International Journal of Engineering and Techniques - Volume 3 Issue 6, Nov - Dec 2017

RESEARCH ARTICLE OPEN ACCESS

Experimental Investigation to Study Surface Quenching Behavior

Chitranjan Agrawal
(Department of Mechanical Engineering, College of Technology and Engineering, Maharana Pratap University of Agriculture & Technology, Udaipur, Rajasthan, India)

Abstract:

Study of surface quenching is of interest particular in the context of emergency core cooling of a nuclear reactor under LOCA conditions. Rewetting is a phenomenon which occurs during the quenching of hot surfaces of high temperature. Rewetting of surface occurs at minimum film boiling point where liquid established direct contact with a hot dry surface. The present investigation deals with experimental investigations on the quenching behavior of a hot horizontal stainless steel surface of 0.25 mm thickness with water jet of 22ºC temperature. Initially, test surface is heated up to 800ºC and water jet is injected through a straight tubes nozzle of 2.5 mm diameter. The observations are made up to 16 mm downstream locations away from the stagnation point. The nozzle exit to surface spacing is kept in the range of 4-16 times of nozzle diameter and Reynolds number in the range of 5000-24000. Rewetting temperature, rewetting velocity and wetting delay are some of the parameters over which rewetting phenomenon has been investigated. During quenching initially, a wet patch was observed at the stagnation point, which progress in downstream direction only when the surface was cooled up to the rewetting temperature. The Rewetting temperature, rewetting velocity both increases with the rise in Reynolds number, however, the wetting delay reduces. This effect is more pronounced for downstream locations away from the stagnation point.

Keywords — **Round Water Jet, Surface Quenching, Surface Rewetting, Transient Heat Transfer,**

I. INTRODUCTION

The jet impingement cooling is being extensively used in many industrial applications due to its higher heat removal capability. A numbers of analytical [1, 22] and experimental [8, 11, 20] work has been published so far for steady and transient state cooling condition. During transient cooling rewetting seems to be an important aspect of study, particularly in the context of emergency core cooling system of a nuclear reactor and cooling of hot metal surfaces. During loss of coolant accident (LOCA) conditions in a nuclear reactor, the clad tubes consisting of fuel rods become over heated even after shut down of the nuclear reactor. Therefore an emergency core cooling system (ECCS) is provided in the reactors to cool clad tubes under LOCA condition. In advance heavy water reactors (AHWR) the water jet impingement cooling techniques is used as a part of ECCS to cool the overheated clad tubes instantly under such condition. Rewetting phenomena have been reported with top-bottom flooding [1, 9], spray cooling [2, 4] and with jet impingement [12, 24] several times. These studies covered the effect of various operating parameters on rewetting phenomena of flat, cylindrical and spherical surface of different materials. The operating parameters were initial surface temperature, jet or spray diameter, surface roughness, coolant temperature and flow rate etc.

When the liquid jet strikes on the hot surface a wet patch was formed in the stagnation region, thereafter the liquid advances along the hot surface in the direction of the flow [7, 17]. Initially cooling commences at a relatively slow rate in the film boiling regime due to separation of the liquid from the surface by continuous vapor blanket. As the surface temperature reduces, rate of cooling increases till the single phase convection boiling occurs, where surface boiling completely ceases [8, 14].

It is assumed that liquid make contact to the hot surface only after the rewetting or Leidenfrost or sputtering temperature [1, 13]. Rewetting temperature does not always remains constant; it depends on surrounding pressure, physical properties of the test section and coolant flow condition. The range of rewetting temperature has been reported so far for the SS and water was 167ºC to the maximum 700- 800ºC [3]. This variation in rewetting temperature is due to the different opinion regarding the point of rewetting to occur. In the stagnation region rewetting temperature is weekly affected by jet impingement velocity and strongly depends on water sub-cooling of 5-45ºC [10]. However hall et al. [11] reported rewetting temperature decreases with reduction in jet velocity and increases with jet diameter. The surface initial temperature marginally affects the rewetting temperature [11].

