Third International Conference on CFD in the Minerals and Process Industries
CSIRO, Melbourne, Australia
10-12 December 2003

ASSESSMENT OF REFRACTORY CONDITION IN A BLAST FURNACE HEARTH USING COMPUTATIONAL FLUID DYNAMICS

Bryan WRIGHT, Paul ZULLI, Frank BIERBRAUER and Vladimir PANJKOVIC

BlueScope Steel Research, PO Box 202 Port Kembla 2505, Australia

ABSTRACT

The campaign life of a blast furnace is intimately linked to the longevity of the hearth refractories. Understanding how much refractory remains in the hearth is crucial to assessing when a blast furnace needs to be relined. A computational fluid dynamics (CFD) model was developed, using the commercial package CFX 4.4, to aid in the assessment of the refractory condition of the hearth. The model incorporates prediction of the fluid flow of molten iron, conjugate heat transfer between the melt and the refractories and conduction through the refractories. Since the development of this BlueScope Steel model in the late 1990s, continual refinements to the model have been made. The latest refinements include ability to model different shaped 'coke-free layers' and a more accurate description of the boundary conditions of the blast furnace hearth. Given these improvements to the model, a detailed analysis of the refractory condition was performed for BlueScope Steel's No. 5 Blast Furnace hearth using the CFD model. The predictions of the CFD model showed excellent agreement with measured plant data and also compared favourably to an independent hearth refractory model also used by BlueScope Steel. The model is now well accepted by production personnel as a tool to help understand the blast furnace hearth.

NOMENCLATURE

- β coefficient of volumetric expansion
- ρ density
- γ porosity
- λ thermal conductivity
- μ_{eff} effective viscosity
- μ_l laminar viscosity
- μ_T turbulent viscosity
- C tuning coefficient
- C_p heat capacity
- d coke particle diameter
- D height of coke-free layer
- H enthalpy
- P pressure
- T temperature
- T_{ref} reference temperature for Boussinesq term
- $\mathbf{u}$ interstitial or true velocity

INTRODUCTION

The ironmaking blast furnace is a complex process, involving the counter-current flow of liquid, solid, powder and gas phases. **Figure 1** shows a generalised process of the blast furnace where coke and ore enter the top of the furnace, hot gases enter the bottom of the furnace and they react in the middle to convert iron ore to molten iron and slag. The molten iron and slag then drip through the remaining coke bed and collect in the hearth. Periodically, the iron and slag are 'tapped' from the hearth to remove the collected liquids for further processing. Due to density differences, the slag floats on top of the molten iron in the hearth. The condition of the hearth plays a very important role in blast furnace operations. First, it must be such to allow easy removal of molten iron and slag otherwise the efficiency of the whole operation suffers. Second, the longevity of the blast furnace hearth is intimately linked to the campaign life of the whole blast furnace, vice versa understanding how much refractory remains in the hearth is crucial to assessing the campaign life of a blast furnace.

Panjkovic and Truelove [1] developed a CFD model of the flow of molten iron and heat transfer in the blast furnace hearth. This conjugate heat transfer problem presents interesting challenges to the CFD model due to the presence of porous and non-porous volumes, large scales (the hearth diameter is greater than 10 metres), natural and forced convection and a wide range of velocities (from several m/s to less than 1 mm/s). BlueScope Steel's CFD model has been named the Coupled Flow-Refractory Model (CFRM) and is now widely used to understand a range of process problems experienced in operating the blast furnace hearth.

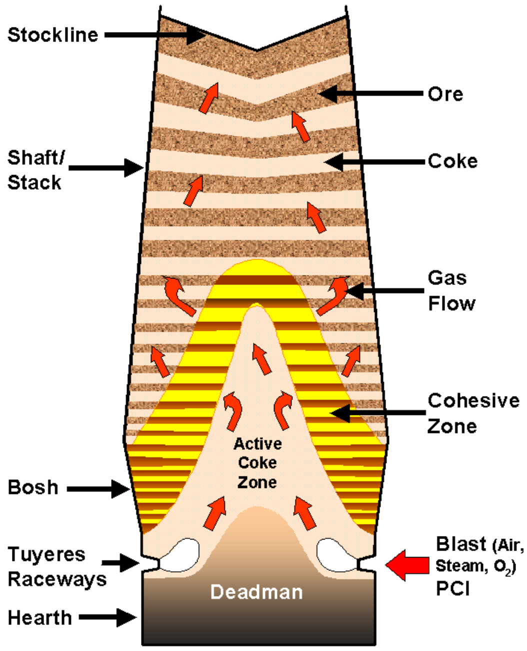


Figure 1: The blast furnace process.

