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Analytical Model for Rewetting Temperature during Jet Impingement Surface Quenching

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ABSTRACT

The jet impingement cooling technique is used for rapid surface quenching that takes place after a certain surface temperature called as the rewetting temperature. In this manuscript a theoretical model to determine the surface rewetting temperature is proposed. The rewetting temperature obtained with this model is compared with the experimental results for hot horizontal flat surface quenching. The proposed model accurately predicts the surface rewetting temperature for the stagnation point. However, for the spatial location up to 12 mm. the rewetting temperature falls within the error band of ± 15 percent. This variation for the downstream locations is due to retardation of jet flow over hot surface. Since, jet velocity has been considered as one of the depending variables in determining the heat transfer, however, its retarding effect for the downstream location has not been incorporated in the model.

Keywords : Jet Impingement, Rewetting Temperature, Surface Quenching, Stagnation Point, Transient surface Heat Transfer, Wetting Delay.

I. INTRODUCTION

Water jet impingement surface quenching is being used in many industrial applications due to its capability of higher heat removal rate [1]. The common application areas of jet impingement surface quenching are metal, electronics, nuclear etc. [2, 3]. The analytical and experimental investigation for jet impingement cooling under steady state condition has been performed several times [4-8]. Whereas, under transient conditions, predominately experimental studies are available [9-16]. The rewetting temperature [10, 11], wetting delay [9-12], rewetting velocity [10, 13] and maximum surface heat flux [14, 15] are some of the parameter to evaluate the transient cooling performance of hot surface with jet impingement method. The surface rewetting temperature is the temperature at which rapid surface quenching is initiated. The effective cooling of hot surface is restricted above the rewetting temperature, due to initial formation of vapour film on the hot surface and that depends upon the thermo-physical properties of cooling fluid, hot surface, surface orientation and the surface initial temperature [17-19]. The consensus over the definition of surface rewetting condition is yet to be established, however, a large number of researchers described rewetting as the onset of transition or minimum film boiling point [15, 18, 19]. Moreover, some researchers have also suggested the location of maximum change in the slope of cooling curves or the location of maximum heat flux as the surface rewetting [20, 21]. Carbajo [22] in his review for the rewetting of hot surfaces discussed the relevance of various theories and reported that the rewetting temperature for different surface-coolant combinations lies in the range of 167–700 ºC.

Several attempts has been made so far for theoretical predication of surface rewetting condition in term of rewetting temperature, wetting delay and heat flux e.g. minimum heat flux or the maximum heat flux as the case may be, applicable to different surface quenching methods [9, 23 – 26]. The present work provides a one dimensional heat transfer model to predict the rewetting temperature for the stagnation point as well as for downstream spatial locations on the hot horizontal surface. The predicted rewetting temperature is further compared with the published experimental results of cooling hot stainless steel (SS-316) surface by jet impingement.

II. THEORETICAL MODELING FOR REWETTING TEMPERATURE

When the cooling of hot surface is initiated with water jet, a water patch of radius R is formed after application of jet impingement within a certain time, td, called wetting delay (Fig 1). The radius of this water patch increases with the elapsed of cooling time. The convective heat transfer from the region outside the water patch is lower as compared to the heat transfer within the patch, due to forced convection. Therefore, for the region outside the wet patch of radius R, a 1-D heat transfer equation for rewetting analysis can be written as.

$$\frac{1}{r}\frac{\partial}{\partial r}\left(kr\ \frac{\partial T}{\partial r}\right)+\dot{q}-\frac{h}{\varepsilon}\left(T-T_a\right)=\rho c\frac{\partial T}{\partial t} \quad (1)$$

Where, ε, can be taken as the thickness of hot surface.

