REWETTING OF HOT SURFACE WITH IMPINGING LIQUID JET

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The rewetting of a heated surface at temperature higher than Leidenfrost temperature with liquid impinging jet is investigated experimentally and analytically. The measurements of water jet characteristic such as mass flow rate and Reynolds number are produced using a long tube with length of 50-jet diameter. The jet diameter of 4 and 7 *mm* are used. The heated surface is mounted horizontally at 0.1 *m* downstream of the water jet. A copper specimen with diameter of 0.15 *m* and thickness of 0.03 *m* was used as a heat transfer target. The specimen was heated up to 700 °C and exposed to the water jet. The change of temperature with time, at five positions inside the metal specimen at 2 *mm* from the heated surface is recorded with a data acquisition system. The surface heat transfer coefficient and rewetting front velocities at Leidenfrost temperature are experimentally estimated from the numerical solution of one-dimensional heat conduction model in transient mode. A comparison between experiments and predictions are made and the agreement was found satisfactory. The effect of jet Reynolds number and mass velocity are found the most dominant parameters on the rewetting front velocity. Closed correlation equations of Nusselt and Stanton numbers have been developed to estimate the surface heat transfer coefficient and rewetting front velocity of a heated surface at Leidenfrost temperature with accuracy of about ± 10 % in the entire range of $7 \times 10^3 \leq Re_j \leq 6 \times 10^4$.

تم دراسة إعادة تبلل السطح الساخن عند درجة حرارة مرتفعة بواسطة ارتطام بوق من السائل عمليا" وتحليليا" ، تم قياس خصائص بوق السائل المرتطم بالسطح الساخن مثل معدل السريان ورقم الرينولدز الناتج باستخدام أنبوب بطول ٥٠ ضعف القطر الداخلى الذى يتراوح من ٤ حتى ٧ مم ، والسطح الساخن تم وضعه أفقيا" على بعد ١٠ سم من فتحة خروج البوق ، والسطح الساخن لعينة من النحاس بقطر ١٥ سم وسمك ٣ سم استخدمت كهدف لارتطام السائل بالسطح الساخن ، وعينة النحاس سخنت حتى درجة حرارة ٧٠٠ °م فى فرن غاز ثم عرضت لبوق السائل ، قياس درجات الحرارة داخل عينة النحاس على بعد ٢مم من السطح تم بواسطة ازدواج حرارى عند خمس مواضع ، تغير درجة الحرارة مع الزمن داخل عينة المعدن سجلت بواسطة دائرة معلومات وحاسب آلى ، حساب درجة حرارة السطح الساخن ومعامل انتقال الحرارة إلى الماء المرتطم بالسطح تم حسابها من الحل العددى لنموذج انتقال الحرارة ذو بعد واحد فى الطور الغير مستقر ، مقارنة النتائج العملية بالنتائج التى تم التنبئ بها كانت مرضية ، وقد وجد أن رقم الرينولدز ومعدل السريان لهما الأثر الأعظم فى إعادة تبلل السطح الساخن ، ومن النتائج المحسوبة تم الحصول على معادلة لرقم نسلت ورقم ستانتن لحساب معامل انتقال الحرارة وسرعة تبلل السطح الساخن بدقة تعادل ١٠ % خطأ لحدود رقم الرينولدز من ٧٠٠٠ حتى ٦٠٠٠٠ .

Keywords: Impinging jet, Surface rewetting, Inverse heat conduction, Leidenfrost temperature, Rewetting mechanism

INTRODUCTION

Liquid impinging jet is often used to provide simple and efficient cooling process. Quenching of steels during rolling processes, cooling of the rollers themselves during hot rolling and hot strip mill in continuous casting machines are of significant importance in metallurgical production. Applications of jet impingement cooling are varied, and include processing of both metals and molded plastics, cooling of high-efficiency aircraft generator coils, and cooling of certain electronic modules. The emergency cooling of fuel elements in water-cooled nuclear reactors during loss-of-coolant accidents (LOCA) is of interest to prevent excessive temperature rise of fuel cladding [1-3]. The design of evaporative cooler and other heat transfer augmentation devices, and more recently, in applications involving the thermal control of high density electronic components and two-phase heat rejection systems for spacecraft thermal control is a function of the liquid jet impingement process [4]. The liquid jets are also being examined as a tool for the thermal management of electronic components [6-7]. The rewetting of liquid film flows over a heated surface at temperature higher than the Leidenfrost temperature is of significant importance in many applications. Circular liquid jets are of particular value in creating extremely high heat transfer coefficients over relatively localized areas. The corresponding piping systems have the added attraction of being inexpensive and easy to install [2]. Such jets lend themselves to either convective boiling or to nonevaporative convection, but in both situations the cooling efficiency varies with the radial distance from the point of impact. Numerous analytical and experimental studies have been conducted and provided substantial data and considerable insight into several aspects of the wetting behavior of the flowing liquid films upon heated surface, some of the resulting conclusions have been contradictory [3].

Historically, it has been assumed that the wetting velocity of thin liquid films was strongly dependent on the initial temperature of the surface over which the liquid was flowing. Since this assumption appeared to be supported by the experimental data obtained in several independent investigations, the initial surface temperature was frequently included in the analytical correlation developed to predict the wetting velocity of these flowing liquid films [3-5]. However a recent analysis [3-7] indicated that the wetting velocity was, in fact, independent of the initial surface temperature. By re-evaluating the previously obtained experimental data it was shown that in the initial investigations, some of the fundamental phenomena were not clearly understood and, as a result inappropriate assumptions were made in the data reduction process [4]. When the liquid jet is directed onto a hot surface at temperature higher than Leidenfrost temperature, the impinging liquid spreads into a thin film and splatters, and does not wet the impinging area. The wetting delay occurs between jet initiation and the formation of a wet under the impinging zone [1]. This wet spreads until the surface is wetted and the liquid flows over the heated surface.

The objective of the present study is to investigate experimentally the effect Reynolds number on the wetting process occurring when the liquid films come into contact with the heated surface at Leidenfrost temperature. The validity of surface rewetting front velocity was examined analytically by investigating the impinging liquid jet upon a heated surface to determine how variations in liquid thickness and average velocity in the liquid sheet affect the surface rewetting front velocity.