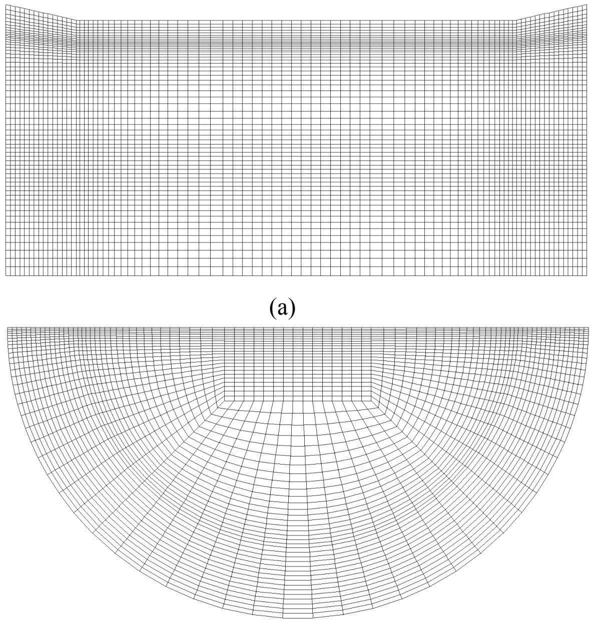
The aim of this paper is to describe some of the improvements to the CFRM and to detail how the model was used to provide an updated representation of the refractory configuration in the hearth based on operational data.

MODEL DESCRIPTION

The CFRM describes the flow of molten iron and assumes the slag/iron interface is fixed above the tap-hole. The CFRM considers the heat transfer between the molten iron and refractories, including the effect of turbulence in porous media (coke bed) on convective heat transfer. The model parameters and boundary conditions used in this study are given in **Table 1**. The bed porosity was set at 0.35 and the coke particle diameter as 0.03m. As the hearth has an axis of symmetry through the tap-hole, only one half of the total hearth volume is considered in the simulation. The flow of molten iron into the hearth in this simulation is considered to be uniform over the cross-sectional area of the hearth. Previous research has shown that hearth phenomena are relatively insensitive to the molten iron inflow distribution due to the fast liquid flow in the plane of the tap-hole (Panjkovic and Truelove, 2000). The mesh used in this study is shown in **Figure 2**.

Iron	
Laminar viscosity	0.00715 Pa s
Thermal conductivity	16.5 W m^{-1} K^{-1}
Heat capacity	850 J kg^{-1} K^{-1}
Thermal coefficient of volumetric expansion	1.4x10^{-4} K^{-1}
Production rate	≈80 kg s^{-1}
Height of liquid above the top of taphole entrance	0.25m
Reference T for calculation of Boussinesq term	1500°C
Refractories	
Heat capacity	1260 J kg^{-1} K^{-1}
Thermal conductivity of BC7S 1)	12.0 W m^{-1} K^{-1} , T≤30°C 13.5 W m^{-1} K^{-1} , T=400°C 15.5 W m^{-1} K^{-1} ,T≥1000°C
Thermal conductivity of BC30S	38 W m^{-1} K^{-1}
Thermal conductivity of firebrick 1)	2.38 W m^{-1} K^{-1} , T≤800°C 2.31 W m^{-1} K^{-1} , T≥1200°C
Thermal conductivity of ceramic cup 1)	2.20 W m^{-1} K^{-1} , T≤400°C
1) Conductivity is assumed to change linearly between discrete temperature values.	2.00 W m^{-1} K^{-1} , T=500°C 2.05 W m^{-1} K^{-1} , T=600°C 2.15 W m^{-1} K^{-1} , T=800°C 2.20 W m^{-1} K^{-1} , T=1000°C 2.30 W m^{-1} K^{-1} , T=1200°C 2.35 W m^{-1} K^{-1} , T≥1400°C
Coke bed	
Particle diameter	0.03 m
Porosity	0.35

Table 1: Model parameters.



