Stationary Measurement for Heat Transfer Coefficient in Droplet-cooling of Hot Metal

By Kazuo ARAKI,** Shin-ichi YOSHINOBU,*** Yoshikatsu NAKATANI** and Akira MORIYAMA**

Synopsis
The purpose of this work is to present a stationary method for measuring heat transfer characteristics between a hot solid surface and impinged droplets. The stationary temperature distribution of the thin metal disk by impingement of a steady stream of uniform water droplets onto its central zone was measured. The results were analyzed to determine the heat transfer coefficient of spray cooling. It was found that the wetting regime was prevailing below 350 °C and the non-wetting regime was above 400 °C of the metal surface temperature. Within a few drops per second, the heat transfer coefficient is independent of collision rate of droplets to the surface in the non-wetting regime, while it is dependent even on such a small rate of droplets in the wetting regime.

I. Introduction
There are numerous processes in which operations are affected significantly by the heat transfer characteristics between hot solid surfaces and liquid droplets in spray, mist and the like. Many fundamental studies on the cooling rate of solids, which can be classified in Table 1 according to the experimental modes, have been made through a wide range of engineering.

As seen in the table, most of the previous works adopted a direct cooling of a larger solid specimen with spray and mist flow and the experimental results have been interpreted in terms of the superficial and conventional parameters such as the flow rate and the back pressure of liquid rather than the nozzle characteristics or droplets properties as more essential parameters. Thus, it is difficult to compare the experimental data of different authors on a common basis and to predict the spray cooling intensity of any specified nozzle because of a lack in the information of relations between droplets behavior, nozzle type and its manipulations.

Factors relevant to the spray cooling intensity may be distributions of size, velocity, momentum and Weber number of sprayed droplets, which control the deformation behavior and contacting conditions of droplets on the hot solid surface. The flow rate and the back pressure of liquid are only dependent to these essential factors. To attain the useful and comprehensive information of the spray cooling intensity, therefore, the distributed properties of sprayed droplets and the dynamic and thermal interactions between droplets and the hot surface should be understood.

The problem consists of four parts:

1) Distributed characteristics of sprayed droplets from various types of nozzles.17-22
2) Deformation behavior of a droplet impinging onto the hot solid surface.50-52
3) Heat transfer characteristics between the hot solid surface and impinged droplets on it.53
4) Statistical summarization of whole informations of above items 1) to 3) for prediction of spray cooling intensity.

Very few studies have been made on the heat transfer processes above-cited in the item 3), the data being restricted to the works of Wachters et al.,2) McGinnis and Holman,4) Pedersen5) and Holman et al.,10) mainly with the droplets of low Weber number5,6,10) and in the wetting regime condition.4,5,10) Their results have not always involved the estimation of the heat transfer coefficient. Moreover, most of the previous authors, as well as Wachters et al.,2) and Pedersen,5) have employed the transient technique of heat transfer experiment. The transient technique has, in general, disadvantages of a more difficult measurement and of uncertainties of an appropriate simulation model in numerical analysis of the data.

It is the purpose of this work to present a stationary technique for measurement of heat transfer characteristics of an impinged droplet onto hot solid surfaces using a steady stream of uniform droplets. Usefulness of the technique was indicated and the experimental results were reasonably analyzed to determine the heat transfer coefficient in spray cooling. Work described in this paper forms part of an analysis programme on spray-cooling operations which is still in progress.

II. Experimental Apparatus and Procedure
The experimental system is shown schematically in Fig. 1, principal components of which are an electrically heated thin metal disk as the droplet-target 7, devices for the temperature measurement of the disk 8 and 9, the droplet emission units 3, 4 and 5, and the regulator of the disk temperature 6.

A uniform series of droplets produced at the tip of a hypodermic needle 8, drops and impinges onto the central zone of the hot metal disk 7. After a sufficient time had elapsed, the steady distribution of the disk temperature was measured with six 0.5 mmΦ C-A seath thermocouples 8 held against the reverse...
side of the disk with the aid of small springs to ensure good contact, one at the center and the others at every 5 mm away from the center. The temperature at the center of the target, i.e., the point of droplet impaction, could be regulated at predetermined values of the temperature by means of a controller unit.

