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Analysis of Existing Temperature-Time Profile of Jet Impingement Cooling System for Steel Production

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ABSTRACT:
Inaccurate deduction of cooling rate of materials, cumbersomeness of model analysis, lack of validation of models and lack of first principle assumptive explanation has given wrong analytical database to impingement jet cooling process using temperature-time profiles. This has affected also the properties of steel grade as published. A review of some of the temperature-time profiles in the literature and their shortcomings has been done- either one is lacking in its accuracy or too cumbersome and consumes a lot of time to analyze, or there is no validation to the model used. Lumped thermal mass analysis (LTMA) is prospective model for better cooling rate accuracy, easy to analyze, validated with Biot number and explained from first principle with a model geometry. The lumped thermal mass analysis of the form $h = \propto \rho w c p$, predicts the convective heat transfer coefficient h, and better rate of cooling for better steel grade properties.
KEYWORDS: *Lumped Thermal Mass Analysis, Temperature-Time Profile, Jet Impingement Cooling, Cooling Rate*

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I. INTRODUCTION

Temperature-Time profile of jet impingement cooling process is a known profile that defines the rate and pattern of cooling showing clearly the temperature gradient, a plot of temperature against time. With the plot the rate of heat dissipation of a particular heated material is known per second or minutes as the case may be. To determine temperature-time profile, a lot of models have been used in analyses-some so inaccurate and others too cumbersome. In all, temperature-time profile has a known plot pattern decreasing from highest temperature to the lowest temperature and increasing from zero time to highest time. Using temperature-time you obtain the amount of heat dissipated per unit time.

Temperature-time profile differ a little based on type of cooling, though pattern remains same – accelerated cooling, direct quenching and direct quenching plus automatic tempering. Jet impingement cooling is under accelerated cooling, fig.1a explains the profiles of temperature-time for various cooling pattern. For accelerated cooling, it shows the time of cooling and when martensitic steel begins to form.

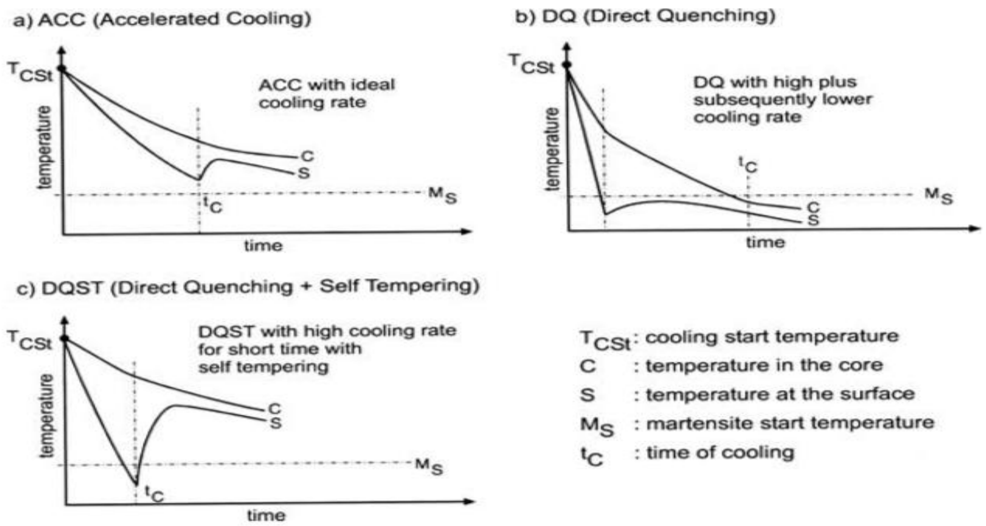

Fig. 1: Temperature-Time Profile of Variant Steel plate Accelerated Cooling (StreiBelberger et al, 2001)

Antonio et al, (2018), further describe the kind of steel formation obtained from temperature-time profile of the variant cooling processes. Showing that controlled cooling and management enhances steel properties. Accelerated cooling, where cooling starts between 800^{o}C and 500^{o}C under rate between 5 to 80^{o}C/s gives ferrite, to pearlite and a mixture of bainite, pearlite and ferrite. Direct quenching give between 5 to 60^{o}C/s as cooling starts from 900^{o}C and ends at 200^{o}C more rapid cooling than accelerated cooling. This give martensite and bainite structures of steel. Obviously, more can be obtained from steel if the heating and cooling are controlled and managed better using the temperature-time profile.

