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MATHEMATICAL MODELLING OF FLOWS AND TEMPERATURE DISTRIBUTIONS IN THE BLAST FURNACE HEARTH

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ABSTRACT

The erosion of hearth refractories typically governs the asset life of a blast furnace. Since operating conditions within the hearth make it practically impossible for direct measurement and visualisation, physical and mathematical models play an important role in understanding and assessing the cause-effect phenomena between the liquid iron, coke bed and refractories. A numerical model has been developed to predict the iron flow and temperature distribution within the packed bed and refractories. A number of case studies have been investigated for Port Kembla's No. 5 blast furnace, which is entering the 15th year of its current campaign. These case studies considered the effects of coke free layers (floating/sitting deadman), hearth deposits, coke bed fouling and localised refractory erosion. The refractory temperature distributions predicted by the model compare well with the blast furnace thermocouple measurements and as a result, the model has become a valuable predictive tool for hearth design and control.

NOMENCLATURE

C_p	heat capacity
d	coke particle diameter
g	gravity
H	enthalpy
P	pressure
T	temperature
T_{ref}	reference temperature for Boussinesq term
$\mathbf{u}$	velocity
β	thermal coefficient of volumetric expansion
ρ	density
γ	bed voidage
λ	thermal conductivity
μ_{eff}	effective viscosity
μ_L	laminar viscosity
μ_T	turbulent viscosity
ζ	coke internal porosity

INTRODUCTION

The ironmaking blast furnace is a complex counter-current packed bed reactor. Liquid iron and slag, produced as a result of reducing reactions between iron ore and coke particles, drip through the coke packed bed and are collected in the hearth. Liquid iron and slag are removed from the furnace at regular intervals through multiple tapping holes (tapholes). A schematic of the Port Kembla Blast Furnace 5 (PKBF5) hearth is shown in **Fig. 1**.

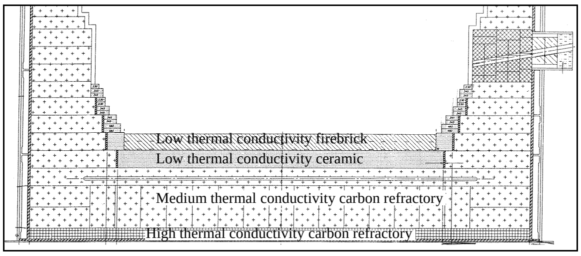


Figure 1: Port Kembla Blast Furnace 5 (PKBF5) hearth showing one taphole (right side) and different refractory materials at the start of its campaign

The campaign life of the blast furnace is governed by the wear of the hearth refractories. Hence, understanding the remaining thickness of refractory is crucial in assessing the remaining campaign life of the furnace. In addition, an indication of the permeability of the coke packed bed within the hearth is very useful for setting up casting practices from the furnace.

Previously, BlueScope Steel has developed a conjugate heat transfer-CFD model of liquid iron flow and refractory heat transfer for the BF hearth (Panjkovic et al., 2002). This model has continuously been improved over recent years (Zulli et al., 2002; Wright et al., 2003). The model, known as CFRM (Coupled Flow-Refractory Model), is widely used in understanding a variety of operating regimes experienced at the Port Kembla blast furnaces.

Applications of the model include the effect of a floating coke packed bed on refractory temperatures, the effect of build-up or deposit layers on refractory life and the recommended location of thermocouples for future monitoring of refractory wear. These are discussed in this paper.

MODEL DESCRIPTION

CFRM describes the flow of molten iron in the hearth and assumes the slag/iron interface is fixed above the taphole level. Heat transfer between the molten iron and refractories, including the effect of turbulence in porous media on convective heat transfer is also considered.

Governing equations

The flow field is described by transport equations of the continuous phase, i.e., three-dimensional, steady-state Reynolds-averaged Navier-Stokes equations, closed by the k-ε turbulence model equations, based on the framework of the software package ANSYS-CFX4.4.