The time elapsed between commencement of jet and initialization of surface rewetting is termed as wetting delay [17]. Mozumder et. al. [15] called wetting delay as resident time and found it as strong function of surface material, surface initial temperature, coolant flow rate and temperature. Wetting delay reduces with the rise in liquid sub-cooling, however increases with the rise in surface thermal conductivity, heat generation rate, jet impact angle and the initial surface temperature [16, 17].once the quenching front starts moving over the surface it does not take much time to cover complete surface [12]. Therefore another parameter to measure surface rewetting is defined as rewetting velocity. Rewetting velocity is the measure of quench front movement between two marked locations over the hot surface per unit time [1, 9]. It was reported that rewetting velocity increases with the rise in liquid sub-cooling, flow rate and surrounding pressure [16], however decreases with the rise in initial wall temperature and residual power input [6]. Effect of flow rate is more on low initial surface temperature than higher surface temperature. At low flow rate and at low sub-cooling rewetting velocity remained more or less constant [16]. Raj et. Al [18] reported that rewetting velocity was near 20-30 percent lower for horizontal tube compare to vertical arrangement. Celata et. Al. [5] reported higher rewetting velocity for spray cooling system compare to film cooling. At high coolant flow rate surface thickness and conductivity has no bearing on rewetting velocity [10]. However surface roughness increases the wetting velocity due to increase in rewetting temperature and heat transfer [9].

It is observed with the available literature that the study on rewetting phenomena associated with high sub cooled water jet impingement cooling particularly on the thin stainless steel sheet is limited. Therefore, an experimental investigation has been carried out to study cooling curves, rewetting temperature, wetting delay and rewetting velocity on the hot horizontal surface during transient cooling. The effect of jet exit to surface spacing and jet Reynolds number on these rewetting parameters has also been examined at different radial locations of the target surface.

II. EXPERIMENTAL PROCEDURE

Experiments were performed for the quenching of a hot stainless steel horizontal surface using normal water jet of 22±1ºC, injected through a straight tube type nozzle. The complete schematic of the set up is shown in the Figure 1.

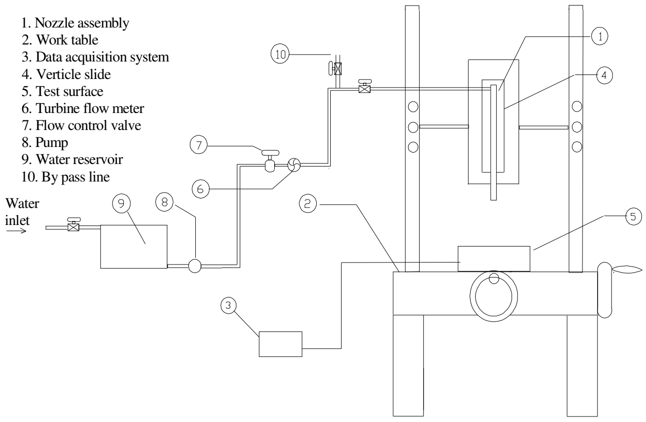
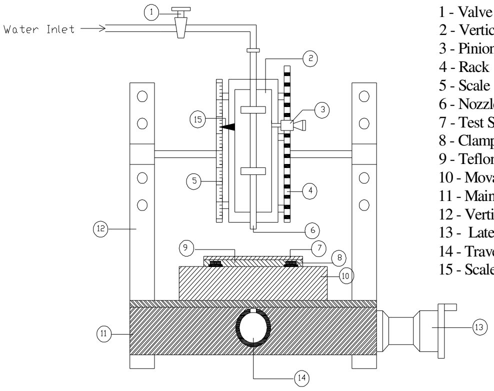


Figure 1 Schematic of experimental set up

Initially water was collected in a reservoir (9) and supplied to the nozzle (1) using a water pump (8). A flow control valve (7) and a turbine flow meter (6) was installed between the pump and a by pass line (10). The nozzle was mounted on a slide (4) free to move in vertical direction over a work table (2). The test surface (5) was placed on the work table beneath to the nozzle assembly. Ungrounded 'K'-

type thermocouples was attached at back side of the test surface and connected to the Data Acquisition System (3). The test surface was heated with a high current and low voltage auto-transformer arrangement. Two copper bus bars from the terminal of auto-transformer are attached at both sides of the test surface to minimize the voltage drop between the transformer and the test surface.



