Eighth Australasian Fluid Mechanics
Conference, University of Newcastle,
N.S.W., 28 November/2 December 1983.

RECIRCULATING GAS FLOW IN THE BLAST FURNACE RACEWAY ZONE

M.J. McCARTHY — CENTRAL RESEARCH LABORATORIES, BHP CO. LTD., SHORTLAND, NSW. 2307 AUSTRALIA

I.J. TAGGART & W.V. PINCZEWSKI — SCHOOL OF CHEM. ENG., UNI. OF NEW SOUTH WALES, KENSINGTON, NSW. 2033 AUSTRALIA

J.M. BURGESS — DEPT. OF CHEMICAL ENGINEERING, UNIVERSITY OF QUEENSLAND, ST. LUCIA, QLD. 4063 AUSTRALIA

SUMMARY A numerical study of gas flow for conditions similar to those existing in the tuyere zone of an iron-making blast furnace is presented. The numerical method used is based on a primitive variable Marker and Cell (MAC) technique, which is applied to the gas flow both within the raceway and the coke bed surrounding the raceway.

Results of the study indicate the presence of strong upper and lower gas recirculation zones within the raceway together with large localised pressure gradients in the coke bed surrounding the raceway. The calculations show that the large pressure gradients in the coke bed adjacent to the raceway are caused by the motion of gas within the raceway and not solely by the accumulation of fines at the back of the raceway as has been previously assumed.

NOTATION

Cp	Pressure Coefficient
d	Coke Diameter
D_R	Depth of Raceway
D_T	Diameter of Tuyere
G	Force/Unit vol. between solid and gas
H_R	Height of Raceway
P	Gas Pressure
$\underset{\sim}{t}$	Time
$\tilde{u}$	Gas Superficial Velocity Vector with (x,y) components (u,v)
V_B	Blast Velocity
ε	Voidage
μ_E	Effective (Turbulent) viscosity
μ	Gas Viscosity
ρ	Gas Density
ψ	Stream Function
∇	Gradient Operator

1 INTRODUCTION

In the ironmaking blast furnace process a hot air blast is introduced into the lower part of the furnace through a system of tuyeres located about the circumference of the furnace. A typical modern high productivity furnace may have upwards of twenty such tuyeres with blast velocities in individual tuyeres being as high as 250 ms^{-1}. The combination of the high velocity air blast and the subsequent coke gasification reaction result in the formation of a high voidage zone in front of each tuyere. This high voidage zone is called a raceway because of the characteristic circular motion of coke particles within this zone.

The raceway plays an important role in determining the stability and productivity of a blast furnace because it is the major source of hot reducing gases required for the important reduction reactions in the upper parts of the furnace and because it has a strong influence on the subsequent distribution of the gas in the upper parts of the furnace. Gas flow through the raceway has therefore been the subject of a number of experimental (Gruel (1974), Nakamura (1977), Hatano (1977) and theoretical (Jeshar (1979)) studies.

Although a considerable volume of experimental data now exists, few theoretical studies have been reported which attempt to analyze this data. Recently Hatano et al (1976 B and 1981) have attempted such an analysis.

In their earlier analysis Hatano (1976 B) modelled gas flow from the raceway by arbitrarily specifying a stream function distribution at the boundary between the raceway and the coke bed. In a later work (Hatano et al 1981) they specified pressure gradients at the raceway boundary. Moreover, these pressure gradients are at variance with experimental measurements reported by the same authors (Hatano 1976 B) and later confirmed by Durnov (1981).

The object of the present work is to develop a mathematical model for gas flow through the raceway zone which will both identify the major factors affecting gas flow and pressure distribution and which will produce predictions which are consistent with the available experimental data.

2 PROPOSED MODEL

Since the purpose of the proposed model is to identify the major factors affecting gas flow, we consider a simple two-dimensional geometry and assume that the gas is isothermal and incompressible. Although the actual problem is three-dimensional, the two-dimensional geometry is computationally simpler and has the additional advantage that cold model laboratory experiments which are usually two-dimensional may be used to test the assumptions made in formulating the model.

Given the above assumptions the following equation has been used to describe a time and volume averaged differential momentum balance, both within and around the raceway. A similar formulation has been described by Vafai (1981)

$$\rho(\tilde{u}.\nabla)\,\frac{\tilde{u}}{\varepsilon} = -\,\nabla P + \mu_E\,\frac{\nabla^2\tilde{u}}{\varepsilon} - \tilde{G} \qquad (1)$$

In equation (1) the left-hand side represents the net inflow of momentum, while the right-hand side represents the sum of forces acting on a fluid element. These latter forces are represented as pressure, fluid-fluid forces and fluid solid forces respectively.

