1. Introduction

There are three steps in tube galvanising: cleaning, fluxing and galvanising. All the steps are important and must be done efficiently to achieve perfect coating on tubes. In the cleaning section, a tube is first degreased in alkaline solution, rinsed in water and then pickled in hydrochloric or sulphuric acid. After rinsing again in water it is generally fluxed with zinc-ammonium chloride to get a temporary protection of its surfaces from oxidation. A properly fluxed tube is dried and preheated to about 100°C and dipped in the galvanising bath at about 460°C. The tube comes out of the zinc bath obliquely (at an angle of about 12 degrees) and passes through an annular air wiper which removes the extra liquid zinc from its external surface. A superheated steam jet is then blown inside the tube for a couple of seconds to remove the extra liquid zinc from the inner surface of the tube. It is then quenched in water and sent to the finishing bay. All the steps are schematically shown in Fig. 1.

It has been observed over years that the gross zinc consumption in the galvanising lines of the Tubes Division of Tata Steel Ltd., India, has been above the benchmark value. The coating thicknesses on tube inner surface along the length of the tubes (6 m) were determined by chemical dissolution method. The inner coating comprising 60–65% of total zinc on the tube was found not to be uniform along the tube length, and about double the required amount toward the middle of the tubes. The excess amount of zinc causes

Simulation of Zinc Solidification and Coating Profile on the Inner Surface of a Tube during Its Galvanisation

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A simulation study was carried out for the first time on zinc solidification and coating profiles in tube galvanising for an industrial line. The entire process was simulated with the help of flow and heat transfer models and surface wave model in this computational heat transfer study. It was observed that the coating on tube inner surface gets solidified for more than one third of its length before the steam blowing to remove the extra zinc. This part of the tube thus becomes insensitive to steam blow for thickness control. The wavy coating profiles developed due to jet blowing of steam were predicted that matched well with the measured profiles from industrially made galvanised tubes.

KEY WORDS: galvanisation; solidification; simulation; heat transfer analysis; steel tubes.

Fig. 1. Schematic view of various steps in tube galvanising.
huge loss of valuable material and affects the economics of the process. In order to reduce the overall zinc consumption, a scientific approach was taken, from finding the mechanism of the formation of wavy coating profiles to optimising the process parameters. A part of the study i.e. the simulation of zinc solidification and coating profile on the inner tube surface during its withdrawal from the liquid zinc pot until the end of steam injection with the help of numerical heat transfer analysis has been discussed here. The zinc–iron alloying reaction during the long dipping time of tubes in liquid zinc has been studied separately and will not be included in this discussion. Although tube galvanising is performed for the work of heat transfer analysis of the solidification and profiles for an application in the industrial production line is being reported.

2. Heat Transfer Analysis

The numerical heat transfer analysis of molten zinc film on the inner surface of tube was done to predict thermal dynamics of the solidification phenomena during the time of withdrawal of the tube from liquid zinc bath to steam injection through the tube, which is 22 s for the concerned process line. The processing and thermo-physical data used in this analysis are shown in Table 1. Based on the actual coating thickness, the initial film thickness of molten zinc carried on the inner tube surface was considered to be 60 μm. Specifications of tubes considered in this numerical study are listed in Table 2. The following assumptions were made for the work of heat transfer analysis of the solidification problem of inner coating:

- As the film thickness and tube wall thickness are too small compared to the inner diameter of tube, the curvature effect is negligible, and the solution can be obtained in Cartesian co-ordinate system. A constant film thickness is assumed for analysis.
- Molten zinc is treated as Newtonian fluid with constant thermo-physical properties.
- x-Axis is chosen along the tube length, and y-axis is chosen along the depth of the film.

2.1. Flow and Heat Transfer Model Equations

For numerical analysis, following model equations in conservative form are considered in order to predict flow and heat transfer transients of the inner layer of molten zinc, tube wall, and the zinc coating on the outer surface of the tube:

(a) A lumped parameter conduction model for zinc coating on outer surface is considered as Biot number for coating film is less than 0.1 due to low internal thermal resistance owing to small coating thickness and large thermal conductivity.

\[
\frac{d}{dt} (m_w C_{pn} T_w) = -k_{zn} A \frac{dT}{dy} \bigg|_{s2} - hA(T_{zn} - T_{air}) = 0
\]

(b) For conduction analysis of tube wall, a similar lumped parameter model is considered.

\[
\frac{d}{dt} (m_w C_{pn} T_w) = -k_{zn} A \frac{dT}{dy} \bigg|_{s3} - k_{zn} A \frac{dT}{dy} \bigg|_{s2} = 0
\]

(c) Steady 1-D x-momentum equation for molten zinc film flow:

It is assumed that the flow of molten zinc film in x-direction is laminar.