Qian et al, (2016) studied heat transfer coefficient and flow characteristics of hot steel plate cooling by multiple inclined impinging jets, using energy balance for determining heat transfer coefficient of plate cooling process by the equation. Though energy balance equation was used for the temperature-time but the experiment did not actually involve the opposite sides of the inclined impinging jet, hence complete energy balance of the impingement cooling process cannot said to be obtained. In their equation radiation heat transfer cannot be taken care of from their combined equation therefore the accuracy of their temperature-time plot stands to be argued. The assumptive model geometry not shown.

Onah, et al, (2018), in their evaluation of temperature-time profile of steel plate under the analysis of pool boiling mechanism developed an equation for the prediction of zero-surface temperature, used for the calculation and plotting of the temperature profile. They studied the pool boiling mechanism to come up with the developed zero-surface temperature. Pool boiling mechanism is too cumbersome to analyze. The accurate study of film, transition and nucleate boiling under pool boiling has not be done without hitches like consideration of Leidenfrost phenomenon for water which requires thorough and careful analysis and calculation. Hence, the need for an easier analytical tool for engineers to save time and cost.

Singh et al, (2019) analyzed air jet impingement cooling of cylindrical objects using slot jets. Their temperature-time profiles obtained from the simulation showed a close agreement with the experimental temperature-time profiles in the wall-jet region of simulated flow field. A normal calculation of Initial temperature of the cylinder was set to 70^{o}c and cooled under air jet impingement using air at room temperature 25^{o}C. Temperatures at various locations were measured 2 mm below the surface, along the circumference of the middle cylinder. They fully relied on software simulation for the temperature-time profile and tried to monitor the thermocouple temperature and read same. Obviously the plot is inaccurate as a lot of errors are associated with the temperature-time profile in terms of monitoring.

Jay et al, (2016) conducted experiment on jet impingement cooling of a hot moving steel plate: an experimental study. 29 experimental runs were carried out. Non-linear regression method was used to fit the second-order polynomial derived from the experimental data and to identify the relevant model terms using the statistical software. A quadratic response model was developed considering all the linear, quadratic, and interaction terms, as in their equation. Looking at the regression equation. The description of the terms are not clear, which is radiation, convection and conduction and what happens to each of them. The ambiguity in their model is arguable since model geometry was not show.

Avadhesh et al (2019), concluded an experimental study on heat transfer and rewetting behavior of hot horizontal downward facing hot surface by mist jet impingement cooling. Water and air mixed for jet impingement cooling. Using Infra-red camera they monitored very closely their temperature and time. A one-dimensional transient conduction model was used to evaluate the heat flux of the test surface temperature. Again energy balance under the transient condition for volume control was used with a specimen length denoted as dx. The model is encompassing and it has all the modes of heat transfer. What is needed is more explanation of the terms in the equation and radiation heat transfer in impingement jet cooling is negligible or not? Model geometry missing in they work.

Purna et al, (2013) modelled numerical state feedback control of jet impingement cooling of a steel plate by pole placement technique. In this work, they considered the modeling to change a dynamic model-based control of the air jet impingement cooling of steel plate. They propose the design procedure based on state space pole placement techniques for the state feedback control design of jet impingement cooling system. The design of State-Space models is not different from that of transfer functions in that the differential equations describing the system dynamics are written first. For state-Space models, models instead of the equations are arranged into a set of first order differential equations in terms of selected state variables, and the outputs are expressed in the same state variables. A new approach to impingement jet modelling though, however, needs more explanation on the state functions on which it relates to heat transfer with clear model geometry, which is missing in their work.

Molana et al, (2013) investigated the heat transfer processes involved liquid impingement jets. In their review they highlighted the corrections of authors for Nusselt number on jet geometries. They compiled temperature time analytically and ones that were virtually read out with thermocouple and had their profile. No clear model seen in their literature describing the heat transfer terms. Non explanation of their model which must be accompanied with a model geometry-however not seen.

However, the overall models used and yet to be used should be easier to use and very clear in description of terms and name the models so that each will be known for what is it up to and also alongside should be validated dimensionally for homogeneity.

II. METHODOLOGY

Each researcher with his own approach, model and mathematical equations. However, two things remain same-the pattern of the temperature-time profile and gradient of the plots.

Qian, et al, 20116) use the equation below for the prediction of temperature-time in their experiment, radiation, conduction and convection were considered.

$$-\rho.c.s.\tfrac{\Delta T}{\Delta t} = qi + qR + q\alpha \qquad (1)$$

Where ρ, c, s are density, specific heat capacity and plate thickness respectively. Also, qi is enthalpy change equal heat transfer by impinging jet, Qr is heat flux by radiation, and qα is convection.