EXPERIMENTAL APPARATUS

Experiments were performed to measure the temperature distribution for a heated surface under the impinging liquid jet. The experimental setup serves two groups of experiments. The first is for measuring the impinging water flow rate. The liquid jets were produced using long tubes with 0.6 *m* length and diameters of 4 and 7 *mm*. The second is concerned with recording the temperature radial distribution of the quenching process inside a copper specimen using a data acquisition system. The K-type thermocouples with outside diameter of 1 *mm* are used to measure all the temperatures inside the metal specimen and the signal are send to a personal computer. The schematic of experimental setup for measuring the temperature is shown in Figure 1.

The water jets are axisymmetric and the liquid from the jet impinges at 0.1 *m* between the jet exit and impinging surface and spreads out radially. The jet is fed by water from a pumping system at an adjustable mass flow rate 0.04 to 0.193 *kg/s*. A copper disc of 0.15 *m* diameter and 0.03 *m* thickness was used as a heat transfer target. Five thermocouples affixed to the underside of the plate at 2 *mm* from the impinging surface. The first thermocouple is at the center of the plate and the other thermocouples at radial pitch of 0.01 *m*. Prior to each experimental run, the upper surface of the specimen was polished with emery paper to mirror-like surface finish and cleaned with Acetone. The copper specimen was heated up to 700 °C in a gas furnace. After the specimen being heated, the water is started by setting the water flow rate as desired and intercepted. Thereafter, the copper specimen is clamped from the furnace and the cooling process is started at about 600 °C until the specimen is cooled to the room temperature. During the cooling process, the temperatures at five positions were monitored and recorded by a data acquisition system (National Instrument trade mark, NI-DAQ board AT-MIO 16 for ISA Desktop PC with 1.25 MS/s sampling rate).

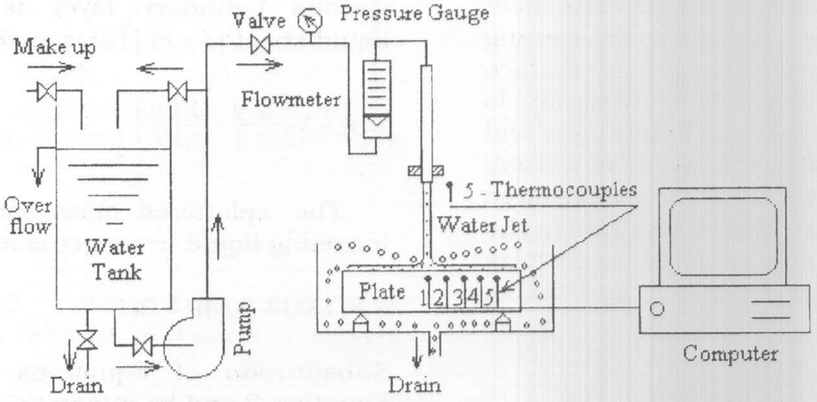


Figure 1 Schematic of the experimental apparatus

MECHANISM OF SURFACE REWETTING

The basic physical mechanism of rewetting a heated surface at temperature higher than Leidenfrost temperature has been discussed in previous studies [2, 8, 9]. When the liquid jet strikes the heated surface, some of liquid is splattered as droplets at impact and the residual liquid spreads into a film along the surface as shown in Figure 2. The associated flow regimes along the surface can be classified as follows,

1. *Impact zone*: A very thin wall boundary layer with a turbulent free stream.
2. *Region before splattering*: Disturbances in the liquid sheet are strongly amplified, the wall boundary layer is affected by turbulence.
3. *Region of splattering*: A portion of the liquid sheet breaks free as droplets owing to the instability of the disturbed liquid sheet.
4. *Region after splattering*: Having lost both mass and momentum in the splattering process, the remaining liquid sheet continuous to flow outwards. The liquid sheet is fully turbulent and a thin vapor layer is formed under the liquid sheet.

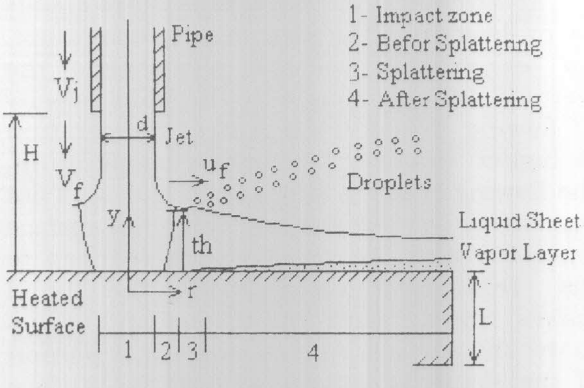


Figure 2 The configuration of surface rewetting mechanism

The heat transfer between the heated surface and the impinging liquid in the impact zone is relatively high due to the deformation of the incoming liquid and turbulance. So the surface temperature at the impact zone is intensively decreased and the wetting occurs after short time from the jet initiation. Outside the impact zone, the heat removal from the surface is weak due to the thin vapor film formed upon the heated surface and separates the flowing liquid from the heated surface. The heat transferred from the surface in the wetting area is by direct contact between the surface and liquid, but outside the wetting area is by conduction through the vapor layer and liquid sheet. Gradually, the radius of wetting area increases until it covers the whole area of the heated surface. The growth rate in the radius of wetting area is called the wetting velocity and is shown in Figure 3 and can be defined as,

$$\int U_w \, d\tau = \int dr \qquad (1)$$

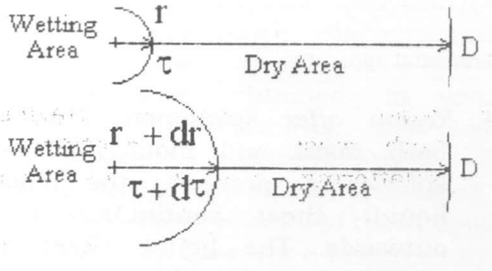


Figure 3 The wetting velocity upon the heated surface

At an initial surface temperature equals to or less than the saturation temperature, no evaporation occurs and hence the wetting velocity equals to the front velocity of flowing liquid. If the surface temperature is higher than the Leidenfrost temperature, the flowing liquid is suspended and does not contact or wet the surface. Once the surface is cooled and the temperature reduces to the Leidenfrost temperature, the liquid makes contact with the surface and begins to wet the surface. At this moment, a portion of the liquid is splattered from the surface and the wetting velocity will be less than the velocity of the flowing liquid. At the radial position just before splattering, the ratio of mass in the boundary layer to the total incoming liquid in the jet ($r/d \leq 4.5$) is as follows [2]:

$$\psi = \frac{2\pi r \int_0^{\delta} u(y)\,dy}{\frac{\pi}{4} d^2 V_f} \qquad (2)$$