1 - Valve
2 - Vertical Slide
3 - Pinion for Vertical Movement
4 - Rack
5 - Scale
6 - Nozzle
7 - Test Surface
8 - Clamps
9 - Teflon Base
10 - Movable Table
11 - Main Frame
12 - Vertical Support
13 - Lateral Movement Handle
14 - Traverse Movement Handle
15 - Scale Pointer

Figure 2 schematic of nozzle assembly

Figure 2 shows the details of test surface assembly. It consisted of a water injection nozzle (6) in the form of a straight tube of 2.5 mm diameter and 250 mm length to deliver fully developed flow at the nozzle exit. This tube type nozzle was mounted on a vertical slide (2) having the rack (3) and pinion (4) arrangement for vertical movement. In fact, the jet exit to target surface spacing was varied through this mechanism. The complete nozzle assembly was mounted on the vertical support (12) attached at the both sides of the main frame (11) of work table. In addition to rack pinion arrangement several holes on the two vertical supports was provided to vary the jet exit to target surface spacing. The vertical movement of nozzle was directly measured using a pointer (15) on the vertical slide having a scale (5). The test section with Teflon base (9) was clamped on a movable work table (10). The table can be moved in lateral and transverse direction to adjust the position of the test surface beneath the impinging jet. For these movements two lead screws were provided in two perpendicular directions. These lead screws were moved separately by using a lateral (13) and transverse movements handle (14). The test section was a 130 mm long, 38 mm wide and 0.25 mm thick stainless steel sheet. K-type mineral insulated ungrounded thermocouple of 500 micron sheath diameter were spot welded at the back side of test surface. The thermocouples were attached at stagnation point just beneath to the nozzle centre axis. The other thermocouple was at 16 mm away from the stagnation point in downstream radial location, along the longer side of test surface. The thermocouple side of test surface was insulated by applying ceramic insulation and Teflon sheet so that all the heat generated in the sheet was dissipated only by the cooling water. Since the test surface was very thin (0.25 mm) and the cooling was very fast, the Biot number for the transient cooling experiments became Bi << 0.1, therefore, the test surface can be treated as a lumped surface. Using 1D conduction heat transfer equation, the temperature drop across the test surface was evaluated less than 0.2 ˚C, thus the temperature at the back of the target surface was assumed identical to the side of surface exposed to the coolant.

TABLE 1
UNCERTAINTY IN THE MEASUREMENTS

Parameter	**Accuracy**
water flow rate	0.10 lpm
nozzle diameter	0.10 mm
test surface dimensions	0.02 mm
test surface thickness	0.01 mm
Thermocouple location	0.50 mm
temperature	1.5˚C at 500-800 ˚C, 0.5˚C at 200-500 ˚C

The surface temperature during transient cooling and the steady state were recorded using a data acquisition system. The water flow rate was measured with the help of a turbine flow meter. The flow rate was manipulated to vary the jet Reynolds number using the flow control valve. The test section was heated by the current supplied through auto- transformer. The voltage drop across the sides of test surface was measured by a digital voltmeter. The corresponding current supplied was measured with the help of an ammeter and a current transformer arrangement. The nozzle diameter was measured with a optical micrometer. The uncertainty in the measurement is shown in Table-1.

