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# A fluid dynamic analysis of the blast furnace trough at Tata Steel

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## ABSTRACT

*The non-drainable trough of 'F' blast furnace at Tata Steel has been fluid dynamically simulated by solving the Navier-Stokes equation in order to predict the velocity field near the trough bed along with other field properties so as to focus on the locations of surface wear on the trough bed. For this purpose a total length of 3.64 m, the most wear prone zone, of the entire trough has been taken in to considerations for modeling. The modeling zone or the computational domain consists of the skimmer plate, iron dam and some portion of the runner. The modeled portion of the trough has always higher wear compared to other locations on the trough so a fluid dynamic analysis has been done for the liquid metal in this particular portion of the trough. Turbulence present in the velocity field has been taken into considerations by imbedding the K-ε turbulent model to the parent differential equations for the velocity field. The entire set of partial differential equations (two for the velocities, one for continuity and one each for the turbulent quantities k and ε) have been solved by employing a strongly non-uniform staggered grid through Phoenics. The predicted velocity field reveals a strong recirculation zone just behind the skimmer plate and comparatively high shear stress just after the iron dam (at the beginning of the runner). The inclination of the iron dam has been varied starting from 90° to 35°. It has been observed that for a 35° iron dam the predicted maximum shear stress on the trough bed has a much lower value than that of the 90° iron dam. From this analysis it has been concluded that the value of the maximum shear stress on the trough bed is an important parameter contributing to the amount of refractory wear and the location of the maximum shear stress signifies the weakest zone on the trough bed which is vulnerable to wear caused by fluid shear. It has also been noticed that the present analysis has offered many qualitative trends which are in agreement with the plant observations.*

## INTRODUCTION

It was observed that in the 'F' blast furnace trough of Tata Steel there was considerable refractory wear on the trough bed compared to the side wall. So it was thought that along with the thermal load on the bed there might be fluid shear present to a large extent which could be causing the refractory wear. In order to investigate such a phenomenon it is necessary to solve the fluid velocities in the trough and thereafter a conclusion can be arrived at with the availability of the shear stress plot on the trough bed. It has to be noted here that the shear stress pattern on the trough bed will depend very much on the profile of the bed. Hence, various bed profiles will have to be tried in order to arrive at a minimum shear stress at the surface of the bed. This will demand various inclinations of the iron-dam with respect to the bed and positions of the skimmer plate to be tried while intending to obtain the shear stress profile on the bed.

The present work is directed towards obtaining a better profile for the bed without having major changes on the existing bed lining. A literature survey indicates that there is not much information available in this particular area so as to have better design parameters for the trough bed. However the work of Cameron and Tudhope[1], although is directed towards the design of a better trough does not reflect on the wear of the trough bed near the iron dam. They consider the differences between pooling and non-pooling type of trough and the wear of the bed near the tap hole and arrive at the conclusion that a pooling type trough has better surface resistance to wear than that of a non-pooling type. The 'F' blast furnace trough at Tata Steel is already a pooling type and there is not much wear on the bed near the tap hole compared to the iron-dam area.

So in the present work we intend to focus on the wear near the iron-dam area and try to locate precisely the positions of the maximum wear and find out a physically plausible reason to account for the wear prone zone by mathematically modelling the fluid flow phenomena in the trough. As we are trying to locate the wear on the trough bed, so it is only required to model the flow field just in the mid plane of the trough and hence a two dimensional fluid dynamic model will be sufficient for the purpose. The slag layer is not taken into consideration in the analysis as there is only liquid metal present after the skimmer plate. However, just before the skimmer plate slag may be present on the top layer because slag removal takes place within a distance of 1 meter from the skimmer plate in the up stream direction. So in the mathematical analysis slag is not modeled.

## THEORETICAL ANALYSIS

In Fig. 1, a schematic view of the blast furnace trough can be visualized. In the figure the skimmer plate, iron dam and the runner are shown. The liquid surface is assumed to be flat and having zero shear stress with respect to the air just above it. Just before the skimmer plate a distance of 1.1 meter (in the up stream direction) is taken into the computational domain and about a meter from the runner (in the down stream direction) is also taken into considerations for properly inserting the boundary conditions there and getting a zone free from the inlet and the exit boundary effects. Fig. 1 represents the computational domain, a portion from the actual trough geometry, where the fluid velocities are computed from the solutions of the following equations according to Dash[2] and the constants used in the model are shown in Table 1.