The velocity distribution in the viscous boundary layer, where the thickness of the viscous boundary layer is less than the liquid sheet ($\delta < h$) [12] is as follows:

$$u(y) = V_f \left[\frac{3}{2}\frac{y}{\delta} - \frac{1}{2}\left(\frac{y}{\delta}\right)^3 \right] \qquad (3)$$

The splattered mass ratio to the total incoming liquid in the jet is as follows:

$$\psi = 13.34\,(r/d)^{1.5}\,Re_j^{-0.5} \qquad (4)$$

Substitution of Equations 3 and 4 into Equation 2 and by integration, we obtain the following relation for the thickness of the viscous boundary layer:

$$\delta = 2.668\left(\frac{rd}{Re_j}\right)^{0.5} \qquad (5)$$

The fraction of the splattered flow to the total incoming liquid from the jet was formulated from the experimental data in Reference 2 and we could get a closed correlation, as shown in Figure 4, as follows:

$$\xi = 5.826 \times 10^{-11}\,\omega^{2.511} \qquad (6)$$

Where ω is a dimensionless group defined as:

$$\omega = We_j \exp\left(\frac{0.971}{\sqrt{We_j}}\frac{H}{d}\right) \qquad (7)$$

The jet-to-surface spacing H was maintained at 0.1 *m* for all experiments. The jet Reynolds and Weber numbers were based on the conditions at jet exit diameter and velocity. The free liquid velocity in the impact zone was corrected for gravitational acceleration by the expression of the following form,

$$V_f = (2gH + V_j^2)^{1/2} \qquad (8)$$

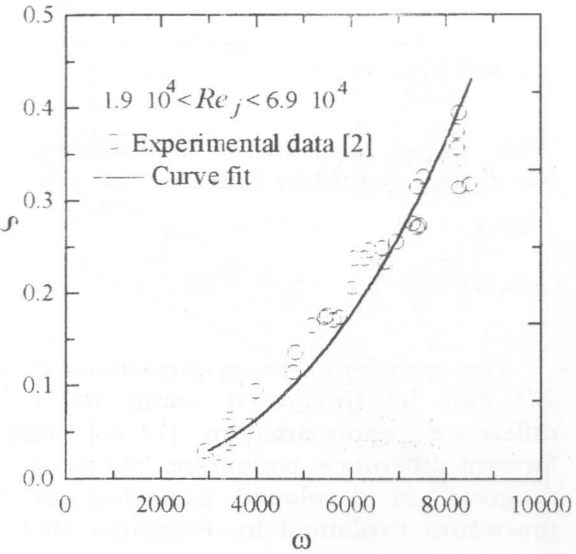


Figure 4 The splattering ratio from incoming mass

The liquid sheet remaining after splattering as shown in Figure 5 carries momentum as:

$$2\pi r\rho\left[\int_0^{\delta} u^2(y)dy + \int_{\delta}^{th} u_f^2 dy\right] = 2\pi r\rho\, th\, u_f^2\chi \qquad (9)$$

Where χ is the ratio of average momentum in The liquid layer at splattering region [2], and is defined as,

$$\chi = 0.125\,(1-\xi)\frac{d}{r} - 0.373\left(\frac{r}{d\,Re_j}\right)^{0.5} \qquad (10)$$

The velocity distribution in the liquid sheet after splattering was measured for laminar and turbulent flow [13], and the 1/7th power law is a good approximation as follows,

$$U(y) = u_f\left(\frac{y}{th*}\right)^{1/7} \qquad (11)$$

The average velocity in the liquid sheet is defined as,

$$u^* = \frac{1}{th^*}\int_0^{th^*} u_f\left(\frac{y}{th^*}\right)^{1/7} = \frac{7}{8}u_f \qquad (12)$$

And,

$$u^{*2} = \frac{1}{th^*}\int_0^{th^*} u_f^2\left(\frac{y}{th^*}\right)^{2/7} = \frac{7}{9}u_f^2 \qquad (13)$$

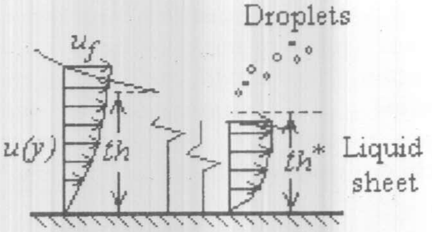


Figure 5 Flow field during splattering

Where u_f is the surface velocity of the liquid sheet after splattering. The balance of mass and momentum flow in the liquid sheet gives the following relations,

$$2\pi r\rho th * \frac{7}{8}uf = \frac{\pi}{4}d^2\rho V_f(1-\xi) \qquad (14)$$

$$2\pi r\rho th * \frac{7}{9}u_f^2 = 2\pi r\rho th u_f^2\,\chi \qquad (15)$$

At a radius with, $r/d \geq 4.5$, and with substitution of Equation 14 into 15 and rearranging the results, we can obtain the following relation for the thickness of liquid sheet as follows:

$$th = \frac{(1-\xi)d^2}{9\chi\, r}\frac{V_f}{u_f} \qquad (16)$$

At this liquid sheet thickness, the surface wetting velocity was assumed to be the mean value of mass velocity in the liquid sheet after multiplying in a similarity factor ϕ. The surface wetting front velocity can be calculated from the mass balance between the liquid sheet and the incoming liquid from the jet after splattering. The global continuity at a given radial position is as follows,

$$2\pi r\, th\rho U_w\phi = \frac{\pi}{4}d^2\rho(1-\xi)V_f \qquad (17)$$

Which upon rearranging yields the surface rewetting front velocity as,

$$U_w = \frac{1}{8\phi}\frac{d^2(1-\xi)}{r\,th}V_f \qquad (18)$$

Where ϕ is a similarity factor (*the similarity between rewetting front velocity and the mean value of mass velocity in the liquid sheet upon the heated surface at rewetting conditions*). We suggested a similarity equation to validate the above procedures, and it is defined as follow,

$$\phi = 25\left(\frac{d}{r}\right)^{0.8} \tag{19}$$

The similarity factor between the average velocity in the liquid sheet and the surface rewetting front velocity is about 4 to 10 times, and it depends on the radial position from the jet centerline. So, the constants 25 and 0.8 are re-adjusted from the present experimental data to reduce the differences between predictions and experiments to ± 5%.