(a)

(b)

Figure 2: Computational mesh used in this study.

Governing Equations and the Standard Model Parameters

The mass conservation and momentum transport equations are given by:

$$\nabla \cdot (\rho\, \mathbf{u}) = 0 \tag{1}$$

$$\nabla \cdot (\rho \mathbf{u} \times \mathbf{u}) - \nabla \cdot (\mu_{eff} \nabla \mathbf{u}) = -\nabla P + \nabla \cdot \left(\mu_{eff} (\nabla \mathbf{u})^T\right) + S_u + \beta \rho g \left(T - T_{ref}\right) \tag{2}$$

The criteria of Gray and Giorgini [2] indicate that the Boussinesq approximation is valid under conditions employed in this work. The effective viscosity is given by Eq. [3] and the resistance to the flow through the coke bed is calculated using Ergun's equation (Eq. [4]).

$$\mu_{eff} = \mu_L + \mu_T \tag{3}$$

$$S_u = -150 \mu_L \frac{(1-\gamma)^2}{\gamma^2 d^2} |\mathbf{u}| - 1.75 \rho \frac{1-\gamma}{\gamma d} |\mathbf{u}|^2 \tag{4}$$

An alternative turbulence model is used in this work. The turbulent viscosity can be determined from the standard k-ε turbulence model. However, in porous media the dimension of eddies depends on the size of pores, and the standard k-ε model cannot be applied directly. The importance of turbulent viscosity is that it can enhance heat transfer in the liquid iron and dampen the flow instability.

The absence of turbulent viscosity caused convergence problems in such layers. The flow was unstable because the laminar viscosity could not provide the dampening effect. A compromise was found in using a formula of the form:

$$\mu_T = C \rho D |\mathbf{u}| \tag{5}$$

where the coefficient C is selected as a value small enough to prevent convergence problems.

The transport equation for enthalpy is given by:

$$\nabla \cdot \left(\rho \mathbf{u} H - \left(\frac{\lambda}{C_p} + \frac{\mu_T}{0.9} \right) \nabla H \right) = 0 \tag{6}$$

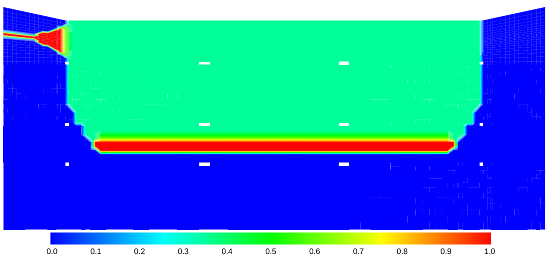
RESULTS

Improvements to CFRM

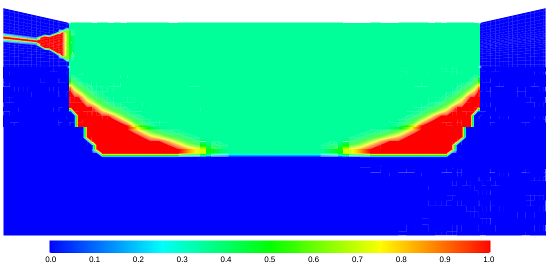
Since the development of the CFRM, a number of improvements have been made to the model including the ability to assess the effect of different shaped coke free layers (CFL). The correspondence between model calculations and furnace data is now very good.

One discrepancy noted in previous CFRM results was the under-prediction of the temperatures at the base of the hearth [1]. The previous CFRM results used an incoming molten metal temperature of 1500°C, which resulted in the temperature of the iron leaving the hearth around 1460°C (after heat is lost to the refractories). At the blast furnace, measured metal temperatures (at some distance from the exit of the hearth) typically exceed 1500°C. The incoming metal temperature has been adjusted up to a value of 1600°C. As a result, the agreement of the measured and predicted refractory temperatures in the base of the hearth has improved significantly. The temperature of the metal leaving the hearth was predicted at 1560°C, which would typically result in actual measured temperatures close to 1500°C some distance from the exit of the hearth.

