1. Introduction

Hot dip galvanizing is the most widely used galvanization process of steel sheets that find increasing demand for applications in car body manufacturing, household appliances and more recently, in industrial and residential buildings. This process can provide sufficient corrosion resistance of the material along with its good formability, weldability and paintability, the required properties particularly for an automobile material. The ever increasing demand for the use of stronger and thinner sheets with a thinner coating has made the galvanizing process more challenging with respect to surface finishing, in particular. The continuous galvanizing operation is a complex metallurgical process where steel sheet is continuously dipped into a molten zinc alloy bath, maintained at about 460°C to produce a protective coating of zinc rich alloy on the sheet surface (Fig. 1(a)). The cold rolled sheet is cleaned, degreased and then annealed in a reducing (hydrogen-nitrogen) atmosphere prior to be fed into the liquid zinc bath. The coating weight is controlled by removing the excess liquid zinc from both surfaces of the sheet during its withdrawal from the zinc pot with the help of a pair of gas-wiping jets. A main sink roll at a depth of more than one meter below the bath surface and a pair of guide rolls steer the strip movement inside the bath. During the process, the desirable and adherent inhibition layer of Fe₂Al₅ forms within a fraction of a second due to the preferential reaction of dissolved aluminum in bath with the steel surface. Since there is always some iron dissolution from steel strip to the bath, a minor fluctuation in bath temperature can also start the formation of Fe₆Zn₅Al intermetallic phases, depending on the solubility limits of Fe and Al in liquid zinc. These intermetallic compounds or the dross particles have been identified as Fe₂Al₅Znx or the “top dross”, commonly found in a galvanizing bath when the bath Al concentration is above the “knee point” (0.136%) and the aluminum saturated δ phase (FeZn10) or the “bottom dross”, generally observed in galvannealing operations with a bath Al content below 0.136%.

Dross pick-up on steel strips is a common coating defect in hot dip galvanizing, which can be significantly controlled through a tight bath management, primarily by maintaining the effective Al in bath within a close range. Fundamental studies on fluid flow and distribution of temperature in strip galvanizing pots can provide vital information on Al transport and circulation of dross particles near the moving strip. A number of studies in this area have been reported in the recent past, both on numerical simulations1–8) and using physical models.9–12) Paré et al.1) used a commercial CFD (FIDAP) software and laminar flow conditions to make a 3-dimensional flow field study in a galvanizing bath. They observed an asymmetrical behavior near the snout region with more liquid zinc drawn towards back of the strip than to the front and 3-dimensional trajectories of particles inside the bath, which end on either side of the strip. Kim et al.13) found the flow pattern to change significantly with strip...
width but not with the line speed and the temperature distribution, although uniform in general, to be affected by charging of cold zinc alloy ingots directly into the bath.

An extensive work has been done by Ajersch and the group\textsuperscript{5–8}) over last ten years to determine the 3-dimensional velocity and temperature fields and to find the effects of various parameters such as line speed, strip width, strip temperature, inductor mixing and ingot addition on them. They have also found that the line speed does not change the global flow pattern but modifies the velocity field in the snout, near the strip, and near the sink and guide rolls. The inductors, when operated at the maximum capacity during ingot melting, have an effect of induced mixing and the density variation due to the thermal effect alter the flow near the inductors and the ingot and never in the entire flow field which is mostly governed by strip motion only. They have also tried to find the transient aluminum distribution in the bath and correlated the results to predict the generation and movement of intermetallic dross particles within certain region in a zinc pot.\textsuperscript{8}) In physical models studies, Toussaint et al.\textsuperscript{8}) used an experimental device to determine the circulation pattern of molten zinc whereas others have used scale-down water models with the help of hot-wire anemometry and LDV (Laser Doppler Velocimetry) techniques,\textsuperscript{10,11,12}) and PIV (Particle Image Velocimetry) technique.\textsuperscript{11,12})

From the literature survey it has been clear that the objective of many researchers has been to study to the flow field inside the galvanizing bath because this probably can give a clue to control dross pick up. The flow field is normally very complicated inside the bath and the movement of the dross particles, which vary possibly from 10 to 60 \( \mu \), follows the flow field and tracking of the group of particles or any individual particles does not bring any extra information about the adherence of the particles to the sheet. So the structure of the flow field remains as a guiding parameter as far as the dross pick up by the sheet is concerned.