**Continuity**

$$\frac{\delta}{\delta x_i}(\rho U_i) = 0 \qquad \text{... 1}$$

**Momentum**

$$\frac{D(\rho U_i)}{Dt} = -\frac{\delta p}{\delta x_i} + \frac{\delta}{\delta x_i}\left[\mu\left(\frac{\delta Ui}{\delta x_i} + \frac{\delta Ui}{\delta x_i}\right) - \rho\overline{u_i u_i}\right] \qquad \text{... 2}$$

**Turbulent Kinetic Energy**

$$\frac{D(\rho k)}{Dt} = D_k + \rho P - \rho\varepsilon \qquad \text{... 3}$$

**Rate of Dissipation of k**

$$\frac{D(\rho\varepsilon)}{Dt} = D_\varepsilon + C_1\rho P\frac{\varepsilon}{k} - C_2\rho\frac{\varepsilon^2}{k} \qquad \text{... 4}$$

where

$$\overline{u_i u_j} = v_i\left(\frac{\delta U_i}{\delta x_j} + \frac{\delta U_j}{\delta x_j}\right), \qquad v_c = 0.09\frac{k^2}{\varepsilon}$$

$$D_\Phi = \frac{\delta}{\delta x_j}\left[\left(\mu + \frac{\mu_i}{\sigma_\Phi}\right)\frac{\delta\Phi}{\delta x_j}\right], \qquad P = -\overline{u_i u_i}\frac{\delta U_i}{\delta x_j}$$

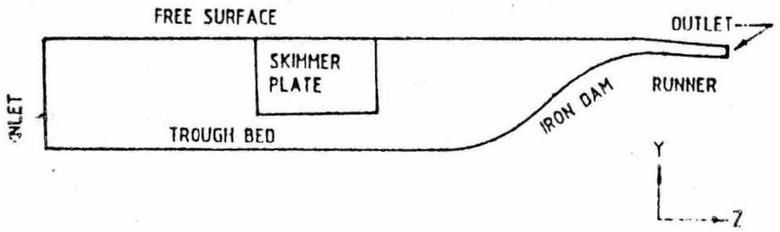


*Fig. 1 : A Schematic view of the blast furnace trough*

*Table -1*

| $\sigma_k$ | $\sigma_\varepsilon$ | $C_1$ | $C_2$ |
|---|---|---|---|
| 1 | 1.3 | 1.44 | 1.92 |

The equations (1-4) are solved with the following set of boundary conditons.

## BOUNDARY CONDITIONS

At the trough bed a no slip boundary condition is applied by putting $U_2$ and $U_3$ (the velocity perpendicular to the trough bed and along the bed respectively) to be zero. The turbulent quantities are bridged by the logarithmic wall function.

At the inlet to the trough (see Fig. 1) an inlet boundary condition is given by specifying $U_3$ to be a particular value which is computed to be the average velocity from the mass flow rate. The turbulent kinetic energy is specified to be at a level of 2%. The dissipation rate $\varepsilon$ is so arranged that the turbulent Reynolds number remains approximately at 10.

At the exit of the trough an outlet condition is specified which imposes the presence of atmospheric pressure and the gradient of $U_3$, k and $\varepsilon$ to be zero along the direction of the bed.

At the free surface of the liquid metal a zero shear stress condition for the velocity along the trough bed is applied. Although this boundary condition is strictly not true but as a first approximation this will give a fairly good idea about the velocity field. This condition in principle is similar to a symmetry boundary condition. Hence, for the turbulent quantities the same condition is applied at the free stream.