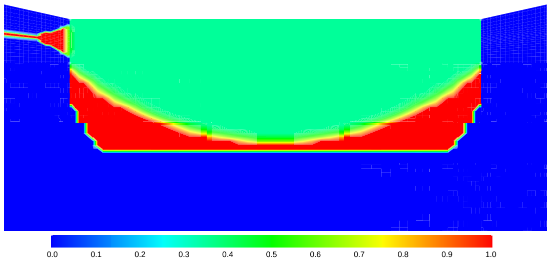
A further improvement to the CFRM was to simulate various CFL shapes. CFLs are very important to the hearth as there is far less resistance to fluid flow in these layers, compared with the fluid flow in the surrounding coke bed, and this has a significant influence on the tapping of the hearth. **Figure 3** shows a number of different shaped CFLs thought to exist in the blast furnace hearth. Previous CFRM work had concentrated on a uniform height CFL. **Figure 4** shows the typical temperature distribution and molten metal flow patterns predicted by the CFRM. This figure examines the flow for the variable height CFL (see **Figure 3c**). The presence of the CFL causes a large recirculation zone in the bottom right hand corner of the metal bath, away from the taphole. The CFL increases the mixing of the molten iron in the bottom of the hearth and results in a more uniform metal temperature distribution.



(a)



(b)



(c)

Figure 3: Different coke free layer shapes (a) uniform height, (b) coke-free gutter and (c) variable height.

Current Refractory Configuration

The operational period chosen for the analysis of the refractory in BlueScope Steel's No. 5 blast furnace was the 1-15 April 2002, just prior to the introduction of pulverised coal injection at that blast furnace. The period was also characterised by stable hearth temperatures. The layout of the thermocouples in the hearth is shown in **Figure 5**. Pad thermocouples in the hearth are located along the north, east, south and west axes of the blast furnace and at three different vertical positions, 300mm, 900mm and 1500mm above the bottom of the hearth refractories. Pad thermocouple data at the 1500mm and 900mm levels were averaged by radial position and height. Sidewall thermocouples are located around the circumference of the hearth at 8 evenly spaced locations. Sidewall thermocouples are paired ie. a 'long' thermocouple inserted 145mm into the refractory are co-located with a 'short' thermocouple inserted 20mm into the refractory. The sidewall thermocouple data was averaged at each elevation.

Boundary conditions

The boundary conditions specified in the CFRM were based on the following average thermocouple temperatures measured during the period :

- Pad thermocouples at the 300mm level ie. just above BC-30 refractories and
- Short sidewall thermocouples.

Assumptions

The current refractory configuration was based on the following assumptions :

- No erosion of the ceramic cup occurred before 1998; and
- That an historic high in the refractory temperature occurs when a CFL has formed.

No attempt was made in this study to determine the change in hearth refractory between 1999 and March 2002. The refractory condition is considered solely based on the thermocouple measurements during the first half of April 2002, ie. CFRM calculations are compared only with data from this period. It should also be noted that CFL positions can change with time but is assumed to constant within the time frame examined within this study.

