

STUDY OF HEAT TRANSFER INVOLVED IN CONTROLLED COOLING OF
STEEL WIRE ROD

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Lamar University

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of the Requirements for the Degree

Master of Engineering Science

by

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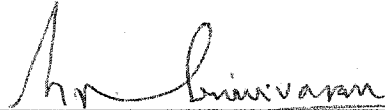
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STUDY OF HEAT TRANSFER INVOLVED IN CONTROLLED COOLING OF
STEEL WIRE ROD

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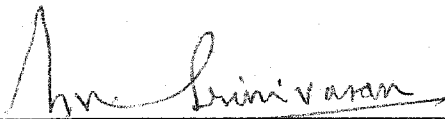
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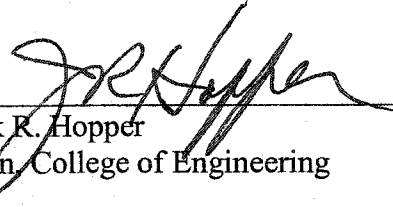
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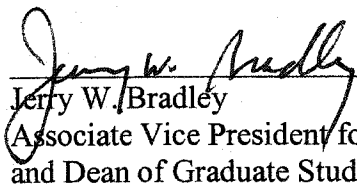
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ABSTRACT

Study of Heat Transfer Involved in Controlled Cooling of Steel Wire Rods

By

Tushar Madhusudan

The heat transfer involved in the controlled water cooling of wire rods passing through water boxes at the rod mill production line at North Star Steel Texas (NSST) is modeled and analyzed in this thesis. The water boxes are situated between the final finishing mill and the Stelmor deck. This cooling stage in the wire rod production process is very crucial and important as the wire rod has to be delivered at the laying head at a proper temperature so as to enable proper austenitizing. The laying head is a unit which coils the wire rod into loops and places them on to the Stelmor conveyor deck. The Stelmor conveyor deck consists of a series of fans placed under the conveyor. These high efficiency fans provide uniform air cooling at controlled rates.

Austenite to pearlite transformation takes place in the Stelmor deck and hence extreme care should be taken to control the inlet temperature at the deck. It is hence necessary to control the parameters that affect the cooling of the wire rod in the water boxes. For a given operating condition, these parameters set a temperature variation from the laying head to the entry of the Stelmor conveyor deck. If the temperature difference is too great then the solid state transformation in the rod may happen prior to the entry of the Stelmor conveyor deck. This would cause the formation of coarse pearlite which will decrease the mechanical properties of the final product. Very high cooling rates may induce the formation of metastable phases like martensite, hence rendering the rod useless for further operations. Good control of the parameters in the water cooling zone will ensure

that austenitic transformation occurs under controlled conditions of the Stelmor conveyor deck, making the steel more responsive to the subsequent patenting operations (Morales et al.1989).

This research considers the rod properties and cooling parameters, termed as Key Input Variables, which control the temperature of the rod surface at the laying head. A numerical model has been developed to estimate the rod surface temperature at the laying head. The model clearly indicates the affect of each key input variable on the laying head temperature. The model has been tested for its accuracy using the data from a similar investigation.

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LIST OF SYMBOLS

Symbol		Description
A	=	Area
A_e	=	Effective Area
C	=	Constant
C_p	=	Specific Heat
d	=	Diameter
F	=	Water Flow Rate
h	=	Heat Transfer Coefficient
h_a	=	Heat Transfer Coefficient of Air
h_c	=	Convective Heat Transfer Coefficient
h_e	=	Heat Transfer Coefficient of Environment
h_r	=	Radiative Heat Transfer Coefficient
h_w	=	Heat Transfer Coefficient of Water
k	=	Thermal Conductivity
l	=	Length
q	=	Heat Flux
r	=	Radius
t	=	Time
t^*	=	Instantaneous Time
T	=	Temperature

T_a	=	Temperature of Air
T_e	=	Temperature of Environment
T_s	=	Surface Temperature
T_w	=	Temperature of Water
T_1	=	Initial Temperature
ΔT	=	Temperature Gradient
v	=	Velocity
W	=	Water Flux
x	=	Distance
σ	=	Stefan-Boltzmann Constant
ε	=	Emissivity
ρ	=	Density

Chapter 1

Introduction

1.1 Overview of the Rod Mill

The Rod making process begins by heating steel billets to a temperature of about 2000°F in a reheat furnace. The metal is then sent through multiple roughing, intermediate, and prefinishing rolling mill stands where the metal is eventually shaped into bar. The final reductions are rolled in the Morgan high speed No Twist Finishing mills. The rod, after exiting the finishing mill, is cooled in the water boxes and then coiled onto the Stelmor cooling conveyor by the inclined laying head. The rod proceeds down the Stelmor conveyor where the cooling rate is controlled to provide the required metallurgical characteristics. The rod spirals are then placed in the reforming tubs and later transferred to the C-hook conveyor system for final cooling. They are then compacted, banded and transferred to storage (Kiefer and Keyzer 1999).

A rod rolling mill, shown in figure 1-1, consists of a series of rolling strands which gradually reduce the cross-sectional area of a starting billet down to a finished wire rod with diameter as small as 5.0 mm at finishing speeds of up to about 120 m/s. Water cooling units, such as water boxes, which control the temperature of the steel are located at various positions in the rod mill. The purpose of these water cooling units is to maintain a pre-estimated temperature of the wire rod at the laying head so as to control austenite grain size and surface scale conditions, hence achieving the desired microstructure. Continuous monitoring and control of the stock temperature along the

rod mill and the use of sophisticated equipment helps in achieving good control of the entire process. Temperature is therefore to be considered as the primary variable that affects the final properties of the rod.

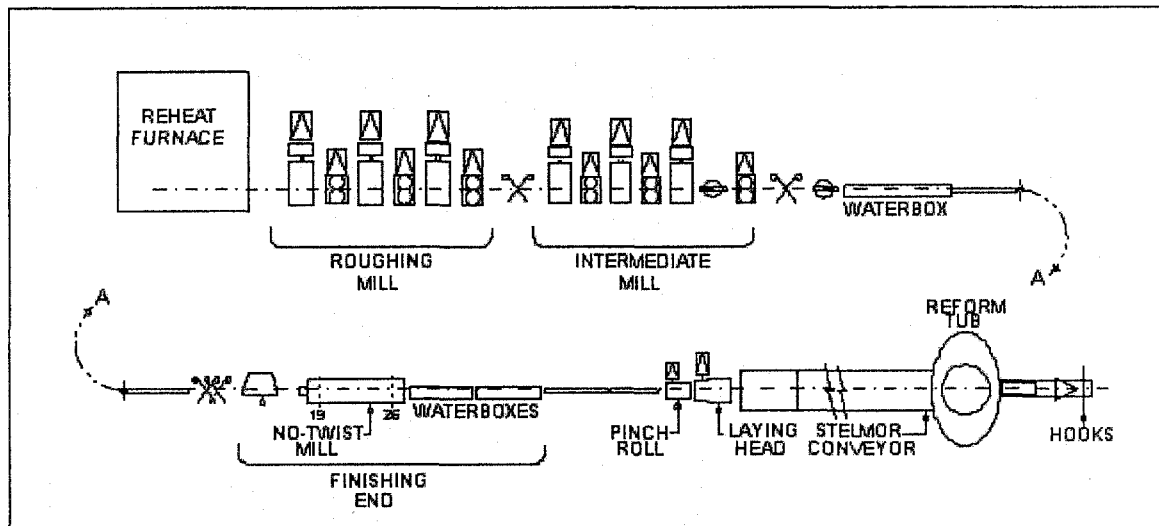


Figure 1-1: Equipment Layout in a High Speed Rod Mill

Source: Morgan Construction Company

1.2 Introduction to the Cooling Process

The cooling of wire rod after it exits the finishing mill can mainly be divided into two stages, the cooling in the water boxes and the cooling in the fan cooling zone also known as the Stelmor deck. Each stage has its own purpose. The cooling in the water boxes is primarily to bring down the temperature to a pre-estimated temperature before the rod can enter the laying head. Once the rod enters the laying head it is transferred to the Stelmor deck which consists of fans and blowers under the deck. This is where the rod undergoes the phase transformation from austenite to pearlite. The primary purpose of the

fan cooling zone is to achieve the desired microstructure. Better microstructure can be obtained if all the parameters in the water cooling zone are in control and under vigilance. Failure to understand the heat transfer phenomena in the water cooling zone would lead to loss of control on the parameters in the Stelmor deck, resulting in poor microstructure. Hence the water cooling zone is very crucial and important in the rod production process. North Star Steels makes use of two water boxes. Each water box is about 7 to 8 m long and consists of a series of water sprays which sufficiently bring down the surface temperature of the rod. The rod undergoes most of the cooling in the water boxes. Each water box is separated by a distance of about 6 to 7 m. When the rod travels between the water boxes, there is no appreciable drop in the surface temperature. The main purpose of this zone between the water boxes is to equilibrate the rod center and surface temperatures through a free radiation to the surroundings. Due to the high rod mill speeds, a visible film of water is usually dragged along the rod in its direction of motion. This enables heat transfer in this zone through radiation. However North Star Steel makes use of high pressure stripper valves at the exit of each water box in order to completely strip off the water film. Hence it may be assumed that no water is carried along the rod through this zone.

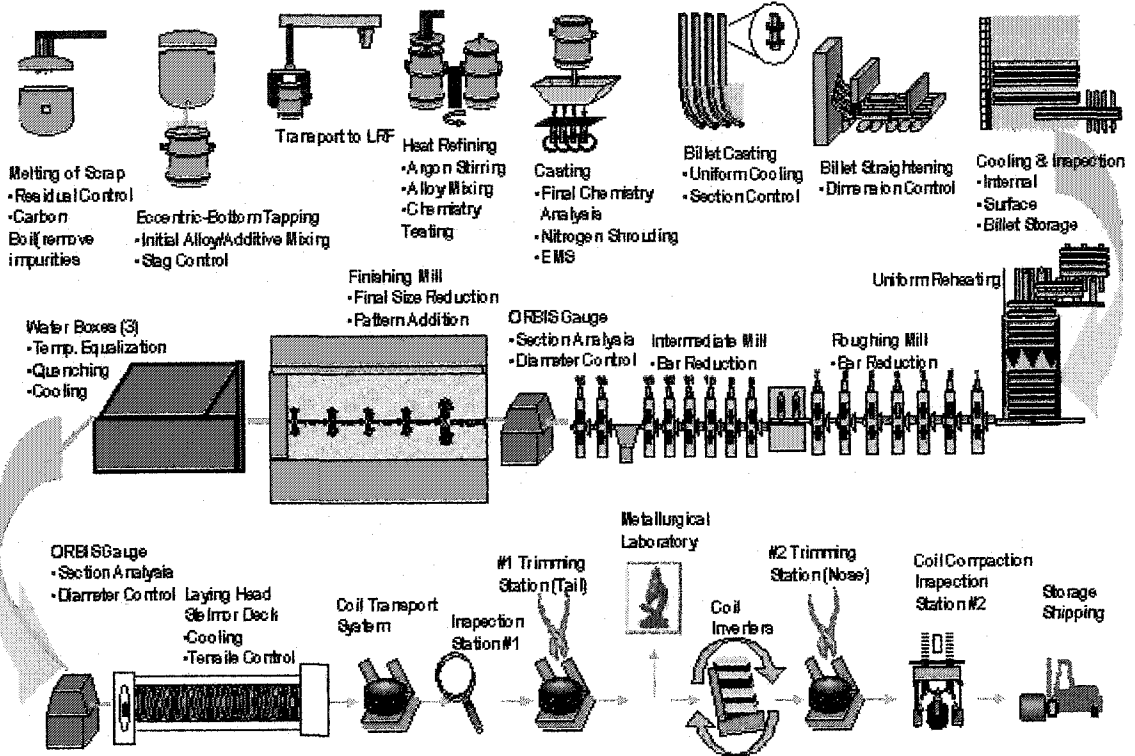


Figure 1-2: North Star Steel Process Flow Chart

Source: North Star Steel

Chapter 2

Background Information

2.1 Heat Transfer Mechanisms

Heat transfer can be defined as the thermal energy in transit when there is a temperature difference. There are three different modes of heat transfer. When there is a temperature difference in a stationary medium, either a solid or a fluid, the heat transfer mechanism is referred to as Conduction. Convection refers to the heat transfer mechanism that occurs between a surface and a moving fluid which are at different temperatures. The third mode of heat transfer is termed as Radiation. This is the heat transfer that takes place between two surfaces at different temperatures in the absence of an intervening medium (Incropera and DeWitt 2002)

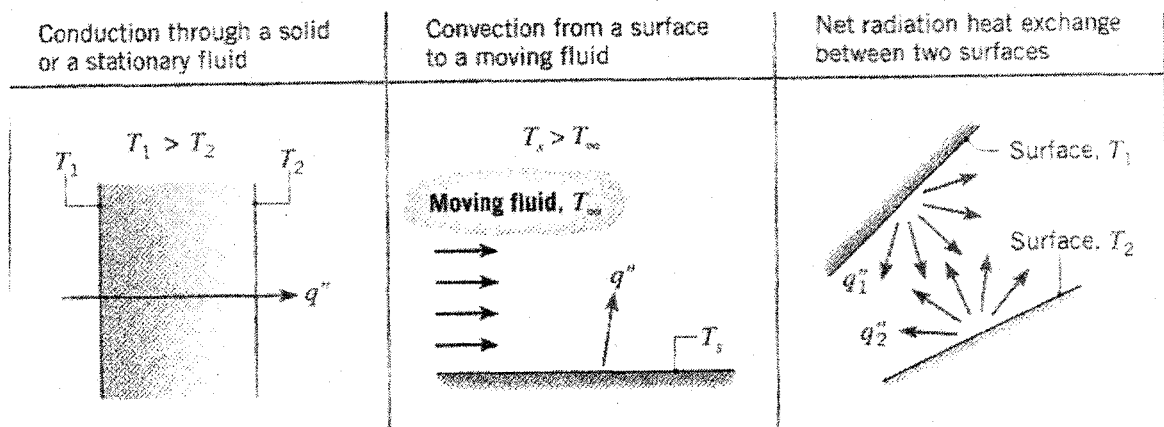


Figure 2-1: Heat Transfer Mechanisms

Source: Heat and Mass Transfer, Frank P Incropera & David.P.Dewitt

2.1.1 Conduction Heat Transfer

Conduction may be considered as the transfer of energy from the more energetic to the less energetic particles of a substance due to interaction between the particles. For example, the exposed end of a metal spoon suddenly immersed in a cup of hot coffee will eventually be warmed due to the conduction of energy through the spoon. Also, on a winter day, there is a significant energy loss from a heated room to the outside air. This loss is principally due to conduction heat transfer through the wall that separates the room air from the outside air. Heat transfer processes can be quantified in terms of appropriate rate equations. The rate equation which is used to heat conduction is known as the Fourier's law. The Fourier's law states that the heat conduction through a homogeneous solid is directly proportional to the area of the section at right angles to the direction of flow and to the temperature difference along the path of the heat flow. The rate equation is hence expressed as

$$\frac{dQ}{dt} \propto A \cdot \frac{dT}{dx} \quad (2.1)$$

considering heat transfer in the x direction per unit area and unit time,

$$q \propto \frac{dT}{dx} \quad (2.2)$$

where q is the heat flux (W/m^2). Under steady state conditions, the temperature distribution is linear and the temperature gradient can be hence expressed as

$$\frac{dT}{dx} = \frac{(T_2 - T_1)}{L} \quad (2.3)$$

finally, we have,

$$q = -k \cdot \frac{(T_2 - T_1)}{L} \quad (2.4)$$

where k is a proportionality constant and is termed as thermal conductivity ($W / m^2 K$).