The continuity and momentum conservation equations are given by:

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

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

A Boussinesq approximation is adopted to calculate the density of liquid iron as a function of temperature. The reference temperature is 1500°C. The last term in **Eq. (2)** represents the resistance to flow in the porous medium. Based on Ergun's equation, the resistance force is given by:

$$S_u = -150 \mu_L \frac{(1-\gamma)^2}{\gamma^2 d^2} |\mathbf{u}| - 1.75 \rho \frac{1-\gamma}{\gamma d} |\mathbf{u}|^2 \qquad (3)$$

The effective viscosity of **Eq. (2)** is given by:

$$\mu_{eff} = \mu_L + \mu_T \qquad (4)$$

The first term on the RHS of **Eqn. 4** represents the laminar viscosity. The second term represents the turbulent viscosity, which is determined by applying the k-ε model modified by Nakayama and Kuwahara (1999), in which an extra source term due to solid particles is added in the turbulence model equations (namely, kinetic energy and its dissipation) for normal fluid flow. The comparison of this turbulence model with other models was discussed by Guo et al. (2003). The adoption of the Nakayama and Kuwahara (1999) turbulence source terms represents a change to the previous formulation of the model (Wright et al, 2003) where turbulent viscosity was a function of an empirical coefficient (Takeda and Lockwood, 1997).

The transport equation for enthalpy is given by:

$$\nabla \cdot \left(\rho \mathbf{u} H - \left(\frac{\lambda}{C_p} + \frac{\mu_T}{0.9} \right) \nabla H \right) = 0 \qquad (5)$$

Hearth Geometry

The model parameters and boundary conditions used in this study are given in **Table 1**. As the hearth has an axis of symmetry through the taphole, only one half of the total hearth volume is considered in the simulation. The flow of molten iron into the hearth is considered to be uniform over the cross-sectional area of the hearth.

Compared with the previous version (Wright et al, 2003), the main differences in formulation shown in **Table 1** relate to the thermal conductivity calculation for liquid iron and coke particles. This calculation has now been made temperature dependent and separate values are calculated for liquid iron and coke particles.

Iron	
Laminar viscosity	0.00715 Pa s
Thermal conductivity	0.0158 × T_{iron} (K), W m^{-1} K^{-1}
Heat capacity	850 J kg^{-1} K^{-1}
Thermal coefficient of volumetric expansion	1.4×10^{-4} K^{-1}
Production rate	7000 tonne day^{-1}
Height of liquid above the top of taphole entrance	0.25 m
Reference T for calculation of Boussinesq term	1500°C
Refractories	
Heat capacity	1260 J kg^{-1} K^{-1}
Thermal conductivity of BC7S	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 firebrick	2.35 W m^{-1} K^{-1}
Thermal conductivity of ceramic cup	2.20 W m^{-1} K^{-1}, T≤400°C
Coke bed	
Particle diameter	0.03 m
Bed voidage (γ)	0.35
Coke internal porosity (ζ)	0.45
Thermal conductivity	[0.973 + 6.34 × 10^{-3} × T_{coke} (K)] × ($1-\zeta^{2/3}$), W m^{-1} K^{-1}

Table 1: Model parameters.

The geometry considered for the study was the Port Kembla Blast Furnace 5 (PKBF5) hearth. This furnace, which commenced its current campaign in 1991, produces approximately 7000 tonne of liquid iron per day and has an inner hearth volume of approximately 140 m^3.

The geometry of PKBF5, in its year 2005 assessed condition, is shown in **Fig. 2**. The original refractory geometry at the time of commissioning was shown in Fig. 1. The main differences consist of the gradual erosion of firebrick and ceramic layers. The current assessed condition of the refractory was derived in a procedure similar to that outlined by Wright et al. (2003), i.e. it was developed through comparison of model outputs with actual blast furnace thermocouple temperatures.