Initially to start the experiments the water pump was started, the main valve near nozzle was kept in closed condition and the bypass line valve remained in open condition. When the cooling of test surface was desired, the bypass line was closed and main valve (1) near nozzle was opened. The test surface was cleaned properly with the acetone and then heated slowly up-to the initial surface temperature of 800 oC by regulating auto transformer. When the test surface temperature was stabilized approximately for 15 minutes and all the thermocouples on the test surface showed temperature within 800 ± 10ºC, the supplied voltage and the current value is recorded. The supplied heat flux to the test surface was calculated by using Equation 1.

$$q'' = \frac{VICos \quad \phi}{A} \qquad - (1)$$

The water was injected through the nozzle on test surface by closing the ball valve mounted on the bypass line and opening the ball valve just before the nozzle. As the cooling water jet impinged on the surface, the surface temperature was dropped drastically within a few seconds of jet impingement. The transient and steady state surface temperature data with time were recorded by the data acquisition system at the rate of 100 samples per seconds.

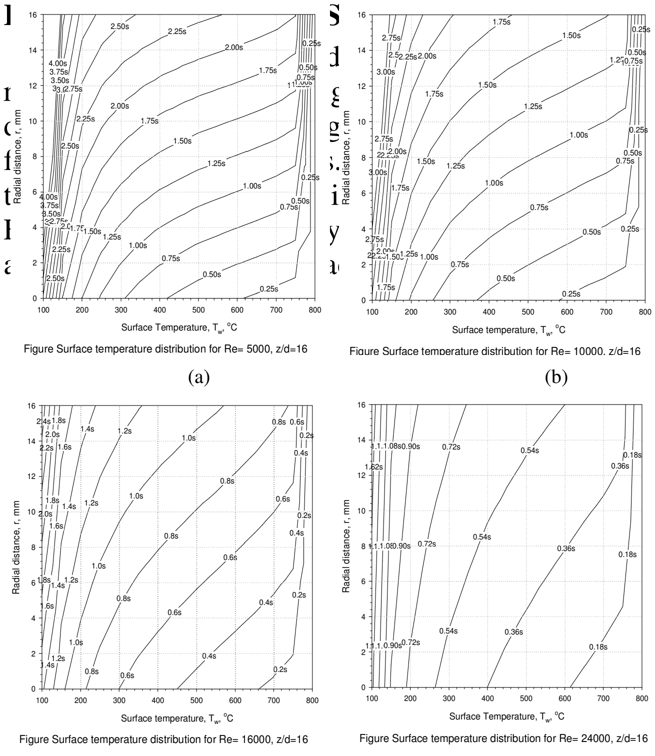
TABLE 2
OPERATING RANGE OF EXPERIMENTAL PARAMETERS

Experimental parameter	**Operating range**
Reynolds number (Re)	5,000 – 24,000
Jet exit to surface spacing (z/d)	4 – 16
Nozzle diameter (d)	2.5 mm
Thickness of test surface (w)	0.25 mm
Water temperature	22 ± 1ºC
Initial surface temperature	800ºC

For every experiment a new heating surface was prepared to avoid any effect of change in surface properties, oxidation and surface deformation from the previous experiment. The surface temperature data were recorded before the commencement of the jet impingement till the steady state cooling condition was achieved. A number of experiments were performed for different jet Reynolds number and jet exit to surface spacing. The jet Reynolds number was varied by manipulating the water flow rate and spacing (z) by changing vertical position of the nozzle on the vertical slide. The operating ranges of experimental parameters have been shown in the Table -2.

III. RESULT AND DISCUSSION

Surface is initially heated up to 800ºC, thereafter, round water jet is impinging over the surface. These data under transient cooling conditions are analysed for different parameters. The radial surface temperature distribution with the time is shown in Figure 3, for all the jet Reynolds number examined at nozzle exit to surface spacing, 'z/d = 16'.