Analytical solution of momentum equation is used for velocity distribution in the film,

\[
v_x = \frac{P_{zn}}{2 \mu_{zn} g} \sin \beta \left[ 1 \left( \frac{y}{\delta} \right)^2 \right]
\]

(d) Unsteady 2-D thermal energy balance equation for molten zinc film comprising of convection and conduction in x-direction and conduction in y-direction:

\[
\frac{\partial}{\partial t} (\rho_{zn} C_{zn} T_{zn}) + \frac{\partial}{\partial x} \left( \rho_{zn} C_{zn} T_{zn} v_x \right) = \frac{\partial}{\partial x} \left( k_{zn} \frac{\partial T_{zn}}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_{zn} \frac{\partial T_{zn}}{\partial y} \right)
\]

(e) Boundary conditions at the free surface of the inner film under molten and solidified condition, in case of both natural convection cooling and steam injection:

\[
-k_{zn} \frac{dT}{dy} \bigg|_{y=\delta} = h(T_{zn} - T_b) \quad \text{..........................(5)}
\]

(f) Boundary condition at solid–liquid interface during solidification:

Table 1. Processing and thermo-physical data used in the analysis.

| Parameter (unit)                  | Value |
|----------------------------------|-------|
| Bath temperature (°C)            | 455   |
| Tube length (m)                  | 6     |
| Outside coating thickness (m)    | 45x10^-6 |
| Inside film thickness (m)        | 60x10^-6 |
| Molten zinc density (kg/m³)      | 6600  |
| Solid zinc density (kg/m³)       | 7140  |
| Molten zinc thermal conductivity (W/mK) | 60     |
| Solid zinc thermal conductivity (W/mK) | 96     |
| Molten zinc specific heat (kJ/kgK) | 0.48   |
| Solid zinc specific heat (kJ/kgK) | 0.34   |
| Molten zinc viscosity (N/m/s)    | 0.00385 |
| Heat of fusion (kJ/kg)           | 100.9 |

Table 2. Specification of tubes.

| Nominal tube size as NB (Nominal Bore) | Outside diameter (mm) | Inside diameter (mm) | Thickness (mm) |
|---------------------------------------|-----------------------|---------------------|----------------|
| 25 mm NB                              | 34.10                 | 28.40               | 2.85           |
| 40 mm NB                              | 48.60                 | 41.40               | 3.60           |
| 65 mm NB                              | 75.80                 | 67.40               | 4.20           |
2.2. Surface Wave Model Equations

Due to steam injection, interaction between flowing steam and the molten zinc layer gives rise to wave formation which eventually solidifies on the inner surface of the tube during its propagation and non-uniform coating thickness results. Mathematical model equations for small-amplitude surface wave formation over molten zinc due to steam injection are as follows.4)

\[ (U_0 - c)^2 = \frac{4\pi \mu c}{\phi \rho' \lambda} \] ........................(12)

\[ c = \sqrt{\frac{g \cos \theta \lambda}{2\pi}} \] ..........................(13)

\[ \lambda = \frac{U_0^2}{g \cos \theta} \] .............................(14)

\[ a = \left( \frac{\phi}{\beta \rho} \right) \frac{U_0^2}{g \cos \theta} \] .............................(15)

Where:
- \( U_0 \): Steam velocity
- \( c \): Wave velocity
- \( \mu \): Liquid viscosity
- \( \rho' \): Steam density
- \( \lambda \): Wave length
- \( a \): Amplitude
- \( \beta, \phi \): Empirical constants
- \( \theta \): Inclination of surface with the vertical

\[ \text{Nu}^{1/2} = 0.825 + \frac{0.387(\text{Gr} \cdot \text{Pr})^{1/6}}{[1 + (0.492 / \text{Pr})^{9/16}]^{27}} \cdot (10^{-1} \leq \text{Gr} \cdot \text{Pr} \leq 10^{12}) \] ..........................(10)

Forced convection:

\[ \text{Nu} = 0.023 \text{Re}^{0.88} \text{Pr}^{0.3} \] ..............................(11)

Where:
- \( v_x \): Velocity in \( x \)-direction (m/s)
- \( C_{\text{pool}} \): Specific heat of molten zinc (J/kg \cdot °C)
- \( \rho_{\text{mol}} \): Density of molten zinc (kg/m³)
- \( k_{\text{mol}} \): Thermal conductivity of molten zinc (W/m \cdot °C)
- \( T_{\text{mol}} \): Temperature of molten zinc (°C)
- \( C_{\text{zinc}} \): Specific heat of solid zinc (J/kg \cdot °C)
- \( \rho_{\text{zinc}} \): Density of solid zinc (kg/m³)
- \( k_{\text{zinc}} \): Thermal conductivity of solid zinc (W/m \cdot °C)
- \( m_{\text{zinc}} \): Mass of the solid zinc cell (kg)
- \( T_{\text{zinc}} \): Temperature of solid zinc (°C)
- \( \alpha_{\text{zinc}} \): Thermal diffusivity of solid zinc (m²/s)
- \( \alpha_s \): Thermal diffusivity of steel (m²/s)
- \( T_s \): Temperature of steel (°C)
- \( k_s \): Thermal conductivity of steel (W/m \cdot °C)
- \( m_{\text{wall}} \): Mass of the wall cell (kg)
- \( \beta \): Inclination of tube with horizontal (degree)
- \( \delta \): Film thickness (m)
- \( \text{Gr} \): Grashof number
- \( \text{Pr} \): Prandtl number
- \( \text{Re} \): Reynolds number