Dross is normally removed from the free surface of the galvanizing bath by scooping the foam that is formed on the bath. So the only way to get rid of dross pick up is simply to avoid the contact of the dross with the sheet while it is moving inside the bath. If there exists any vortex in the flow field near to the strip then the dross can be fed back to the strip so the chance of dross pick up by the sheet increases to a large extent. If the self feeding mechanism due to the vortex motion of the flow field can be broken then the chances of getting dross pick up can be lower. This is the main objective and the direction of the present work where we intend to study the flow field inside the bath and try to change the danger zone into a more amiable zone by changing the local flow field by placement of plate baffles which has been addressed by Lee et al.\textsuperscript{12}) only for their water model, but not for an industrial size galvanizing bath.

\section{Physical Description of the Problem}

The flow field in the galvanizing bath, in the presence of plate baffle, of a Continuous Galvanizing Line is the subject of the study in the present work. The line diagram of the bath is shown in Fig. 1(b) and Fig. 2 along with the geometrical dimensions sufficient for a CFD computation. The geometry of the bath confirms to a real life industrial size galvanizing process. The region up to air wiping by air jet is not included in the CFD study. The region of simulation is the entire zinc bath and the portion of the snout immersed into it along with other components such as the sink and the guide rolls. The galvanizing bath has been taken to be half the size in \( Z \) direction because of symmetry about
the plane $Z=1600$. The sheet can be seen in Fig. 1(b) as well as in Fig. 2, which is moving into the bath over the sink roll and guided by the guide roll to come out of the bath. The objective is to compute the flow field inside the bath and examine if there exists any self feeding vortex for the dross and devise a way to eliminate the vortex so that dross pick can be less.

3. Mathematical Formulation and Assumptions

The flow field is assumed to be isothermal because natural convection inside the bath can be neglected due to homogenization of temperature except during ingot charging where a maximum of $4^\circ$C temperature variation exists from the core of the bath to the surface of the ingot after about 15 min. The zone of interest is the V region in the bath where the strip moves over the sink roll and passes to the guide roll. In this region flow is mostly governed by forced convection. So in order to obtain the flow field mathematically we use the conservation of mass and momentum along with the $k$–$\epsilon$ turbulence model which are described below:

Continuity

$$\frac{\partial}{\partial x_i}(\rho U_i) = 0 \quad \text{(1)}$$

Momentum

$$\frac{D(\rho U_i)}{Dt} = \rho g_j - \frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial U_j}{\partial x_j} + \frac{\partial U_i}{\partial x_i} \right) - \frac{\rho u_i u_j}{\rho} \right]$$

$$\text{...........................................(2)}$$

Turbulent kinetic energy

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

Rate of dissipation of $k$

$$\frac{D(\rho \epsilon)}{Dt} = D_\epsilon + C_1 f_i \rho P \frac{\epsilon}{k} - C_\mu f_i \frac{\rho \epsilon^2}{k} \quad \text{..............(4)}$$

Where,

$$\frac{\bar{u}_i \bar{u}_j}{\rho} = \frac{2}{3} k \delta_{ij} - \nu_i \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right)$$

$$\nu_i = C_{\mu} f_j k^2/\epsilon$$

$$D_\epsilon = \frac{\partial}{\partial x_j} \left[ \frac{\mu + \mu_1}{\sigma_\epsilon} \frac{\partial \phi}{\partial x_j} \right], \quad P = -\bar{u}_i \bar{u}_j \frac{\partial U_i}{\partial x_j}$$