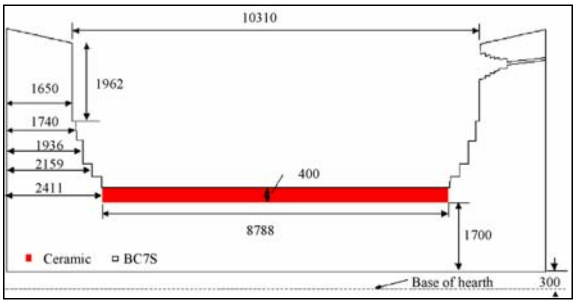


Figure 2: Geometric dimensions of PKBF5 hearth

The numerical computations were performed with the general purpose fluid flow package CFX4.4. A three dimensional, block structured numerical grid for the hearth geometry is shown in **Fig. 3**. Higher grid resolution is present near the taphole and near the low thermal conductivity ceramic cup layer. The grid consists of approximately 148,000 control volumes.

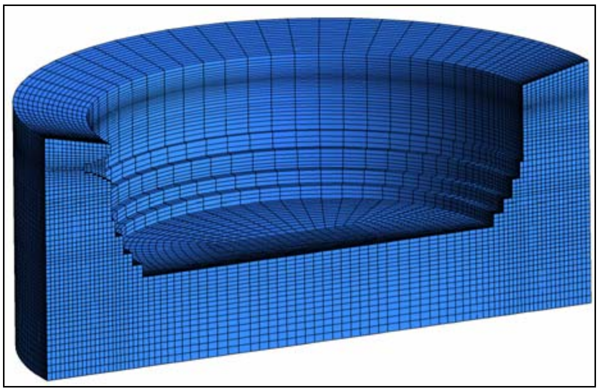
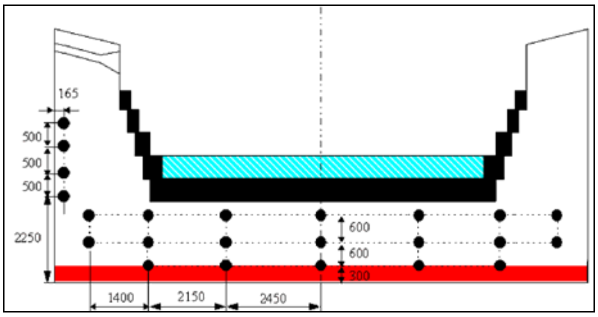


Figure 3: Computational grid of the hearth geometry (refractory shown)

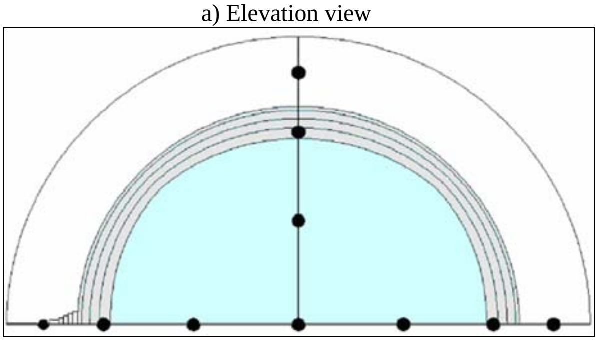
The bottom boundary corresponds to the interface between the medium thermal conductivity and the high thermal conductivity carbon refractories, 300 mm from the base of the furnace. This interface was selected as the bottom boundary because of the availability of thermocouples at this height that can be used to set temperature boundary conditions, as elaborated below.

Boundary Conditions

The liquid iron production rate was assumed to be 7000 tonne/day at an inlet temperature of 1600^{o}C. The external temperature boundary conditions of the refractory were a function of furnace thermocouple data for the respective periods under investigation. Pad and sidewall thermocouples are located in the refractory, as shown in **Fig. 4**.



a) Elevation view



b) Plan view

Figure 4: Schematic showing the position of refractory pad thermocouples at PKBF5

Temperature boundary conditions were based on the thermocouple readings at the 300mm level (bottom boundary surface) and the sidewall thermocouples were used for the external face.

