Chapter - 1

Introduction

1.1 Motivation

Cooling of moving material along with phase transformation in operations like hot rolling, extrusion, continuous casting, drawing etc., are important aspects of these manufacturing processes. Liquid jet cooling is widely used to extract heat from micro-electronic components (Ma and Bergles[1]), neutron beam targets etc. Air jets are used in paper and textile mills (Martin[2]).

In rolling operation, a series of counter-rotating rollers give the strip its final thickness, plastically deforming the original strip. Plastic deformation, as well as friction between the moving strip and the roller surface supply additional heat energy to the hot moving strip. After the final pass, the material is cooled by several water jets impinging on it (Kohring[3]), as shown in Fig. 1.1. As the strip runs along the table, it cools from around 1000^oC to 650^oC accompanied with metallurgical phase transformation. The strip then goes to the down coiler where fine grain size of iron-carbide is preserved by self-annealing.

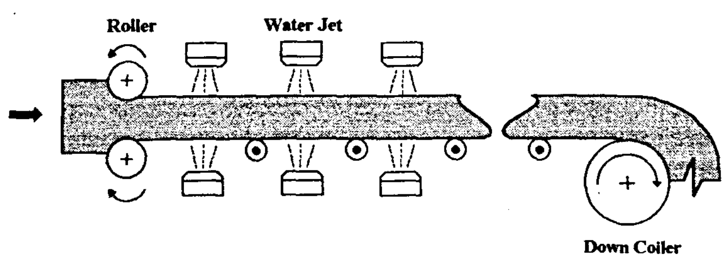

Figure 1.1 : *Runout Table Cooling*

The properties of steel are greatly influenced by its grain size, contents of alloying elements, dislocation density and phase composition. Metallurgical phase transformation is very much temperature dependent. Controlled cooling after rolling is, therefore, imperative in achieving a product of desired specification. Cooling of hot strip is a complex process. It involves heat transfer due to water jet impingement, film boiling and radiation from both surfaces of the plate. Metallurgical phase transformation is preceded by the so called incubation period, which starts only after temperature falls below a critical value. This interwoven thermometallurgical process becomes even more involved for a moving continuum.

In the present work, the power of bondgraph modelling technique has been exploited to create a model for the above thermometallurgical process taking into consideration all its dynamical components. Once a bondgraph model is created, derivation of governing system equations becomes systematic and can be handled by any bondgraph software. Simulation studies with such a model is of great advantage in developing cooling strategy for producing materials with desired phase composition.

1.2 Process Description and Modelling : Bird's-eye View

Heat transfer and metallurgical phase kinetics are two interdependent issues involved in the thermometallurgical process of the runout table. This section presents description of the processes and a brief review of relevant literature.

1.2.1 Heat transfer

In quenching of steel, uniform and fast cooling rate is required. Nonuniform quenching makes steel microstructurally heterogenous. Heat transfer in runout table from the hot metal surface during water quenching consists mainly of two phases : Forced convection due to water jet impingement and film boiling. In forced convection, intensive heat transfer between the strip surface and water occurs. This process extends upto the point of vapour film formation on the strip surface. This zone is called impingement zone. From the end of impingement zone, vapour film starts developing that acts as an insulative layer and thereby reduces heat transfer rate. In this film boiling zone, heat transfer is due to conduction through the vapour film and through radiation. Along the metal strip, as the temperature falls, vapour film becomes unstable and ultimately it breaks down. At this stage, heat transfer takes place in the form of nucleate boiling and convection. Heat transfer due to water cooling from metal surface is not only a temperature dependent phenomena, but it also depends on other factors, such as, geometric configuration, hydro-mechanical variables such as, pressure, water velocity, turbulence etc. In the hot strip cooling process, temperature is so high that film boiling can easily take place (Collier[4]). Farber and Scorah[5] and McAdams *et al.*[6] had experimentally shown the various regimes of pool boiling with an electrically heated wire submerged horizontally in water at saturation temperature. Nukiyama[7] was the first to obtain the characteristic curve of pool boiling.

Forced convection (jet impingement)

Kestin *et al.*[9] and Kestin[10] found that the induction of turbulence, in presence of pressure gradient in the impingement zone, enhances the heat transfer in laminar boundary layer. Scholtz and Trass[12], Sparrow and Wong[14] experimentally investigated heat and mass transfer at the stagnation line in the impingement zone. Sparrow and Lee[15], van Heiningen *et al.*[16], Saad *et al.*[18], Arbourise[22] analysed heat transfer in the impingement zone, considering parabolic distribution of impact velocity. Yanagi[17] used empirical formulae of heat transfer coefficients for various modes of heat flows. He compared his results with experimentally observed heat flows for laminar, as well as, spray jets.

Miyasaka *et al.*[19] showed the effects of impinging velocity on heat transfer in pool and forced convection nucleate boiling region. Miyasaka *et al.*[20] also discussed the high subcooling of water at the stagnation point. Their discussion is based on experimental observations of heat flux and its relation with jet velocity and pressure at the stagnation point. Kokado *et al.*[23] in their experiments observed that when cold water impinges on a hot plate, a circular black spot appears that grows with time. They were able to measure the black zone photographically, for different cooling condition. Hatta *et al.*[24] developed a model for the cooling process of the hot steel plate by laminar water bar. They obtained an empirical relation for the overall heat transfer coefficient, using Nusselt number, Prandtl number, and the Reynolds number, at the impinging zone. They compared their results with experimental observations. Devadas and Samarasekera[25] used the above relation to create a mathematical model to predict temperature distribution in the runout table. Hatta *et al.*[27] modified their previous model for the case of laminar water curtain, coming out from a slit nozzle of large aspect ratio. They verified their numerical results with experimental ones. Zumbrunnen *et al.*[28] considered parabolic pressure distribution within the stagnation zone as observed on stationary plate. They have shown the effects of impingement velocity and jet width on heat transfer within that zone.