The surface temperature outside the water patch is considered as constant i.e. equal to initial surface temperature, with neglecting precursor cooling effect, the equation (1) becomes

$$\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\dot{q}}{k}=\frac{h}{k\varepsilon}\left(T-T_a\right) \quad (2)$$

The heat transfer coefficient outside the water patch, h, can be written as

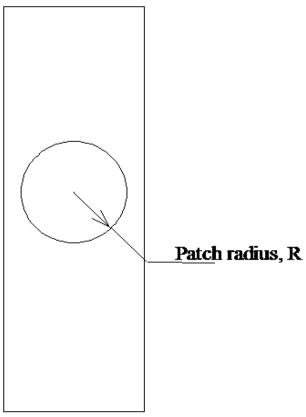

Figure 1 Cooling zone on hot surface

$$h=\frac{\dot{q}\varepsilon}{\left(T_i-T_a\right)} \quad (3)$$

The equation (2) becomes

$$\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}=\frac{h}{k\varepsilon}\left(T-T_i\right) \quad (4)$$

$$\frac{\partial^2 \theta}{\partial r^2}+\frac{1}{r}\frac{\partial \theta}{\partial r}-m^2\theta=0 \quad (5)$$

Where $m=\frac{h}{k_s\varepsilon}, and \theta=\left(T-T_i\right)$

The solution of equation (5) can be written as

$$\theta(r)=c_1 I_0(mr)+c_2 K_0(mr) \quad (6)$$

Where I0, and K0, are modified zero order Bessel function of first and second kind.

With the following boundary conditions the solution of equation (6) can be written as equation (7)

With in the patch at r = R; T= Tw,

And outside the patch r = ∞; T = Ti

$$\left(T-T_i\right)=\frac{\left(T_w-T_i\right)}{K_0(mR)}K_0(mr) \quad (7)$$

By using the equation (3) the equation (7) can be written as

$$T\ -T_a-\frac{\dot{q}\varepsilon}{h}=\left(T_w-T_a-\frac{\dot{q}\varepsilon}{h}\right)\frac{K_0(mr)}{K_0(mR)} \quad (8)$$

$$T_w=T_i+\left(T\ -T_i\right)\frac{K_0(mr)}{K_0(mR)} \quad (9)$$

Within the wetting delay, td, energy balance for water patch.

Energy removed by film boiling over the patch = Loss of energy stored under patch + energy conducted into patch + Energy generated under patch

$$\bar{h}\pi r^2\int_0^{t_d}\left(T_w-T_{sat}\right)dt=\pi r^2\varepsilon\int_{T_{wet}}^{T_i}\rho c_p dT + 2\pi r\varepsilon\int_0^{t_d}\left(-k\left.\frac{\partial T}{\partial r}\right|_R\right)dt+\pi r^2\varepsilon\int_0^{t_d}\dot{q}dt \quad (10)$$

Since, surface temperature under the water patch, Tw, does not remains constant, it varies over the time td, the average surface temperature can be written as

$$\bar{T}_w=\frac{\int_0^{t_d}T_w dt}{\int_0^{t_d}dt} \quad (11)$$

Differentiating equation (7) we can also get

$$\frac{\partial T}{\partial r}=m\left(T_w-T_i\right)\frac{K_1(mr)}{K_0(mR)} \quad (12)$$

Where K1 is first order Bessel function of second kind, thus, at r = R, equation (12) become

$$\left.\frac{\partial T}{\partial r}\right|_R = m(T_w - T_i)\frac{K_1(mR)}{K_0(mR)} \qquad (13)$$

Using equation (10) and (12) we have

$$\bar{h}\pi r^2\left(\int_0^{t_d} T_w dt - \int_0^{t_d} T_{sat} dt\right) = \pi r^2 \varepsilon \int_{T_{wet}}^{T_i} \rho c dT$$
$$+ 2\pi r\varepsilon(kmK_0')\left(\int_0^{t_d} T_i dt - \int_0^{t_d} T_w dt\right) + \pi r^2 w\int_0^{t_d} \dot{q} dt \qquad (14)$$

After re-arranging for the rewetting temperature, TRW, equation (14) can be written as

$$T_{RW} = \frac{1}{\rho c w}\left[\begin{array}{l}\rho c \varepsilon T_i - \bar{h}(\bar{T}_w - T_{sat})t_d \\ + \frac{2}{x}\varepsilon(kmK_0')(\bar{T}_i - \bar{T}_w)t_d + \dot{q}\varepsilon t_d\end{array}\right] \qquad (15)$$

