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Development of transient mathematical models for a large-scale reheating furnace using hybrid zone-CFD methods

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Abstract

While providing an accurate means of simulating radiative heat transfer within a furnace, the major limitation of the classical zone method of radiation analysis has been the difficulty of incorporating furnace flow patterns within the model. This aspect is of particular importance in furnaces where the flow pattern may be highly complex due to the burner arrangement and variations in the flow pattern may be significant during transient furnace operation. This paper is concerned with the development of a hybrid modelling approach to simulate transient thermal performances of a large scale reheating furnace. In particular, this new modelling approach combines the advantages of the zone method and Computational Fluid Dynamics (CFD) in a robust manner. The hybrid model has been validated using comprehensive experimental data collected during an instrumented bloom trial period that includes a long production delay. The results suggest that the model predictions are in good agreement with actual measurements, and that the model is able to respond correctly with respect to the production delay. Furthermore, the hybrid approach has a relatively modest computing demand so that it may be used efficiently for off-line (or near real-time) simulations to investigate problems related to furnace optimisation and control.

1. Introduction

For economic reasons, current supervisory furnace temperature control models [1-3], often referred to as level-2 models, rely on piecewise linearly interpolated temperature profiles derived from a limited number of thermocouples installed along the roof and hearth to estimate the source radiation temperatures to the top and bottom surfaces of the stock. Given that these limited thermocouple measurements cannot

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fully represent the temperature map over large control zones within the furnace, and that their responses are not always representative of the temperature in a control zone. In view of the above, more comprehensive mathematical models are needed to meet the challenge of adapting to different operating conditions with reduced dependency on the limited temperature measurements available whilst also being able to simulate the dynamic thermal behaviour of the furnace.

Nomenclature

Abbreviations

CFD	Computational Fluid Dynamics
ZM	Zone Model

Symbols

$a_{g,n}$	weighting coefficient in mixed grey gas model, -
A_d	area of furnace door, m^2
A	area of surface zone, m^2
E_c	combustion efficiency, $1+(Q_a/Q_f)-(Q_e/Q_f)$ as a percentage, -
E_f	furnace efficiency, Q_b/Q_f as a percentage, -
$\overrightarrow{G_JG_1}, \overrightarrow{G_1S_1}, \overrightarrow{S_JS_1}, \overrightarrow{G_JS_1}$	directed flux area, m^2
$k_{g,n}$	grey gas absorption coefficient, -
$\dot{m}$	mass flow rate, $kg\ s^{-1}$
Q_a	preheated air energy input, MW
Q_b	energy transferred to steel blooms, MW
Q_{wc}	energy transferred to the furnace water cooling, MW
Q_e	energy in exhaust gases as they leave the furnace, MW
Q_f	fuel energy input, MW
Q_l	energy losses to furnace walls, including energy losses to furnace door, MW
$\dot{Q}_s$	heat transferred to surface zone, W
$\dot{Q}_{air}$	heat release from air, W
$\dot{Q}_{fuel,net}$	heat input of fuel, W
$\dot{Q}_{conv}$	heat convection term, W
$\dot{Q}_{enth}$	enthalpy transport term, W
$\dot{q}_{conv}$	heat flux to a surface zone by convection, $W\ m^{-2}$
SEC	specific energy consumption, $GJ\ t^{-1}$
T_g	temperature of gas zone, °C
T_s	temperature of surface zone, °C
V_i	volume of gas zone i, m^3
σ	Stefan-Boltzmann constant (5.6687×10^{-8}), $W\ m^{-2}K^{-4}$

The developed mathematical models in this work are based on the so-called zone method of radiation analysis [4], namely 'zone model'. Zone models have modest computational requirements and have been successfully used to simulate the transient behaviour of gas-fired furnaces, see for examples [5,6]. A particular challenge associated with the zone model is that it does not calculate the furnace flow pattern, and thus this information must be determined by some other means. Previous work at the University of South Wales [7] has been directed at demonstrating that sufficiently accurate furnace flow patterns can be obtained by 'one-off' isothermal CFD simulations if allowance is made for the density changes which occur in the actual (non-isothermal) furnace chamber. However, the fact that the flow patterns are transient, as the zone firing-rates are continually adjusted to meet heating demand, makes it almost

impossible to run the isothermal CFD 'on the fly' in order to adapt to the relatively fast simulation speed of the transient zone model. In view of this, the Reheating and Thermal Transfer group within TATA Research and Development developed a methodology for constructing models which predict the internal time-varying flow patterns within the furnace chamber sufficiently accurately in real-time using data from several isothermal CFD simulations. Then, the time-varying flow patterns were further incorporated into zone models to predict transient thermal behaviour of the reheating furnace.