Onah et al, (2018), developed the equation below for the prediction of temperature-time in jet cooling. The equation is a zero-surface temperature for predicting surface temperatures of heated materials. They used Taylor's series by discretizing the sampled plate into equal number of parts. The temperature take care of the temperature at the surface in between and at the bottom. $T_{i,\ n+1}$ takes care of the next temperature after the first is obtained, T_{i+1n} takes care of the first and initial surface temperature and T_{in} is the middle temperature and T_{i-1n} the bottom surface temperature.

$$T_{i,\ n+1} = 0.092T_{i+I,n} + 0.816\ T_{i,n} + 0.092\ T_{i-1,n} \qquad (2)$$

Jay et al, (2016), using regression analysis, as shown in equation 3 below, designed with correlation independent parameters with dependent variables (cooling rate and CHF) by using a response surface methodology to optimize the process parameters to maximize the cooling rate and critical heat flux (CHF). Within this methodology, a four-factor, three-level BBD has been applied to study the combined effect of all four parameters (water flow rate Fw, nozzle height H [distance between hot surface to nozzle exit], speed of the steel plate Pv, and amplitude of oscillation Sn) on the cooling rate and CHF.

$$Y = C_o + \sum C_i X_i + \sum C_{ii} X_{ii}^2 + \sum C_{ij} X_i X_j + \in \qquad (3)$$

Where Y is predicted yield, C_o is constant, C_i, c_{ii}, c_{ij} is linear coefficient, quadratic coefficient and cross-product coefficient respectively. The sample was cooled from 900°C to room temperature by using water jet nozzle.

Avadhesh, et al (2019). From their model, it has a long equation and it takes care of all the heat transfer modes and the subscripts are not clearly explained.

$$\rho cpdv\frac{\partial T}{\partial t} = q_{cond,x}A - q_{cond,x+\Delta x}A - q_{rad,b}dA_{s,b} - q_{conv,b}dA_{s,b} - q_{rad,t}dA_{s,t} - q_{conv,t}dA_{s,t} + q_{edv} \qquad (4)$$

Here, dT/dt denotes the change in surface temperature of the sampled material at a location with time. While, $\mathbf{q_{cond\ x}}$, **and** $\mathbf{q_{cond\ x+x}}$, refer the axial heat flow into and from the test material at distance x and **x+Δx** respectively. Also, $\mathbf{q_{rad\ b}}$, $\mathbf{q_{rad\ t}}$, $\mathbf{q_{conv\ b}}$, $\mathbf{q_{conv\ t}}$, and $\mathbf{q_e}$ denote the radiative heat flux from the bottom surface, radiative heat flux from the top surface. Convective flux from the bottom surface, convective heat flux from the top surface and volumetric heat generation due to electrical heating, respectively. While ρ, T and A denote the density and specific heat, surface temperature and cross-sectional area of the test specimen, respectively.

Purna et al, (2013) their State models are directly derived from the original system equations. The standard form of the State-Space model equation is

X(t) = AX(t)+Ă(t) – State equation, Using control symbols they arrived at the final equation as X (t) = (A-BK) X (t) (5)

Using continuous-time model predictive control framework the model geometry is not seen for analysis from principle on how it is obtained. From their work, is shows that it is in nonlinear form. Considering the nonlinearity as strain rate in convective heat transfer.

Molana et al, (2013) after an elaborate review of all correlation of dimensionless numbers Prantl, Reynolds, Peclet and Nusselt for optimal values. They came us with their optimal correlation after taking into account Nano fluids particles and nozzle geometry. Though, worked with nozzle geometry but had the model geometry missing.

$$Nu = 0.2464(1.0 + 2.2061\emptyset^{0.3464}Pe^{0.2715}Re^{0.5375}Pr^{\frac{1}{3}} \qquad (6)$$

where, Nu, φ, Pe, Re, H and D, are the Nusselt number, volume fraction of nanoparticles, Peclet number, Reynolds number, jet to target distance and diameter of nozzle, respectively.

III. RESULTS AND DISCUSSIONS

From Fig. 2 the temperature was highest at around 790°C - 800°C from zero seconds and sub-cooled to around 670°C to 650°C in 45sec. The gradient maintained the same pattern despite the shape of the plot, difference in each of them is that cooling starting point and the ending. Cooling is an accelerated controlled cooling.