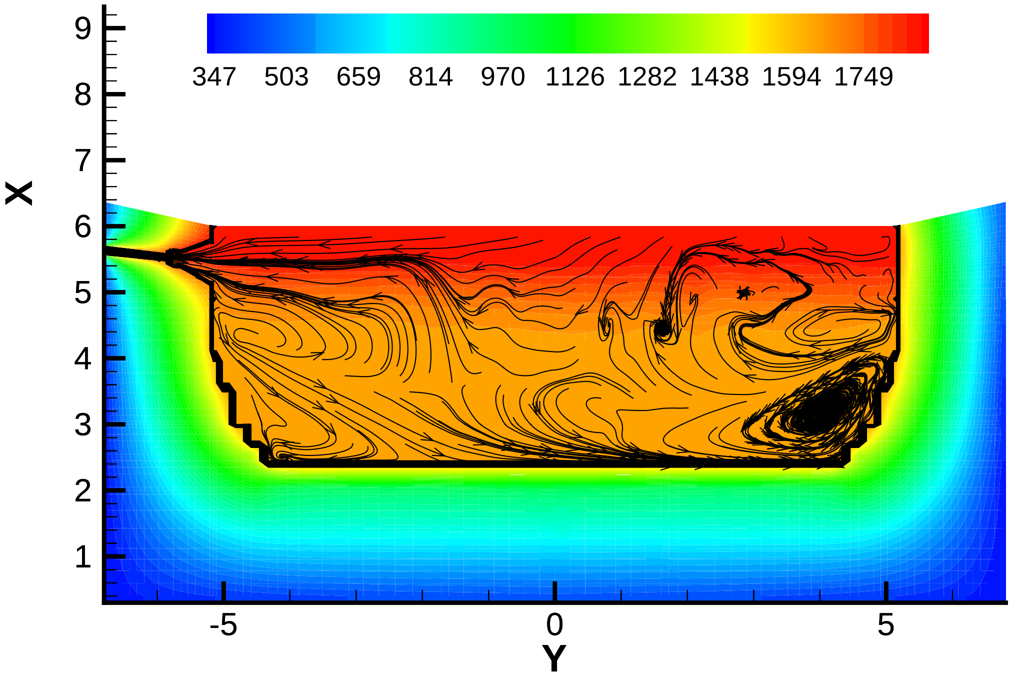


Figure 4: Typical temperature distribution (in Kelvin) within iron melt and refractories with molten iron streamlines for variable height coke free layer simulation (dimensions in metres).

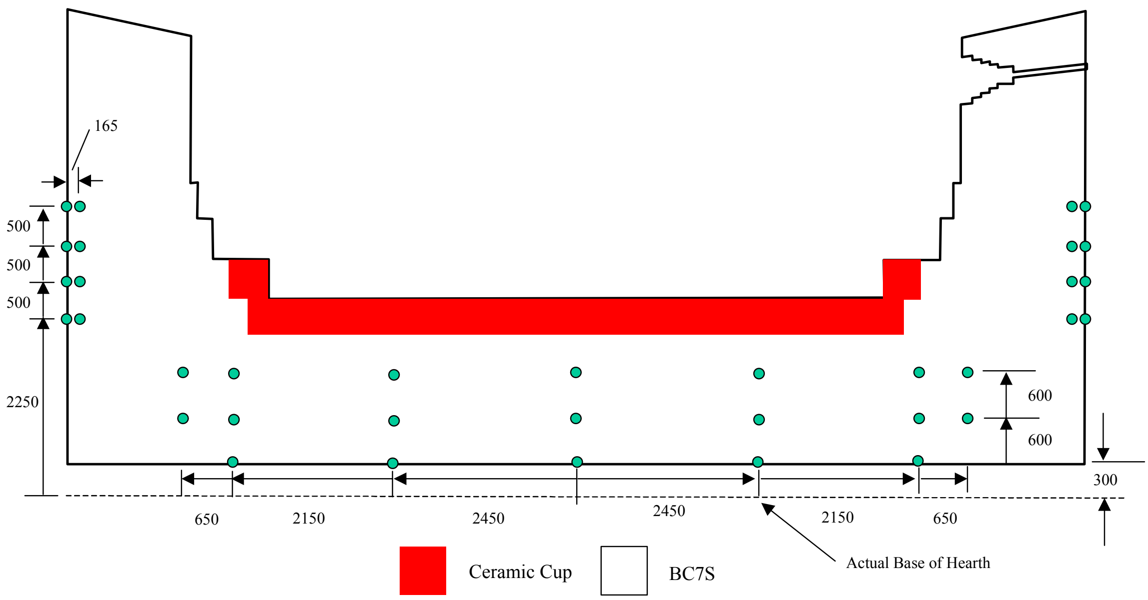


Figure 5: Location of thermocouples (green points) in the blast furnace hearth.

A trial and error approach was adopted to estimate the refractory configuration, where refractory was gradually removed until a reasonable match was obtained between measured and calculated temperatures.

The best match between calculated and measured pad thermocouples for the period 1-15 April 2002 occurred when the ceramic cup refractory was eroded by 100mm (see **Figure 5**).

The refractory assessment was then further refined through investigation of the effect of various CFL shapes (as noted in **Figure** 3). The results show a very good agreement between the predicted and measured thermocouple data for the pad thermocouples for the case of the uniform height CFL (**Figure 6**). In the case of the sidewall thermocouples, the best match between the CFRM and plant data also occurs for the uniform height CFL (**Figure 7**). The coke-free gutter and variable height CFL's produce higher refractory temperatures than observed at the blast furnace during this period at the highest positioned sidewall thermocouple. However due to the close location of the sidewall thermocouple to the boundary, the sidewall thermocouple are strongly influenced by the boundary condition, resulting in small temperature differences for given CFL shapes.