(a) (b)

(c) (d)

Figure 3 Surface temperature distribution at z/d = 16 for (a) Re = 5000 (b) Re = 10000 (c) Re = 16000 (d) Re = 24000

The Figure 3 is in line with the transient curves obtain by many investigators for jet impingement [14, 15], for spray cooling [4, 5], and for film cooling system [1, 9]. With these figures it is evident that immediate cooling is started in the stagnation region and a wet patch is formed. However for transition (1≤ (r/d) ≤ 2.5) and wall jet region (2.5≤ r/d) cooling is slightly delayed. This is due to flow retardation towards the wall jet region

[7, 11]. It has also been observed that at high Reynolds number cooling is fast for all the region compares to low Reynolds number. The surface temperature reduces form 800ºC to 150ºC with in 0.88 sec at stagnation point and at 16 mm downstream it reaches in approx 1.3 sec, for the Re = 24,000. Whereas at Re = 5000 it takes 1.74 sec and 3.6 sec respectively. The lesser difference in time value with the higher Reynolds number can be attributed by the high flow rate coupled with the higher Reynolds number. The larger liquid flow covered wider area and cooled the surface with much faster rate. It was observed that the jet exit to surface spacing does not have significant effect on the cooling curves. The variation in transient cooling time was observed within 5 - 10% for all the value of 'z/d' examined without any particular trend. The transient cooling performance of the surface was further evaluated on the basis of Rewetting temperature, wetting delay and Rewetting velocity.

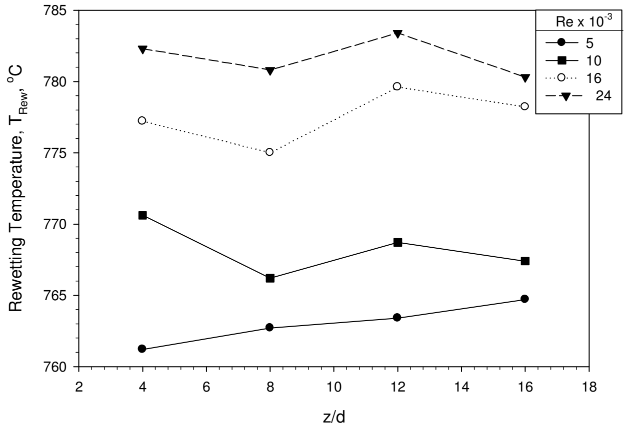


Figure 4. Rewetting Temperature with z/d

The time variant surface temperature value during the cooling is used to evaluate the temperature gradient. The surface temperature gradient is obtained by taking the difference of two consecutive temperature data. The surface temperature is considered as the rewetting temperature when a sharp rise in temperature gradient value is observed [21]. The sharp rise in temperature gradient is observed when the temperature gradient falls in the range of 250 - 300 ˚C/s. Thus the surface temperature corresponding to these gradient values is considered as rewetting temperature. The time difference between the initialization of jet impingement and the time at which surface rewetting starts is termed as wetting delay [15, 17]. The rewetting velocity at particular radial location is the measure of the radial distance travel by the wetting front from the stagnation point. Thus at a particular radial location it is obtained by taking the ratio of radial distance of that location from the stagnation point to the wetting delay at the same location [9].

Rewetting temperature reduces for downstream locations away from stagnation point for entire range of Reynolds number examined. As the jet strikes on hot surface at the stagnation point a wet patch was formed with in 0.08sec for Re=5000. Whereas this patch formation takes only 0.04 sec for Re=24000. The formation of wet patch at stagnation region can be due to immediate cooling or wetting of that region. The temperature of the surface at this condition was recorded around 794 – 796ºC. The rise in surface temperature gradient was also seen at these temperatures value. Thus, rewetting of surface at stagnation point was assumed to be at 794 – 796ºC. The rewetting temperature at 16 mm radial location was observed in the range of 761-765ºC for Re=5000. These value increased to 766-771ºC, 775-780ºC and 781-784ºC for Re=10000, 16000, 24000 respectively. The drop in rewetting temperature at radial distance may be due to rise in temperature of fluid over the surface at some radial location as compare to fresh fluid which strikes at the stagnation point. The effect of fluid temperature rise on rewetting temperature at radial location was the same as the effect of liquid sub cooling on the rewetting temperature [8].