The minus sign indicates that heat is transferred in the direction of decreasing temperature (Incropera and DeWitt 2002).

2.1.2 Convection Heat tTransfer

Convection involves the transfer of heat by the motion and mixing of macroscopic portions of the fluid, that is the flow of a liquid over a solid surface. Convection heat transfer may be classified according to the nature of the flow. The term natural convection is used if the motion and mixing is caused due to density variations resulting from the temperature differences within the fluid. For example, the heat transfer from a metal rod cooling in a vessel filled with water is natural convection. When the motion and mixing is caused due to an external force, such as a pump or fan, it is termed as forced convection. The transfer of heat from the surface of a heat exchanger to the bulk of a fluid being pumped through the heat exchanger is an example of forced convection. Regardless of the particular nature of the convection heat transfer process, the appropriate rate equation is given by the Newton's law of cooling. Newton's law of cooling states that the rate of change of temperature of an object is proportional to the difference between the temperature of the object and its surroundings.

$$\frac{dT}{dt} \propto c.(T_1 - T_e) \quad (2.5)$$

We also know that heat change is proportional to the change in temperature. Therefore,

$$dq \propto dT \quad (2.6)$$

So this finally results in

$$\frac{dq}{dt} = h.(T_1 - T_e) \quad (2.7)$$

where h is the heat transfer coefficient ($W/m^2 K$). Considering heat change per unit time,

$$q = h.(T_1 - T_e) \quad (2.8)$$

where q is the convective heat flux (W/m^2).

2.1.3 Radiation Heat Transfer

Thermal radiation is defined as the energy emitted by matter that is at a finite temperature. This energy can be emitted either from solids or liquids or gases. While the transfer of energy by conduction or convection takes place in the presence of a material medium, the transfer of energy by radiation does not require any such medium. Radiation transfer occurs most efficiently in vacuum. The rate equation for heat transfer by radiation can be formed using the Stefan-Boltzmann law. The law states that the energy radiated by a black body radiator per unit area and unit time is proportional to the fourth power of its absolute temperature.

Therefore,

$$q = \sigma.T^4 \quad (2.9)$$

where $\sigma = 5.67 \times 10^{-8} \text{ W / m}^2 \text{ K}^4$ is the Stefan-Boltzmann constant. For hot objects, other than ideal radiators, the emissivity term comes into picture. Therefore,

$$q = \sigma \cdot \varepsilon \cdot T^4 \quad (2.10)$$

ε is the emissivity and it is defined as the ratio of energy radiated by a surface to the energy radiated by a black body at the same temperature. For an ideal radiator, $\varepsilon=1$. If the hot object, in this case the steel wire rod, is emitting energy to its cooler surroundings, the radiation heat loss rate takes the form,

$$q = \sigma \cdot \varepsilon \cdot (T_1^4 - T_e^4) \quad (2.11)$$

where T_e is the temperature of the surrounding.

2.1.4 Film Boiling

Film boiling occurs when a layer of liquid is in contact with a surface, and the surface temperature is higher than the saturation temperature of the liquid. During this condition, the layer of liquid closest to the surface turns into vapor due to the temperature difference between the liquid and the surface. Due to the mass exchange occurring at the vapor liquid interface, bubbles of vapor periodically form and migrate upwards. Film boiling plays a very vital role in the present study. When the steel wire rod passes through the water boxes, a thin film of water tends to get carried along with the moving rod. This has a major effect on the nature of heat transfer that takes place at the surface of the rod. North Star Steel makes use of stripper valves in order to strip off the water film from the surface of the steel wire rod when it exits the water boxes. These stripper valves are located at the beginning and ending of each water box. North Star Steel employs three stripper valves for each water box.

2.2 Layout of the Rod Mill

The water cooling zone is situated at the finishing end of the rod mill. An example of the finishing end of the rod mill is depicted in figure 2-2. North Star Steel has two lines of the water cooling zones. This section of the rod mill consists of the finishing mill, water boxes, laying head and the Stelmor conveyor deck. A brief description of the components is presented in this section.

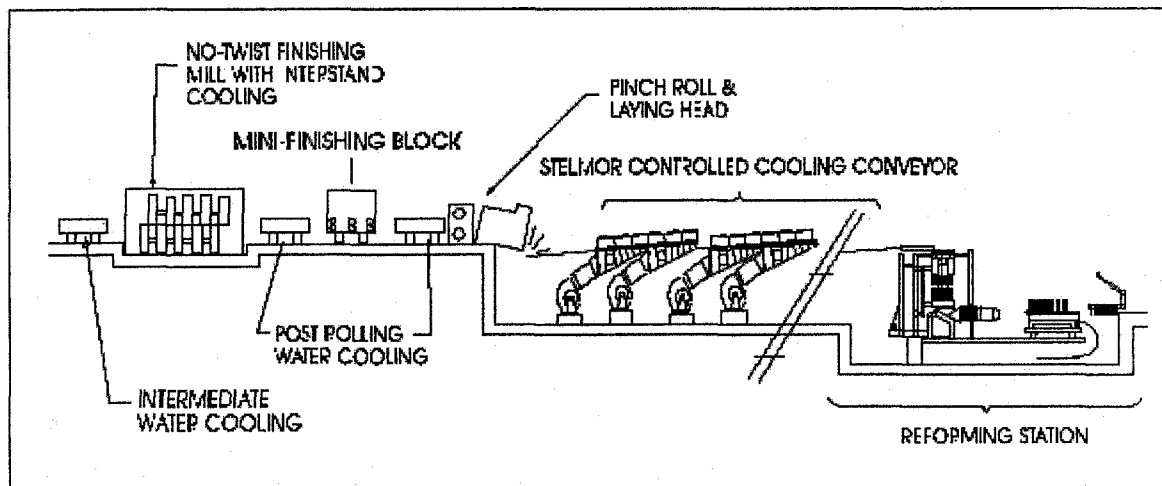


Figure 2-2: Finishing End of Rod Mill

Source: Morgan Construction Company



Figure 2-3: Water Cooling Zone Layout

Source: North Star Steel Texas

2.2.1 Finishing Mill

The main purpose of the roughing mill is to gradually reduce the size of the billet to a wire rod of the final customer specifications. The rod enters the finishing mill for its final reduction after it passes through the roughing mills. The power capacity of the mill is usually about 16000 horsepower and it can take up to seven passes in order to reduce the hot billet down to a wire rod of the required specifications.

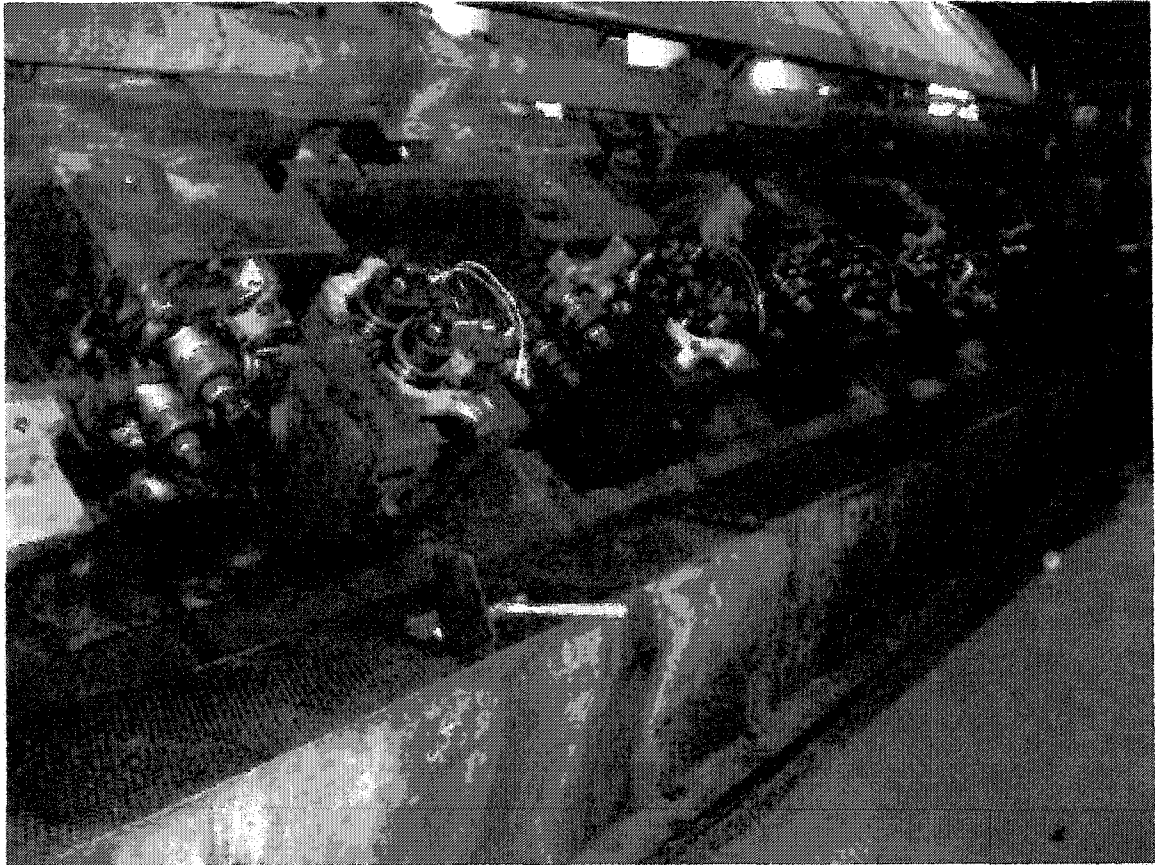


Figure 2-4: View of the Finishing Mill

Source: North Star Steel

2.2.2 Water Boxes

The water boxes are the cooling units located after the finishing mill. The rod mill at North Star Steel has three water boxes in all but employs only two of them for the water cooling process. Each water box is 7.04 m long and consists of nine nozzles through which water is sprayed on the wire rod that passes through them.



Figure 2-5: View of the Water Box

Source: North Star Steel

2.2.3 Nozzles

The nozzles are the medium through which cooling water is sprayed on the rod surface to initiate cooling. Cooling water is actually brought in contact with the rod by means of a flooded pipe through which the rod passes. This flooded pipe is referred to as nozzle.

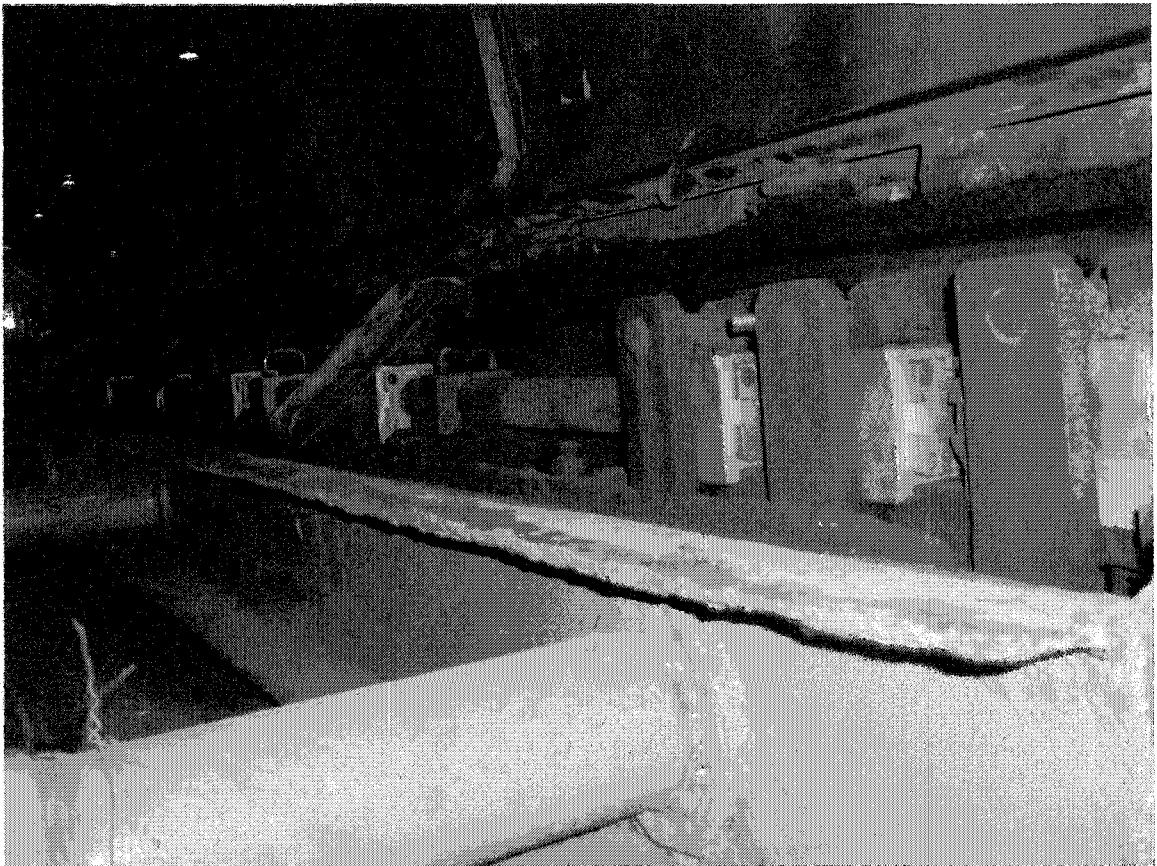


Figure 2-6: View of the Nozzles

Source: North Star Steel

2.2.4 Stripper Valves

Stripper valves are actually nozzles through which water is supplied at high pressure against the direction in which the rod travels. These stripper valves, usually located at the end of each water box, serve the purpose of stripping the cooling water from the surface of the rod before the rod leaves the water box. North Star Steel employs three stripper valves in each water box.