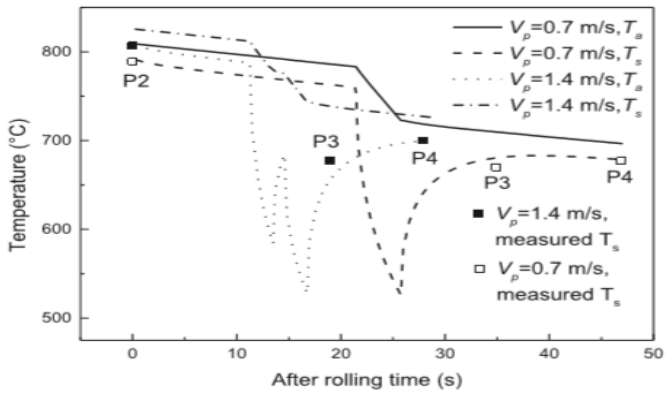

Fig. 2: Temperature-time profile of equation 1

From Fig. 3 temperature was highest at 450°C at zero seconds and sub-cooled to 260°C at time of 7440 seconds. Clearly, the temperature-time pattern shows accelerated cooling, which is obvious jet impingement cooling profile.

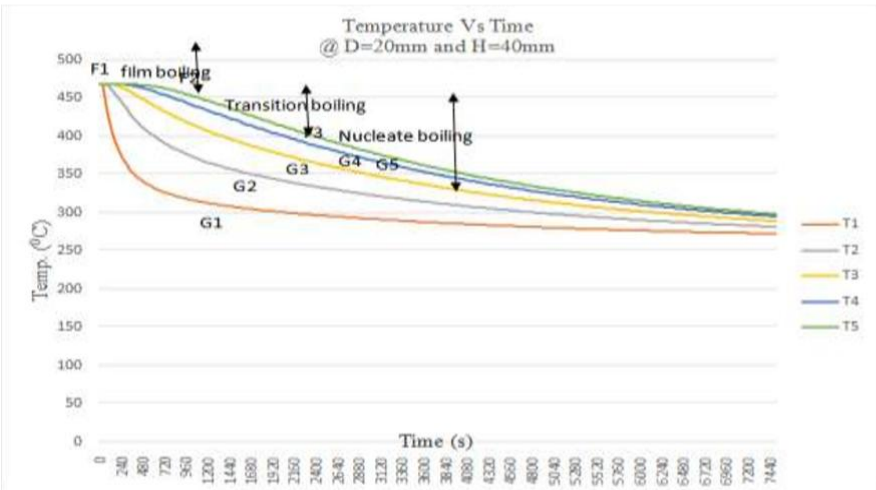

Fig. 3: Temperature-time profile of equation 2

In Fig. 4 there is a sharp drop of the temperature which depict a different type of cooling-direct quenching of heated sample. From the scaled temperature it was highest at 1°C and sharply drops to 0.2°C at around 0.3secs.

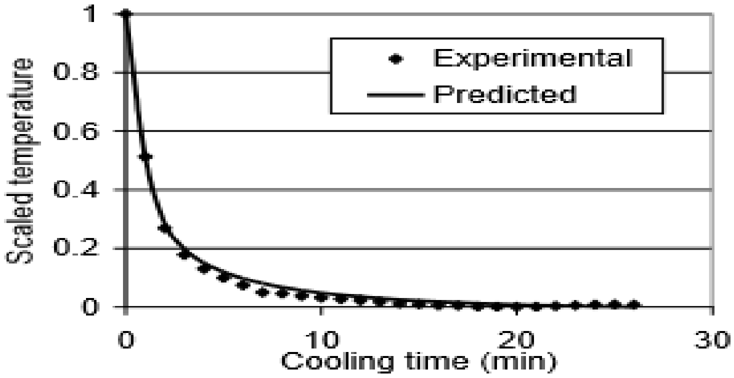

Fig. 4: Temperature-Time Profile of Singh et al, (2019)

Fig. 5 showed zig zag profile which identified the nanoparticle of the fluid. From their correlation they had the optimal temperature-time profile from 900°C to 600°C at 35.45sec.