The effect of Reynolds number and jet exit to surface spacing, 'z/d' on rewetting temperature is shown in Figure 4. It is observed that with the rise in Reynolds number Rewetting temperature increases whereas spacing 'z/d' does not affects it significantly. The rise in Reynolds number is corresponding to the rise in liquid mass flux and it was well established that with the rise in mass flux rewetting temperature increases [8, 13]. With the rise in spacing, ‘z/d’, rewetting temperature rises continuously for Re = 5000, whereas at higher Reynolds number it has no particular trend. The increasing trend in rewetting temperature with the rise in spacing at Re = 5000, may be due to effect of gravity on jet velocity striking at surface. The jet velocity increase with the rise in jet exit to surface spacing and the effect of spacing is more at lower Reynolds number than the higher value. With the rise in jet velocity rewetting temperature increases as the surface cooling take place much faster than the lower velocity jet.

The variation in wetting delay with the Reynolds number and jet exit to surface spacing at 16 mm radial location is shown in Figure 5. With the rise in Reynolds number wetting delay reduces drastically. However the effect of change in spacing, ‘z/d, is 5 percent without any specific trend. The wetting delay at 16 mm radial location is in the range of 1.81-1.91 sec for Re = 5000, which reduces by 22 percent, 65 percent and 80 percent respectively for Re = 10000, 16000 and 24000.

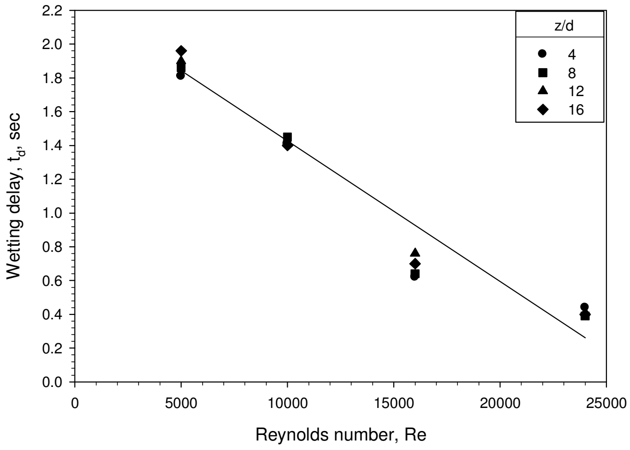


Figure 5. Wetting Delay with z/d

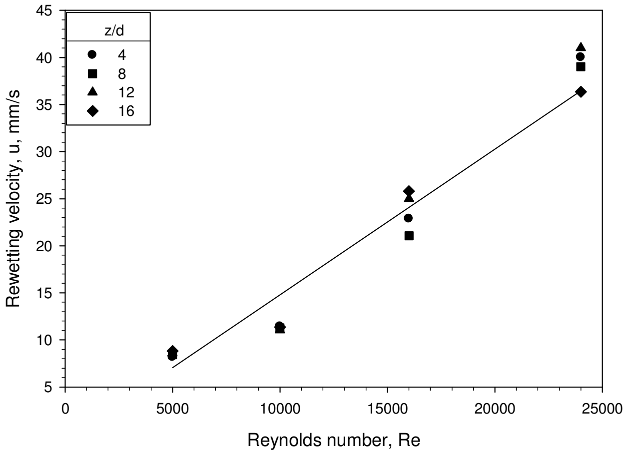


Figure 6. Rewetting Velocity with z/d

Contrary to the wetting delay, the rewetting velocity for 16 mm radial location increases with the rise in Reynolds number. The variation of rewetting velocity with the Reynolds number is shown in Figure 6. For Re = 5000 rewetting velocity observed was 8-9 mm/s which increases to 37 - 41 mm/s at Re = 24000. The increase in rewetting velocity with the rise in Reynolds number is due to higher heat transfer rate and higher jet flow associated with the higher Reynolds number. The higher heat transfer rate in the wet region can further lead to precursory cooling of nearby dry region. This results in lower surface temperature for downstream location and with the lower surface temperature the rewetting velocity increases [6, 19]. Both these two factors, increase in flow rate and reduction in surface temperature results leads to rise in rewetting velocity. The effect of change in jet exit to surface spacing on rewetting velocity is also observed in the range of 5 percent with the average value.