Constants used in the $k$–$\epsilon$ model

$$C_1 = 4.4, \quad C_\mu = C_\mu = 1.92$$

$$\sigma_\epsilon = 1.0, \quad \sigma_\epsilon = 1.3, \quad f_1 = f_2 = f_\mu = 1, \quad C_\mu = 0.09$$

3.1. Boundary Conditions

The boundary conditions used to solve the partial differential equations, Eqs. (1) to (4) can be seen from Fig. 1(b). The top plane of the bath is taken as a pressure outlet condition on which there can be flow into or out of the domain. This is a realistic condition because in reality the flow really comes out with the strip and goes in to the bath along with the strip. The $Z=1600$ mm plane is a symmetry plane and all other faces are regarded as wall where no slip condition is given. The snout that is extending into the bath is regarded as wall and the zone inside the snout containing the strip is a fluid medium. The strip is a moving wall with a speed of 2.5 m/s in the direction of its path as shown in Fig. 2. So boundary conditions on the strip are provided as no slip condition while the strip itself is moving at 2.5 m/s. Of course one has to give the proper components of this velocity in the direction of $x$ and $y$ in order to activate the solution procedure. No component of strip velocity exists in the $z$ direction. The sink roll rotates at a uniform angular speed of 7.692 rad/s and the guide rolls rotate at 25 rad/s corresponding to a strip speed of 2.5 m/s. The strip width is taken to be 900 mm.

3.2. Method of Solutions

The partial differential equations, Eqs. (1) to (4) have been solved numerically along with the above boundary conditions in a finite volume technique by discretizing the entire volume of the galvanizing bath into 736000 cells. The differential equations are integrated over the control volume to obtain linear algebraic equations, which are solved simultaneously by employing an algebraic multi-grid solver of Fluent. The pressure correction equation was employed to be a SIMPLE type where the body forces were incorporated in the Y direction. The top plane of the bath, which was kept as a pressure outlet boundary, was prescribed to be at 0 pa relative to the ambient. The symmetry plane was prescribed a symmetry condition where the gradients of all the variables perpendicular to the plane were set to zero. The turbulent quantities like $k$ and $\epsilon$ near the wall and the strip were prescribed from a log law wall function. On the top plane of the bath zero gradient conditions for $k$ and $\epsilon$ were prescribed in the vertical direction. The movement of the strip was prescribed in the velocity component form where the angle of the strip movement was computed from the geometry of the layout, which is shown here in Table 1.

The convective terms in the momentum equation as well as in the $k$–$\epsilon$ equations were discretized according to second order up wind scheme. Grid adoption near the strip was performed to make the cell size half in the zones near to the strip, the sink roll and the guide rolls, so accurate solution could be obtained for the galvanizing bath. Figure 3 shows the cell arrangements on the vertical cross sectional symmetry plane at $z=1600$ mm on which the preliminary com-
putation was done and after that the grid adoption was done to make the cell size half near the strip. Final computation was carried out on the finer cells again. The solution process could converge in about 150 iterations when the whole field residuals of all the discretized Eqs. (1) to (4) fall below \(0.001\). The density of molten zinc was taken to be 6.575 kg/m\(^3\) and the viscosity to be \(3.85 \times 10^{-3}\) kg/m-s.

4. Results and Discussions

The motion of the strip and the sink roll as well as the guide rolls generates the flow field in the zinc bath. There is no other mechanism or extraneous forces present in the zinc bath other than the strip motion and the guide rolls, which creates a flow field in the bath. When the strip moves in the galvanizing bath and the rolls rotate they push the liquid present around them in their direction of motion. Due to fluid viscosity the velocity generated in the nearby fluid becomes less than the strip velocity and also the velocity around the rolls become less than the roll velocity. This way a boundary layer develops in the near by region of the strip and the rolls. This boundary layer in fact drives the flow in the near by vicinity of the strip and the rolls. The equations used for the simulation in the present study take care of the full effect of the boundary layer because no compromise has been made to reduce the equation into a parabolic form.

