batch operation. In the simulations, the typical operating parameters are used including: W_{solid} = 100,000 kg, C_{psolid} = 900 J/(kg.K), $H_{converter}$ = 5.2× 10^6 J/kg, $W_{converter}$ = 150 kg/s. The reaction constant k= 4.54 × 10^{-4} s^{-1} is the identified

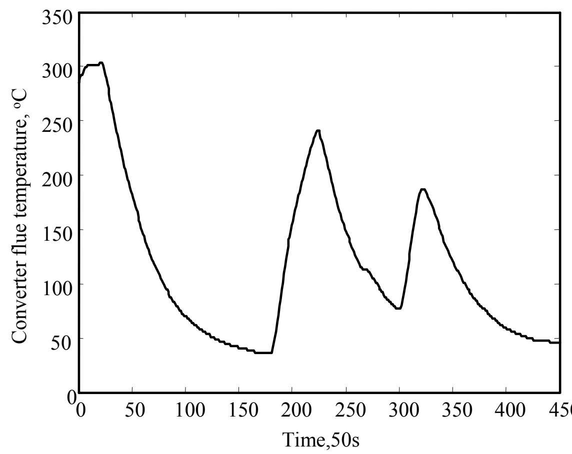

Fig. 6: Industrial measured data of a converter flue temperature

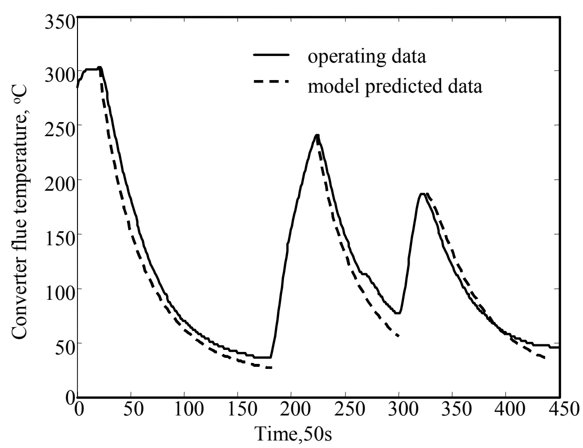

Fig. 7: Comparison of the model predicted data with the industrial measure data for the converter flue temperature

value using the first temperature decrease period data in Fig. 6 (data points from 20 to 120).

Fig. 7 displays a comparison between the operating data and the model predicted data for the converter flue temperature. It indicates that Equation (31) can closely describe the off-gas temperature variations in the converters. The converter is operated such that it stops as the iron concentration reaches 2%. But the iron concentration can only be infrequently measured and can hardly be used as a variable for the control purpose. From Equation (30) and (31), it is possible to estimate X_{Fe} using the temperature measurement.

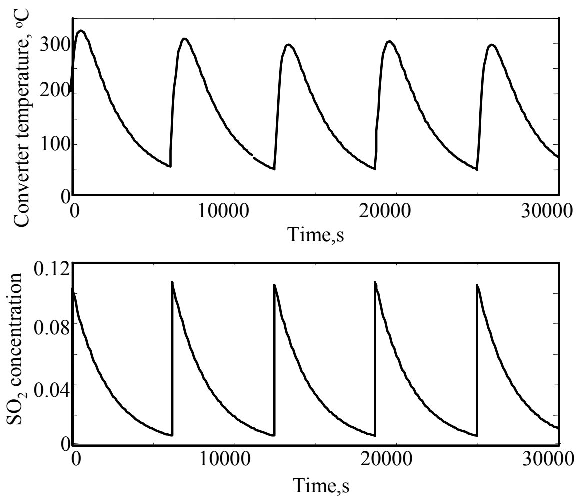

Fig. 8: Periodic evolution of converter variables at an ideal condition

Neglecting idling, loading and preparation periods of the converters, Fig. 8 shows the simulated evolvement of two important variables in the ideal conditions, assuming that each run starts with the constant matte compositions with $X_{Fe}^{0} = 0.34$. It indicates that the converter variables vary periodically due to the batch operations. One possible solution of reducing SO_2 atmospheric emission is to have the converter off-gas go through the acid plant before emitting to the stack. The periodic variations of the off-gas temperature and SO_2 concentrations would give rise to the increased difficulties in the acid plant operations and some measures would have to be taken to mitigate the periodic variable variations.

CONCLUSIONS

In this paper, a detailed dynamic model is developed for an industrial furnace and converter off-gas system in a Nickel smelter using mass continuity, momentum and energy conservation law. Dynamic behaviours of the system are investigated via simulations. Simulations show that increasing the fan speed is effective in reducing the off-gas pressure and temperature, but can significantly raise the mass of the off-gas flow and thus increase the energy use. The louver opening, the manipulated variable for temperature control in the industrial operations, can serve to control the louver off-gas temperature efficiently when the opening is small, but it displays the opposite effects on the furnace freeboard temperature and the louver temperature. The disturbance coke flow-rate affects the temperature greatly with a minor disturbance to the off-gas pressure. For the converters, the model predicted data are compared with the industrial operating data and a good agreement is obtained. The modelled correlation between the temperature and iron concentration suggests that it is possible to develop a soft sensor for the iron concentration based on the temperature measurement. The developed models provide a foundation for control development and process improvement in reducing hazardous gas emissions to the atmosphere and decreasing the energy use.

The model is developed based on an industrial furnace and converter off-gas system in a Nickel smelter. With slight modifications, it should be applicable to some other mineral off-gas handling system in other smelters.

ACKNOWLEDGEMENT

The authors gratefully acknowledge financial support provided by Natural Sciences and Engineering Research Council of Canada (NSERC) and Xstrata Nickel Sudbury Smelter.

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