Period under investigation

The centre axial pad thermocouples provide an adequate representation of changes in the state of the refractory and the coke packed bed. The variation with time of the centre (axial) pad temperature at 1500 mm level (uppermost level of pad thermocouples) is shown in **Fig. 5**. The graph spans January 2002 onwards. May 2002 saw the commencement of Pulverised Coal Injection (PCI) at the Port Kembla blast furnaces. PCI involves replacement of coke fed in the burden with coal injected into the hot blast, and this has an effect on the variability of the coke bed permeability.

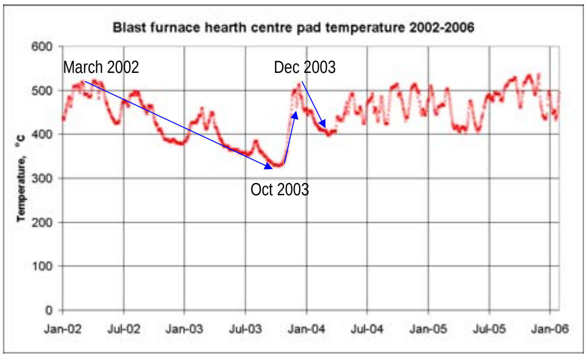


Figure 5: Centre pad temperature data for PKBF5 for January 2002 onwards

A few periods have been highlighted in **Fig. 5**. There was a gradual reduction in refractory temperature during the period of March 2002 to October 2003. Then a rapid increase in temperatures took place, peaking late December 2003. This was followed by another gradual decrease through to March 2004. The temperatures have since fluctuated between 400^{o}C-500^{o}C.

The fluctuation in centre pad temperature from March 2004 onwards is consistent with coke bed floating and sitting cycles. That is, buoyancy forces acting on the coke bed overcome gravitational and frictional forces to lift it above the hearth pad. This allows a stream of liquid iron to come into direct contact with the refractory, thereby increasing the convective heat transfer. The height of this Coke Free Layer (CFL) determines the extent of temperature increase in the pad temperatures. The subject of coke free layers and its effect on refractory temperatures was discussed previously (Panjkovic et al., 2002; Zulli et al., 2002; Wright et al., 2003).

The centre pad temperature variation before March 2004 is however more difficult to explain. This is because the temperatures measured in October 2003 were among the lowest temperatures for the furnace campaign. Subsequently a rapid 180^{o}C temperature increase occured.

The period of interest shown in **Fig. 5** can be put into context by comparing it with historical PKBF5 campaign data. This is shown in **Fig. 6**.

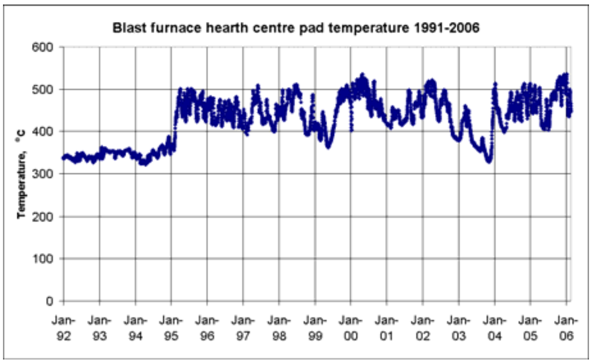


Figure 6: Campaign centre pad temperature data for PKBF5

From **Fig. 6** it can be seen that the temperatures experienced in October 2003 are comparable to the temperatures experienced at the beginning of the campaign, when the furnace refractory was in pristine condition. The original refractory layout was shown in **Fig. 1**, noting that a 500 mm thick protective firebrick layer was present in the pad. Because of its low thermal conductivity (2.3W/m K), the firebrick layer provided a high thermal resistance. The work of Panjkovic et al. (2002) concluded that the firebrick layer was lost during early 1995, and this led to the rapid increase in temperatures observed in **Fig. 6**.