V. CONCLUSIONS

With the experimental investigation of round jet impingement of 78ºC sub-cooled water on the hot SS surface of 800 ºC initial temperature, the following conclusions has been made.

A wet patch is formed at stagnation region, immediate as water jet strikes on the hot surface. The Formation of wet patch is not affected by change in Reynolds number and jet exit to surface spacing, ‘z/d’. However at 16 mm radial location rewetting temperature and rewetting velocity increases with the rise in jet Reynolds number from 5000 - 24000. Whereas wetting delay reduces with the rise in the jet Reynolds number. The rise in flow rate and heat transfer with the rise in Reynolds number is responsible for such behavior.

The effect of change in jet exit to surface spacing on wetting delay and rewetting velocity is found in the range of 5 percent with the average value without any specific trend for all jet Reynolds number.

NOMENCLATURE

A	*surface area of sheet, m^2*
Bi	*Biot number, hw/k_{sur}*

d	*nozzle exit or tube exit diameter, m*
h	*heat transfer coefficient,* $W/m^2.K$
I	*current, A*
k	*thermal Conductivity of coolant, W/m.K*
q"	*heat flux,* W/m^2
Re	*Reynolds number; ud/υ,*
r	*radial distance, m*
t	*time, sec*
T	*temperature,* ^oC
u	*rewetting velocity, m/s*
U	*jet exit velocity, m/s*
V	*voltage drop, V*
v	*volume of sheet*
w	*thickness of sheet, m*
z	*distance between jet exit to target surface, m*
z/d	*dimensionless jet exit to surface spacing*

Greek symbols

ρ	*density of material,* kg/m^3
υ	*kinematic viscosity of air,* m^2/s
α	*thermal diffusivity of surface,* m^2/s
$Cos\phi$	*power factor*

Suffix

e	*experimental values*
j	*jet*
o	*stagnation value*
p	*predicted values*
rew	*rewetting*
wet	*wetting*
s	*surface*

REFERENCES

1. *Barnea Y. and Elias, E., 1994, "Flow and Heat Transfer Regimes During Quenching of Hot Surfaces", Int. J. Heat Mass Transfer, Vol. 37, pp 1441−1453, 1994*

2. *Bernardin, J.D., and Mudawar, I., 1999, "The Leidenfrost Point: Experimental Study and Assessment of Existing Models", ASME Journal of heat transfer, vol. 121, pp 894 - 903.*

3. *Carbajo, J.J., 1985, "A Study on the Rewetting Temperature", Nuclear Engineering and Design, vol. 84, pp. 21-52.*

4. *Casamirra, M., Castiglia, F., Giardina, M., Lombardo, C., Celata, G.P., Mariani, A., and Saraceno, L., 2005, "Rewetting of a hot vertical surface by liquid sprays", Exp. Thermal and Fluid Science, vol. 29, pp. 885-891.*

5. *Celata, P. G., Cumo, M., Mariani, A., and Saraceno, L., 2009, "A comparison between spray cooling and film flow cooling during the rewetting of a hot surface", Heat and Mass Transfer, vol. 45, pp. 1029 -1035.*

6. *Chan, A. M. C. and Banerjee, S., Refilling and Rewetting of a Hot Horizontal Tube, PartI: Experiments, Trans. ASME, Journal of Heat Transfer, Vol. 103, pp. 281−286, 1981.*

7. *Chen, S.J., Kothari, J., and Tseng, A.A., 1991, "Cooling of a Moving Plate with an Impinging Circular Water Jet", Experimental Thermal and Fluid Science, vol 4, pp. 343-353*

8. *Dhir, V.K., Duffey, R.B., and Catton, I., 1981, "Quenching studies on a Zircaloy rod bundle", J. of Heat Transfer, vol. 103, 1981, pp.293-299*