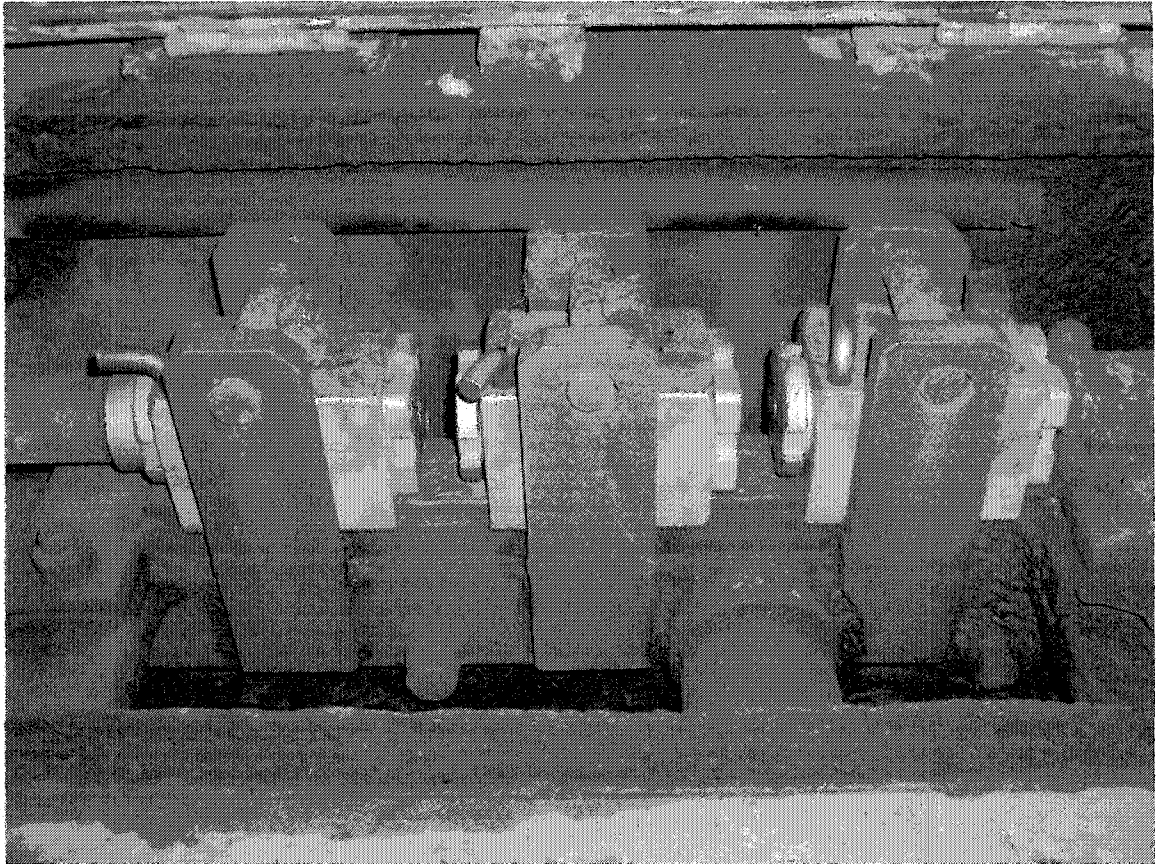


Figure 2-7: View of the Stripper Valves

Source: North Star Steel

2.2.5 Laying Head

The laying head consists of a spinning structure containing a spiral shaped path for discharging the rod. Each revolution of the laying head produces one ring of the wire rod and places it on the Stelmor cooling deck. The size of the ring that the laying head produces is determined by the length of the rod passing through the laying head during the time required for one revolution (Morgan Construction Company 2003).

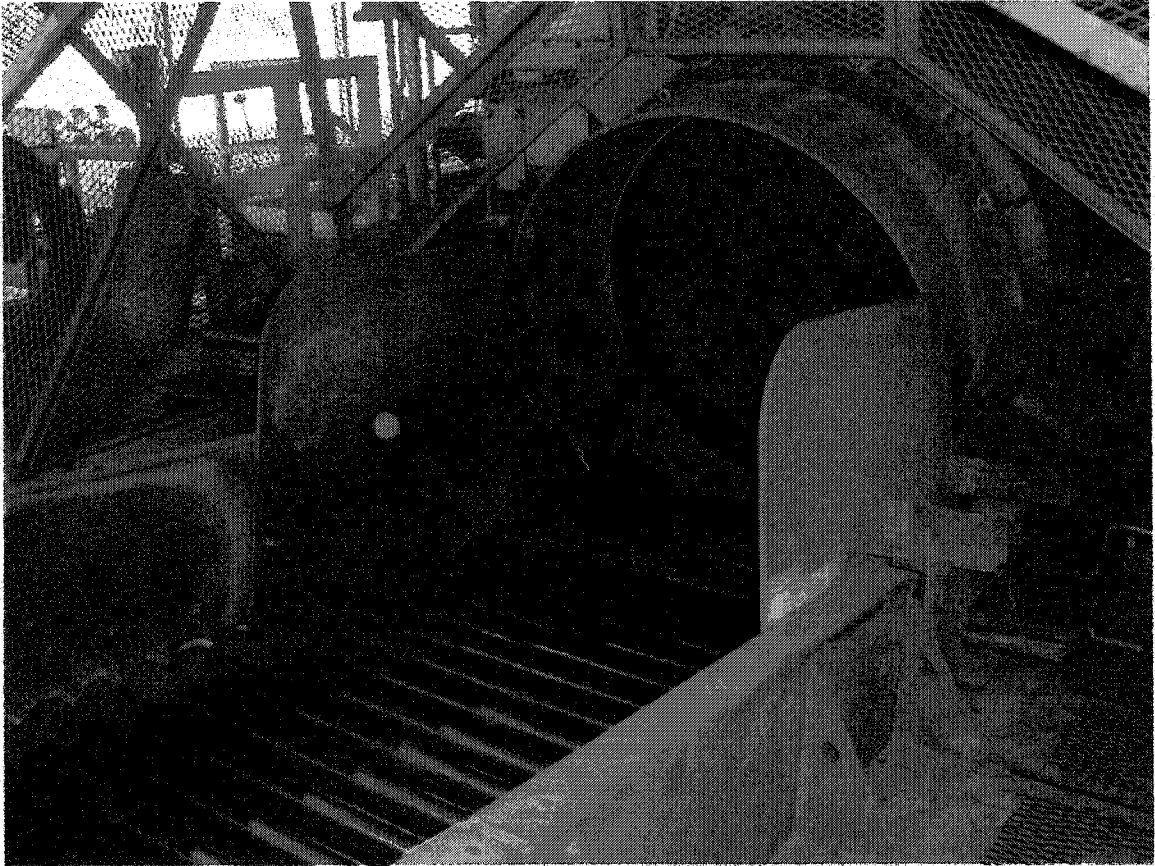


Figure 2-8: View of the Laying Head

Source: North Star Steel

2.3 Cooling Sequences

The sequence of cooling can be divided into three different categories namely initial quench, delayed quench and equalized quench (Morgan Construction Company 2001).

During initial quench the wire rod is cooled by the water box immediately after exiting the finishing mill. This removes the thermal energy needed for grain coarsening and limits the scale formation. Hence this form of cooling is used when a refined rod structure.

During delayed quench, the time between the exit of the last finishing mill and quenching is maximized. The energy of deformation along with the increased rod temperature is made use in this process to coarsen the rod structure. The high temperatures at this stage of the process promote the formation of scales and therefore this form of cooling is appropriate when large grain size is desired. This form of cooling is used in the case of low carbon steels in order to decrease tensile strength.

The last form of cooling is called equalized quench. This process maximizes the time required for equalization of temperature between the water boxes and hence minimizes the surface to centre temperature differential. This approach of cooling is implemented for hardenable grades.

2.4 Work Done By Previous Researchers

The numerical model presented in the next chapter has been used by various researchers and scientists to predict the surface temperature of the wire rod at the laying head at many different rod mills. A brief report on the work of two researchers is presented in this section.

2.4.1 Work of R.D. Morales, A.G. Lopez and I.M. Olivares

Heat Transfer Analysis during Water Spray Cooling of Steel Rods was carried out by the above mentioned researchers at Puebla Steelworks in Mexico. The main objective of this work was to study the influence of operation parameters such as rod size, rod speed, rod temperature at the finishing mill, water flow rate and spray cooling sequence on the final temperature distribution within the rod before it enters the Stelmor conveyor. A

mathematical model was developed to predict the rod cooling behavior of steel wire rods under the action of water sprays in the precooling system.

This work indicated that the spray cooling sequence affects the temperature distribution inside the rod considerably. It was also found that failure of the water flow in the spray cooling system drastically alters its cooling efficiency. The model was tested using the different correlations for convective heat transfer coefficient indicated in Table. The equations for calculating the water flux density have not been discussed. It was also predicted that as the rod leaves the first water box, there is a surface reheating of upto 200 C before the rod enters the second water box. The variation of temperature with time for a rod of radius 0.006 m predicted by this model is presented below.

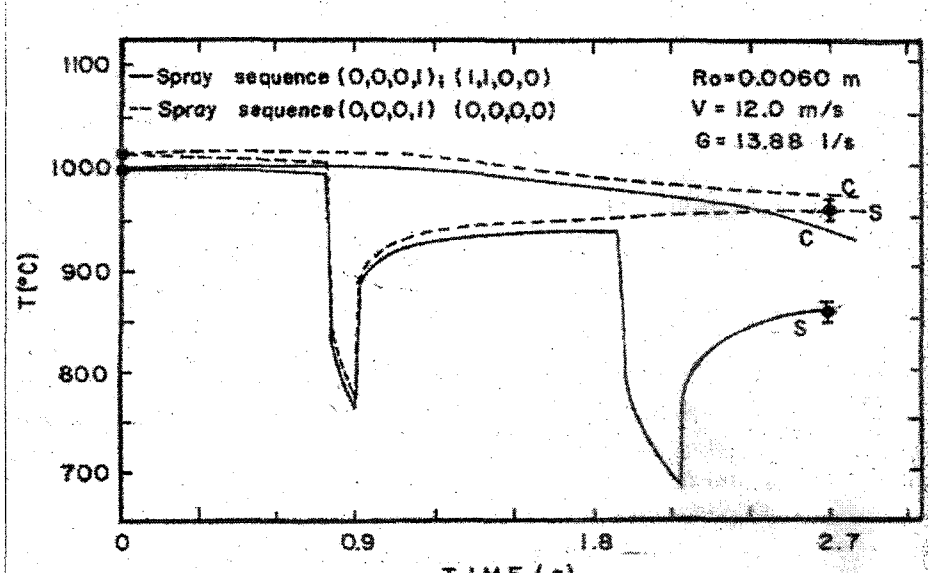


Figure 2-9: Temperature Variations Predicted at HYLSA, Mexico

Source: Heat Transfer Analysis During Water Spray Cooling of Steel Rods, R.D.Morales, A.G.Lopez and I.M.Olivares

The important conclusions drawn by this study are as follows.

1. Reheating phenomena may go up to 200°C at the rod surface. The magnitude of these reheatings are dependent on the cooling conditions and the rod radius.
2. The cooling efficiency of the rapid cooling system is strongly dependent on the water flow rate supplied to the cooling sprays. The heat transfer coefficient at the spray cooling zone follows a simple linear relationship with water flux.
3. The spray cooling sequence directly affects the temperature gradient across the rod diameter at the laying head.

2.4.2 Work of Alexandra Kulas

The work of Alexandra Kulas is on Design and Analysis of Steam Patenting. In this research, a brief technical report on the water cooling zone at North Star Steel has been presented. The numerical model given by Morales et al has been used to simulate the results for the process at North Star Steel. The graph of temperature prediction obtained by North Star Steel has been superimposed on the available graph given by Morales et al. The value of the water flux density for the curve that most closely matches with that of North Star Steel has been employed in the calculations. Again, there are no details available for the calculations of water flux density. The temperature prediction at North Star Steel, which is presented in the report, is described below.

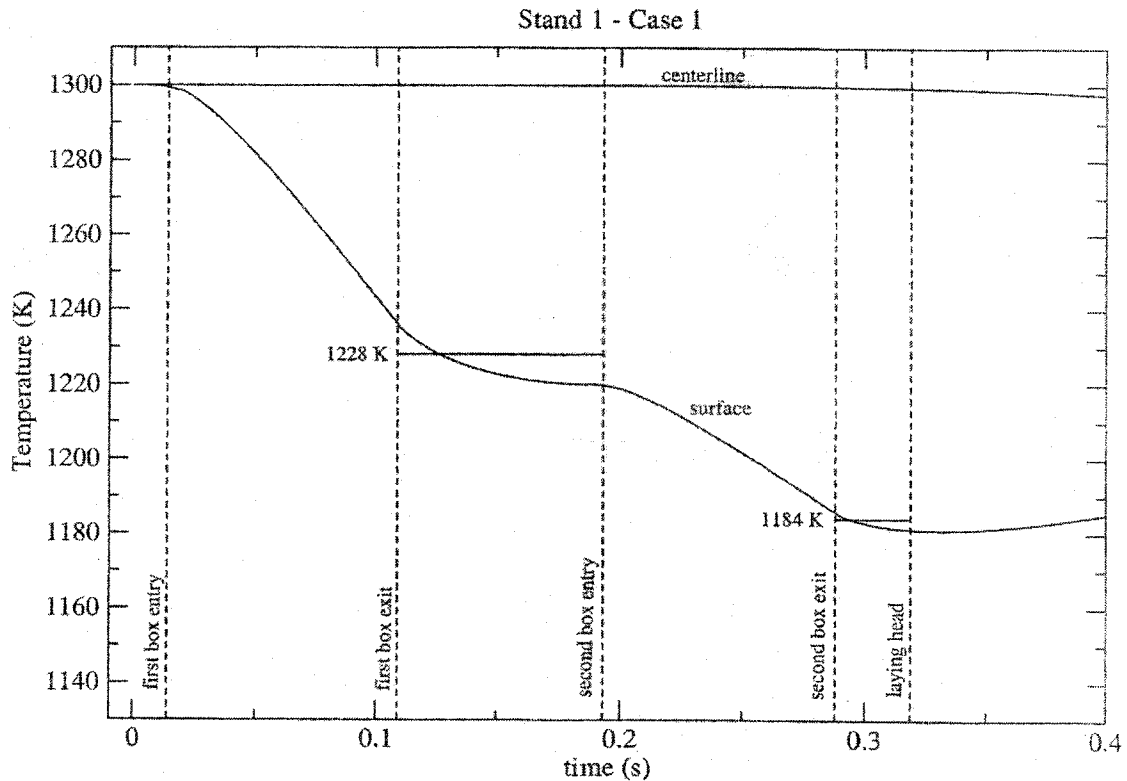


Figure 2-10: Temperature Variations Predicted at North Star Steel

Source: Design and Analysis of Steam Patenting, Alexandra Kulas

2.5 Problem Statement

The basic scope of the project is to develop and present the analysis of a heat transfer model for the cooling of steel rod passing through the water boxes of a rod mill production system. The key input variables are to be identified and their measurement and quantified contributions to the controlled cooling of wire rod should be noted.

Extensive survey is to be done on the literature for the formulas and assumptions needed to estimate the heat content of the rod at given surface temperatures and times for various sizes of rod.

2.6 Objectives

The main objectives of the research are:

1. To study the heat transfer principles involved in the process
2. To identify the Key Input Variables that control the laying head temperature
3. To present and analyze the model for estimating surface-center temperature differential of the rod at the laying head

2.7 Organization of the Thesis

This thesis totally consists of five sections: introduction, literature survey, methodology, results and discussion, and finally conclusions. The chapter on introduction discusses the subject in brief, the problem statement and the objectives of the research. A brief overview of the different heat transfer principles and the work done by previous scientists and researchers on this topic are discussed in the literature survey. The various Key Input Variables that control the temperature of the rod at the laying head are listed under methodology. The method of constructing the numerical model is also discussed in this section. The results drawn by this numerical model are analyzed in the chapter on results and discussion.