HEAT TRANSFER ANALYSIS

The problem of interest in this particular investigation is to determine the rewetting front velocity of liquid flowing upon the heated surface at initial temperature higher than the Leidenfrost temperature. To solve this problem, the following assumptions were made:

1. The transient heat conduction in the copper specimen is one-dimensional and no additional heat was supplied to the specimen.
2. The liquid flowing is at bulk temperature of incoming liquid from the jet except a thin layer adjacent to the surface at saturation temperature.
3. The heat transfer coefficient between the heated surface and liquid includes evaporation and radiation heat.
4. The liquid begins to wet the surface when the surface temperature decreases from initial temperature to the Leidenfrost temperature.

Utilizing these assumptions, the one-dimensional heat conduction model can be recognized as,

$$k_s(T)\frac{\partial^2 T}{\partial y^2} = \rho_s\, C_s(T)\frac{\partial T}{\partial \tau} \tag{20}$$

With initial temperature of specimen and the surface boundary condition as,

$$\begin{aligned} &T(y, r, \tau) = T_0, \qquad \text{at } \tau = 0 \\ &-k_s(T)\left.\frac{\partial T(y,\tau)}{\partial y}\right|_{y=0} = h_s(T_s - T_{sat}) \end{aligned} \tag{21}$$

The transient energy (Equations 20 and 21) can be integrated using the finite-difference approximation [14,15], and a forward-difference technique. A calculation program is developed according to the procedure explained in Reference 16-19 to predict the temperature distribution inside the specimen and is compared with the measured values at each position. The calculation steps are repeated at each interval of time until the surface temperature and surface heat transfer coefficient are readily obtained. After that, we may now calculate the Nusselt and Stanton number on the surface at rewetting front velocity as,

$$Nu_s = \frac{h_s d}{k_l} \tag{22}$$

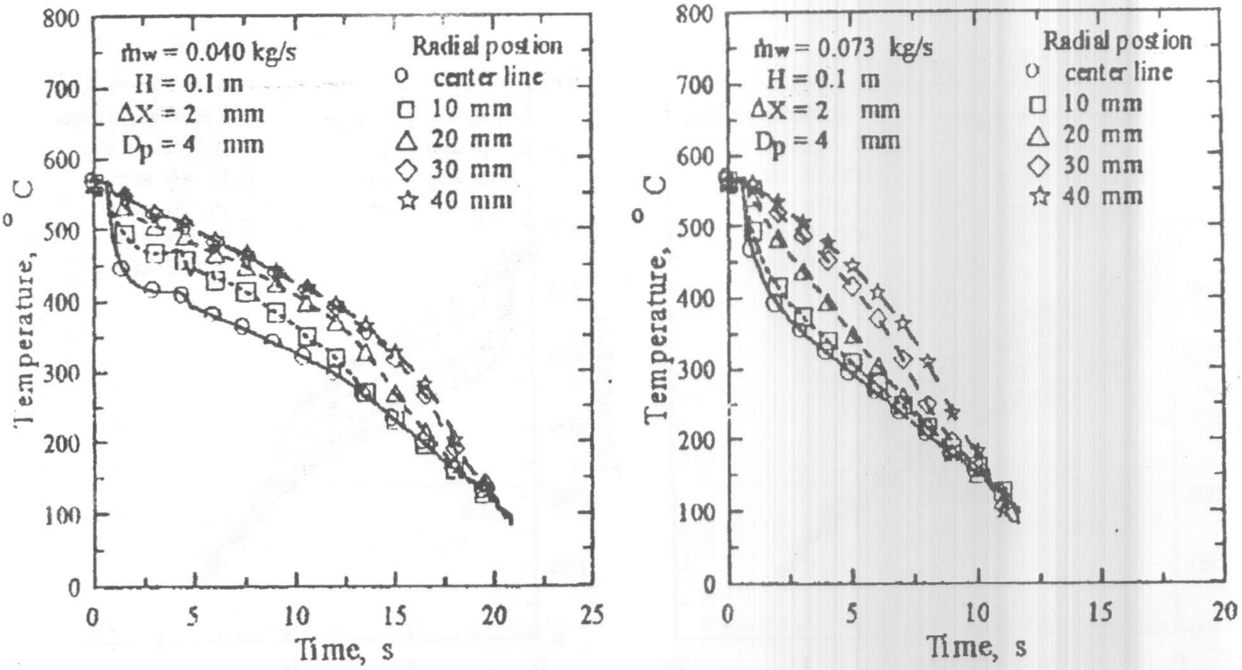
$$St_s = \frac{h_s}{\rho_l\, C_p\, U_w} \tag{23}$$

Where h_s is the surface heat transfer coefficient at rewetting condition and Leidenfrost temperature, which includes the evaporation and radiation heat.