## METHOD OF SOLUTION

The continuity, momentum and the partial differential equations for the turbulent quantities k and ε were solved by the help of the above boundary conditions through the fluid dynamic software Phoenics in a finite volume method. The boundary fitted coordinate system was used with non-linear staggered grids in order to take into account the different inclinations of the iron-dam. The use of a porosity method (porosity = 0) was utilized in order to represent the skimmer plate as a blob body in the computational domain. The whole domain had a maximum dimension of 3.64 x 0.59 m in (3 and 2 direction) z and y directions respectively. The computational domain has been fitted with a non-linear algebraic grid of 35 x13 in the z and y directions respectively which was found to be the optimum for such computation. Finer grids of size 45x18 and 45x22 were used to do the same computation but it was observed that there were marginal changes in the values of the maximum shear stress on the trough bed. The relaxation parameters for the velocities were kept at 0.8 and for the turbulent quantities at 0.05 for first 100 iterations. Thereafter the values were gradually increased to 0.6 for velocities and 0.4 for the turbulent quantities. Converged solutions were obtained in about 800 iterations for all the iron-dam inclinations and skimmer plate positions.

In order to get a feel for the accuracy of the solutions obtained from Phoenics a similar solution wih almost same kind of boundary conditions was carried out near a backward facing step for laminar flow of Reynolds number 150, where the shear stress on the wall was available from the experiments of Durst et. al.[3] and also computational results available from the study of Melaaen[4]. Fig. 2 shows the comparison of the wall non-dimensional wall shear stress obtained from the numerical computation of Melaaen[4] and the experi-

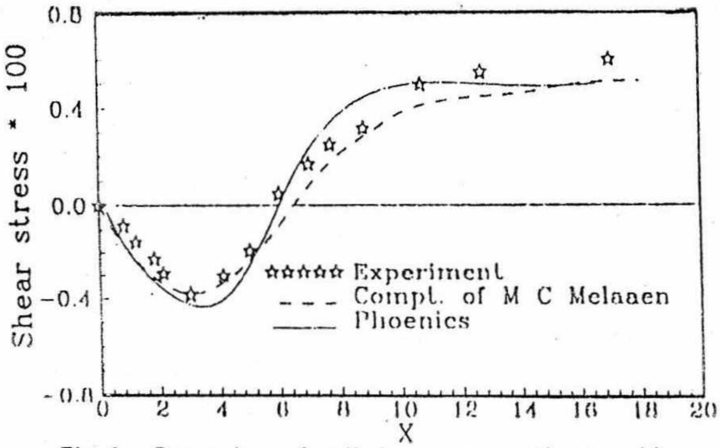


*Fig. 2 : Comparison of wall shear stress on the step side wall of a backward facing step*

ments of Durst et al[3] with the values obtained from Phoenics. The agreement of the shear stresses obtained from Phoenics seems to be quite satisfactory when compared with both the computational and experimental results. With this confidence all other omputations for the trough geometry were carried out.

## RESULTS AND DISCUSSION

In Fig. 1 the schematic view of the blast furnace trough is shown where the fluid dynamic analysis of the liquid metal is carried out. The entire trough has a length of about 8.5 meters including the runner. But for the purpose of modelling it is not necessary to take the entire length into consideration. As more wear was observed on the trough bed near the iron dam and in the vicinity of the skimmer plate, so it was thought proper to take only this portion of the trough which include the skimmer plate and the iron dam. Towards the up stream direction of the skimmer plate there is about 3.5 m of the trough length available and this length is almost sufficient to have a fully developed flow. So in the modelling we have only taken 1.1 meter of trough length from the up stream direction of the skimmer plate and put there a uniform velocity condition. Although this condition is strictly not true but still its use will not deteriorate the shear stress profile significantly after the skimmer plate. Because just after the skimmer plate there is a strong recirculation zone hence, it is very much likely that important information brought forward by a non-uniform inlet velocity condition would be lost due to the strong elliptic flow (in the recirculating zone) and its impact on the shear stress profile would not be significant. So a simple uniform inlet velocity condition is applied for the study of fluid flow in the trough. The top surface of the liquid is a free surface and we assume a zero shear stress condition here in order to get a first hand information.