Use has been made of the effective viscosity concept of Gosman (1969) in representing the effect of turbulence on the transport of momentum. This correlation, for the present study, takes the following form

$$\mu_E = .012\; D_R^{2/3}\; H_R^{-1/3}\; \rho V_B \left(\frac{\pi D_T^2}{4}\right)^{1/3} \qquad (2)$$

This is thought to be the same expression as used by Hatano (1981) in his simulations. This equation indicates that the effective viscosity increases with raceway depth and decreases with raceway height. More sophisticated turbulence models are available in the literature (Gosman 1969) but their introduction is not warranted in view of the limited data presently available on flow within the raceway cavity. The presence of large diameter particles further complicate the application of more sophisticated turbulence theories.

In equation (1), $\tilde{G}$ represents the interaction force between the solid and fluid. In a packed bed this term accounts for the flow resistance offered by the solid matrix. The correlation proposed by Ergun (1952) for the pressure drop in packed beds has been used for $\tilde{G}$. Thus,

$$\tilde{G} = 150 \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu}{d^2} \tilde{u} + 1.75 \frac{(1-\varepsilon)}{\varepsilon^3} \frac{\rho(\tilde{u}.\tilde{u})}{d\,|\tilde{u}|} \qquad (3)$$

Here, $\tilde{u}$ represents the relative velocity between the gas and solids. The second term in equation (3) which depends upon the square of the relative velocity, dominates here. The magnitude of the first term is usually an order of two less than this term.

The relative importance of the terms appearing in equation (1) depend upon the magnitude of the voidage. Inside the raceway, where the voidage is high, the convection terms are significant whilst those involving solid gas-interaction are small. Conversely, in the packed bed region the convection terms and the viscous terms are small in comparison to the resistance offered by the bed. A simplifying assumption used here is that the voidage inside the raceway is 1 while outside it is uniform at 0.5.

In addition to the momentum equation, an equation describing conservation of mass is required. For the conditions assumed here this equation takes the following form

$$\nabla . \tilde{u} = o \qquad (4)$$

To complete the problem, conditions of no normal velocity at rigid boundaries and the specification of (a) velocities at inflow and outflow boundaries and (b) an overall pressure reference are required. No extra conditions need to be imposed on the pressure or velocities at the raceway boundary, as conditions here are determined by the overall gemoetry and boundary conditions of the system as a whole.

2.1 Raceway Geometry

No attempt has been made to predict raceway geometry from first principles. This is due to a lack of information concerning the distribution of horizontal and vertical stresses in the solid matrix around the raceway boundary. Rather, actual raceway geometry is input to the model. The simulations undertaken here utilise the experimental results of Nakamura (1977) concerning D_R, the depth of raceway penetration and H_R, the height of the raceway as they vary with blast conditions.

It is assumed that:

(i) The bottom boundary of the raceway extends a maximum distance equal to the D_R below the tuyere centreline (Nakamura 1977).

(ii) The majority of the boundary of the raceway can be described by an ellipse with axes D_R and H_R and centre h, k relative to an origin at centre of the tuyere nose.

(iii) The boundary immediately above the tuyere is the tuyere wall that is, along the line joining (0, DT/2) and (0,k).

(iv) The boundary immediately below the tuyere and outwards to the point of maximum distance below the tuyere be given by a line joining $(0, -\frac{D_R}{2})$ and $(h, -D_T)$

Incorporating these ideas to a finite difference simulation is straightforward. The final construction is shown in Figure 1.

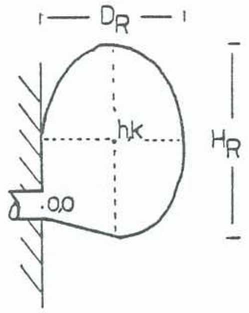

Figure 1. Construction of Raceway Geometry given D_T, D_R and H_R.

2.2 Solution Outline

The equations of motion, along with the specified boundary conditions, have been solved using a primitive variable Marker and Cell technique (MAC) as proposed by Hirt (1975). Unlike Hatano (1981), who used a stream function and vorticity formulation inside the raceway and a stream function formulation outside the raceway, the present simulation retains velocities and pressure as the basic unknowns. For two-dimensional problems this approach requires three equations to be solved compared to two in the case of the stream function vorticity approach. The advantage gained, however, is improved accuracy through the use of a staggered grid (implicit in the MAC technique) and the fact that no abrupt change in solution technique is required as we cross the raceway boundary. Moreover, mass is conserved across the raceway boundary.