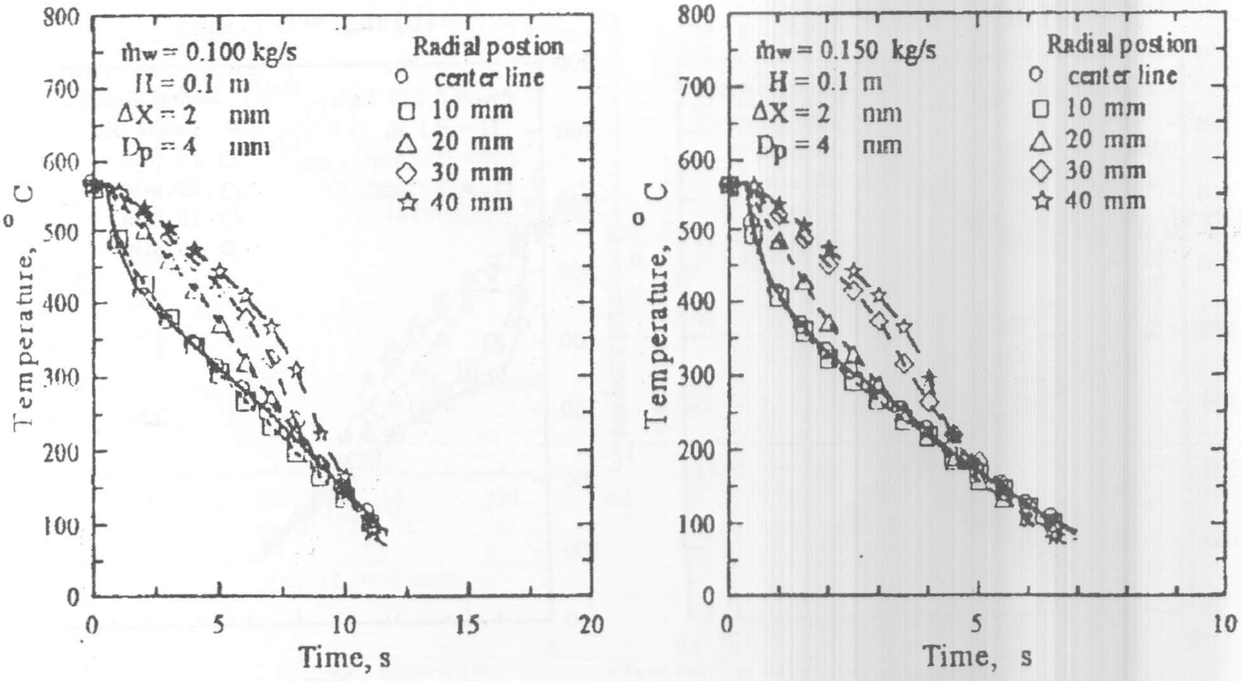
RESULTS AND DISCUSSION

Surface Heat Transfer

The results of the experimental program are presented in Figures 6 to 9. The five measured temperatures at 2 *mm* from the surface of the copper specimen versus time were illustrated in Figures 6 and 7 at various impinging liquid mass velocity.

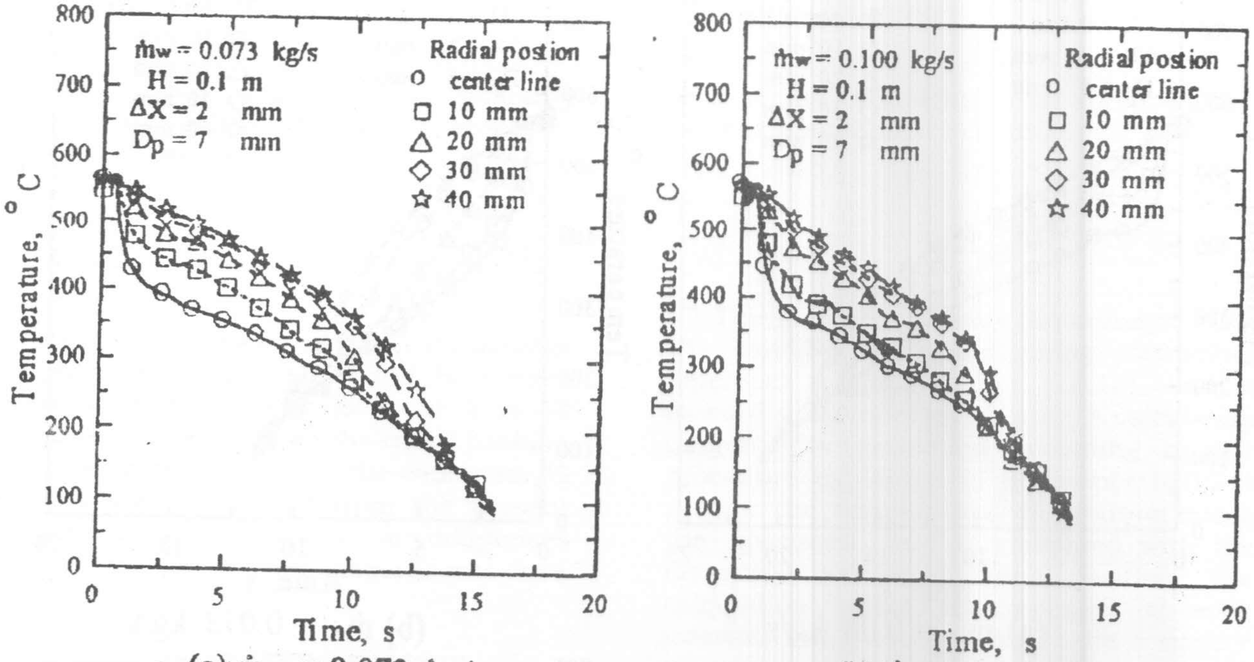


(a) $\dot{m}_w = 0.04$ kg/s (b) $\dot{m}_w = 0.073$ kg/s



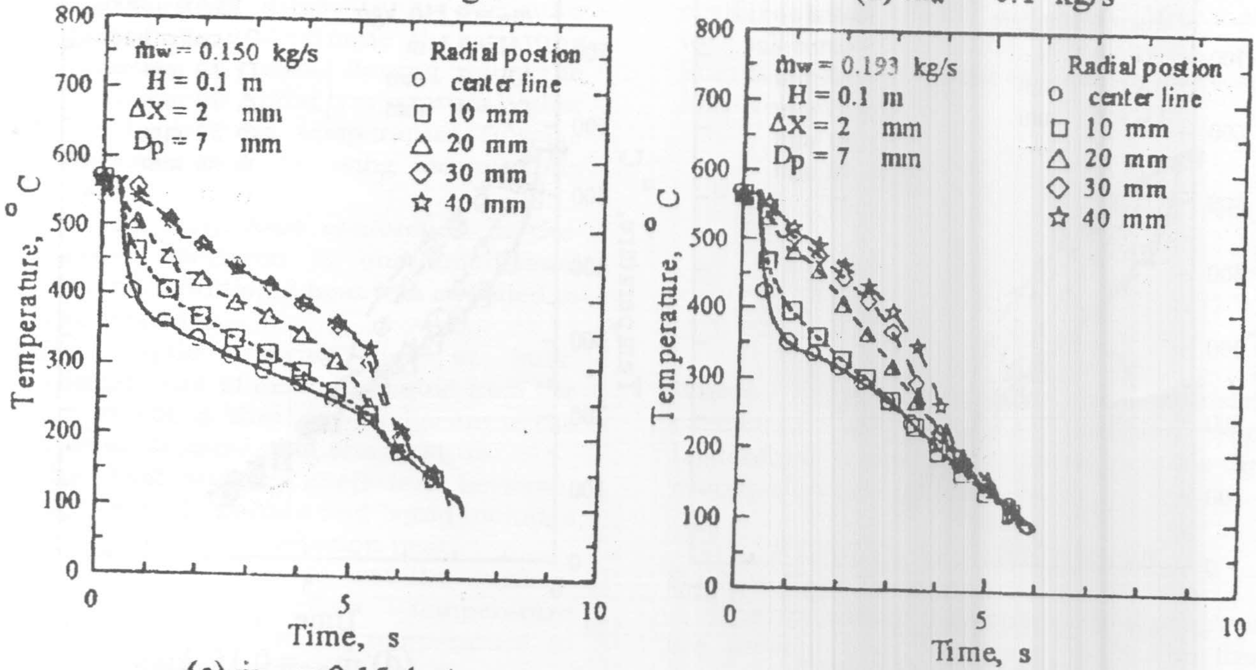
(c) $\dot{m}_w = 0.1$ kg/s (d) $\dot{m}_w = 0.15$ kg/s