Fig. 3 shows the boundary fitted grid in the computational domain of the trough. In this figure a 35° iron dam is shown. Similar grid arrangements were done for other iron dam inclinations. The skimmer plate in Fig. 3 is shown by heavy dark line and it includes only 5x6 gride in the YxZ directions respec-

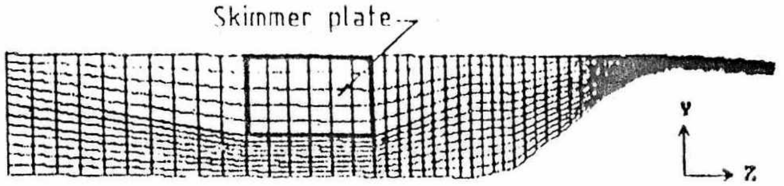


*Fig. 3 : Boundary fitted grid lines generated in the computational domain of the blast furnace trough*

tively for which the porosity values were set to be zero. This means no flow can take place in the skimmer plate. Just after the skimmer plate there will be recirculation in the flow field. In order to capture the details of the recirculation a finer grid is required there which is provided in the computational model. In the up stream direction of the skimmer plate the flow is mostly parallel and without any recirculation, so the grid requirement is not very high there. As a result coarse grids have been utilised there.

The flow field in the trough with different slopes of the iron dam have been shown in Fig. 4. It can be observed in general that the flow velocities are nearly parallel before the skimmer plate (blank area in the vector field) and they tend to come towards the bed as they approach the skimmer plate. As the skimmer plate has a narrow passage for the fluid to flow under it so the velocity of the fluid increases as it comes under the skimmer plate. As long as it is flowing under the skimmer plate it tries to attain a fully developed condition but before it could attain such a condition it comes out of the skimmer plate into a much bigger area because of which the velocity again reduces there and a recirculation zone starts. The recirculation is present for all slopes of the iron dams namely, 90°, 47° and 35°. In case of the 90° iron dam the fluid comes up to the runner with a much higher velocity (see Fig. 4a) compared to 47° and 35° iron dam, while in case of the 35° iron dam the fluid has a very smooth entry into the runner (Fig. 4c). Fig 4d shows the expanded view of the flow field near the 35° iron dam and in its runner. The flow field for his case is much smoother near the iron dam and in the runner compared to 90° and 47° iron dam.

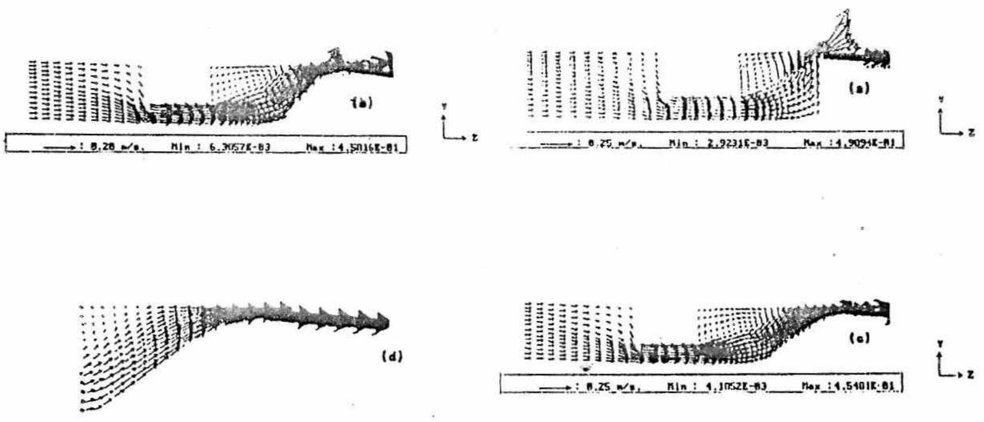

*Fig. 4 : Flow field in the trough with different inclinations of the iron dam. (a) 90°, (b) 47°, (c) 35° iron dam, (d) expanded view of the flow field at the outlet of the 35° iron dam.*

Having described the flow field we will now make use of it in order to describe the shear stress pattern on the trough bed which is shown in Fig. 5. The upper three curves in Fig. 5 with the marks 1, 2 and 3 represent the trough bed with 90°, 47° and 35° iron dams respectively to the scale. The rest of the other three curves represent the shear stress on the bed for each of the three cases of the iron dams. If it is desired to read the value of the shear stress at a particular location on the trough bed starting from the beginning of the bed (that is from z=0) then just locate the point on the trough bed and read the stress value directly under or above it from the particular shear stress curve.