Given an initial guess at the velocities and pressures it is unlikely that the momentum and mass conservation equations will be satisfied. Instead, the steady state elliptic problem is posed as a pseudo unsteady state, parabolic one. The parabolic problem is then marched out until the solution no longer changes with time. Such an approach is typical of most iterative techniques to elliptic problems.

The MAC technique used here uses explicit approximations for velocity and implicit approximations for pressure to advance u and v across one timestep, using the momentum equations. At the start of a timestep however, advance values of pressure are not available and so the previous time values must be used. The continuity equation is then used to adjust pressure according to

$$\Delta P_{ij} = - \beta_{ij} (\nabla.\tilde{u}) \qquad (5)$$

where β_{ij} is a relaxation parameter defined by Hirt (1975). This change in pressure necessitates, in turn, a refinement of velocities. The whole process for a single timestep is repeated until equation (5) is satisfied to within a specified tolerance.

The above sequence is then repeated over subsequent timesteps until the solution no longer changes with time. The termination criterion used here is that the maximum percentage change in velocities be less than 10^{-5}.

3. SIMULATION CASE STUDIES

Table 1 summerises the hot model experimental results of Nakamura (1977). These seven cases have been simulated, using the techniques described above, on a 55 by 70 non-uniform difference grid. Earlier attempts using a 20 by 25 grid proved too coarse to adequately resolve localised pressure gradients and recirculation zones.

TABLE I

VARIATION OF RACEWAY GEOMETRY

Case	D_T mm	V_B ms^{-1}	Re	$\mu E/\mu$	d mm	D_R mm	H_R mm
A	30	20	6600	140	14.1	100	140
B	30	60	19800	500	14.1	240	300
C	17	20	3700	90	14.1	50	100
D	17	60	11200	190	14.1	160	100
E	30	28.3	9300	250	5	160	270
F	30	28.3	9300	180	15	120	140
G	30	28.3	9300	160	25	80	100

The Reynolds' number has been calculated using the tuyere diameter as the length scale and using gas density the viscosity data at 1000°C. To aid in the visualisation of the flow pattern, the stream function has been calculated from the final velocity distribution via,

$$\psi(x,y) = \int_0^y u(x,y)\, dy \qquad (6)$$

and normalised, so that it varies from 0 to 1 over the tuyere inlet.

Thus, values of ψ less than zero correspond to lower recirculation zones, and values of ψ greater than one correspond to upper recirculation zones. The maximum absolute value of ψ, in these cases, then represents the fraction of flow, compared to the blast volume, occurring in these zones.

Figures 2 and 3 show the streamline and isobar patterns for cases E and G respectively. These cases represent the effect of coke size variation from small to large.

These diagrams show that the blast exits the tuyere in the form of a jet. The inertia of this jet is sufficient to carry it to the rear of the raceway cavity. Here, it is decelerated and caused to change direction. The result of this is the generation of large static pressures similar to those encountered with stagnation flows. However, unlike a stagnation flow, some of the flow proceeds directly through the rear of the raceway wall. The rest is deflected upwards and around, before finally exiting the raceway boundary.

On either side of the incoming jet recirculation zones are developed with the larger one towards the top. It is these gas recirculation zones which would provide the means for coke recirculation and combustion in an actual raceway. The reverse circulation of particles at the bottom of the raceway has been observed in experiments reported by Hatano (1976 A).

In the case of the raceway E, for a bed of smaller coke particles with lower permeability, the model predicts an increased proportion of gas flowing up the rear wall of the raceway as compared to case G. Such an upwards directed gas flow may be the cause of the reported disproportionate rise in raceway height with decreasing coke size (Hatano et al 1976 A).

3.1 Comparison with Cold Model Studies

Figures 2 and 3 also show that case E develops a greater degree of upper gas recirculation but does not develop the same pattern of isobars adjacent to the tuyere, as does case G. This is due to the greater degree of jet deceleration in the latter case. A measure of this deceleration is the non-dimensional pressure coefficient c_p, defined as:

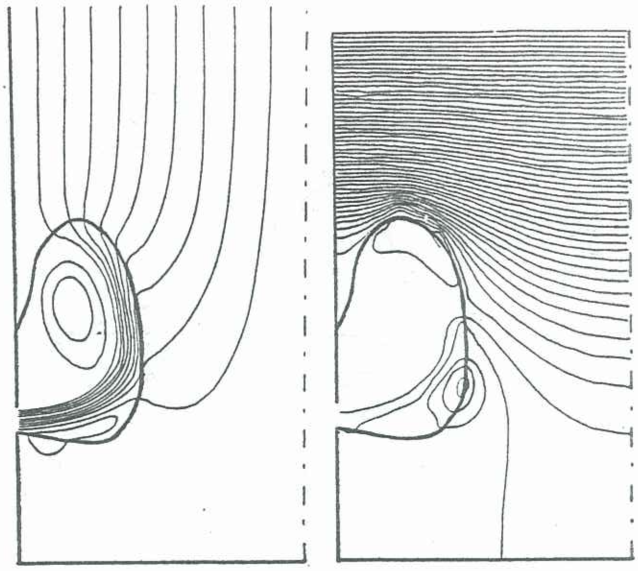

Figure 2. Streamline and Isobar Distribution for Case E. ($\Delta\psi$ = .1 , $\Delta P = 0.6\ P/\rho V_B{}^2$)

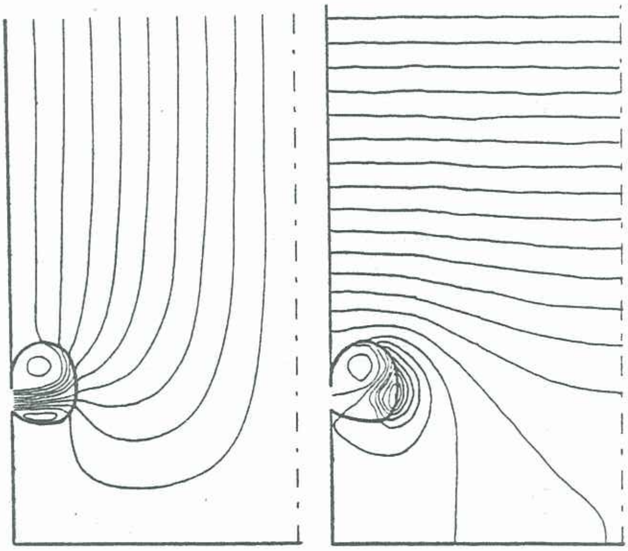

Figure 3. Streamline and Isobar Distribution for Case G. ($\Delta\psi$ = .1 , $\Delta P = 0.6\ P/\rho V_B{}^2$)

$$c_p = \frac{P - P_o}{\frac{1}{2}\rho V_B{}^2} \qquad (6)$$

where P_o is the pressure measured at the tuyere nose and P is the pressure at the raceway wall.

Hatano (1976 B), presented the distribution of c_p along with an inferred distribution of ψ around the raceway wall. His model consisted of a two-dimensional cold slice using soya beans to represent coke.

Figures 4 and 5 show a comparison between case B and his results. Hatano reports a maximum value for c of 0.3 which is in excellent agreement with the prediction shown in Figure 4. The majority of cases examined have maximum values higher than 0.3, however, they show the same general variation of c_p around the boundary of the raceway. The stream function distribution shows that very little gas leaves through the bottom of the raceway cavity. The bulk of the gas exits the boundary at points above tuyere level. Thereafter, the distribution of gas leaving the raceway becomes approximately uniform with angle.

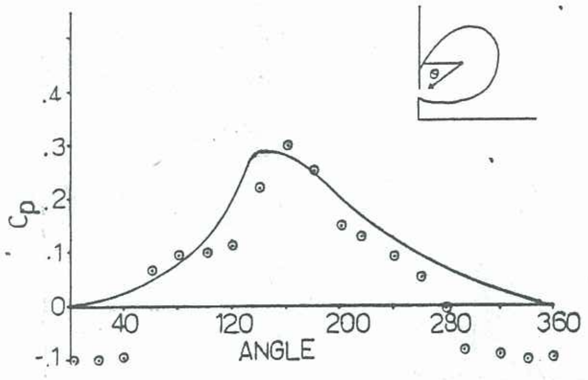

Figure 4. Variation of c_p, with Angle, Around Raceway Boundary for Case B. Solid Curve is that of Hatano (1976 B)