Chapter 3

Modeling

3.1 Assumptions

The following assumptions are made during the numerical modeling:

1. The nozzle parameters are same in both the water boxes.
2. Heat is dissipated only across the diameter of the wire rod.
3. Heat flow in the axial direction is neglected as the length of the wire rod is much greater than the radius.
4. The stripper valves completely remove all the water from the surface of the wire rod when it exits the water boxes hence eliminating heat transfer due to film boiling.
5. Since there is no means to measure the temperature at the inlet of the first water box, this temperature is assumed to be the same for all rod sizes.
6. The heat flux from the rod surface is constant about the circumference of the rod at any given time.

3.2 Modeling Procedure

Rapid cooling systems usually consist of two cooling water boxes that gradually reduce the surface temperature of the wire rod. The cooling line at North Star Steel consists of three water boxes among which only two water boxes are used for the controlled water cooling process. Each of the water boxes consist of nine internal nozzles placed at equal distances. It is essential that the temperature distribution along the cross

section of the rod is uniform at the laying head and hence extreme care should be taken to control the input variables. In this regard a numerical model that predicts the rod surface temperature at the laying head needs to be presented. A schematic view of the entire layout is shown in figure 3-2. A solution for calculating the temperature distribution in the rod as a function of time and its radial position can be found by solving the unsteady heat conduction equation in a cylindrical coordinate system with cylindrical symmetry. This equation is given by (Morales et al. 1989)

$$\frac{\partial}{\partial r} \left(k \cdot \frac{\partial T}{\partial r} \right) + \frac{k}{r} \left(\frac{\partial T}{\partial r} \right) = \rho \cdot C_p \cdot \frac{\partial T}{\partial t} \quad (3.1)$$

where ρ is the density of the carbon steel and C_p is its specific heat. The thermophysical properties C_p and k depend on the temperature and can be straight line adjusted as shown in figure 3-1. The equations to calculate these values are shown in Table 1. In this study, a constant value of thermal conductivity will be assumed due to high finishing speeds and sudden temperature drops in the water boxes.

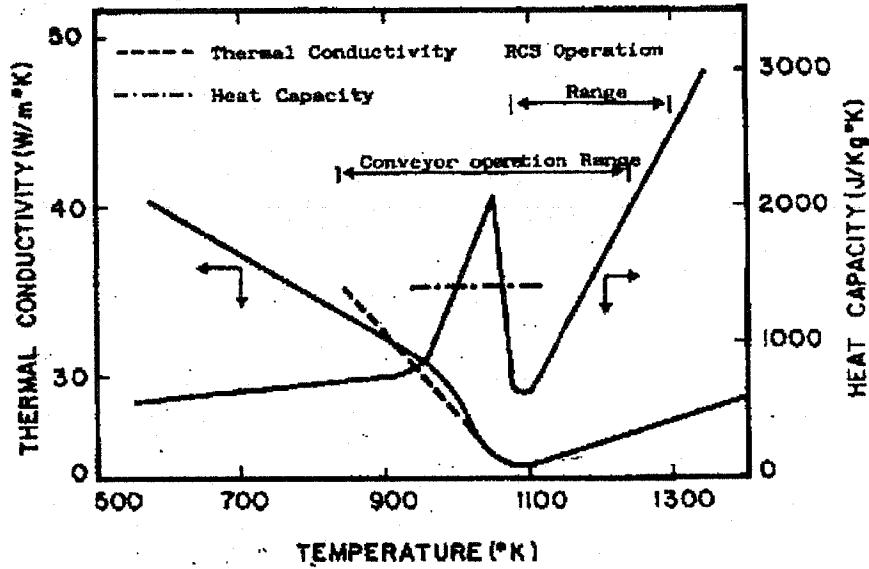


Figure 3-1: Thermophysical Properties as Functions of Temperature for Eutectoid Steels

Source: Heat Transfer Analysis During Water Spray Cooling of Steel Rods, R.D.Morales

Table 1: Thermophysical Properties of Steel

Property	Unit	Correlation	Observation
Heat capacity	J / KgK	$C_p = 493.71 + 2.3T$	$1075^\circ K \leq T \leq 1350^\circ K$
		$C_p = 1400$	$950^\circ K \leq T \leq 1075^\circ K$
		$C_p = 281.4 + 0.5066T$	$550^\circ K \leq T \leq 950^\circ K$
Thermal conductivity	W / mK	$k = 75.42 - 0.047T$	$830^\circ K \leq T \leq 1075^\circ K$
		$k = 9.83 + 0.013T$	$1075^\circ K \leq T \leq 1350^\circ K$
Density	Kg / m^3	$\rho = 7850$	Constant

Source: Heat Transfer Analysis During Water Spray Cooling of Steel Rods, R.D.Morales

3.3 Boundary Conditions

Equation 3.1 can be solved using the following boundary conditions (Morales et al. 1989)

1. At $r = r$ and $t = 0$, $T = T_s$
2. At $r = 0$ and $t = t$, $\frac{dT}{dr} = 0$
3. At $r = r$ and $t = t^*$, $T = f(r, t^*)$

The solution of equation 1 gives the temperature profile in a transverse slice of steel rod that travels through the rapid cooling system from the last roll of the finishing mill to the laying head. The first boundary condition is based on the assumption that the temperature in the cross section of the rod leaving the last roll of the finishing mill is uniform. The second boundary condition establishes the temperature profile symmetry. The third boundary condition can be considered as an initial condition at an instantaneous time t^* corresponding to the starting of every cooling zone.

3.4 Solution

The numerical model is created by considering the entire rapid cooling system to be divided into five different zones as shown in figure. Equation 3.1 is solved at each zone by considering the initial and boundary conditions at the respective zones.

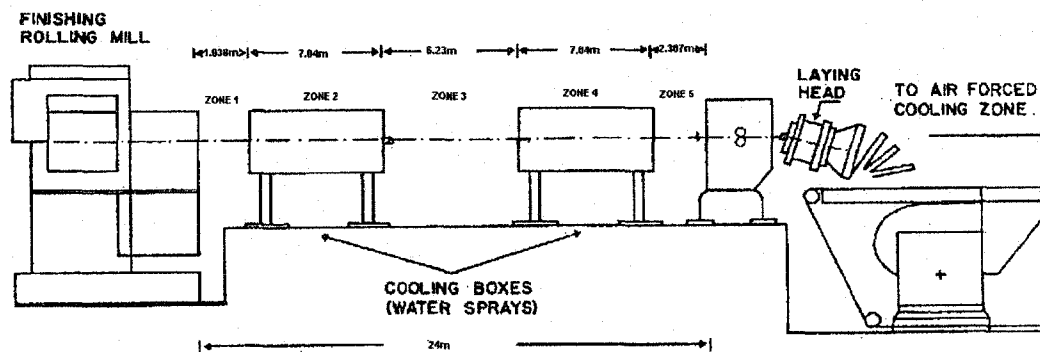


Figure 3-2: Layout of Rapid Cooling Zone

Source: Heat Transfer Analysis During Water Spray Cooling of Steel Rods, R.D.Morales

Zone 1 is the region between the last roll of the finishing mill and the entry to the first water box. This is the zone where the wire rod exits the finishing mill after undergoing its final reduction. Cooling water is circulated around the rod at the exit of the finishing mill and due to the absence of stripper valves in this zone, the wire rod tends to carry a film of water on its surface when it enters the first water box. Due to the presence of the water film on the surface of the wire rod, it is difficult to measure the temperature in this zone. Hence a constant temperature of $1338.7^{\circ} K$ is assumed to be the inlet temperature for the first water box. This zone is 1.038 m long.

As seen from the figure, the first water box is considered as zone 2. The length of this zone is 7.04 m. This is the zone where the cooling takes place and the surface temperature is expected to drop appreciably. The rod passes through nine nozzles which spray water on the surface of the rod at a controlled water flow rate. The heat transfer in

this zone is a combination of forced convection due to the presence of water sprays and radiation from the water vapor film formed at the rod surface. Hence we have,

$$q = [h_w \cdot (T_s - T_w) + \sigma \cdot \epsilon \cdot (T_s^4 - T_w^4)] \cdot A \quad (3.2)$$

where A is the surface area of the rod and is given by $2\pi \cdot r \cdot L$, L being the length of the water box. h_w is the heat transfer coefficient due to convection. This value primarily depends on the water flux density, $W \text{ l / m}^2 \text{ s}$ in a linear manner. Various correlations have been presented for calculating the value of the convective heat transfer coefficient, given the values of water flux and the surface temperature. Among these correlations, it was found that the most suitable correlation for controlled water cooling is (Morales et al. 1989)

$$h = 0.1W \quad (3.3)$$

Since there is no sufficient data available to calculate the value of the water flux density, in this report, temperature data from the mill has been used to predict the best value of W . This value can be further related to the water flow rate in the water boxes, which will be discussed later.

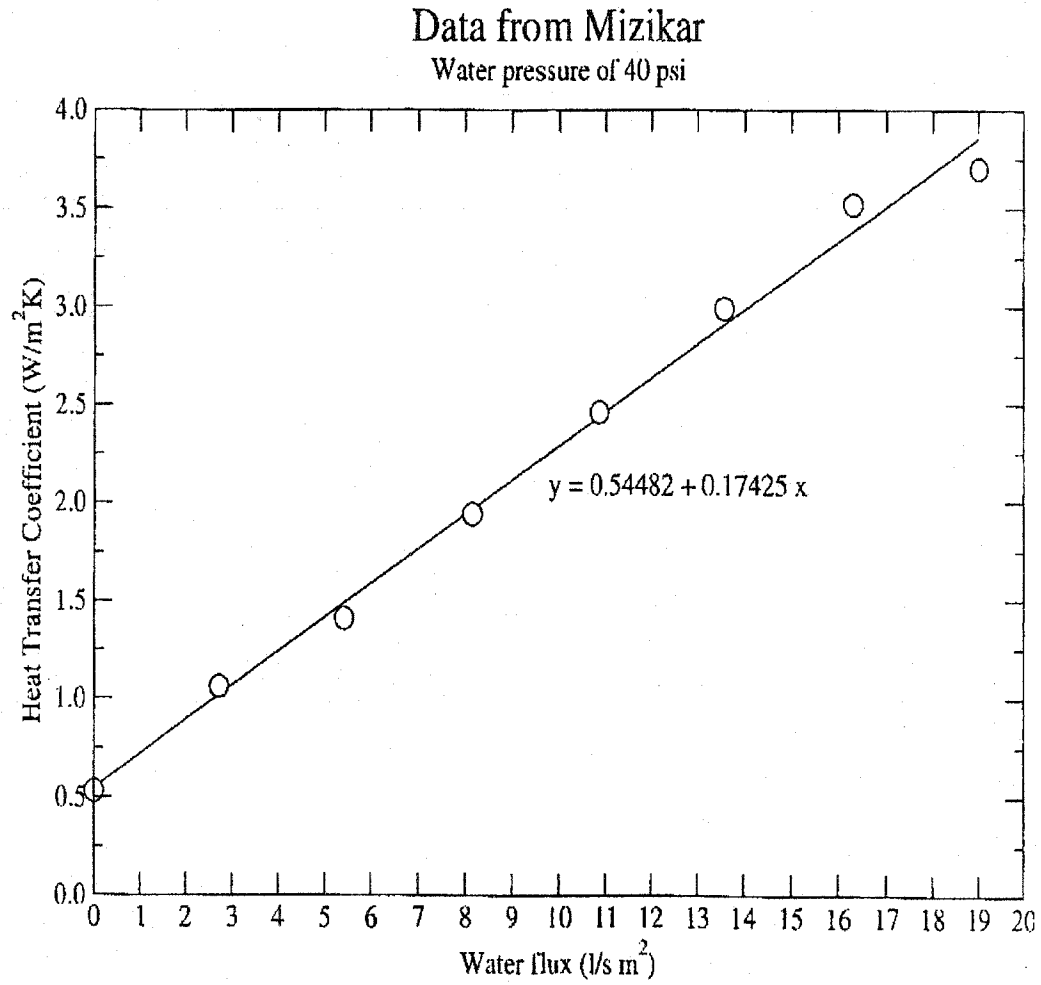


Figure 3-3: Relationship Between Heat Transfer Coefficient and Water Flux as Presented by Mizikar

Source: Design and Analysis of Steam Patenting, Alexandra Kulas

The heat transfer mechanism in the second water box, that is zone 4, is similar to that of zone 2.

Table 2: Heat Transfer Coefficient for Spray Cooling Systems

Correlation	Observation
$h = 2.6612 \times 10^5 W^{0.616} / T_s^{2.445}$	W in $l / m^2 \text{ min}$, T_s in C
$h = 708W^{0.75} / T_s^{-1.2} + 0.116$	W in $l / m^2 s$, T_s in C
$h = 0.581W^{0.451} (1 - 0.0075T_w)$	W in $l / m^2 s$, T_w in C
$h = 1.57W^{0.55} (1 - 0.0075T_w)(1 / \alpha)$	W in $l / m^2 s$, T_w in C, $\alpha = 4$
$h = 0.423W^{0.556}$	W in $l / m^2 s$
$h = 1.57W^{0.55} (1 - 0.0075T_w)$	W in $l / m^2 s$, T_w in C
$h = 0.360W^{0.556}$	W in $l / m^2 s$
$h = 0.0776W$	W in $l / m^2 s$
$h = 0.1W$	W in $l / m^2 s$
$h = 1.1611 \times 10^{-3} \text{antilog}(0.663 \log W - 0.00147T_s)$	W in $l / m^2 \text{ min}$, T_s in C
$h = 1.611 \times 10^{-3} \text{antilog}(2.030 + 0.793 \log W - 0.00154T_s)$	W in $l / m^2 \text{ min}$, T_s in C

Source: Heat Transfer Analysis During Water Spray Cooling of Steel Rods, R.D.Morales

Zone 2 sets a temperature gradient across the cross section of the wire rod. Hence the main function of zone 3, the area between the two water boxes, is to equilibrate the center and surface temperature of the rod through a free radiation to the surroundings. This zone is also called the Temperature Equalization Zone and is 6.23 m long. Due to the high rod delivering speed, a layer of water vapor film tends to be dragged along the rod in its

traveling direction. Hence the heat transfer mechanism in this zone is similar to that of a hot steel rod plunged into a pool water as in the quenching process. Consequently the heat transfer mechanism is considered to be a combination of both convection and radiation. The concept of film boiling is considered to describe the heat transfer equations in this zone. However, North Star Steel employs stripper valves at the end of the water box preceding each of the Temperature Equalization Zones so as to remove the water film on the surface of the rod. Also, as the length of this zone is small and due to the high rod delivering speed, it is assumed that no appreciable heat transfer takes place in this zone. Moreover, the pyrometers installed at the exit of the first water box and at the entry of the second water box indicate that there is a temperature increase of only about 10 degrees at the rod surface. Hence most of the cooling is expected to take place in zones 2 and 4.