9. *Dua S.S., and Tien, C.L., 1978, "An Experimental Investigation of Falling-Film Rewetting", International journal of Heat and Mass Transfer, vol. 21, pp. 955− 965.*

10. *Duffey, R.D., and Porthouse, D.T.C., 1973, "The physics of rewetting in water reactor emergency core cooling", Nuclear engineering and design, vol 25, pp. 379- 394.*

11. *Hall, D. E., Incropera, F.P., and Viskanta, R., 2001, "Jet Impingement Boiling From a Circular Free-Surface Jet During Quenching: Part 1—Single Phase Jet", ASME Journal of Heat Transfer, vol. 123, pp. 901-909.*

12. *Hammad, J., Mitsutake, Y., and Monde, M., 2004, "Movement of maximum heat flux and wetting front during quenching of hot cylindrical block", International Journal of Thermal Sciences, vol. 43, pp. 743–752.*

13. *Iloeje, O. C., Plummer, D. N., Rohsenow, W. M. and Griffith, P., 1982, "Effect of Mass Flux, Flow Quality, Thermal and Surface Properties of Materials on Rewet of Dispersed Flow Film Boiling", ASME, Journal of Heat Transfer, Vol. 104, pp. 304−308.*

14. *Islam M.A., Monde M., Woodfield P.L. and Mitsutake, Y., 2008, "Jet impingement quenching phenomena for hot surfaces well above the limiting temperature for solid–liquid contact", International Journal of Heat and Mass Transfer, vol. 51, pp. 1226–1237.*

15. *Mozumder, A.K., Monde, M., and Woodfield, P.L., 2005, "Delay of wetting propagation during jet impingement quenching for a high temperature surface", International Journal of Heat and Mass Transfer, vol. 48, pp. 5395–5407.*

16. *Piggott, B. D.G., and Porthouse, D.T.C., 1975, "ACorrelation of Rewetting Data", Nuclear Engineering and Design, vol 32, pp. 171-181.*

17. *Piggott, B.D.G., White, E.P., and Duffey, R.B., 1976, Wetting Delay Due To Film And Transition Boiling On*

Hot Surfaces", Nuclear Engineering and Design, vol 36, pp. 169-181.

18. *Raj, V. V., 1983, "experimental investigation on the rewetting of hot horizontal annular channels", Int. Comm. Heat Mass Transfer, vol. 10, pp. 299- 311.*

19. *Saxena, A.K., Raj, V.V., and Rao, V.G., 2001, "Experimental Studies on Rewetting of Hot Vertical Annular Channel", Nuclear Engineering and Design, vol. 208, pp 283−303.*

20. *Stevens, J. and Webb, B.W., 1991, "local heat transfer coefficients under an axisymmetric, single- phase liquid jet", ASME Journal of Heat Transfer, vol. 113, pp. 71- 78.*

21. *Ueda, T, And Inous, N., 1984, "Rewetting Of A Hot Surface By A Falling Liquid Film-Effects Of Liquid Subcooling", International Journal Of Heat Mass Transfer, Vol. 27(7), pp. 999 -1005.*

22. *Wang X. S., Dagan, Z. And Jiji, L.M., 1989, "Heat transfer between a circular free impinging jet and a solid surface with non-uniform wall temperature or wall heat flux-l. Solution for the stagnation region", Int. J. Heat and Mass Transfer. Vol. 32 (7) pp. 1351-1360*

23. *Wolf, D.H., Viskanta, R., and Incropera, F.P., 1995, "Turbulence Dissipation in a Free -Surface Jet of Water and Its Effect on Local Impingement Heat Transfer From a Heated Surface: Part 2-Local Heat Transfer," ASME Journal of Heat Transfer,vol.117, pp.95-103.*

24. *Womac, J., Ramadhyani, S., and Incropera, F.P., 1993, "Correlating Equations for Impingement Cooling of Small Heat Sources With Single Circular Liquid Jets", ASME J. of heat transfer, vol. 115, pp. 106-115.*