2. Furnace zoning arrangement and operating conditions

The furnace studied has an effective length of 36 m and width of 10 m (illustrated in Figure 1). The furnace height varies between 4.0 m and 4.7 m along the length of the furnace. In total 71 burners are installed within 6 control zones which fire low-calorific-value mixed enhanced fuel gas. Control zones 2 and 4 are slaves to control zones 1 and 3 respectively. The hot combustion gases leaving the furnace pass through a radiant recuperator. In accordance with the zone method, the furnace was split into 16 sections (across its length) × 3 sections (across its height) × 6 sections (across its width).
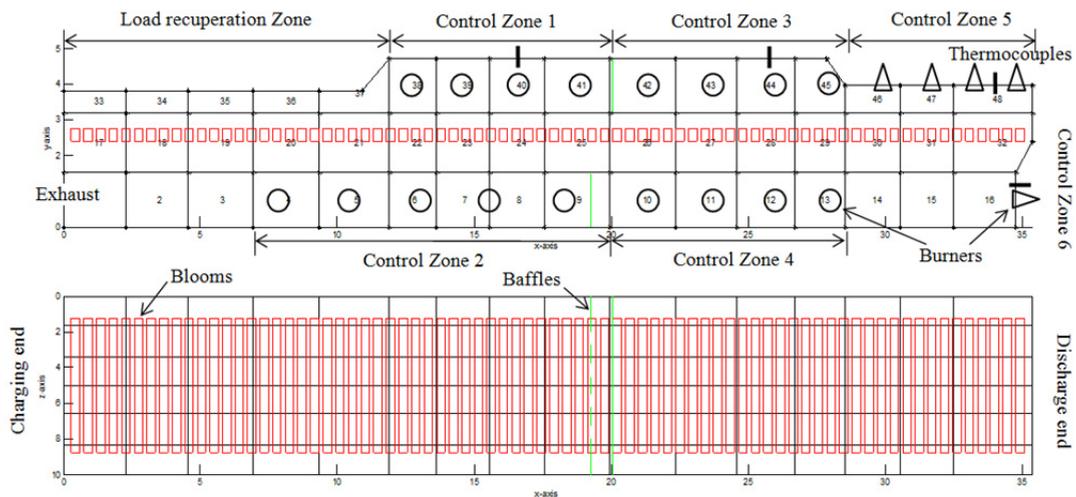

Figure 1 Outline of the furnace and zoning arrangement in *XY* plane (upper) and *XZ* plane (lower)

Previously, Tata Steel has conducted an instrumented bloom trial to investigate the actual stock heating profile. During this trial period, the furnace was operating at a production rate of 127 tonne h^{-1}. As a result, a bloom is discharged approximately every 180 s. At 150 mins into operation, a delay in production was triggered that lasted for approximately 120 mins before production resumed again at 270 mins. In total, 466 tonnes of steel were heated to an average mean bulk temperature of 1250 ºC during the 341 mins of furnace operation.

3. Zone method

In accordance with to the zone method of radiation analysis, an energy balance was formulated for each volume or surface zone (as shown in Figure 2) taking into account radiation interchange between all zones, the enthalpy transport, source terms associated with the flow of combustion products and their heat release due to combustion [8].
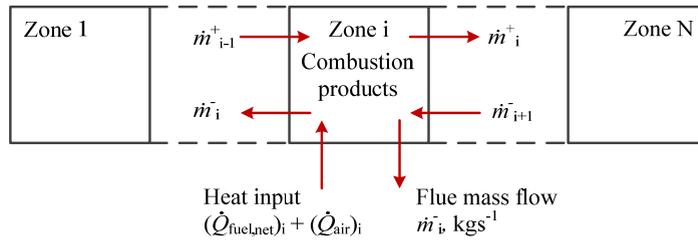
Figure 2 Flow field specifications for the zone model [8]

Furthermore the radiation term in the energy balance equations is written in terms of exchange factors know as directed flux areas [8] (denoted by $\overrightarrow{G_J G_I}, \overrightarrow{G_I S_J}, \overrightarrow{G_J S_I}, \overrightarrow{S_J S_I}$ for gas-gas, gas-surface, surface-gas, and surface-surface exchange respectively in Eq. 1 and 2), which allow for the effects of surface emissivity and the non-grey behaviour of the radiant interchange within the furnace enclosure. The energy balances on all zones yield a set of simultaneous non-linear equations which can be solved to determine the temperature and heat flux at each zone. The time-dependent internal node temperatures of blooms and wall lining can also be calculated by incorporating a transient conduction model.