Zone 5 is also a Temperature Equalization Zone and serves the same purpose as zone 3. This zone is 2.307 m long.

The numerical model is based on the fact that the total heat transfer at the surface of the rod must balance the heat conducted from the center of the rod to its surface (Morales et al. 1989). Within the water boxes in zones 2 and 4, where most of the cooling is expected to take place, the heat transfer mechanism is due to forced convection and radiation, as stated earlier. This should be equal to the heat conducted from the rod center to its surface. As explained in chapter 2, the heat conduction equation is given by,

$$q = k \cdot \frac{dT}{dr} \cdot A_e \quad (3.4)$$

A_e is the effective area and is equal to $2 \cdot \pi \cdot \frac{r}{2} \cdot L = \pi \cdot r \cdot L$

Hence we have,

$$k \cdot \frac{(T_c - T_s)}{r} = 2 \cdot h_w \cdot (T_s - T_w) + \sigma \cdot \epsilon \cdot (T_s^4 - T_w^4) \quad (3.5)$$

This equation can be further simplified in order to predict the temperature differential at each zone as,

$$k \cdot \frac{(T_c - T_s)}{r} = 2 \cdot h_e \cdot (T_s - T_e) \quad (3.6)$$

where h_e is a lumped heat transfer coefficient and T_e is the environmental temperature. The values of h_e and T_e keep changing at each zone. In the water boxes, that is zone 2 and 4, the environment is water and hence $T_e = T_w$, the temperature of water. The value of h_e in this zone is a combination of both convective heat transfer coefficient and radiative heat transfer coefficient. Whereas, in zones 3 and 5, the wire rod passes through free air. Hence $T_e = T_a$, the temperature of air. The value of h_e in this zone is equal to the radiative heat transfer coefficient.

$$h_e = h_w + h_r \quad (3.7)$$

Where h_r is the radiative heat transfer coefficient. Therefore,

$$h_e = h_w + \sigma \cdot \epsilon \cdot \frac{T_s^4 - T_w^4}{T_s - T_w} \quad (3.8)$$

Solving this equation will give us the temperature differential at that particular zone.

From observations, it is seen that the center temperature of the rod drops by an amount of

about 50° C in the whole process. This data can be used to obtain the temperature at the rod surface after each zone.

There is no sufficient data available for the calculation of water flux density. Hence the value that best suits the conditions at North Star Steel needs to be determined. The temperature of the rod surface at the entry and exit of the first water box were obtained from the mill and these values were plugged into the equation. The equation was then solved for the value of convective heat transfer coefficient. The value of water flux density is then obtained from the relation $h = 0.1W$. This value is used for predicting the rod surface temperature at the exit of the second water box, considering that the nozzle conditions in both the water boxes are the same.

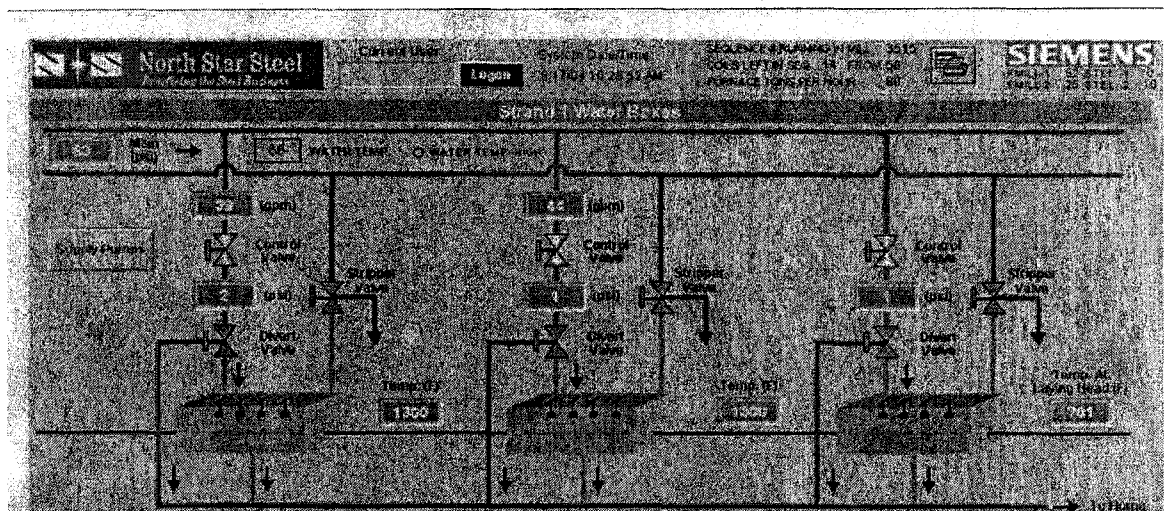


Figure 3-4: Computer Monitoring of the System at North Star Steel

Source: North Star Steel

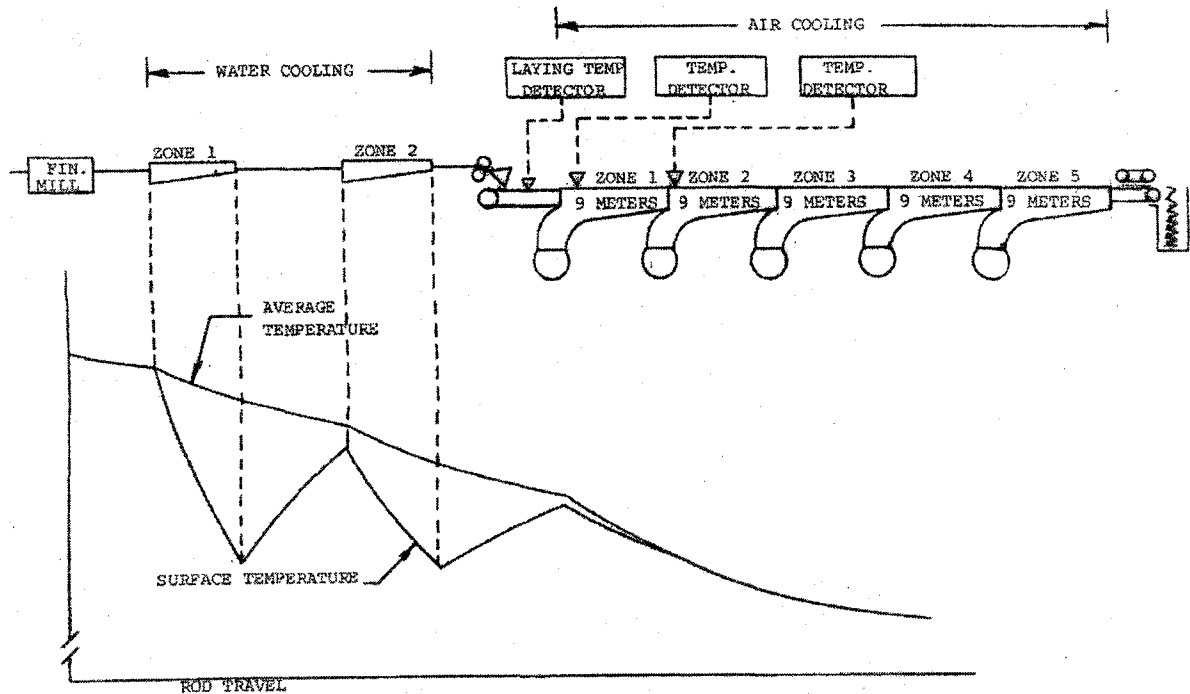


Figure 3-5: Temperature Variations Predicted by Morgan Construction Company

Source: Morgan Construction Company

3.5 Calculations

The equation for calculating the heat content at the laying head is based on the concept that the heat transfer at the surface of the rod is equal to the heat conducted from the center of the rod to its surface. As discussed earlier, inside the water boxes, the heat transfer at the surface of the rod is the summation of both convection and radiation.

Based on this concept, we have,

$$k \frac{dT}{dr} = 2 \cdot [h_w \cdot (T_s - T_w) + \sigma \cdot \epsilon \cdot (T_s^4 - T_w^4)] \quad (3.9)$$

Where, k is the thermal conductivity of the rod

$dT = (T_c - T_s)$ is the temperature difference between surface and center

T_s is the surface temperature = $1300^\circ K$

$dr = r$ is the radius of the rod = 0.00275 m

h is the convective heat transfer coefficient

T_w is the water temperature = $300^\circ K$

σ is the Stefan-Boltzmann constant = $5.67 \times 10^{-8} W / m^2 K^4$

ε is the emissivity of the rod = 0.8

We have the thermal conductivity of the rod as $k = 9.84 + 0.013T$ for

$$1075 \leq T \leq 1350^\circ K$$

For $1300^\circ K$, we obtain the value of thermal conductivity as $k = 27 W / mK$.

From literature, it is seen that the center temperature changes by just about 50° from the finishing mill to the laying head. From the data received from North Star Steel, the temperature at the exit of the first water box is $1200^\circ K$. Therefore $dT = (T_c - T_s)$ can be taken as 100° . Substituting these values in the equation, we have,

$$h = 361.72 W / m^2 K$$

h is the heat transfer coefficient due to convection. Inside the water boxes, this value primarily depends on the water spray flux. Theoretically this value is computed using data about the nozzle parameters but there is no proper explanation available for the calculations for the same. But it has been proved that h is proportional to the water flow rate. Hence a clear relation between the temperature and the water flow rate can be established.

$$W \propto F \quad (3.10)$$

where F is the water flow rate in l/s . From this relation we obtain

$$W = C.F \quad (3.11)$$

where C is a constant.

For the present data, the value of water flow rate in the first water box was $13 l/s$.

Therefore we obtain the value of C as

$$C = \frac{3617.2}{13} = 278.2$$

In the zone between the water boxes, the heat transfer is plainly due to radiation.

Therefore we have,

$$k \frac{dT}{dr} = \sigma \cdot \varepsilon \cdot (T_s^4 - T_a^4) \quad (3.12)$$

Where T_a is the ambient air temperature and is equal to $300 K$. It is to be noted that the surface temperature tends to increase slightly due to the reheating factor. Solving this equation for this zone it is observed that there is 19° increase in the surface temperature.

In the second water box, the water flow rate employed for the given conditions is $7 l/s$.

This gives us the value of heat transfer coefficient as

$$h = 0.1W = 0.1 \times C \times F = 194.74 W / m^2 K$$

Substituting this value in the equation, we obtain the temperature at the exit of the second water box as $1162^\circ K$

Again using the radiation equation, we obtain the surface temperature at the laying head as $1170^\circ K$. The laying head temperature obtained from the mill for the same input values is $1150^\circ K$. Now considering a drop of 50° at the rod center, it is seen that the

temperature difference between the surface and the center of the rod at the laying head is approximately 80° .

Considering same water flow rates in both the water boxes, a temperature gradient of 104° at the laying head is obtained. This can be correlated with the results presented in an earlier study (Kulas 2003). Hence it can be assumed that the previous work considered same water flow rates in both the water boxes. The present report considers more realistic conditions, wherein, the water flow rates in the water boxes are different, as employed by NSST.

Different values of water flow rates are employed for different grades of steel, initial temperatures, water temperatures and wire rod diameter. For further calculations, it will be assumed that the water flow rates in both the water boxes are the same.

Chapter 4

Results and Discussion

For a wire rod of diameter 0.0055 m, the temperature differential between the surface and the center of the rod at the laying head, for the cooling conditions at North Star Steel is found to be approximately 80° . This temperature gradient can be controlled by controlling the parameters in the cooling process. The important parameters, termed as Key Input Variables, and their effect on the temperature gradient at the laying head are discussed below.

4.1 Key Input Variables

The Key Input Variables are those parameters that affect the temperature gradient between the surface and the center of the wire rod at the laying head. These input variables have such an impact on the temperature difference that varying these values can alter the laying head temperature to a great extent. Hence, understanding the influence of these variables on the laying head temperature helps in attaining a better hold over the entire process. The numerical model presented in the previous chapter clearly shows the affect of most of the Key Input Variables such as the initial temperature of the rod, radius of the rod, temperature of water, etc on the temperature differential at the laying head. The affect of these Key Input Variables on the laying head temperature are discussed in detail in this section.

4.1.1 Initial Temperature

The surface temperature of the wire rod just before the entry to the first water box is taken as the initial temperature. It is assumed that there is no change in the surface temperature of the wire rod between the last roll of the finishing mill and the first water box. As discussed earlier, due to the water carried on the rod surface from the finishing mill in this zone, there is no means to measure the exact surface temperature here. North Star Steel assumes a surface temperature of $1300^{\circ} K$ when a wire rod of diameter 0.00275 m is being rolled. It is clearly seen from the numerical model that the initial surface temperature of the rod plays a key role on the laying head temperature. The relationship between the initial surface temperature and the temperature gradient at the laying head can be analyzed by plotting a graph between the two variables. The variation of the temperature gradient at the laying head with the initial surface temperature of $1100^{\circ} K$, $1150^{\circ} K$, $1200^{\circ} K$, $1250^{\circ} K$, $1300^{\circ} K$ and $1350^{\circ} K$ are presented in the graph. The other variables like the speed of the rod, water flow rate, etc are considered to be the same for all these temperatures. The values of the other variables considered for this analysis are as follows

Water Temperature = $300^{\circ} K$

Air Temperature = $300^{\circ} K$

Mill Speed = 70 m / s

Table 3: Calculations for Different Values of Initial Temperature

Initial Temperature (°K)	Water Box 1		Water Box 2		Temperature Gradient at Laying Head
	Entry (°K)	Exit (°K)	Entry (°K)	Exit (°K)	
1100	1100	1028	1038	973	77
1150	1150	1071	1083	1013	78
1200	1200	1115	1129	1053	86
1250	1250	1158	1174	1092	95
1300	1300	1200	1219	1131	104
1350	1350	1242	1264	1170	113

The above table shows the temperature of the rod at each stage and finally the temperature gradient at the laying head, for a given initial surface temperature of the wire rod. Using this data, a graph between the initial surface temperature and the temperature gradient at the laying head is plotted.