The average film boiling heat transfer, $\bar{h}$, in Equation 15 can be obtained by the following empirical correlations shown in equation 16 and 17 as below:

$$\bar{h} = 0.95 \times 10^3 \exp(-0.0054\Delta T_{sat}) \qquad (16)$$

$$\bar{h} = 1.65 \times 10^4 \left(\frac{U^{0.83}}{d^{0.42}}\right)\left(\frac{1 + 0.235\Delta T_{sub}}{T_{RW} - T_j}\right) \qquad (17)$$

The correlation equation (16) has been proposed by Tong (1972) [27] and the equation (17) has been proposed by the Seiler et al. (2004) [25]. The rewetting temperature, TRW, is determined by Equation (15) for any radial location R, within wetting delay time, td, for input value of average heat transfer coefficient at the rewetting condition and flat plate thickness. A computer program based on the Newton-Rapson method for the iteration is developed and the determined rewetting temperature is compared with the experimental rewetting temperature for the flat surfaces. The assumptions made for this one dimensional heat transfer analysis are as below.

1. The change in temperature along the thickness has been ignored.
2. The fluid travel over the surface with constant velocity i.e. wetting front velocity is uniform over the hot surface.
3. The complete hot surface is divided into three different regions i.e. wet (Under water patch), boiling and the dry regions, with a sharp temperature gradient at the interface of boiling and wet regions.
4. The thickness of the boiling region is negligible.
5. Heat transfer coefficient, within the one region is constant.
6. The surface temperature within the wet region approaches to saturation temperature of the impinging fluid and at the interface of wet and boiling regions the surface attains the rewetting temperature.
7. Outside the wet patch or in the dry region the surface temperature is considered equal to the initial surface temperature.
8. Outside the wet patch the effect of precursory cooling has been neglected.
9. The heat transfer within the wet region is through forced convection, at the interface there is film boiling and in the dry region free convection and radiation heat transfer is assumed.
10. The effect of gravitational force on the flow is neglected.

Since the surface properties vary with the temperature, however calculations are performed with surface properties at the average of surface initial temperature and the rewetting temperature. The surface properties were obtained by flowing relations.

$$k_s = 9.01 + 1.5298 \times 10^{-2}(T_s + 273)$$
$$\rho = 8 - 9.5 \times 10^{-4} T_s + 4.665 \times 10^{-7} T_s$$
$$c_p = 365.45 + 0.4065(T_s + 273)$$
$$-1.73 \times 10^{-4}(T_s + 273)^2$$

III. EXPERIMENTAL DATA

The published experimental rewetting temperature obtained during jet impingement cooling of hot horizontal stainless steel (SS-318) surface at 800 °C initial temperatures are used for comparing the theoretically predicted data. The experimental data are for round water jet of 2.5 – 4.8 mm from straight tube type nozzle and 2.5 – 5 mm from sharp edge type nozzle at 22 ±1 ˚C temperature. The operating ranges of experimental parameters are shown in Table (1) and (2).

TABLE 1. OPERATING PARAMETERS OF EXPERIMENTS

Parameters	***Range***
Spatial location on test surface, mm	0,2,4,6,8,10, 12
Initial surface temperature, °C	800 ±10 °C

Water jet temperature, °C	22 ±1 °C
Test surface Thickness, mm	0.25
Test surface Material	SS-316
Nozzle exit to test surface spacing, z/d	4

TABLE 2. OPERATING RANGES FOR JET FLOW

Reynolds number	***Jet velocity, U, m/s*** d=2.5	d=3.5	d=4.8	d= 5.0
5000	1.76	1.25	0.92	0.87
10000	3.53	2.51	1.80	1.74
160000	5.60	3.98	2.90	2.80
240000	8.40	5.98	4.37	4.18

IV. RESULT AND DISCUSSION

The value of rewetting temperature determined by equation (15) is compared with the published experimental data for certain downstream locations. The comparisons for the determined rewetting temperature with the experimental rewetting temperature for the horizontal flat surfaces are shown in Figures (2) and (3).

The comparisons of theoretical rewetting temperature and experimental results are for the tube type and sharp edge nozzle with hot flat horizontal surface by using Tong (1972) correlation for the average heat transfer coefficient (Equation 16) is shown in Figure (2). Whereas, comparison of experimental and evaluated rewetting temperature by using Seiler et al. (2004) correlations (Equation 17) for heat transfer coefficient is shown in Figure (3), for tube and sharp edge nozzle separately.