For a system of *N* volume zones and *M* surface zones, the following energy balances can be written.

For the *i*-th volume (gas) zone:

$$\sum_{j=1}^{N} \overrightarrow{G_J G_I} \sigma T_{g,j}^4 + \sum_{j=1}^{M} (1 - \frac{A_d}{A_i}) \overrightarrow{G_I S_J} \, \sigma T_{s,j}^4 - 4 \sum_{n=1}^{n_g} a_{g,n} \, k_{g,n} V_i \sigma T_{g,i}^4 - \left(\dot{Q}_{conv}\right)_i$$
$$+ \left(\dot{Q}_{fuel,net}\right)_i + \left(\dot{Q}_{air}\right)_i + \left(\dot{Q}_{enth}\right)_i + \left(\dot{Q}_{wc}\right)_i = 0. \tag{Eq. 1}$$

Likewise, for the i-th surface zone:

$$\sum_{j=1}^{M} \left(1 - \frac{A_d}{A_i}\right) \overrightarrow{S_J S_I} \sigma T_{s,j}^4 + \sum_{j=1}^{N} \overrightarrow{G_J S_I} \, \sigma T_{g,j}^4 - A_i \varepsilon_i \sigma T_{s,i}^4 + A_i (\dot{q}_{conv})_i = \dot{Q}_{s,i} \tag{Eq. 2}$$

Note that the presence of a door on the furnace does not affect the quantity of radiation arriving at the zone *i* (volume or surface zone) from all other zones, and it does however reduce the radiation that is emitted from this zone. The door was assumed to occupy a fixed fraction (A_d/A_i) of a specified surface zone *j*. The emitted radiation is assumed to be reduced by a factor (1-A_d/A_i) in Eq.1 and Eq.2 when the door is open while a bloom is discharged. Moreover, in Eq.1 the determination of heat losses through the water-cooled skid and upright structure ($\dot{Q}_{wc}$) follows that of Newton's law of cooling by specifying an appropriate overall heat transfer coefficient from the gas to water side and the respective exposed surface areas in each gas zone.

4. Results and analysis

As actual measurements are limited, the initial furnace boundary condition was accomplished by running the zone model first from cold start-up until the furnace reaches a steady production condition. Based on the established initial conditions, simulation was continued for a further 341 mins that span the entire duration of the instrumented bloom trial as described in Section 2. Predictions from the zone model were also compared with that from the level-2 model used within exiting furnace temperature control system. The predicted top, centre, and bottom temperature histories also compared well, in general, with actual measurements as illustrated in Figure 3. It is clear that predictions from the zone model

outperformed those of the existing level-2 model in most instances which demonstrated the effectiveness of the modelling methodology.
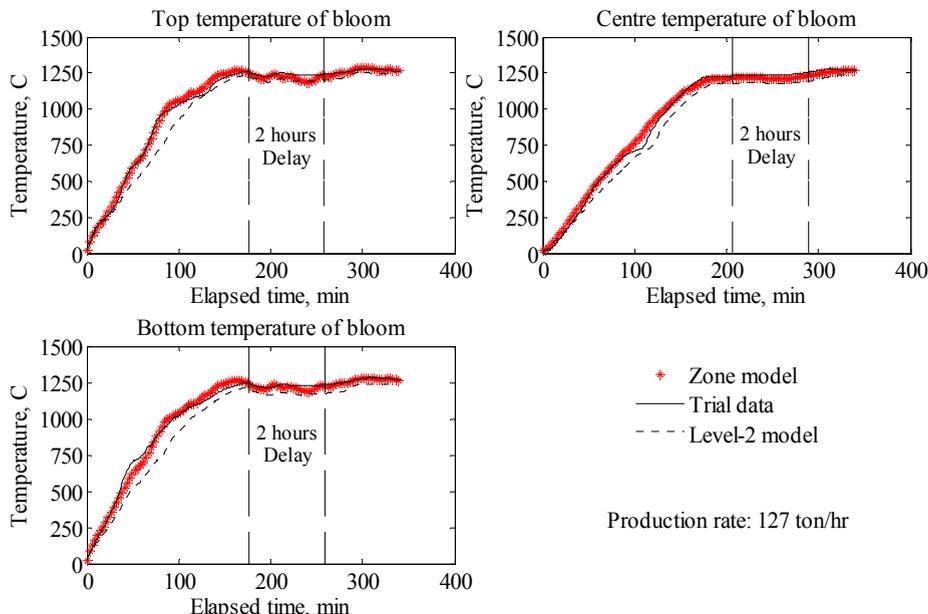

Figure 3 Predictions of the top, centre and bottom temperature histories of the instrumented bloom

During simulation of the trial period, the cumulative thermal energy entering and leaving the furnace were also calculated as shown in Table 7 and these were compared with the benchmark energy balance derived from the same trial. First a benchmark simulation was conducted with time-step of 20s and the known water-cooled load adjusted to approximately 19% of the fuel thermal input. Subsequently with all model parameters fixed, simulations were repeated with two further time-steps of 5s and 45s. Examination of Table 1 suggests that the zone model was able to predict the overall thermal behaviour of the furnace with reasonable accuracy.