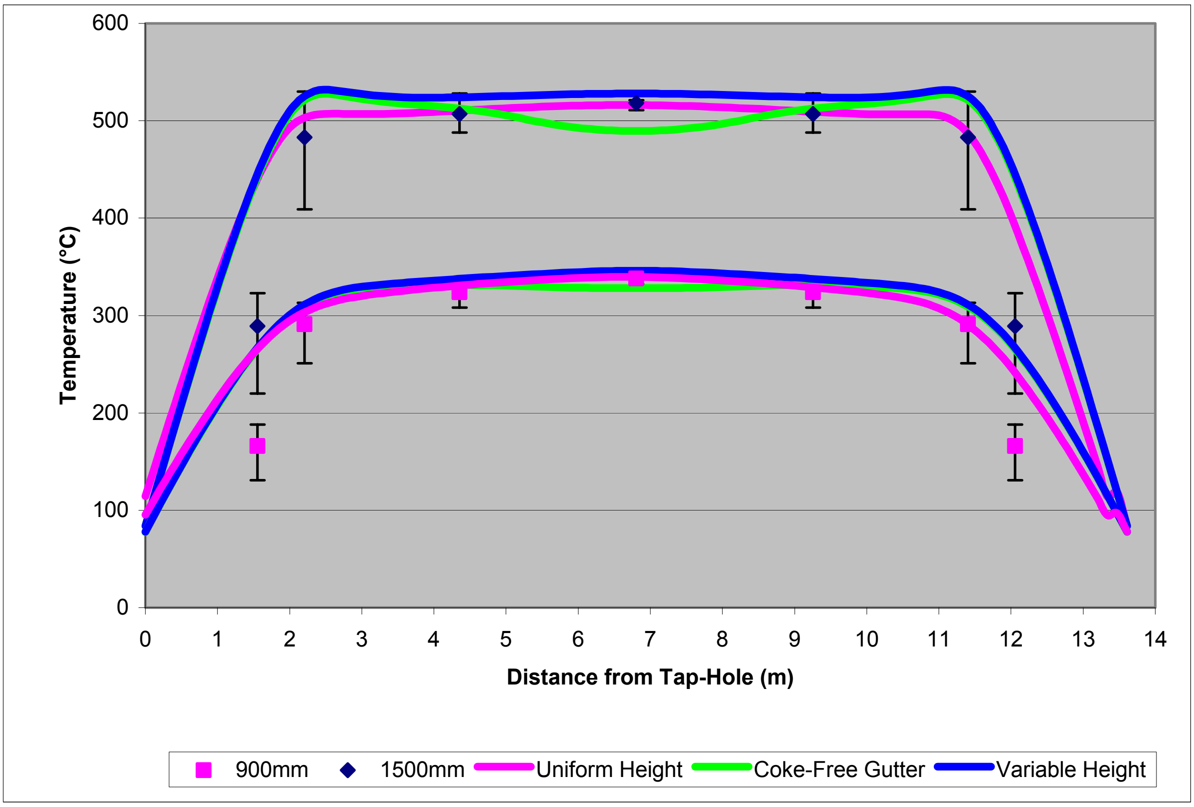


Figure 6: Comparison of pad thermocouple with predictions of CFRM for different CFL shapes.