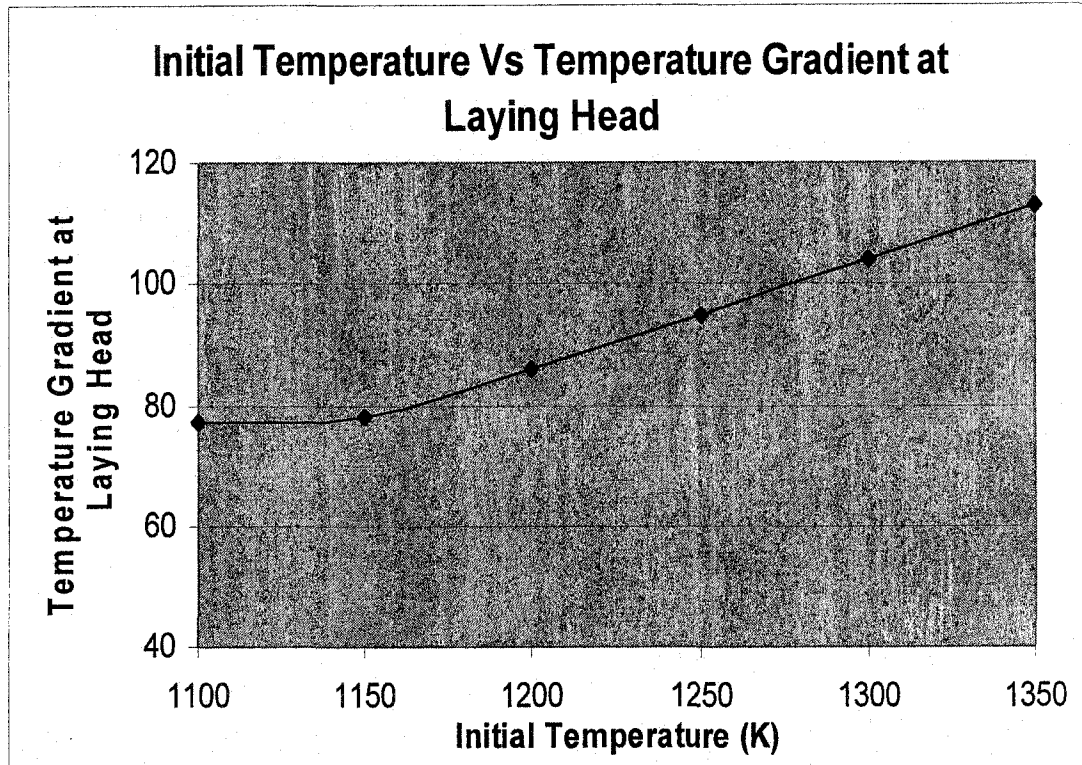


Figure 4-1: Plot of Initial Temperature Vs Temperature Gradient at the Laying Head

It is clear from the above graph that the temperature gradient at the laying head increases as the initial surface temperature of the rod increases. It is hence necessary to maintain an appropriate temperature at the entry to the first water box in order to achieve a pre estimated laying head temperature.

4.1.2 Water and Air Temperature

The temperature of water and ambient air is a very important factor that has to be considered for achieving the desired laying head temperature since most of the cooling takes place inside the water boxes. For studying the affect of cooling water temperature

on the laying head temperature, the numerical model is analyzed for different water temperatures.

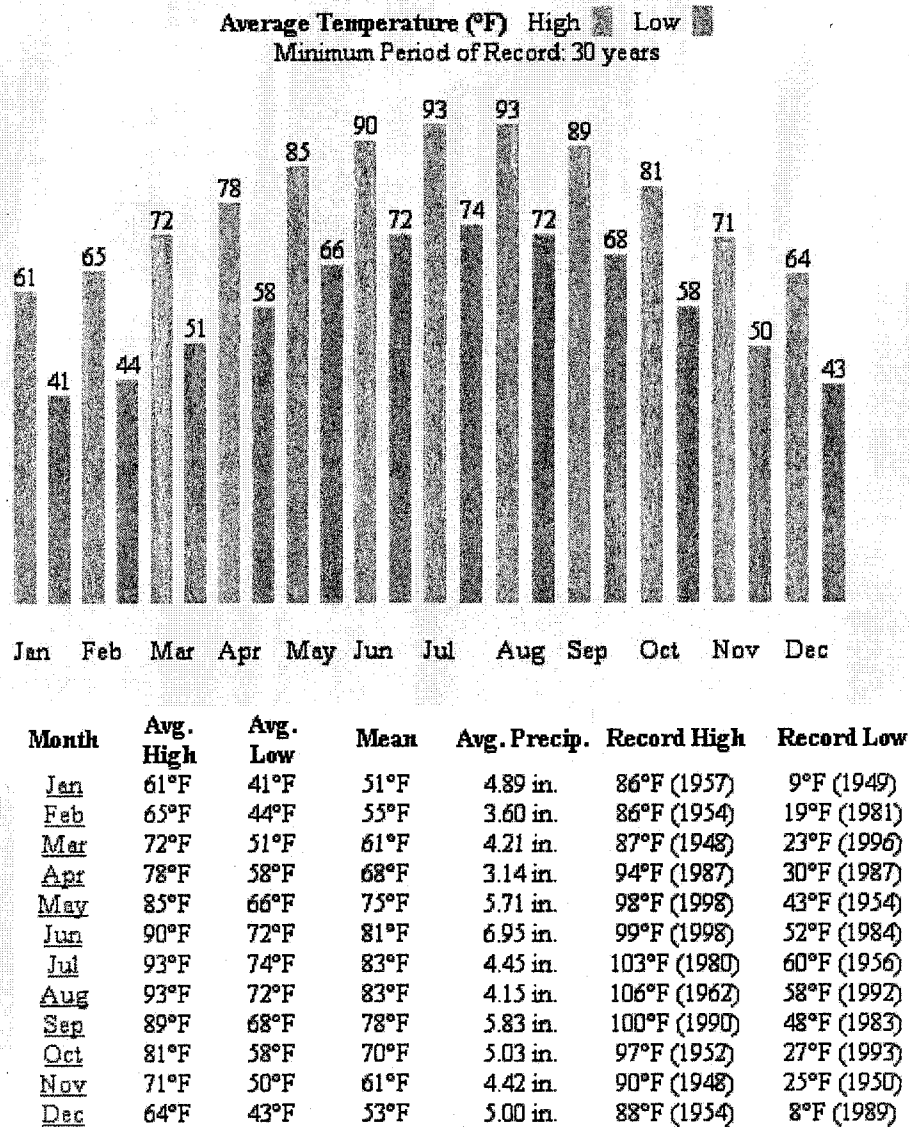


Figure 4-2: Temperature Data for Beaumont

Source: Holy Cross Monastery, Beaumont, Texas

The above figure shows the mean temperature during each month in Beaumont for a period of 30 years. It can be observed from the data above that the highest temperature recorded during a period of 30 years is $106^{\circ} F$ in August 1962 and the lowest temperature recorded is $8^{\circ} F$ in December 1989. It is assumed that the temperature of water on any given day is equal to the temperature of air. The variation of the temperature of the wire rod at each stage with water temperature is calculated and shown in the table below.

Initial Temperature of the Rod = $1300^{\circ} K$

Mill Speed = 70 m/s

Table 4: Calculations for Different Values of Water Temperature

Water Temperature ($^{\circ} K$)	Water Box 1		Water Box 2		Temperature Gradient at Laying Head
	Entry ($^{\circ} K$)	Exit ($^{\circ} K$)	Entry ($^{\circ} K$)	Exit ($^{\circ} K$)	
260	1300	1197	1215	1125	110
270	1300	1198	1217	1127	109
280	1300	1199	1217	1128	107
290	1300	1199	1218	1129	106
300	1300	1200	1219	1131	104
310	1300	1201	1221	1134	102
320	1300	1202	1222	1136	100

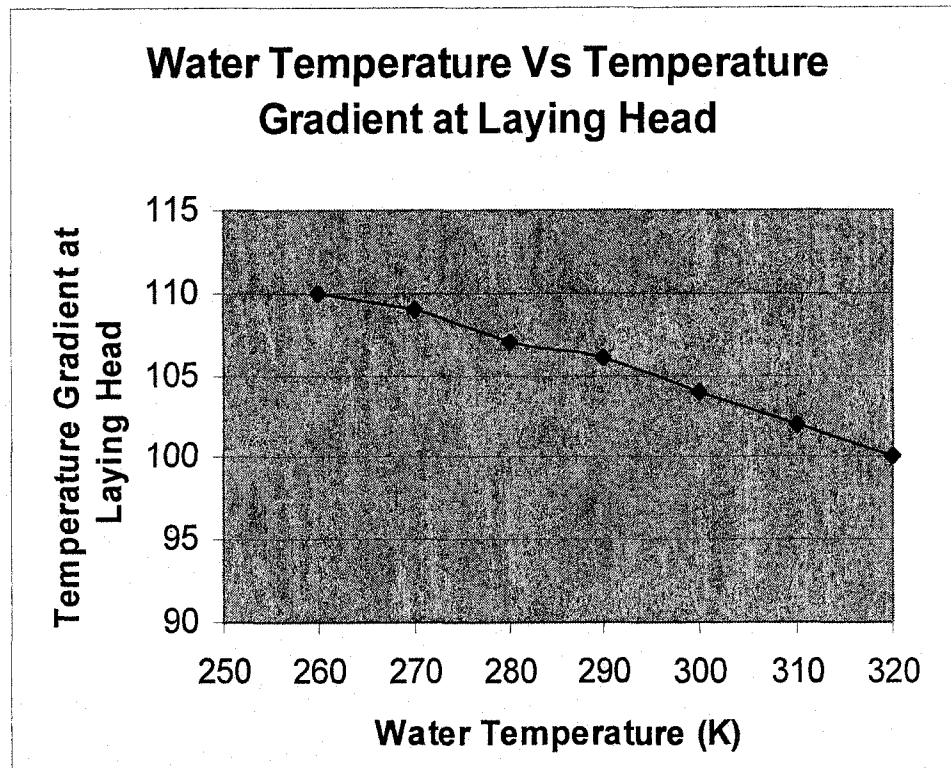


Figure 4-3: Plot of Water Temperature Vs Temperature Gradient at Laying Head

It is observed from the above graph that the temperature gradient at the laying head decreases as the temperature of water increases. Hence it can be expected that on a hot day, with the same working conditions as on any other day, the temperature gradient between the surface and the center of the wire rod at the laying head is comparatively less.

Using the data, the variation of temperature gradient at the laying head can be studied by plotting a graph between the temperature gradient and the water temperature at that particular month. It is assumed that the working conditions are the same for every month.

Table 5: Average Variation of Temperature Gradient at Laying Head over the 30 Years

Month and Water Temperature ($^{\circ}K$)	Water Box 1		Water Box 2		Temperature Gradient at Laying Head
	Entry ($^{\circ}K$)	Exit ($^{\circ}K$)	Entry ($^{\circ}K$)	Exit ($^{\circ}K$)	
January (284)	1300	1199	1217	1128	108
February (286)	1300	1199	1217	1128	108
March (289)	1300	1199	1218	1129	106
April (293)	1300	1199	1218	1129	106
May (297)	1300	1199	1218	1129	105
June (300)	1300	1200	1219	1131	104
July (301)	1300	1200	1219	1131	104
August (301)	1300	1200	1219	1131	104
September (299)	1300	1200	1219	1131	104
October (294)	1300	1199	1218	1129	106
November (289)	1300	1199	1218	1129	106
December (285)	1300	1199	1217	1128	108

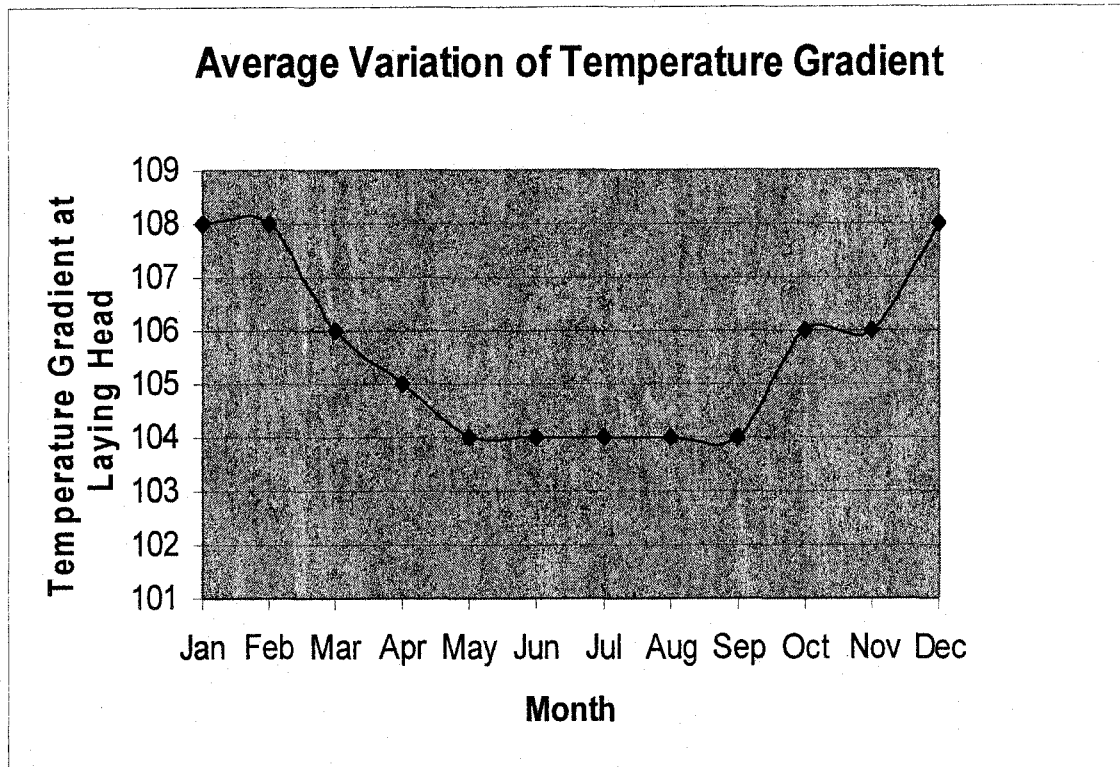


Figure 4-4: Variation of Temperature Gradient at the Laying Head

The above graph shows the variation of the temperature gradient at the laying head during each month of the year. The temperature recorded for each month is the mean temperature over a period of 30 years.

4.1.3 Rod Diameter

North Star Steel produces wire rod of diameters ranging from 5.5 mm to 17.46 mm. It can be observed from the numerical model that the radius of the wire rod is directly proportional to the temperature gradient. Hence it can be established that the size of the wire rod has an affect on the temperature gradient at the laying head. In order to study the

variation of the temperature gradient with the size of the wire rod, rods of different diameters are considered and their results are analyzed using the numerical model.

Temperature of water = $300^{\circ} K$

Temperature of air = $300^{\circ} K$

Initial surface temperature = $1300^{\circ} K$ (Assumed)

Mill Speed = $70 m/s$

Table 6: Calculations for Different Values of Initial Rod Diameter

Rod Diameter (<i>m</i>)	Water Box 1		Water Box 2		Temperature Gradient at Laying Head
	Entry ($^{\circ} K$)	Exit ($^{\circ} K$)	Entry ($^{\circ} K$)	Exit ($^{\circ} K$)	
0.0055	1300	1200	1219	1131	104
0.0071	1300	1170	1192	1083	151
0.0087	1300	1142	1167	1039	194
0.0103	1300	1113	1130	987	247
0.0119	1300	1084	1111	951	283
0.0134	1300	1056	1084	912	322

The analysis of the numerical model for different diameters shows that for a constant initial surface temperature of $1300^{\circ} K$ and the same working conditions as for a wire rod of diameter 0.0055 mm, the temperature gradient at the laying head varies a lot. Hence,

during cooling operations, different water flow rates are employed for rods of larger diameter so as to maintain a controlled rate of cooling. It should also be noted that the rolling parameters are different for different diameters. Hence, the initial temperature of the wire rod after the last roll of the finishing mill is also different for different diameters. In the calculations shown above, it is assumed that the initial temperature of the wire rod is same for all diameters.