Hence in order to simulate the low temperatures observed in October 2003, a high thermal resistance will need to be present. It was proposed that low conducting build-up or deposit layers were gradually formed during June 2002-October 2003 following the introduction of coal injection. Build-up or deposit layers can consist of high melting point materials such as titanium carbonitride, Ti(C,N), or frozen slag. They generally form in areas of low bed permeability, where the flow of hot iron is low (Bergsma and Fruehan, 2001; Takeda et al., 1999).

RESULTS

Cases Considered

Simulation results for three time periods are presented. For the different periods under study, a trial and error approach was adopted to estimate the packed bed and refractory configuration. Packed bed and refractory conditions were gradually modified until a reasonable match was obtained between measured furnace and calculated temperatures.

1. Period during <u>March 2002</u> whereby centre pad temperatures were typically 510°C, simulated using a uniform (flat) 400 mm coke free layer (floating coke bed on pool of iron). This is represented in **Fig. 7**.
2. Period during <u>October 2003</u> whereby centre pad temperature was 330°C, simulated using a sitting coke bed and deposited low thermal conductivity protective layers. This is represented in **Fig. 8**.
3. Period during <u>December 2003</u> whereby temperatures increased to their March 2002 level. One possible representation is as **Fig. 7**, while other options consist of **Figs. 9-10**. The latter figures consist of a floating coke bed with a raised hemispherical shaped coke free layer shape as opposed to a uniform coke free layer.

The peripheral region of the coke bed may be more buoyant because of the effect of the blast air, which is injected above the hearth throughout the furnace periphery. In **Fig. 10**, an 800 mm CFL is assumed.

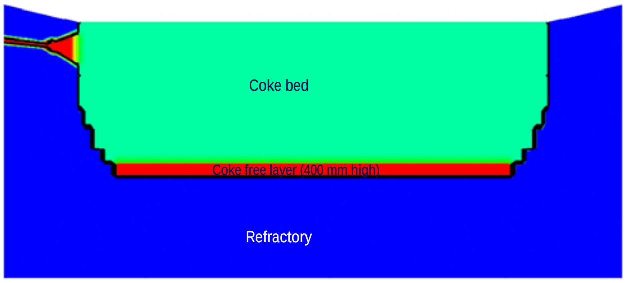


Figure 7: March 2002 simulation

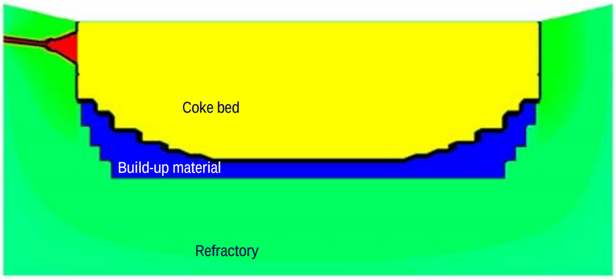


Figure 8: October 2003 simulation

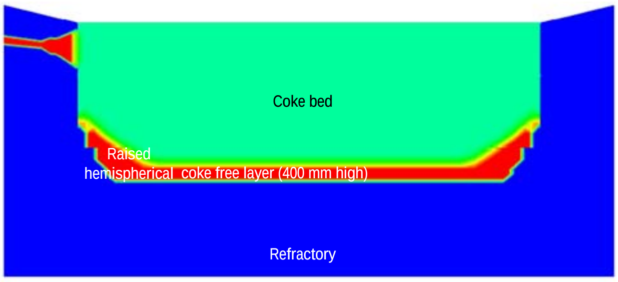


Figure 9: December 2003 simulation

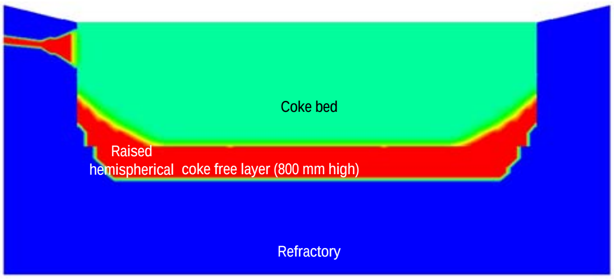


Figure 10: Alternate December 2003 simulation

Temperature comparison

Comparisons between furnace temperatures and predicted model outputs are carried out for the top row of pad thermocouples, located 1500 mm from the furnace bottom. The comparisons for the different cases studied are shown in **Figs. 11-13**.