Figure 6 Temperature-time history for jet diameter, D_p = 4 mm.



(a) $\dot{m}_w = 0.073$ kg/s

(b) $\dot{m}_w = 0.1$ kg/s



(c) $\dot{m}_w = 0.15$ kg/s

(d) $\dot{m}_w = 0.193$ kg/s

Figure 7 Temperature-time history for jet diameter, D_p = 7 mm

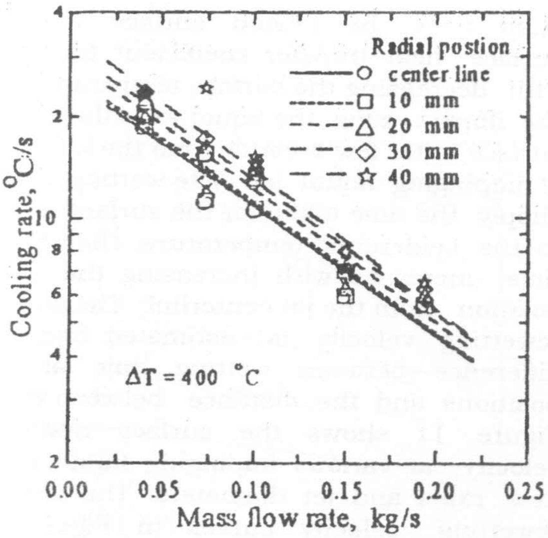


Figure 8 Effect of impinging mass on cooling rate

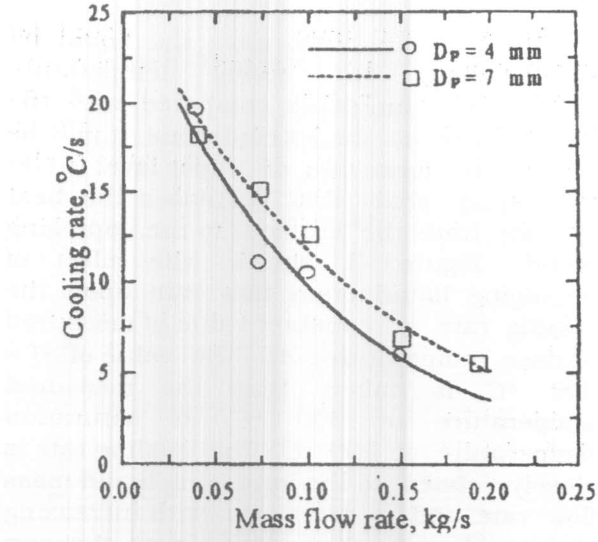
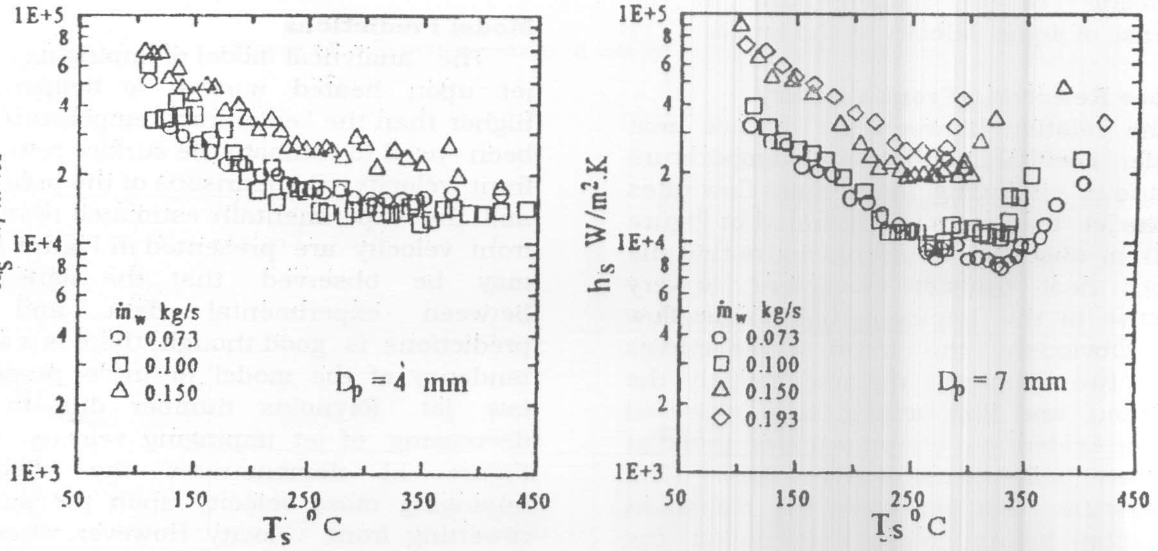