It is observed in Figure 2 that majority of theoretical rewetting temperature falls in ± 5 percent range of the experimental rewetting temperature obtained for the tube type nozzle of d = 2.5 mm to 4.8 mm and sharp edge nozzle of d = 2.5 to 5 mm at Re = 5000 to 24000. However, at Re = 5000, variation of 6 percent and 8 percent respectively is observed with jet diameter d = 2.5mm and 3.5 mm from the tube type nozzle, particularly for the extreme downstream measured locations (Figure 2a). Whereas, beyond 10 mm radial location, with 2.5 mm jet diameter of sharp edge nozzle at Re = 5000 and 10000 this deviation rises up to 20 percent (Figure 2b). Similarly it is observed that 99 percent of theoretical rewetting temperature obtained by

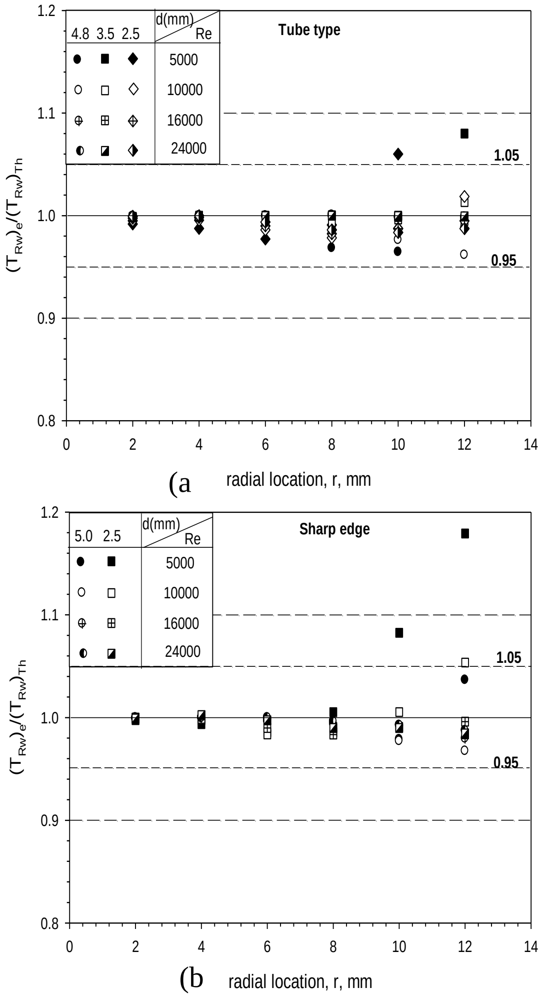

Figure 2. Comparison of predicted rewetting temperature with experimental data using Tong (1972) correlation for