Table 1 Comparison of furnace energy balance by trial data and zone model (ZM) results with different time-step setting

	Units	Energy input		Energy output				Performance		
		Q_f^1	Q_a^2	Q_b^3	Q_e^4	Q_{wc}^5	Q_l^6	E_c^7	E_f^8	SEC^9
Trial data	MW	41.6	5.5	18.9	15.9	8.1	4.2	75.1	45.5	1.76
	%Q_f	100.0	13.0	45.0	38.0	19.0	10.0			
ZM (dt = 5s)	MW	41.4	5.1	18.3	15.8	7.9	4.3	73.9	44.4	1.81
	%Q_f	100.0	12.2	44.4	38.3	19.0	10.4			
ZM (dt = 20s)	MW	41.1	5.0	18.2	15.7	7.9	4.2	74.0	44.4	1.79
	%Q_f	100.0	12.2	44.4	38.3	19.1	10.3			
ZM (dt = 45s)	MW	41.2	5.1	18.2	15.8	7.9	4.3	73.8	44.2	1.80
	%Q_f	100.0	12.3	44.2	38.4	19.1	10.5			

Even with consumer-level PC hardware, the efficiency of the zone model is fairly promising, as indicated in Figure 4, it is up to 170 times faster than the actual run time and given that there is additional scope for parallelizing the zone model program architecture, in particular the transient conduction module. The zone model is capable of real time simulation and has great potential to be used for parametric studies of furnace operating conditions or be incorporated directly into dedicated furnace optimisation and control algorithms.
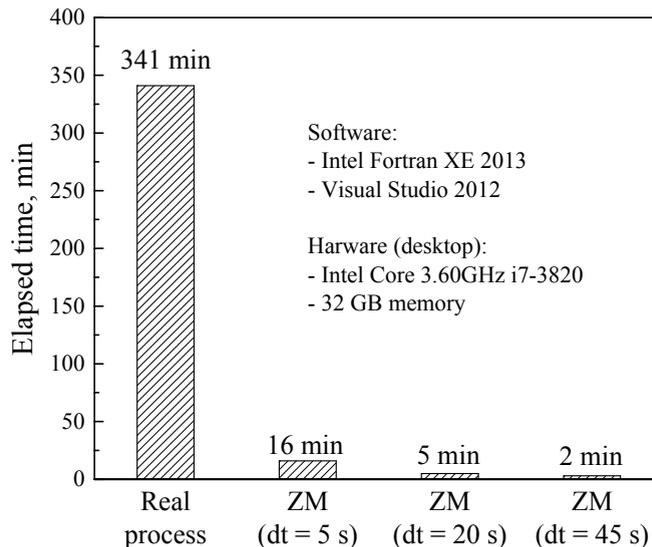

Figure 4 Comparison of the computing time of the cases with different time-step setting

5. Conclusions

In the advent of more affordable computing resources, comprehensive three-dimensional mathematical models for large-scale reheating furnaces are becoming achievable. This development is demonstrated in the current paper which highlights a novel approach to adapting the classical zone method with CFD-based internal flow model. A particular advantage of the developed model arises from the full energy balance derived from first principles which facilitates evaluation of the furnace specific fuel consumption and efficiency. The developed mathematical model has been validated by actual measurements from a large-scale reheating furnace and has been shown to outperform the semi-empirical level-2 model used in the existing plant. Further, up to 170 times faster than the actual run time, the model was still able to predict the overall thermal behaviour of the furnace with reasonable accuracy. Combined with its relatively short computing time the mathematical model may be suited for incorporation into supervisory temperature control system or as off-line model for investigating furnace optimisation and control problems.

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Biography

Yukun Hu was born in Yichang, China, in Feb. 1980. He obtained his PhD degree in Chemical Engineering, at Royal Institute of Technology, Sweden, in Feb. 2013. Presently he is a Research Assistant at the University of South Wales. His current research interests include process modeling and its applications in industry.