Figure 9 Effect of jet diameter on cooling rate



(a) $D_p = 4$ mm

(b) $D_p = 7$ mm

Figure 10 h_s verses T_s at various impinging liquid jet

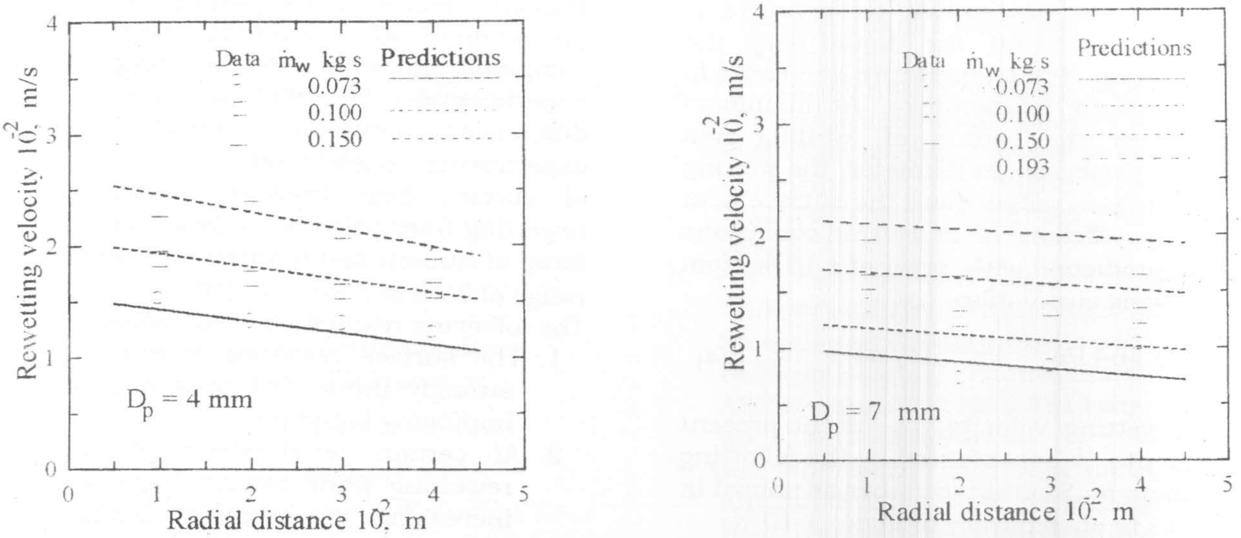
At a certain time, after the liquid jet impingement, the radial temperature distribution increases compared with the temperature at the jet centerline. It may be due to the formation of vapor layer under the liquid sheet that decreases the heat transfer from the surface to the impinging liquid. Figure 8 shows the effect of impinging liquid mass flow rate upon the cooling rate at constant value of measured surface temperature, ΔT. The value of $\Delta T = 400\ ^{o}C$ is taken from the measured temperature of $500\ ^{o}C$ to saturation temperature of $100\ ^{o}C$. The cooling rate is closely related to the impinging liquid mass flow rate and it decreases with increasing the liquid mass flow rate. Figure 9 shows the effect of jet diameter upon the cooling rate at various impinging liquid mass flow rate. At certain impinging liquid mass flow rate, the cooling rate increases with increasing of jet diameter due to the decrease of liquid velocity in the liquid.

Surface Rewetting Front Velocity

The relation between the surface heat transfer coefficient and surface temperature at various impinging liquid mass flow rates at two jet diameters is illustrated in Figure 10. It is observed from this figure that the surface heat transfer coefficient is very sensitive to the impinging liquid mass flow rate. Obviously, the trend of the curves shows two important regions, namely, the transition and film boiling. It is observed that the Leidenfrost temperature occurred at a surface temperature of 280 to 320 °C. The temperature that separates the transition and film boiling regions is called the Leidenfrost temperature, (*temperature limit between film and transition boiling*). At the film boiling region and high surface temperature, the flowing liquid did not wet the heated surface due to the formation of vapor layer under the liquid sheet. But after the surface temperature has decreased to the Leidenfrost temperature, the flowing iquid wets the heated surface and the surface heat transfer coefficient increases with decreasing the surface temperature. At the impact zone, the liquid wets the heated surface after few seconds from the initiation of impinging liquid jet. The wetting time is simply the time taken for the surface to cool to the Leidenfrost temperature. The wetting time increases with increasing the radial position from the jet centerline. The surface rewetting velocity is estimated from the difference between wetting time at two positions and the distance between them. Figure 11 shows the surface rewetting velocity at various impinging liquid mass flow rates and jet diameters. The surface rewetting velocity curves in Figure 11 indicate that the rewetting velocity increases with the impinging liquid mass flow rate and decreases with increasing the radial position from the jet centerline.

Model Predictions

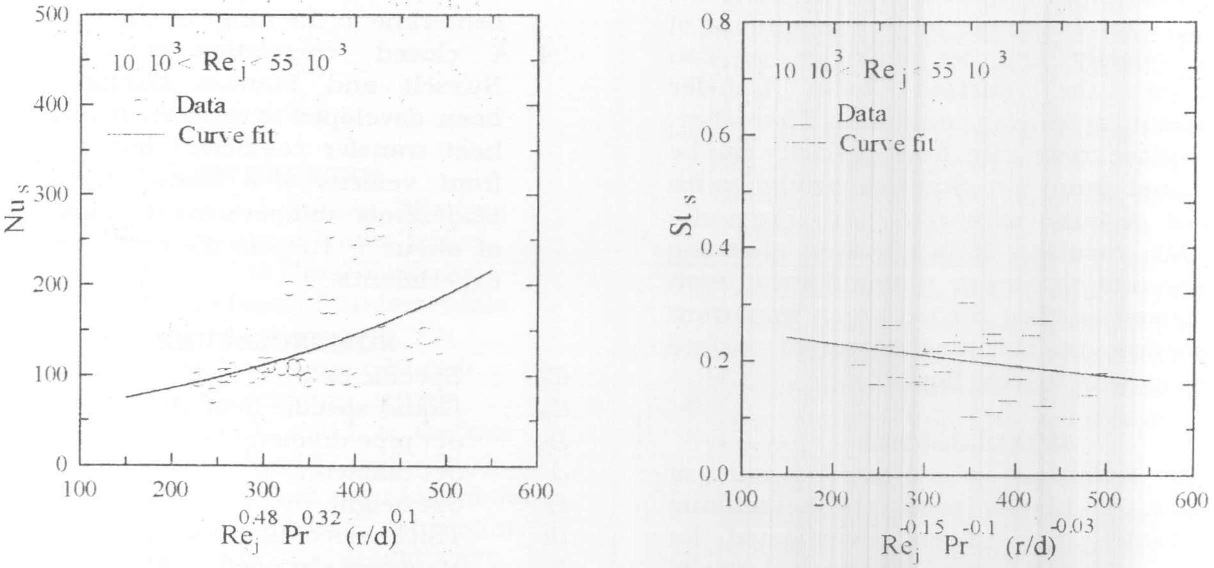
The analytical model of impinging liquid jet upon heated surface at temperature higher than the Leidenfrost temperature has been used to estimate the surface rewetting front velocity. Comparisons of the predicted and the experimentally estimated rewetting front velocity are presented in Figure 11. It may be observed that the agreement between experimental data and the predictions is good though; there is a slight tendency of the model to under predict at low jet Reynolds number due to the decreasing of jet impinging velocity. Also, Figure 11 demonstrates the effect of impinging mass velocity upon the surface rewetting front velocity. However, when the jet mass flow rate is kept constant and decreasing the jet diameter increases the jet velocity, the rewetting velocity increases due to the increase of the mean liquid velocity in the liquid sheet upon the heated surface. It is evident that the jet impinging velocity plays an important role in the wetting delay time and rewetting front velocity.