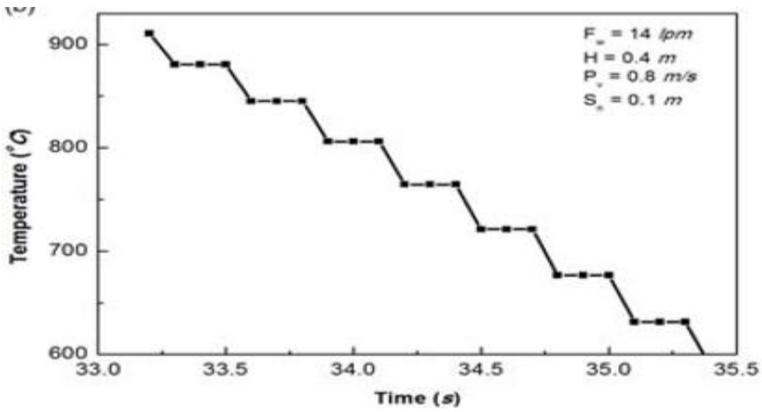

Fig. 5: Temperature-time profile of equation 3

From fig. 6 shows clearly accelerated cooling pattern of temperature-time. At 500°C the sampled material was maintained for about 0.1sec before cooling starts and it cooled down to about 150°C at 0.1sec, 0.15sec, 02sec, to 0.4sec.for different geometry.

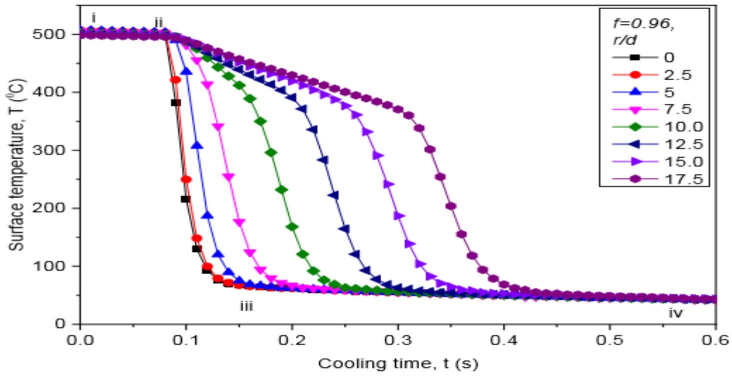

Fig. 6: Temperature-Time Obtained from Equation 4

Fig 7 showed a sinusoidal and linear pattern of temperature-time profile in comparism, where highest temperature was at 800°C cooled down to 755°C in 20secs. This cooling is auto-direct quenching – in between accelerated cooling and direct quenching.

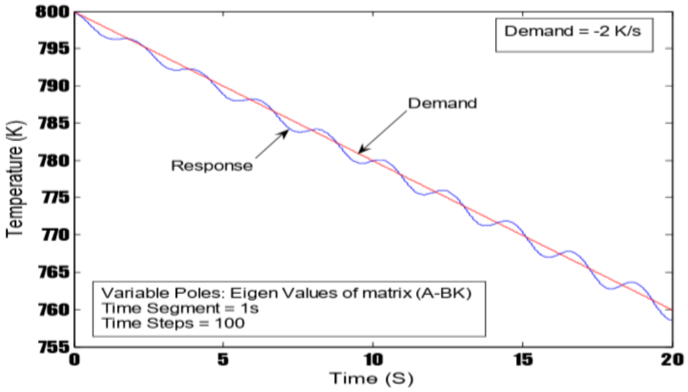

Fig. 7: Temperature-Time Obtained from Equation 5

Fig8. Displayed highest temperature of 350°C cooled down to below 150°C in 300secs. Very low temperature and longer time of cooling. Also an accelerated controlled cooling.

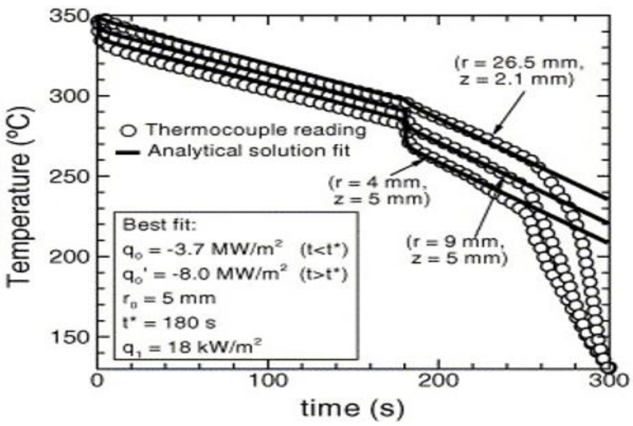

Fig. 8: Temperature-Time Profile of Molana et al, (2013)

In the analysis of all these temperature-time profile of impingement jet cooling, it showed that either one is cumbersome to analyze and takes much of the engineers time or it does not clearly explain the terms and what assumptions therein in the model or there is not known validation of the model using dimensionless parameters or dimensional analysis. With these the temperature-time though will maintain the same standard pattern will not be accurate in deducing the cooling rate of the sampled material. Hence, the need for a clear model that encompasses all the shortcoming therein in the reviewed works.