4.1. No Baffle Plate

Figure 4 shows the velocity field on the vertical cross sectional plane of symmetry at \(z=1,600\) mm when the galvanizing bath has no plate barriers in it. The magnitudes of velocity seen in Fig. 4 are from 0.002 to 0.876 m/s and subsequently in all the vector plots we will use this scale of velocity so there will be no further mention of the magnitude of the velocity in any vector plot. It can be seen from Fig. 4 that there are 4 vortex or recirculation zones near the strip in the V region. The velocity of the fluid is towards the strip when the strip just comes into the bath through the snout. But on the right side of the strip there is a vortex, which feeds the fluid on to the strip always. An expanded view of the V region is shown in Fig. 5 where all the 4 vortices can be seen clearly. Out of these 4 vortices vortex 1 is more dangerous in terms of feeding the dross particle to the strip compared to vortex 2, 3 and 4. The dross generation area is somewhere near the snout so the freshly generated dross particles come in to contact with the strip due to vortex 1. Vortex 4 brings the dross from the top free surface as well as vortex 3. But these vortices are not that dangerous because there is dross removal from the top surface from time to time. The dross removal from vortex 1 and 2 can not be done in a practical situation. Moreover, air jet injection takes place on to the strip the moment the strip comes out of the bath, so even if vortex 3 and 4 are present in the flow field they can not feed dross on to the strip due to the air jet removing the dross from the top surface.

Dross pick up in the zinc bath is mainly done due to the vortices present in the flow field. If the strength of the vortex is high the dross pickup capability of that vortex is also high. The strength of vortex can simply be specified as the average angular velocity of the vortex about the eye of the vortex. The strength of all the four vortices is shown in Table 2 for different arrangement of the plate baffles. We will subsequently discuss which case is the best probable case to be adopted in a plant.

Figure 6 shows the flow field at \(z=1,200\) mm, (just near to the edge of the strip), and it can be marked from the flow field that the structure of the flow field in the V region is like that of the flow field created at \(z=1,600\) mm with some
minor deviations. The vortex 1 still exists in the flow field at $z=1200$ mm which is seen very clearly from the expanded view of the V region in Fig. 7. Vortex 2 has been killed to some extent but vortex 3 and 4 exists with less pronounced effect. This means that vortex 1 exists all through the width of the strip. Several other computations with different width ($1560$ mm) have been carried out at different strip speed and it has been observed that the flow field is almost like Figs. 4 and 6 at $z=1600$ and $1200$ mm respectively. So we are not showing the flow field for any other case because the flow field does not show any change with strip speed from $1$ m/s to $2.5$ m/s with a variation of strip width up to $1560$ mm. The vortex 1 which is created near the strip, is driven by the energy coming from the strip motion directly, so that always persists along the width of the strip. Other vortices, (2, 3 and 4) although gain energy from the strip but not directly from it but some energy they acquire from the near by flow field for which they decay along the width of the strip. So, it is vortex 1 which can continuously feed the dross to the flow and hence create a higher chance for the dross particles to be picked up by the strip.

### 4.2. Parallel Plate Baffle

Figure 8 shows a parallel plate having the same width as the strip, put at a distance of $144$ mm away from the strip. The detail geometrical implementation of the plate is shown in Fig. 9 on the symmetry plane at $z=1600$ mm. This plate acts as a flow modifier and removes vortex 1 thus helping to avoid dross pickup by the strip.

<table>
<thead>
<tr>
<th>Baffle arrangement</th>
<th>Vortex 1</th>
<th>Vortex 2</th>
<th>Vortex 3</th>
<th>Vortex 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>No baffle</td>
<td>0.36</td>
<td>0.8</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>Parallel plate baffle</td>
<td>Vortex almost removed</td>
<td>0.39</td>
<td>0.15</td>
<td>0.40</td>
</tr>
<tr>
<td>Perpendicular plate baffle</td>
<td>Vortex removed</td>
<td>1.0</td>
<td>0.61</td>
<td>0.25</td>
</tr>
</tbody>
</table>