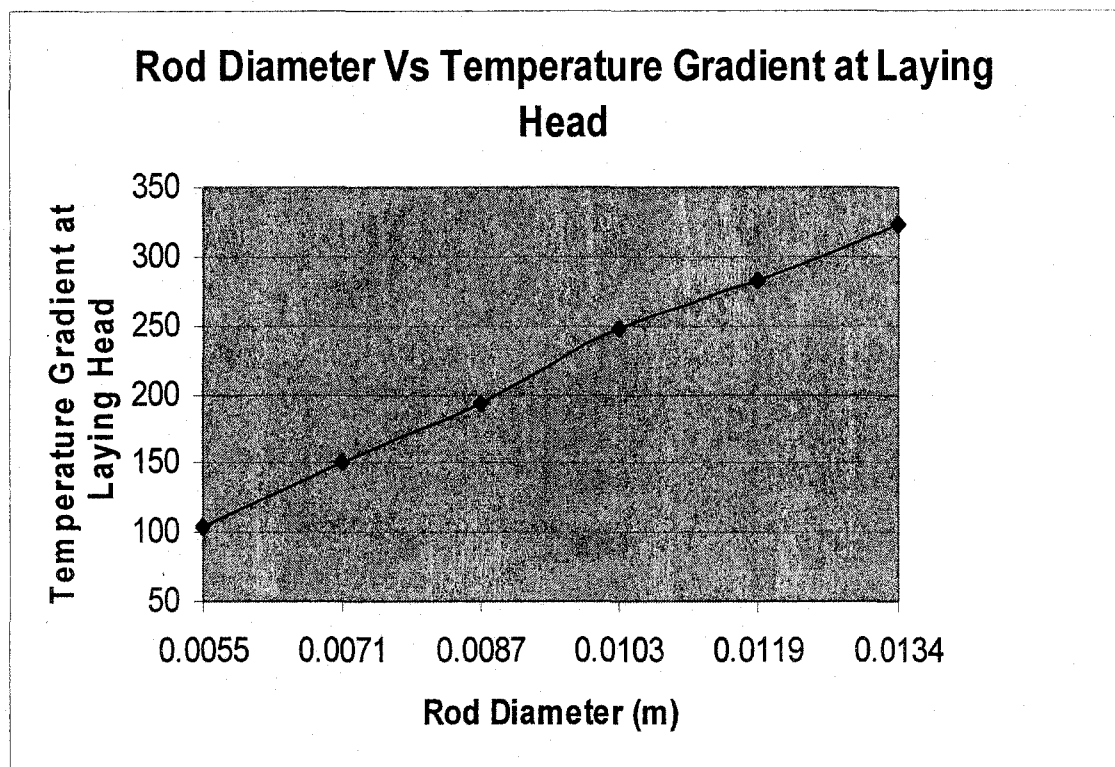


Figure 4-5: Variation of Temperature Gradient at Laying Head with Rod Diameter

4.1.4 Mill Speed

The speed with which the rod travels through the rapid cooling system plays a key role in controlling the process. Since speed is inversely proportional to time, if the speed with which the rod travels is more then the time of contact of the rod with the environment in that zone is less. To study the affect of the mill speed on the temperature gradient at the laying head, a simple equation can be used.

$$v = \frac{x}{t} \quad (4.1)$$

where v is the speed of the rod in m/s

x is the distance traveled in m

t is the time required to travel the distance in s

When the temperature readings were taken for the first water box, the mill speed was $70 m/s$. Considering the first water box, that is zone 2,

Length of the water box = $x = 7.04$ m

Mill speed = $v = 70 m/s$

Therefore the time of residence of the rod in this zone is 0.1 seconds. The amount of heat generated in this zone can be calculated by solving either the right hand side or the left hand side of the equation. We hence obtain the heat generated as $490905.28 W/m^2$.

The rate of heat transfer is therefore $4909052.8 W/m^2 s$.

It can therefore be established that the amount of heat generated and hence the temperature gradient at the laying head changes as the mill speed changes.

The mill speed varies from 65 m/s to 85 m/s . To study the effects of the mill speed on the final temperature gradient at the laying head, the equation is solved of each of the speeds.

Water Temperature = 300° K

Air Temperature = 300° K

Initial Surface Temperature = 1300° K

Table 7: Calculations for Different Values of Mill Speed

Mill Speed (m/s)	Water Box 1		Water Box 2		Temperature Gradient at Laying Head
	Entry (° K)	Exit (° K)	Entry (° K)	Exit (° K)	
65	1300	1192	1212	1118	116
70	1300	1200	1219	1131	104
75	1300	1206	1223	1140	94
80	1300	1212	1228	1149	87
85	1300	1217	1234	1160	76

The above table shows the values of the surface temperature of the wire rod at each zone for different mill speeds.

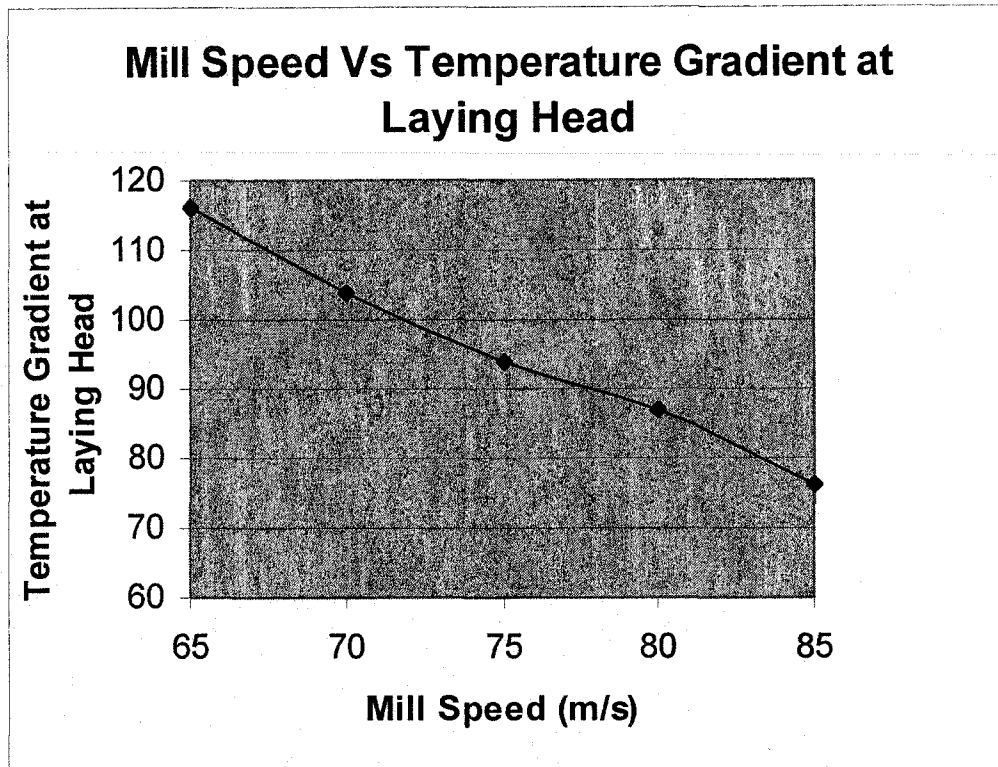


Figure 4-6: Variation of Temperature Gradient at Laying Head with Mill Speed

It is clear from the calculations and the graph above that the temperature gradient at the laying head falls as the mill speed increases. Inside the water boxes, when the mill speed is high, the time of contact of the wire rod with water is less and hence the temperature drop of the rod surface is comparatively less. This results in a lower temperature gradient between the center and the surface of the wire rod. In order to achieve sufficient cooling as well as minimal temperature gradient between the surface and center of the wire rod, the time required for reheating of the rod surface should be more.

4.1.5 Water Flow Rate

The amount of water sprayed on the rod surface inside the water boxes contributes to the major amount of cooling. As discussed earlier, inside the water boxes, the heat transfer coefficient is primarily due to the water flux density of the spray. A relationship can be established between the water flux density and water flow rate as follows.

$$W \propto F$$

where W is the water flux density in $l / m^2 s$

F is water flow rate in l / s

$$W = C.F$$

where C is a constant and has the units m^{-2} . The value of C primarily depends on the dimensions of nozzles. The water flow rate in the water boxes when the readings were taken was $13 l / s$

we therefore have the value of C as

$$C = \frac{W}{F} \quad (4.2)$$

which gives us $C = 278.2 m^{-2}$

Using this data, we can study the variation of the temperature gradient at the laying head with the water flow rate in the nozzles.

Initial Temperature = $1300^\circ K$

Water Temperature = $300^\circ K$

Mill Speed = $70 m/s$

Table 8: Calculations for Different Values of Water Flow Rate

Water Flow Rate (<i>l/s</i>)	Water Box 1		Water Box 2		Temperature Gradient at Laying Head
	Entry (°K)	Exit (°K)	Entry (°K)	Exit (°K)	
11	1300	1211	1231	1152	82
12	1300	1206	1226	1142	92
13	1300	1200	1219	1131	104
14	1300	1194	1213	1121	114
15	1300	1189	1208	1111	125

It is hence seen that as the water flow rate in the water boxes increases, the temperature gradient between the surface and center of the wire rod also increases. It should be noted that North Star Steel uses different values of flow rates in each box. The value of water flow rate depends on the initial temperature of the wire rod, the temperature of water, the grade of steel and the diameter of the wire. This report assumes that the water flow rate in both the boxes is equal.

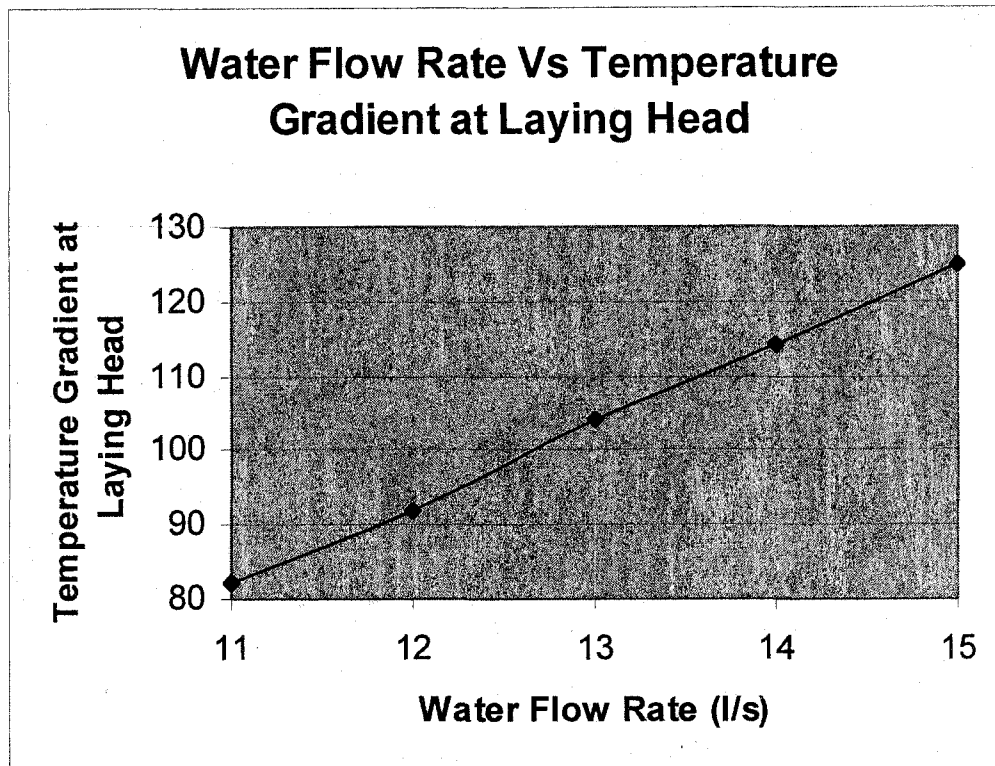


Figure 4-7: Variation of Temperature Gradient at Laying Head with Water Flow Rate

Hence it is observed that as the water flow rate increases for a given value of initial surface temperature, water temperature and mill speed, the temperature gradient at the laying head also increases.

4.2 Quantification of Key Input Variables for a Pre-Estimated Laying Head Temperature

North Star Steel aims at a laying head temperature of 1170 K for a 5.5 mm diameter rod. In order to obtain the pre-estimated laying head temperature, the key input variables need to be changed for different values of initial surface temperature. It is observed that the mill speed and the water flow rate are the two variables that affect the laying head temperature widely.

4.2.1 Quantification of Water Flow Rate

From the calculations presented in Table 7 and Table 8, it can be observed that the temperature drop in the first water box is 1.11 times that of the second water box. Using this relation, the temperature drop in each water box can be estimated. With the value of the temperature drop in each water box, the water flow rate that is required to cool the wire rod from the given initial temperature to a pre-estimated laying head temperature can be determined. The data presented in section 4.1.5 can be used to relate the values.

Water Temperature = 300 K

Mill Speed = 70 m/s

Table 9: Quantification of Water Flow Rate for a Given Laying Head Temperature

Water Flow Rate (l/s)	Water Box 1		Water Box 2		Temperature Gradient at Laying Head
	Entry (°K)	Exit (°K)	Entry (°K)	Exit (°K)	
6	1250	1195	1214	1163	30
10	1300	1217	1237	1164	80
13	1350	1242	1260	1165	130
16	1400	1264	1284	1168	180
19	1450	1285	1304	1168	230

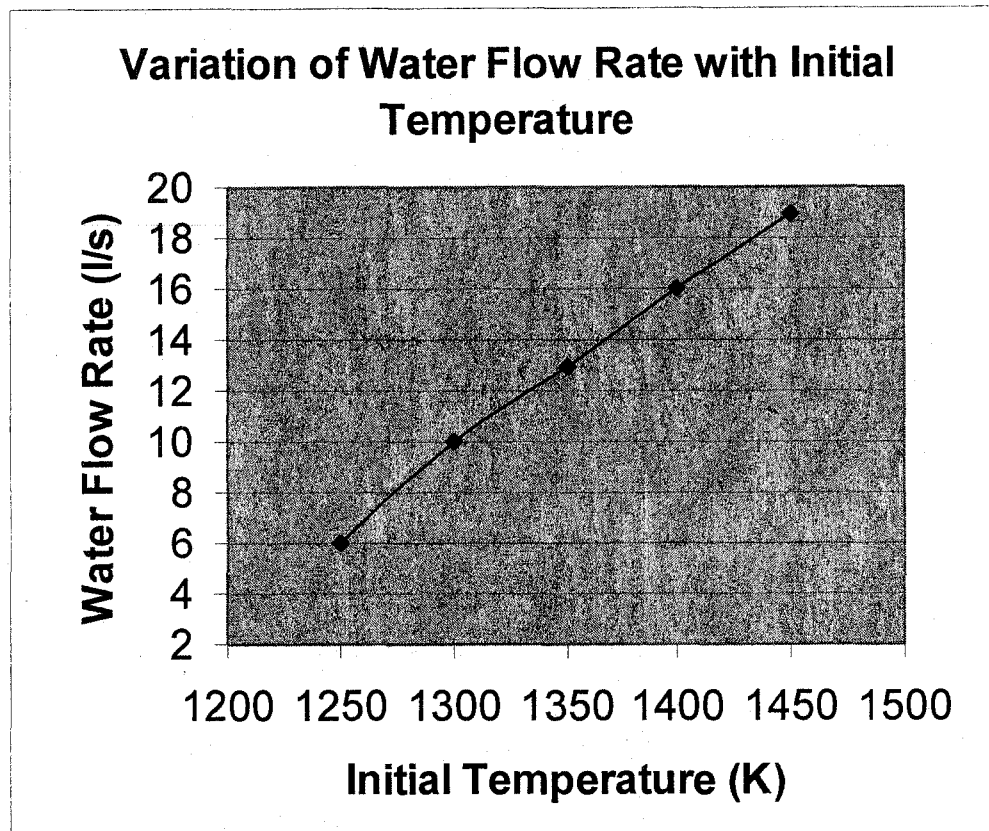


Figure 4-8: Variation of Water Flow Rate with Initial Temperature for Pre-Estimated Laying Head Temperature

4.2.2 Quantification of Mill Speed

For quantifying the mill speed to obtain a pre-estimated temperature at the laying head, the data presented in section 4.1.4 can be used. The values of temperature drop in each water box can be estimated and the heat generated during cooling the wire rod to the calculated temperatures can be obtained. This value can be related to the value obtained in section 4.1.4 and the corresponding mill speed can be estimated.