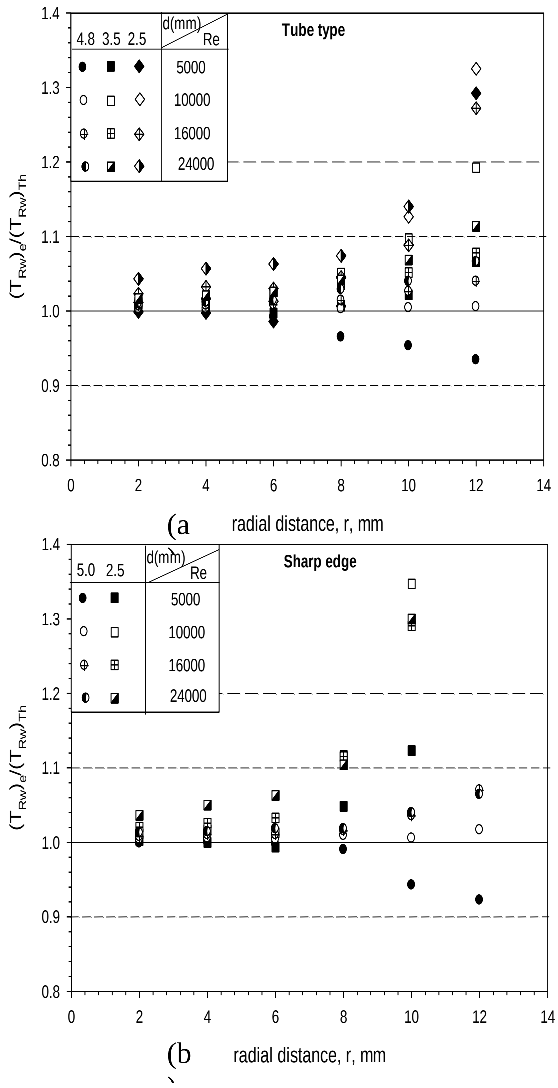

Figure 3 Comparison of predicted rewetting temperature with experimental data using Seiler et al. (2004) correlation for

using Seiler et. al. (2004) correlation for heat transfer coefficient lies in the range of ± 10 percent deviation, for the tube type nozzle of d = 2.5 mm to 4.8 mm (Figure 3a). However, approximately 75 percent of theoretical data falls with in the deviation of ± 5 percent. Whereas for sharp edge nozzle 87 percent of theoretical data falls in ± 10 percent error band, in which 66 percent of data lies within ± 5 percent error band (Figure 3b).

It has been observed in Figure 2 and 3 that there is larger deviation of predicted rewetting temperature with the experimentally data, particularly, for extreme downstream radial location away from the stagnation point. This larger variation is due to retardation of jet flow over hot surface towards the downstream locations. Since, Tong (1972) correlation for heat transfer coefficient and the equation (15) for the rewetting temperature does not have any variable for considering the flow retardation effect. Moreover, Seiler et al. (2004) correlation has considered jet velocity as one of the depending variable in determining the heat transfer coefficient, but the jet velocity at the stagnation point is no more remained the same for the downstream locations due to flow retarding effect. Therefore, larger deviations between the experimental and theoretical rewetting temperature is observed particularly for the extreme downstream locations. The variation in the rewetting temperature between the theoretical and the experimental data can also be attributed by the precursory cooling effect of the hot surface. The effect of precursory cooling reduces the rewetting temperature for the downstream radial locations. Since any factor for the precursory cooling has not been considered in Equation (15), therefore, theoretical rewetting temperature may be overpricted by the experimental data, particularly for the extreme downstream locations.

V. CONCLUSIONS

In this work a one dimensional theoretical model was presented to determine the surface rewetting temperature obtained during water jet impingement cooling. The predicted rewetting temperature was compared with the experimental rewetting temperature obtained with sub cooled water jet from tube type and sharp edge nozzle. The proposed semi empirical equation for rewetting temperature was able to predict the majority of experimental rewetting temperature with in the 5 percent deviation. This deviation rises even up to 30 percent particularly for the extreme downstream locations. Therefore, this analysis cannot be recommended to determine the rewetting temperature beyond 10 mm downstream location. As, for downstream locations, the effect of flow retardation of jet fluid and the effect of surface precursory cooling has not been incorporated in the analysis that results in enhanced deviation in predicted data with experimental results.

VI. NOMENCLATURES

c	specific heat of the surface material, kJ/kg K
d	jet diameter, m
h	heat transfer coefficient, W/m^2.K
h_{fg}	latent heat of evaporation for coolant, *kJ/kg*
k	thermal conductivity, W/m. K
$\dot{q}$	heat generation per unit volume of test- surface, W/m^3
q	surface heat flux, W/m^2
Re	Reynolds number, U*d/υ*
r	radial distance from the stagnation point on flat test-section, m
t	time, s
t_d	wetting delay, s
T	temperature, ºC
T_a	ambient temperature, ºC
T_w	surface temperature within wetted surface, ºC
ΔT_{sat}	wall super heat temperature, (T_i - T_{sat}), ºC
ΔT_{sub}	coolant sub cooling, (T_s - T_{sat}), ºC
U	jet velocity at nozzle exit, m/s

Greek symbols

ε	surface thickness, m
ρ	density of surface material, kg/m^3

Subscripts

f	liquid state
g	gaseous state
i	initial value
j	jet
o	stagnation value
p	predicted value
RW	rewetting

s	surface
sat	saturation
x	local spatial position

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