Controlled volume of lumped Thermal Mass Model Analysis for Evaluation of Convective Heat Transfer Co-efficient h

The basic concept in the analysis of lumped thermal mass model, is that the inside temperature of body remains basically constant during the whole period of heat transfer process. Temperature of this kind of body are only dependent on time, $T = T(t)$. This also means that in the analysis, no temperature gradient exists -which means that the inside resistance of such body (conduction) is negligible in comparison with its external resistance (convection). In this model, when a mass, which can be a well-conducting solid like steel or a well-mixed fluid like impingement fluids, is subjected to heating or cooling by contact to an environment with which it exchanges heat, one assumes that temperature variations within the mass can be neglected in comparison with temperature difference between mass and surrounding fluid. (Shankar, 2019). The control volume of lumped thermal mass model of impingement process of Fig.9 simplifies the complicated modelling process of impingement cooling which involves conduction and convection. In this process, we assumed that:

i. Heat transfer from the hot steel plate is seen as a lumped mass.

ii. The rate of mass resistance to heat is negligible when compared with rate of resistance of heat with impinging fluid.

iii. The volume of the mass remains unchanged.

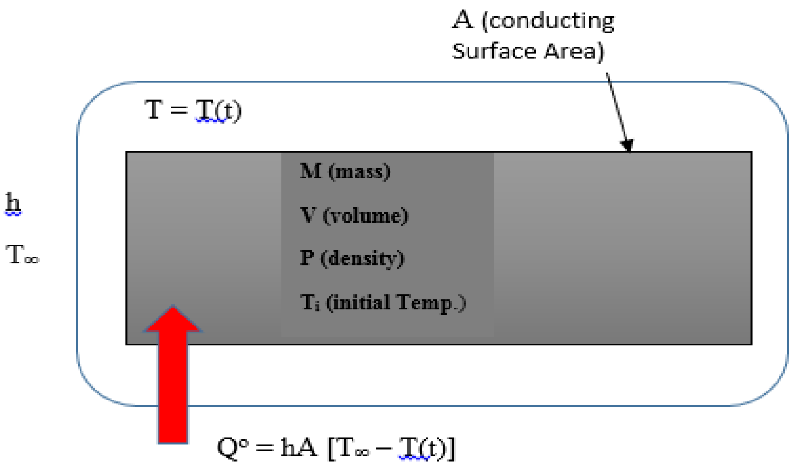

Fig. 9: Control volume of lumped thermal mass model Analysis of impingement process

By the lumped mass method based on control volume of the steel plate Fig. 9, mass behaves as a single lump of temperature, T. Thus equating conduction heat transfer at bottom to that conducted at top by convection, since boiling heat is infinitesimal, we have this equation

$$\text{gradient is } -\propto = \frac{-hAt}{mcp} \qquad (7)$$

From which, $h = \propto \rho wcp$ (8)

Where h is convective heat transfer co-efficient W/m^{2}k

$for\ steel, density\ \ \rho = \frac{7900hg}{m^3},\ specific\ heat\ Cp = \frac{500J}{kgk};\ sampled\ thickness\ w = 0.012m, \propto,$ is gradient from equation (7)

Validity of Experimental Model

From our initial assumptions in the lumped thermal mass model, we assumed that temperature variation within mass is very small as compared to the surroundings. This variation can be neglected and assuming whole mass to a single lump of temperature. This will be correct when

Therefore, validity of the model lies within the equation below

$$\frac{{}^{L}/_{KA}}{{}^{1}/_{hA}} \ll 1 \qquad (9)$$

$$\frac{hL}{Ks} \ll 1 \qquad (10)$$

Equation 10 is dimensionless number called Biot number, validates the lumped thermal mass model.

IV. CONCLUSIONS

Therefore, the use of lumped thermal mass analysis gives accurate rate of cooling and it is not cumbersome to analyze, it is validated with Biot number and its assumptions are clearly spelt out.

It is strongly recommended for impingement jet cooling process to use the lumped thermal mass analysis of the form $h = \propto \rho wcp$ for the evaluation of convective heat transfer coefficient h, which will enable one to obtain other dimensionless numbers associated with fluid flow.

It revealed that with this model accuracy of cooling rate on any sampled materials will not be questioned. Hence a better steel grade properties will be obtained.

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