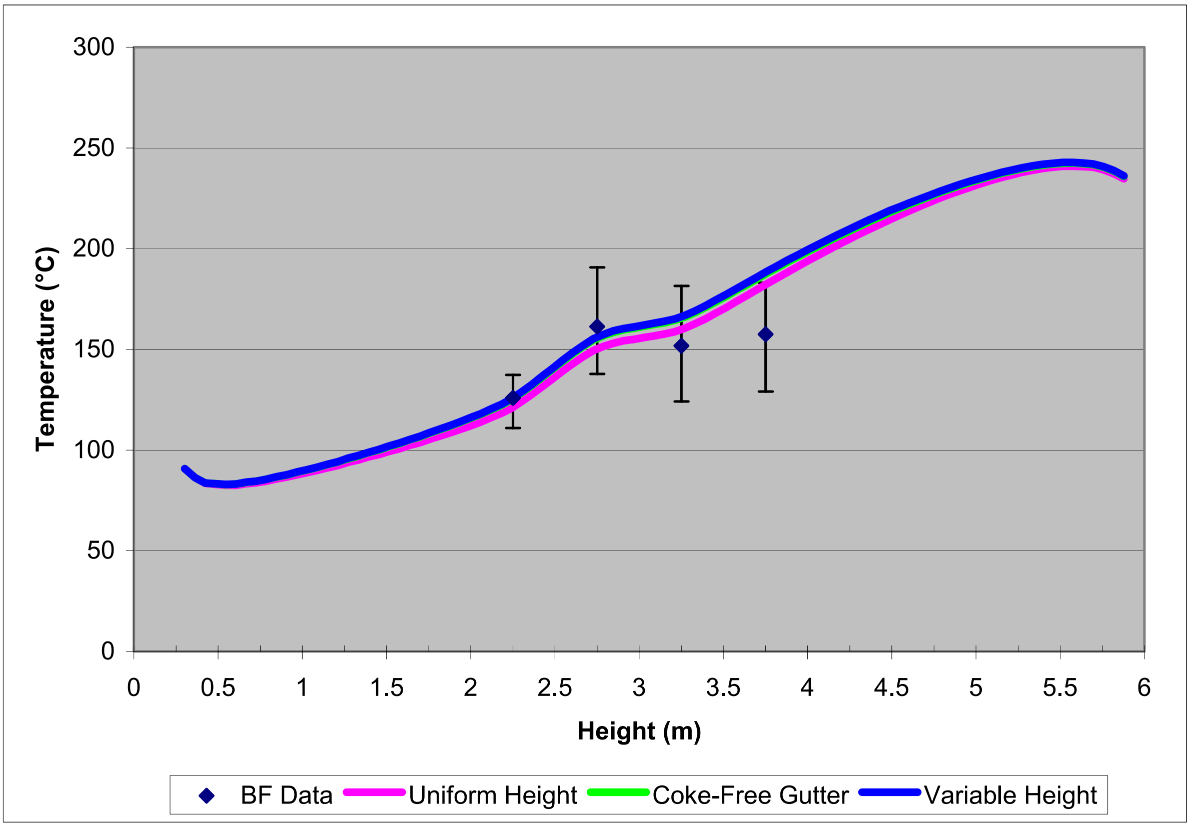


Figure 7: Comparison of sidewall thermocouple with predictions of CFRM for different CFL shapes.