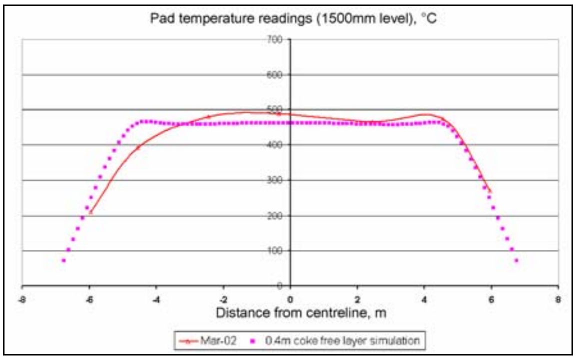


Figure 11: Comparison of pad thermocouple with model predictions for a uniform 400 mm coke free layer simulation (see Fig 7)

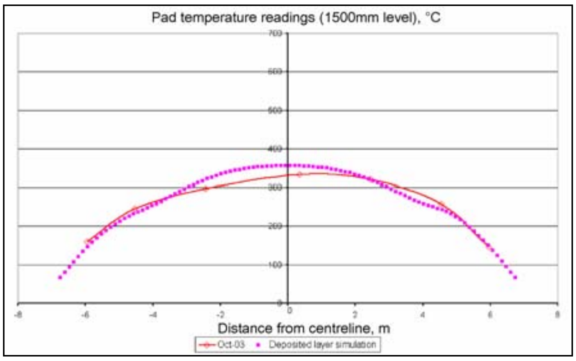


Figure 12: Comparison of pad thermocouple with model predictions for case with build-up layer (see Fig 8)

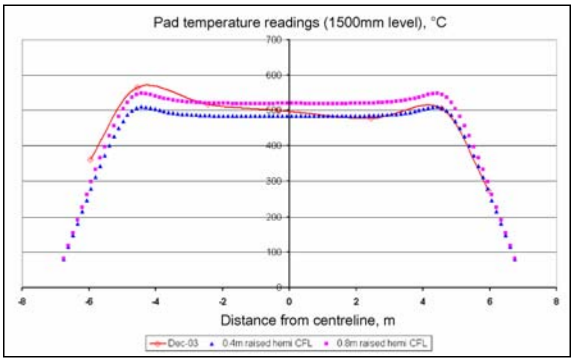


Figure 13: Comparison of pad thermocouple with model predictions for 400 mm and 800 mm raised hemispherical shaped coke free layer (see Figs 9-10)

Figs 11-13 show very good comparisons between the furnace temperatures and the model output. Hence the most likely explanation for the sequence of temperatures observed between early 2002 and late 2003 is as follows:

- Coke bed was floating, with a typical coke free layer height of 400 mm (March 2002)
- During the subsequent months, the bed became progressively inactive, most likely due to the introduction of pulverised coal injection. PCI leads to a reduction in coke fed to the burden, thereby increasing its residence time in the furnace, which results in more coke fine generation. The bed inactivity led to the formation of high melting point protective layers, which deposited on the refractory pad (October 2003). This resulted in pad temperatures being recorded similar to 1995 levels, where the refractory was in its original condition.
- Following the relatively long period of bed inactivity, a change in the balance of buoyancy, gravitational and friction forces in the hearth led to a period of bed floating (December 2003). As a result the protective layers were eroded and the refractory was exposed to liquid iron flow, which led to a rapid rate of temperature increase. This rate of temperature increase was similar to the period experienced during 1995, where the 500 mm thick protective firebrick layer was lost.

Thermocouple layout design

As a result of this study, recommendations were made to increase the coverage of thermocouples in the hearth pad. An opportunity for the recommendation to be implemented will be during the scheduled reline of PKBF5, expected in late 2007.