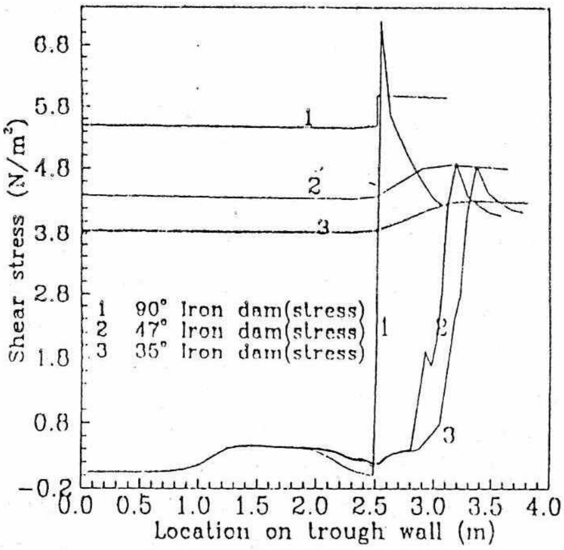


*Fig. 5 : Shear stress distribution on the trough wall with different slopes of iron dam.*

As the fluid enters almost parallely into the computational domain of the trough with an average velocity (computed from the mass flow rate of the blast furnace) of about 0.45 m/s, so the shear stress remains very low at the entry to the trough for all the three cases. However when the fluid proceeds towards the skimmer plate it passes through the bottom of the skimmer plate which is much lower in height (about 200 mm), as a result the velocity proportionately increases which gives rise to higher shear stress at the trough bed. When the fluid flows under the skimmer plate it has a tendency to develop (redistribute the momentum across the gap of the skimmer), so the shear stress gradually decreases on the bed. Just when it comes out of the passage of the skimmer it sees a much higher area to expand because of which the shear stress again decreases on the bed. When the fluid climbs up the iron dam it undergoes a decreasing cross sectional area (because the free surface is at a constant height with respect to the bed) for which the velocity increases near the bed and hence the wall shear stress. The shear stress keeps on increasing as the fluid tries to pass over the iron dam and it attains a peak just at the end of the iron dam (as seen from the stress curves of 1, 2, 3 from Fig. 5). The moment the fluid enters the runner it gets a chance again to readjust its momentum amongst its various layers for which the shear stress on the trough bed decreases.

The decrease of the wall shear stress along the runner is observed for all the three cases and the reason for it is already explained above. The shear stress on the bed in between the skimmer plate and the iron dam is increasing in nature because the fluid is continuously being squeezed in to a smaller and smaller cross section as it travels up the iron dam. The free surface is located at the same distance from the bed for all the three cases but the rise in the shear stress decreases as the slope of the iron dam decreases. In the case of the 90° iron dam the fluid gets a chance to go in to the corner where its velocity naturally reduces and it does not contribute much momentum to the main flow which is traveling towards the runner. In addition to this the presence of the recirculation zone takes away much of the available space for the main flow because of which the bulk velocity of the liquid remains at a higher value and reflects directly on the increase of wall shear stress. In case of the 47° and 35° iron dam the depth of the recirculation zone is shorter compared to the 90° iron dam and the corner zone gets fully utilised by the fluid for its travel along the slope because of which its bulk velocity remains lower resulting in lesser wall shear stress compared to the 90° iron dam. Therefore it can be observed from the stress curve that the peak value of the shear stress for 47° and 35° iron dam remains much lower compared to the case of 90° iron dam. It also can be observed from Fig. 5 that the wall shear stress on the 35° iron dam remains much lower compared to the 47° iron dam although the maximum shear stress for the 35° iron dam is marginally lower compared to that of the 47°.

It is well understood that the fluid shear will contribute significantly towards the surface wear of the trough bed along with other damaging properties. So all other damaging properties remaining constant at their respective values, more surface wear can be expected on the bed of the trough where there is more wall shear stress. So in our above study of the different slopes of the iron dam it is expected that there will be more wear on the bed at the entrance to the runner (compared to all other positions on the trough) for all the three cases because that is the location of the highest shear stress in the entire trough. When compared amongst the slopes of the iron dam a 90° slope for the iron dam will produce more surface wear compared to the 47° and 35° iron dam. This fact has been visually confirmed at the 'F' blast furnace of Tata Steel. So the 'F' blast furnace trough was changed from 90° to about 47° which is the present set up and the trough life has significantly increased. However, the present study supports a still lower slope of (about 35°) iron dam which is more wear resistant compared to the 47° iron dam.