#### Table 2. Vortex strength of individual vortices in the zinc bath (rad/s).
It can be seen that while vortices 2, 3 and 4 exist in the flow field vortex 1 has almost vanished. So the self-feeding mechanism of the dross on to the flow field is spoiled to a large extent by this modification. It is believed that such a flow field is more amenable to galvanizing rather than the flow field crated without a plate baffle. However, with the parallel plate baffle the dross particles those are brought into the sink roll will try to adhere to the strip and some of them will be fed back to the strip by vortex 2. But the strength of vortex 2 has now decreased which will help not to feed in much amount of the dross on to the strip again. It can be marked from Table 2 that the strength of the vortices 2 and 3 have fallen a little bit while the strength of vortex 4 has gone up by two times. Vortex 2 gets the dross from the sink roll and also from vortex 1. If vortex 1 is killed then the chance of feeding dross by vortex 2 also decreases.

4.3. Perpendicular Plate Baffle

In another alternative attempt to make vortex 1 vanish from the flow field a perpendicular plate baffle is created near the strip as shown in Fig. 12. This figure shows all details of the geometrical implementation, which can really be done in the plant. Here the width of the plate baffle is same as the width of the strip. The flow field on the vertical symmetrical plane at z=1600 mm is shown in Fig. 12 for the perpendicular plate baffle. The expanded view of the V region for this case (Fig. 13) is shown in Fig. 14. It can be seen from Fig. 14 that vortex is completely eliminated but vortex 2 stays along with vortices 3 and 4. The strength of the vortices has also increased due to the perpendicular plate baffle. However, it has been discussed that vortices 3 and 4 are not very prone to induce dross pick up by the strip. Now vortex 2 will not get as much dross as it was getting when there was no plate baffle or even when the parallel plate baffle was there. So self-feeding of dross on to the strip near vortex 2 will decrease tremendously (because now vortex 2 starves from dross) although the strength of the vortex has been increased. As vortex 1 is now absent so the dross particles created near the snout will glide along the plate baffle to the top free surface where they can be picked up from time to time. Moreover, the air injection on
to strip will keep the dross particle away from the strip and hence the possibility of the dross being picked up by the strip will remain low. So it is strongly believed that such a flow field will help to eliminate dross pick up by the strip even better than the parallel plate baffle. The increase of the flow field will help to eliminate dross pick up by the strip will remain low. So it is strongly believed that such a flow field without any gap between the perpendicular plate and the strip can feed dross on to the flow again. By placing a parallel plate baffle near the strip the self-feeding vortex could be removed and the flow field becomes more amenable for galvanizing. However, by placing a perpendicular plate baffle it has been marked that the self feeding vortex gets removed completely and the inside vortex which was getting dross from the self feeding vortex starves of dross particles, so the perpendicular plate baffle is more suitable for galvanizing rather than the parallel plate baffle. So the choice remains with the plant operator as to which plate baffle can be used for a particular plant.

Acknowledgements

The first author SKD gratefully acknowledges the financial support given to him by Tata Steel for executing this project for which the present work could be accomplished.

Nomenclature

$k$: Turbulent kinetic energy
$p$: Pressure
$t$: Time
$u$: Mean velocity
$x$: Coordinate for measure of distance
$\rho$: Density of the fluid
$\mu$: Co-efficient of viscosity
$v$: Kinematic viscosity
$u_i u_j$: Average turbulent stress
$\varepsilon$: Rate of dissipation of turbulent kinetic energy
$\phi$: Either $k$ or $\varepsilon$

Subscript

$i, j, k$: Three Cartesian coordinate directions $x, y$ and $z$

REFERENCES

2) M. Gagné and M. Gaug: Proc. of 4th Int. Conf. on Zinc and Zinc Alloy Coated Steel Sheet (GALVATECH ’98), ISIJ, Tokyo, (1998), 90.

Fig. 14. An expanded view of the flow field (Fig. 13) near the strip, the sink and the guide rolls with a perpendicular plate baffle at $z = 1,600$ mm, strip width $= 900$ mm, speed $= 2.5$ m/s.