From **Fig. 4b**, which showed the existing thermocouple coverage in the furnace pad in plan view, it can be seen that thermocouple coverage exists in only the two main axis (North-South and East-West axis).

The new thermocouple layout for the next campaign of this furnace is shown in **Fig. 14**.

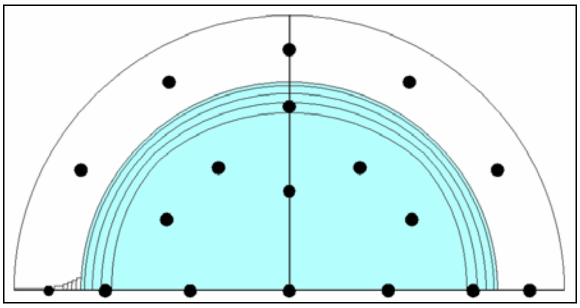


Figure 14: Proposed thermocouple coverage in the pad (1500mm and 900 mm levels) – plan view

The improved thermocouple layout will allow more detailed predictions of the packed bed condition and refractory state to be made using the model.

With the existing thermocouple layout (**Fig. 4b**), model comparisons can only be made in two main directions (separated by 90 degrees). With the new layout, predictions will be able to be made in 6 directions (30 degree separation in radial direction).

CONCLUSIONS

The application of a numerical model for the prediction of molten iron flow and heat transfer in the blast furnace hearth have been presented. Improvements to model formulation from a previous model version were made by introducing a new turbulence model and new thermal conductivity calculation for the coke bed and liquid iron.

Temperature fluctuations observed in the refractory pad of Port Kembla's Blast Furnace 5 were analysed. Findings from the model led to the conclusion that low thermal conductivity protective layers had previously formed in the hearth, associated with an inactive coke bed. When the bed floated, the protective layers were lost and the refractory temperatures increased rapidly.

On the basis of the model results, a new thermocouple layout within the refractory pad has been recommended. This layout will be implemented for the next campaign of the furnace. This will improve refractory monitoring and model predictability.

REFERENCES

PANJKOVIC,V., TRUELOVE, J.S., ZULLI, P., (2002), "Numerical Modelling of Iron Flow and Heat Transfer in Blast Furnace Hearth", *Ironmaking and Steelmaking*, **29**, 390-400.

ZULLI, P., TANZIL, F., PANJKOVIC, V., WRIGHT, B. and NIGHTINGALE, R., (2002), "Hearth Process Design and Control", *International BF Lower Zone Symposium*, Wollongong.

WRIGHT, B., ZULLI, P., BIERBRAUER, F. and PANJKOVIC, V., (2003), "Assessment of Refractory Condition in a Blast Furnace Hearth Using Computational Fluid Dynamics", *Fourth International Conference on CFD in the Process Industries.*

NAKAYAMA, A. and KUWAHARA, F., (1999), "A macroscopic turbulence model for flow in a porous medium," *J. Fluids Eng*., **121**, 427-433.

GUO, B., YU, A., WRIGHT, B. and ZULLI, P., (2003), "Comparison of Several Turbulence Models Applied to the Simulation of Gas Flow in a Packed Bed", *Fourth International Conference on CFD in the Process Industries.*

TAKEDA, K. and LOCKWOOD, F., (1997), "Integrated Mathematical Model of Pulverised Coal Combustion in a Blast Furnace", *ISIJ International*, **37**, 432.

BERGSMA D. and FRUEHAN R., (2001), "Fundamentals of Titanium Rich Scaffold Formation in the Blast Furnace Hearth," *Ironmaking Conference Proceedings*, 297-312

TAKEDA, K., WATAKABE, S., SAWA, Y., ITAYA, H., KAWAI, T. and MATSUMOTO, T., (1999), "Prevention of Hearth Brick Wear by Forming a Stable Solidified Layer", *Ironmaking Conference Proceedings*, pp. 657-65.