In Fig. 6 the wall shear stress on the trough bed is shown when the skimmer plate has been shifted to its right by 500 mm. As the plate is shifted to its right so the stress curve just under the skimmer gets pushed to the right by about 500 mm. However, the stress pattern beyond the skimmer plate remains almost the same for the two cases except for a marginally lower stress on the runner for the case of the shifted skimmer plate. So this arrangement can possibly be exploited in order to provide more trough length on the up stream side of the skimmer plate so that the slag separation can be more effective while still having the benefits of the lower wear on the iron dam and the runner.

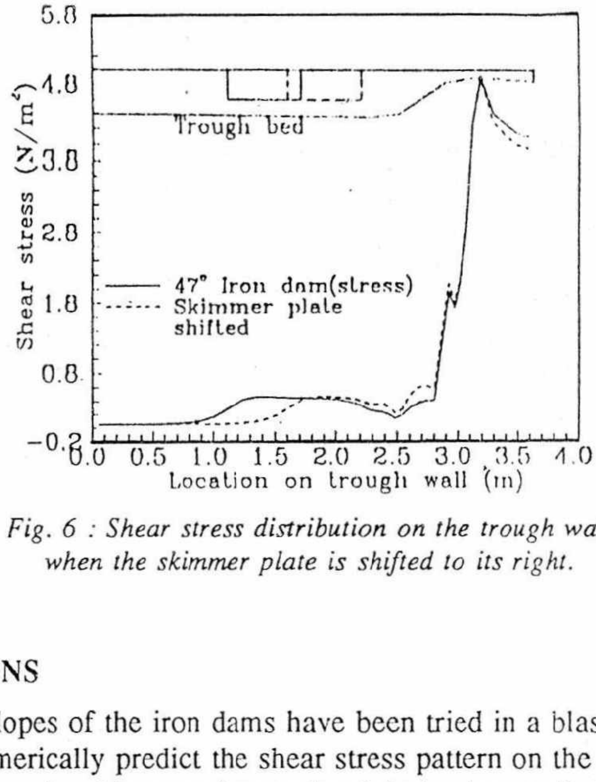


*Fig. 6 : Shear stress distribution on the trough wall when the skimmer plate is shifted to its right.*

## CONCLUSIONS

Different slopes of the iron dams have been tried in a blast furnace trough in order to numerically predict the shear stress pattern on the trough bed. The effect of shifting the skimmer plate to its right is also studied to arrive at the shear stress on the trough bed. From the two-dimensional turbulent fluid dynamic model it has been predicted that there will be more wear on the bed at the entrance to the runner irrespective of the slopes of the iron dam and the 90° iron dam will have more wear compared to all other slopes of the iron dam. A 35° iron dam will have less wear compared to the other two cases of 90° and 47°. Shifting the skimmer plate towards the iron dam will bring advantages to the system.

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## LIST OF SYMBOLS

$d$ = height of the backward facing step

$k$ = turbulent kinetic energy

$\varepsilon$ = rate of dissipation of k

$t$ = time

$U$ = average velocity

$u$ = fluctuating velocity

$u_i u_j$ = Reynolds stress

$x_i$ = distance in the cartesian coordinate direction i

$X$ = non-dimensional distance measured from the backward facing step

= $x/d$

$\rho$ = density

$\mu$ = viscosity

## REFERENCES

[1] Ian A. Cameron and John M Tudhope, Improved trough design using water modeling, *Iron making conference proceedings*, 1988, pp. 505-515.

[2] Sukanta K.Dash, Heatline visualization in turbulent flow, *Int. J. Num. Method for Heat and Fluid Flow*, 1995 (in Press)

[3] M. G. Carvalho, F. Durst and J. C. F. Pereira, Predictions and measurements of laminar flow over two Dimensional obstacles, *Appl. Math. Modell.*, Vol. 11, 1987 pp. 23-34.

[4] M C Melaaen, Non-Staggered calculation of laminar and turbulent flows using curvilinear non-orthogonal coordinates, *Numerical Heat Transfer*, Part A, Vol. 24, 1993, pp. 375-392