Wolf *et al.*[29] conducted experiment to find out the effect of non-uniform velocity profile on convective heat transfer coefficient. Zumbrunnen[30] used similarity solutions to the Navier-Stokes equations to find out the flow velocity in the stagnation zone. He determined temperature distribution by numerically solving the conservation equations for energy, where he calculated velocity components from similarity solutions. Filipovic *et al.*[31] considered an experimentally obtained pressure variation in the impingement zone for a stationary plate, which causes the normal component of the impact velocity to vary from the stagnation line. For different nozzle discharge velocities and heights of impingement, normal components of the impact velocity were calculated to find out the heat flux at each point within the impingement zone. Filipovic *et al.*[32] performed a parametric study using their earlier model [31] to determine heat transfer from a moving flat plate. They had shown that the nozzle width has the largest influence among the other control parameters on the thermal behaviour of the metal strip. Zumbrunnen *et al.*[33] formulated a boundary layer model to evaluate the heat transfer coefficient in the impingement zone for a hot moving plate cooled by a non-uniform planar jet. Evans *et al.*[34] used an empirical relation of overall heat transfer coefficient for the impinging zone. But this model makes no difference between the impinging widths at the top and bottom surfaces. Packo *et al.*[35] did time-temperature analysis of a hot moving strip, using finite element method for a constant heat transfer coefficient within the impingement zone.

In the present work, the model of Filipovic *et al.*[31] has been used for calculation of heat transfer coefficient in the forced convection zone. The same has been used for its convincing approach to obtain the variation of impact jet width and also impact jet velocity with the nozzle discharge flow rate.

Film boiling

Motte and Bromley[36] have experimentally shown the effect of subcooling on heat transfer in turbulent flow. Berenson[37] did a very significant work on the Taylor-Helmholtz hydrodynamic instability and its importance in the case of film boiling heat transfer from a stationary horizontal surface. He derived an analytical expression for the heat transfer coefficient. However, because of high metal strip temperature and plate velocity as in rolling, the above analysis is not applicable. Cess and Sparrow[38] analyzed film boiling for both saturated and subcooled liquid on a stationary isothermal plate using similarity approach. They did not consider the radiation effect, interface waviness and film instability in their analysis. Radiation becomes predominant when the strip temperature is too high. Horvay[39] had shown the temperature distribution in a plate, moving through chambers at different temperatures, assuming a fixed heat transfer coefficient. Koh[40] analyzed two-phase flow in laminar film boiling for a vertical surface. Sparrow[41] has shown both radiatively participating and non-participating effects in laminar film boiling.

Apart from metal strip cooling, there are a few studies on glass and polymer fibre cooling by Glicksman[43], Bourne and Dixon[46] and Kuiken[47].

Thermal analysis of manufacturing processes, such as drawing, extrusion, rolling and continuous casting were performed by Tadmor and Klein[45], Fisher[48], and Altan *et al.*[49]. Jaluria and Singh[52] analyzed the temperature distribution in a moving plate and in a circular rod. Reiners *et al.*[53] developed a method for determination of heat transfer coefficient in the stable film boiling range in spray cooling. They applied this method in continuous casting process.

Inada *et al.*[51] estimated local heat transfer coefficients in the impingement as well as uniform parallel flow zone for stationary plate with constant heat flux. They verified the analytical results with their experimental observations. Kokado *et al.*[23] developed a mathematical model to obtain the heat transfer in the film boiling zone around a circular jet impinging on a stationary plate. Their results were consistent with experimental observations. Karwe and Jaluria[55] performed heat transfer analysis from a plate to the environment, employing thermal buoyancy effect. The same authors performed numerical analysis of heat transfer from a plate moving with constant velocity after emerging from a die or a furnace. The effect of upstream thermal condition on the downstream temperature variation was investigated.

Zumbrunnen *et al.*[57] derived the heat transfer coefficient for a laminar two-phase flow over a moving plate. He has shown the effect of surface motion on heat transfer. Zumbrunnen *et al.*[58] developed an experimental method and apparatus for measuring the heat transfer coefficients at various zones over a flat plate, moving and also stationary, cooled by planar liquid jet. Filipovic *et al.*[31] developed a mathematical model for heat transfer at various regions of a moving hot plate. They assumed one-seventh power distributions for liquid and vapour velocities in the boundary layers which led to a unique non-dimensional interface velocity. This analysis pertains to parallel flow only. Filipovic *et al.*[60] also performed similarity analysis of film boiling in laminar flow on a moving isothermal plate. They considered linear distribution for both velocity and temperature in the vapour layer, and second order polynomials for the liquid layer. In another work, Filipovic *et al.*[61] developed a two-phase boundary layer model considering both similarity and integral methods and had shown the effect of subcooling on vapour layer thickness, non-dimensional interface velocity and the Nusselt number in turbulent film boiling on an isothermal moving surface. Chen *et al.*[62] determined the convective heat transfer coefficient for an array of submerged air jets impinging on a moving plate of constant temperature. The model takes care of the interaction between two neighbouring jets. The above works of Zumbrunnen *et al.*[57] and Filipovic *et al.*[31][32][60][61] are very significant in this area of heat transfer analysis.

There is no work on the stability of the vapour film applicable to runout table. Vapour film stability and the collision of water layers on the moving plate surface between two adjacent jets are important factors in estimation of the heat transfer coefficient in this zone. In this work the two-phase model of Zumbrunnen *et al.*[57] has been adopted to obtain the heat transfer coefficient in the film boiling zone.