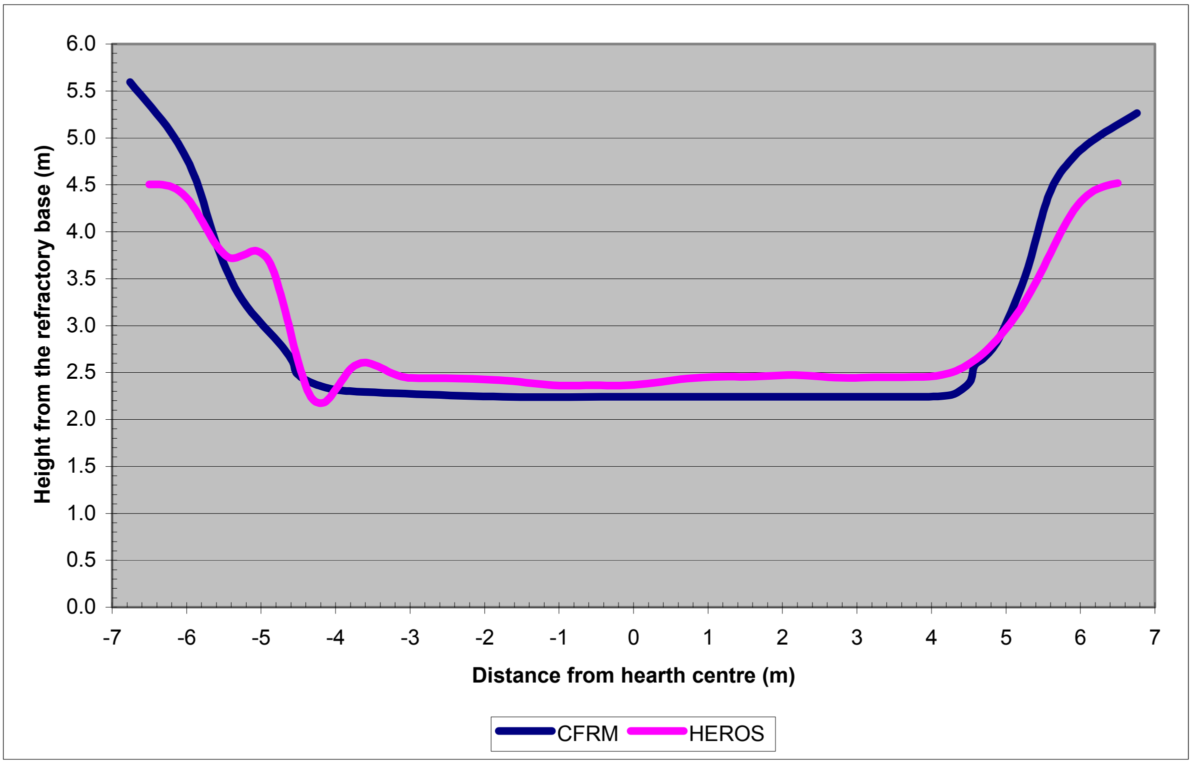


Figure 8: Comparison of the position of 1150°C isotherm for CFRM and HEROS model.

Validation of CFRM Results with HEROS

HEROS is BlueScope Steel's original model for the determination of refractory thickness in the hearth [3]. HEROS is a steady state heat conduction model which uses measured thermocouple data to extrapolate the position of the 1150°C isotherm. This isotherm represents the eutectic point on the iron-carbon phase diagram and is the minimum temperature for the presence of liquid iron; hence it is a reasonable estimate for the position of the refractory/molten iron interface.

A comparison of the 1150 °C isotherm was made between the HEROS model and the CFRM (**Figure 8**). The results show excellent agreement between the HEROS and the CFRM models for the pad and lower sidewalls.

DISCUSSION

The assessment of hearth refractory condition has shown the strong effect of the position of the CFL in the hearth. This study focussed on predicting the refractory condition of the hearth and not on the analysis of the short-term variation in the thermocouple temperatures (eg. the period during the formation of the CFL). These temporal variations are related to transient hearth phenomena such as porosity variation, metal penetration of refractories, molten iron flow changes, etc. These phenomena and their effects of hearth thermocouple trends require further investigation. Further refinement of the model for the prediction of the temperature and wear in the sidewalls of the hearth is required. These refractories are subject to the highest heat loads and are most susceptible to rapid erosion, hence of high importance to the integrity and safety of blast furnace operations.

CONCLUSIONS

The results of a computational fluid dynamics model for the prediction of molten iron fluid flow and heat transfer in the blast furnace hearth has been presented. A number of improvements have been made to a previously developed model to enhance the prediction of the refractory condition in the blast furnace hearth. Better correspondence between hot metal temperatures and the ability to examine the effect of different coke-free layers has been demonstrated. The model is now used to assess the degree of refractory wear in the hearth, using operational data to set the boundary conditions and to determine the accuracy of the modelling predictions. Current results revealed that coke-free layers may have a significant effect on both the fluid flow and heat transfer within the blast furnace hearth.

REFERENCES

PANJKOVIC, V. and TRUELOVE, J. (1999) "Computational Fluid Dynamics Modelling of Iron Flow and Heat Transfer in the Iron Blast Furnace Hearth", Second International Conference on CFD in the Minerals and Process Industries, CSIRO, Melbourne Australia, 6-8 December.

GRAY, D.D. and GIORGINI, A. (1976), "The Validity of the Boussinesq Approximation for Liquids and Gases", *Int. J. Heat Mass Transfer*, **19**, pp. 545-51.

REX, A, ZULLI, P, PLAT, P, TANZIL, W, SKIMMINGS, T and JELENICH, L. (1993), "Determination of the State of the Hearth of BHP Steel's Blast Furnaces", 52nd Ironmaking Conference of the Iron and Steel Society, Dallas, USA, 28-31 March.