Water Temperature = 300 K

Water Flow Rate = 13 l/s

Table 10: Quantification of Mill Speed for a Given Laying Head Temperature

Mill Speed (<i>m/s</i>)	Water Box 1		Water Box 2		Temperature Gradient at Laying Head
	Entry (°K)	Exit (°K)	Entry (°K)	Exit (°K)	
140	1250	1199	1209	1163	30
95	1300	1223	1233	1163	80
70	1350	1246	1256	1163	130
55	1400	1260	1270	1163	180
47	1450	1294	1304	1163	230

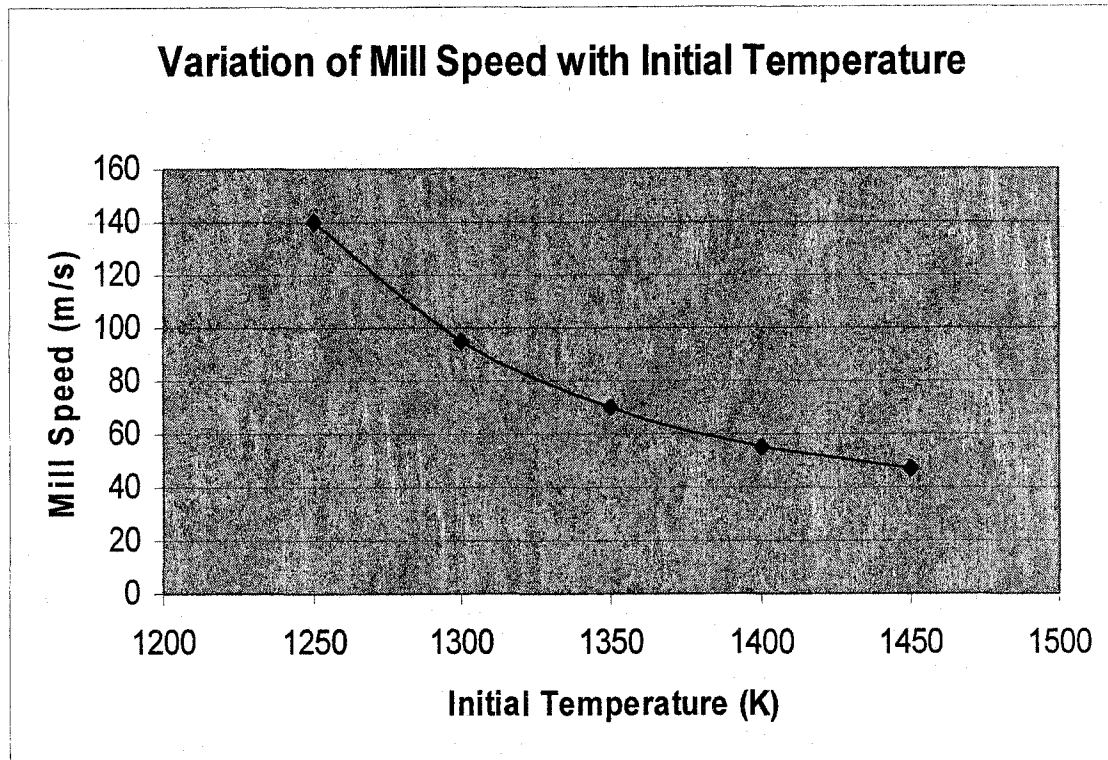


Figure 4-9: Variation of Mill Speed with Initial Temperature for Pre-Estimated Laying Head Temperature

4.3 Microstructure Predictions

The variation in the laying head temperature affects the austenite grain size and hence good control of laying head temperature results in a better microstructure of the wire rod. If the laying head temperature is high, then the microstructure of the wire rod reveals coarser austenitic grain size. And if the laying head temperature is low, the microstructure of the wire rod shows finer austenitic grain size.

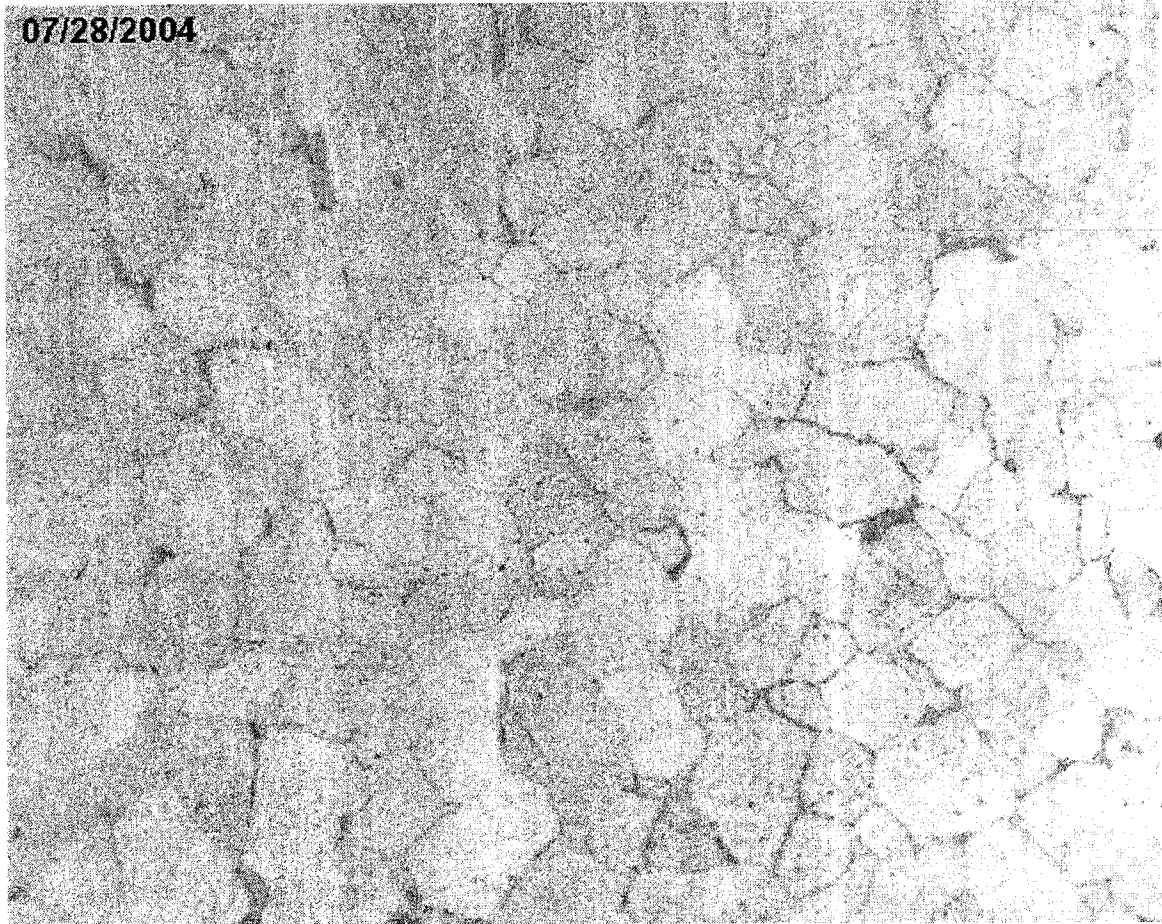


Figure 4-10: Microstructure of Rod at High Laying Head Temperature of 1650° *F*

Source: Effect of Boron on Tensile Gain of Low Carbon Steels, Vinaya Bushan

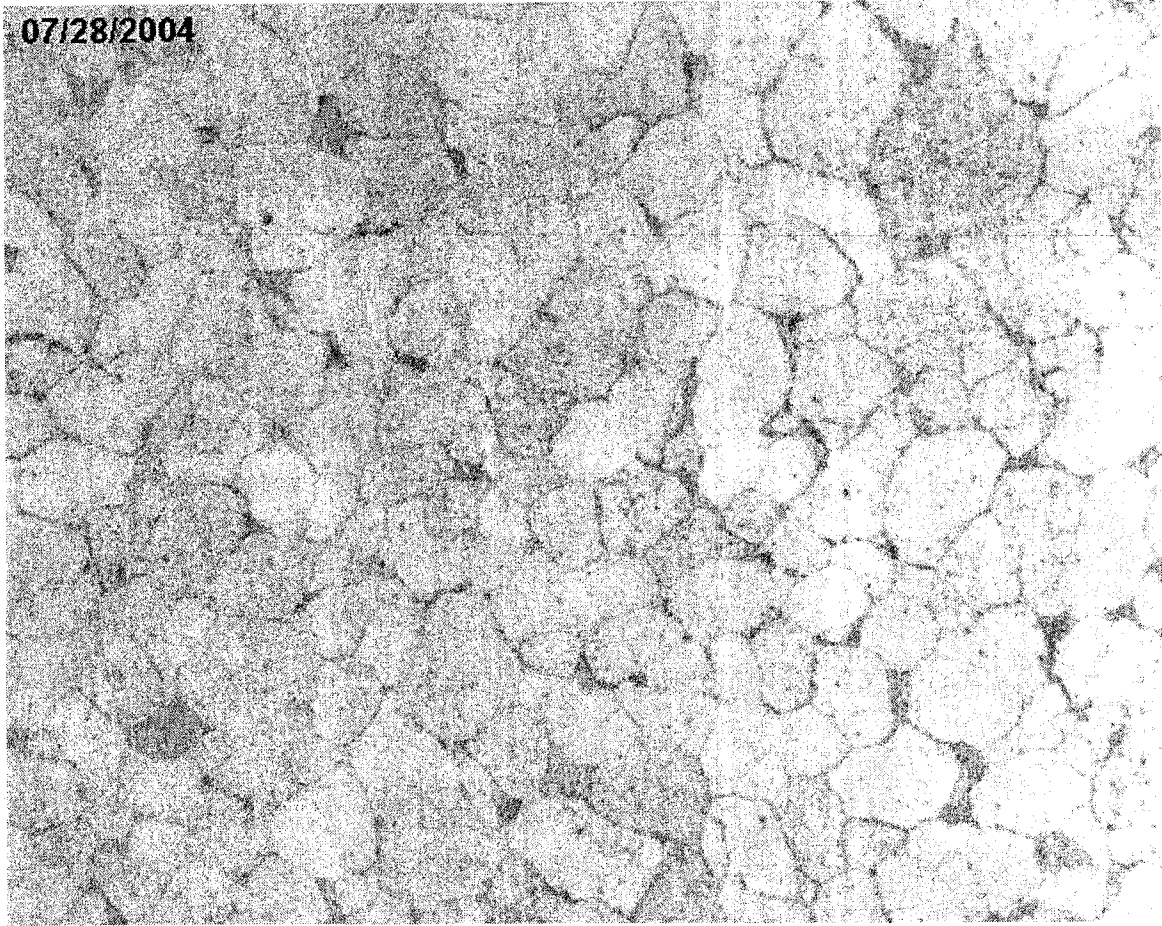


Figure 4-11: Microstructure of Rod at Low Laying Head Temperature of 1500° *F*

Source: Effect of Boron on Tensile Gain of Low Carbon Steels, Vinaya Bushan

Chapter 5

Conclusions and Recommendations

The numerical model presented in this report has been analyzed for different conditions and values of the input variables. In order to validate the results of this model, the results were compared with the data acquired from North Star Steel and were found to be in good agreement.

5.1 Conclusions

The major conclusions of the present study are as follows:

1. The temperature gradient at the laying head decreases as the initial surface temperature of the wire rod decreases. The temperature of the surface of the wire rod just before the entry to the first water box is considered as the initial temperature.
2. It is seen that as the water temperature decreases, the temperature gradient at the laying head also decreases. It can be hence inferred that the temperature gradient at the laying head is less during winters.
3. The values of key input variables are different for different sizes of wire rods. For a wire rod of larger diameter, the temperature gradient at the laying head is found to be higher if the same operating conditions as for a 5.5 mm diameter wire rod is employed.
4. The mill speed plays a very important role in the cooling process. If the wire rod travels through the rapid cooling zone at low speed, then the time of contact of the wire rod with water is higher. This results in more cooling of the rod surface. As a result, the temperature gradient at the laying head is higher.

5. Another variable which plays a very important role in the cooling process is the water flow rate inside the water boxes. The water flow rate and mill speed are the two variables that primarily control the laying head temperature and hence the temperature gradient at the laying head. It is seen that as the water flow rate through the nozzles increases, the cooling of the surface of the wire rod also increases, resulting in a lower laying head temperature.

5.2 Recommendations

The following are the recommendations for future work that can be carried out.

1. The exact value of the center temperature of the wire rod needs to be determined. Theoretically, it can be assumed that the center temperature of the wire rod drops by a very small amount during the entire cooling process. By using a thermocouple at the center of the wire rod, the exact value of the center temperature of the wire rod may be determined.
2. The value of water flux density has been calculated using the data from the mill due to insufficient literature available for the same. The exact method for calculating the water flux density needs to be found out.
3. This report considers that all the nozzles in the water boxes are turned on. The affect of the number of nozzles and their dimensions, on the cooling rate needs to be determined.
4. The stripper valves use high pressure water to strip off the water film from the surface of the wire rod. This sufficiently affects the cooling of the water surface. The report doesn't deal with the stripper valves separately. An experiment can be conducted by

switching on and switching off the stripper valves to determine the individual affect of the stripper valves on the cooling process.

5.3 Economic Benefits

It is understood that North Star Steel loses about 900 tons of wire rod every year due to poor response to tensile tests. This happens due to unfavorable microstructure of the wire rod at the laying head. The approximate cost of 1 ton of wire rod is US\$300. Hence, if this project helps in obtaining the desired microstructure at the laying head by controlling the key input variables, the approximate savings would be US\$127,000 per year.

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BIOGRAPHICAL NOTE

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