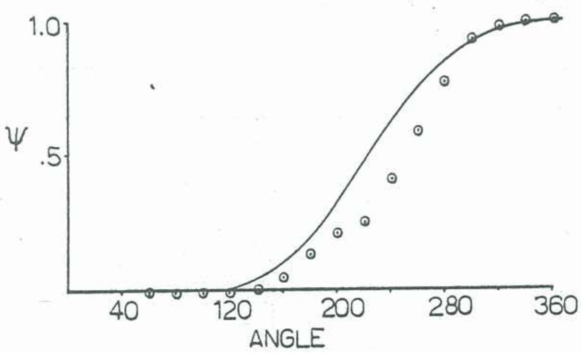

Figure 5. Variation of ψ with Angle, Around Raceway Boundary for Case B. Solid Curve is that of Hatano (1976 B)

3.2 Recirculation Variation

Comparison of the streamline pattern of cases E and G show that more recirculation occurs in the former case whilst the latter has more flow leaving the rear of the raceway, and therefore more closely approaching stagnation conditions. This suggests a relationship between the strength of recirculation and c_p. Table 2 presents this data, and shows that such a relationship does indeed, exist. Note that it is the smaller raceways, caused by larger coke sizes or smaller velocities, which appear to generate the largest c_p.

TABLE II

RECIRCULATION AND PRESSURE COEFFICIENTS IN SIMULATIONS

Case	ψ_{max}	ψ_{min}	c_{Pmax}
A	1.2	.03	.8
B	1.5	.02	.3
C	1.2	.01	.9
D	1.5	.07	.4
E	1.3	.07	.5
F	1.2	.04	.7
G	1.1	.03	.8

4 CONCLUSION

The development of a model to represent the motion of gas in and around the raceway region has been presented and used to predict flow patterns from previously reported raceway geometries.

The simulations predict the existence of upper and lower recirculation zones above and below the incoming blast. It is these zones which are responsible for the rotary movement of entrained particles. Results indicate that the amount of recirculation increases with increasing raceway size.

Even with the specification of uniform bed properties, the existence of localised pressure gradients was shown to occur in the region at the rear of the raceway. Care must therefore be exercised, when interpreting results from hot and cold models, that such behaviour is not solely attributed to low permeability caused by fines generation in this region.

5 REFERENCES

Durnov, V., Babushkin, N., Kitaev, B., Scherbatsky, V., Shabelzon, B. (1981). Investigation of Raceway Dynamics in a Model. Int, Blast Furnace Hearth and Raceway Symp., Newcastle, Australia. Aus.I.M.M.

Ergun, S. (1952). Fluid Flow Through Packed Columns. Chem. Eng. Prog. 48, 89, 94.

Gosman, A. D., Pun, W. M., Runchal, A. K., Spalding, D. B., and Wolfshtein, M. (1969). Heat and Mass Transfer in Recirculating Flows. Academic Press, London and New York.

Gruel, M., Hillnuter, F., Kister, H., Kruger, B.(1974). Investigation Using an Endoscope of the Phenomena of Movement in Front of the Tuyeres of a Blast Furnace. Stahl, u. Eisen 94 (12), 533-539.

Hatano, M., Fukuda, M. and Takeuchi, M. (1976 A). An Experimental Study of the Formation of a Raceway Using a Cold Model. Tetsu to Hagane 62 (1), 25-32.

Hatano, M. and Kurita, K. (1976 B). Effect of Raceway, Tuyere Diameter and Accretions on Gas Flow in Blast Furnace. Tetsu to Hagane 62 (8), 953-961.

Hatano, M., Hiraoka, B., Fukuda, M., Masuiki, T.(1977). Analysis of the Combustion Zone in the Experimental Blast Furnace. Trans. I.S.I.J. 17, 102-109.

Hatano, M., Kurita, K. and Tanaka, T. (1981). Aerodynamic Study of the Raceway in the Blast Furnace. Int. Blast Furnace Hearth and Raceway Symp., Newcastle, Australia. Aus.I.M.M.

Hirt, C., Nichols, B., Romero, N. (1975). SOLA - A Numerical Solution Algorithm for Transient Fluid Flows. Los Alamos Scientific Laboratory Report LA-5852.

Jeshar, R., Potke, W., Ehlert, K. and Mavroudis, M. (1974). Model Tests to Investigate the Configuration of the Turbulence Zone and the Phenomena of Movement Ahead of the Tuyeres in the Blast Furnace. Stahl u. Eisen 94 (12), 525-532.

Nakamura, M., Sugiyama, T., Uno, T., Hara, Y., Kondo, S. (1977). Configuration of the Raceway in the Experimental Furnace. Tetsu to Hagane 63 (1), 28-36.

Vafai, K., Tien, C. (1981). Boundary and Inertia Effects on Flow and Heat Transfer in Porous Media. Int. J. Heat Mass Transfer, 24, 195-203.