2.3. Solution Procedure

For numerical analysis of the governing differential equations, the solution domain was subdivided into number of cells as shown in Fig. 2 where the tube inclination and velocity are schematically given in Fig. 2(a) and the grid arrangement for inner film is shown in exaggerated form in Fig. 2(b). In case of inner film of molten zinc, a fixed grid finite volume based explicit numerical scheme was used for solving model Eq. (2) along with initial and boundary conditions. The basic solution algorithm comprises the following steps: as the tube rises from the bath, outside coating film temperature is calculated during a particular time step using convective cooling equation. The new temperature of the outer coating cell acts as the boundary condition for tube wall cell for its temperature calculation. Now tube
wall temperature acts as the boundary condition for the adjacent molten zinc cell on the tube inner surface. As wall temperature is lower than the initial temperature of the molten zinc cell, heat flows out from molten zinc cell and cooling dynamics in the film is set in. The procedure was repeated for all cells spanned over 22 s within which steel tube draw out time of 8 s from molten zinc bath, free run and waiting of 12 s in the process line, and steam injection for 2 s were accommodated with internal time tracking algorithm in the computer code developed for the simulation work.

2.4. Industrial Validation

Actual coating profiles of galvanised tubes of three different diameters from an industrial line were generated to validate the numerical heat transfer analysis. Six samples were cut at 1 m interval from all 6 m long coated tubes; each at the middle of 1 m segment. Three similar samples from different tubes were used and the average value was considered for every record. The coating thickness was determined by chemical dissolution and weight difference method. The coating profiles were plotted and a comparative analysis was done with the simulation results.

3. Results and Discussion

It was observed from the simulation results that the temperature in any computational cell dropped linearly with time until the start of steam injection after 20 s, irrespective of tube specification. The results also revealed that at any time the temperature variation through the depth of zinc film thickness (i.e. in all grids) at a particular length of the tube was negligible. This blunt distribution of temperature was due to small thermal resistance in Y-direction for very small film thickness (in order of microns) and high thermal conductivity of liquid zinc. Hence an average temperature of all the cells at a particular level at any time may be considered as the representative temperature. Figure 3 shows the average temperature along the inner film for all three types of tubes after 20 s i.e. just before the start of steam blowing. No significant difference in average temperature was observed for different tubes since the difference in steel wall thickness could not make any considerable change in thermal resistance values. The length of solidified zinc film in all tubes after 20 s was more than 2 m from the leading edge. This implies that the zinc film on the inner surface of one third of the tube length solidifies before the start of steam injection. Hence steam injection would be ineffective for this part of the tube in controlling the coating thickness.

The general trend of average temperatures for the top, middle and bottom cells of a 25 mm NB tube are shown in Fig. 4 with respect to process time starting from tube withdrawal to the end of steam injection. It is evident from the figure that during the first 20 s the film temperature reached below the freezing point of zinc (419.5°C) for the front part of the tube, whereas the middle part was yet to achieve the freezing temperature, and the tail part was much above it. This happens as the 6 m long tube takes about 8 s to come out of the liquid zinc bath, which makes a difference in available time for natural convection from the front end to the tail end of the tube. In all cases, temperature dropped rapidly after 20 s as high heat transfer coefficient results from high velocity steam injection. Similar results were obtained for the other two sizes of tube.

As the steam injection starts inside the tube to remove extra zinc, wave is generated due to interaction between high velocity steam and free liquid surface. The wave velocity depends on the steam velocity; higher the steam velocity, higher will be the wave velocity. Figures 5(a), 5(b) and 5(c) shows the propagation of a single wave due to steam injection. In this computation, the volumetric flow rate of steam was considered to be same for all three specified tube dimensions. The steam velocity was therefore higher for smaller diameter tubes, which pushed the wave at the end of the tube. Thus the profiles are different for tubes of different diameters; the maximum thickness or the peak of the wave is at the tube end for lower diameter tube, which shifts towards the middle for higher diameter tubes. This shift of peak value is possibly due to the lower average velocity of steam through higher diameter tubes. The actual
coating profiles on the inner surface of tubes produced in a commercial tube galvanised line as measured by wet chemical method mentioned earlier are also shown at the right side in Figs. 5(d), 5(e) and 5(f). It is interesting to notice the similarities of the simulated coating profiles and the wave peak positions with the actual ones. The simulation predicts fair agreement with respect to the maximum thickness of solidified coating (basic film thickness plus the peak value of wave amplitude) with the plant data. The small differences can be attributed to the simplicity of the model and measurement errors, if any.

4. Conclusions

The main results from this simulation study can be summarised as:

(1) For the first time a simulation study on coating solidification and profiles during tube galvanising has been done for an application in the industrial production line.

(2) There is hardly any difference in temperature profiles of the inner zinc film along the length for different diameter tubes until the steam blowing starts.

(3) The inner coating on more than one third of the tube gets solidified before the steam blowing and becomes insensitive to steam blow for thickness control.

(4) The final coating profiles with a wavy nature that develop due to jet blowing of steam have been predicted. They match well with the actual measured profiles for industrial tubes with different diameter.

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