(a) D_p = 4 mm

(a) D_p = 7 mm

Figure 11 Rewetting velocity at two impinging liquid jet diameter



(a) D_p = 4 mm

(a) D_p = 7 mm

Figure 12 Nu_s and St_s number versus Peclet number

The surface heat transfer coefficient, h_s, and the rewetting front velocity, U_w, are plotted as functions of the dimensionless Peclet number as shown in Figure 12. It was found that the Leidenfrost temperature is about 300 °C, and the liquid wets the surface when the temperature decreases to the Leidenfrost temperature. At the impact zone, when the radius of wetting area becomes twice the jet diameter, the wetting area increases radially and the surface heat transfer coefficient, h_s, at wetting conditions can be predicted with error of ± 10 % from the following correlation:

$$\mathrm{Nu}_s = 0.464\,\mathrm{Re}_j^{0.48}\,\mathrm{Pr}_l^{0.32}(r/d)^{0.1} \qquad (24)$$

The wetting velocity, U_w, of the present experiments is represented by the following correlation of Stanton number as shown in Figure 12 to an accuracy of about ± 10 %:

$$\mathrm{St}_s = 1.14\,\mathrm{Re}_j^{-0.15}\,\mathrm{Pr}_l^{-0.1}(r/d)^{-0.03} \qquad (25)$$

For engineering applications, it is important to estimate the surface rewetting front velocity and heat transfer coefficient at the Leidenfrost temperature. First, from the Nusselt correlation at jet flow conditions of mass velocity and jet diameter, we can calculate the surface heat transfer coefficient at wetting conditions. Thereafter, the surface rewetting front velocity can be calculated from the Stanton correlation for surface radius, with $r/d \leq 15$. From the previous results, it is apparent that the velocity and thickness of liquid sheet upon the heated surface are extremely important parameters on the mechanism of surface rewetting with flowing liquid.

CONCLUSIONS

The rewetting of a heated surface at temperature higher than the Leidenfrost temperature has been investigated for impinging liquid jet. A theoretical model with semi-empirical equations of impinging liquid jet upon a heated surface solves the equations of mass and momentum balance enabling the instantaneous thickness of flowing liquid and velocity to be calculated. The surface heat transfer coefficient and the rewetting front velocity were experimentally estimated from the numerical solution of one-dimensional heat conduction model in transient mode. The experimental data and predictions of rewetting velocity are compared and refinements are suggested for experimental formula to reduce the difference between predictions and experiments to less than ± 5 %. The results of surface heat transfer coefficient and rewetting front velocity are formulated in the form of Nusselt and Stanton numbers in the range of $7 \times 10^3 \leq \mathrm{Re}_j \leq 6 \times 10^4$.

The following results are summarized:

1. The surface rewetting front velocity is strongly influenced by the velocity of impinging liquid jet.
2. At certain jet diameter, the surface rewetting front velocity increases with increasing of impinging liquid mass flow rate and decreases radially from the jet centerline.
3. The similarity factor between the average velocity in the liquid sheet and the surface rewetting front velocity is about 60 to 30 times, and it depends on the radial position from the jet centerline in the range of $r/d \leq 15$.
4. A closed correlation equations of Nusselt and Stanton numbers has been developed to estimate the surface heat transfer coefficient and rewetting front velocity of a heated surface at Leidenfrost temperature with accuracy of about ± 10 % in the entire range of experiments.

NOMENCLATURE

C_s : Specific heat, *J/kg.K*
C_{pl} : Liquid specific heat, *J/kg.K*
D_p : Jet pipe diameter, *m*
d : Jet diameter, *m*
H : Jet height, *m*
th : Thickness of liquid sheet, *m*
h_s : Heat transfer coefficient, *W/m².K*
g : Gravitational acceleration, *m/s²*
k_s : Thermal conductivity, *W/m. K*
L : Thickness of copper specimen, *m*
$\dot{m}$: Jet mass flow rate, *kg/s*
Nu : Nusselt number, $h_s d/k_l$,

P : Jet supply pressure, *Mpa*
P_r : Prantdl number, $C_{pl}\mu/k$
q : Heat flux, W/m^2
Re : Reynolds number, $\rho V_f d/\mu$
r : Radial coordinate, m
r_w : Radius of wetting area, m
T : Temperature, K
St : Stanton number, $h_s/\rho_l C_{pl} U_w$
U_w : Wetting front velocity, m/s
u_f : Liquid surface velocity, m/s
V_j : Liquid jet velocity, m/s
V_f : Liquid impinging velocity, m/s
We : Weber number, -
Δx : Thermocouple surface distance, m
y : Vertical coordinate, m
χ . Constant in momentum balance, -
δ Boundary layer thickness, m
ϕ : Similarity factor, -
ρ : Density, kg/m^3
σ : Liquid surface tension, N/m
ω Dimensionless group, Equation 7,-
ψ : Mass velocity ratio, -
ζ : Splattering fraction, -
τ : Time, s

Subscript

j : Jet
$Leid$: Leidenfrost
l : Liquid
sat : Saturation
s : Surface
$*$: After splattering

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