The droplet emission unit was composed of a liquid reservoir, a needle valve, and a hypodermic needle. The reservoir head was held at fixed level by overflowing liquid and the emission rate of droplets was adjusted through the needle valve. The hypodermic needle of 24 gauge was ground, polished and square-edged for uniform size of the droplet. Uniformity of the droplet size could be ascertained by weighing technique. The emission rate and the size of droplets could be maintained within 2 and 4% of the specified values of magnitude under any given conditions, respectively. The impact velocity of the droplet onto the metal surface was adjusted in terms of the distance from the needle tip to the surface, and estimated as that for freely falling motion of a sphere in a stagnant air. The satisfactory agreement between the estimated velocity and the observation on the high-speed-cine-film has been demonstrated elsewhere.

The disk as the droplet target, 0.3 mm thick stainless steel plate of 12 cm diameter, was heated at the peripheral zone on both the right and the reverse sides by a pair of the electric heater assembly, as shown in Fig. 2. This assembly consists of a set of the circular heating element and two annular stainless steel blocks of 1 cm high, 12 cm O.D and 6 cm I.D, which served as a uniform heating medium for the droplet target. The target and its heating assembly were surrounded with the insulating bricks except a narrow circular region at the center of the disk being exposed to atmosphere for introducing the droplet onto the hot disk. In order to prevent an undesired retention of the impinged droplet on the hot disk and to ascertain the rapid discharge out of the heating assembly, the upper stainless steel block was provided with a guiding slit and the entire system of the target was inclined about 15 deg.

### Table 1. Experiments in the previous work hitherto reported.

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Application form of liquid</th>
<th>Heat transfer process</th>
<th>Surface temperature (°C)</th>
<th>Size of droplet (mm)</th>
<th>Application rate*</th>
<th>Velocity of droplet (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mizikar</td>
<td>spray</td>
<td>transient</td>
<td>93~1000</td>
<td></td>
<td>2.5&lt;Q&lt;15</td>
<td>4.5&lt;v&lt;6</td>
</tr>
<tr>
<td>Wachters et al.</td>
<td>single droplet</td>
<td>transient</td>
<td>200~400</td>
<td>2.3</td>
<td>3.2&lt;Q&lt;15</td>
<td>40&lt;v&lt;77</td>
</tr>
<tr>
<td>Toda</td>
<td>mist</td>
<td>transient</td>
<td>150~330</td>
<td>t&lt;0.2</td>
<td>5&lt;N&lt;15</td>
<td>1.0&lt;v&lt;5.0</td>
</tr>
<tr>
<td>McGinnis and Holman</td>
<td>uniform droplets</td>
<td>stationary</td>
<td>93~315</td>
<td>2.8~3.8</td>
<td>N=100</td>
<td>2.4&lt;v&lt;10</td>
</tr>
<tr>
<td>Pedersen</td>
<td>uniform droplets</td>
<td>transient</td>
<td>140~600</td>
<td>0.2~0.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tanaka et al.</td>
<td>spray</td>
<td>transient</td>
<td>200~800</td>
<td></td>
<td>10&lt;Q&lt;1000</td>
<td></td>
</tr>
<tr>
<td>Burge</td>
<td>liquid metal spray</td>
<td>transient</td>
<td>550~1000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M. Shimada and Mitsutaka</td>
<td>spray</td>
<td>transient</td>
<td>300~930</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wachters et al.</td>
<td>mist</td>
<td>transient</td>
<td>200~400</td>
<td>t=0.06</td>
<td>200&lt;Q&lt;2500</td>
<td></td>
</tr>
<tr>
<td>Holman et al.</td>
<td>uniform droplets</td>
<td>stationary</td>
<td>93~315</td>
<td>0.5~3.1</td>
<td>N=10</td>
<td>4.5&lt;v&lt;6</td>
</tr>
<tr>
<td>Aramaki and Yanagi</td>
<td>fog</td>
<td>transient</td>
<td>400~950</td>
<td>0.1~0.15</td>
<td>17&lt;Q&lt;50</td>
<td>0.3&lt;v&lt;0.8</td>
</tr>
<tr>
<td>Mitsutaka and Fukuda</td>
<td>mist</td>
<td>transient</td>
<td>150~800</td>
<td></td>
<td>1&lt;Q&lt;1000</td>
<td></td>
</tr>
<tr>
<td>Yanagi et al.</td>
<td>fog</td>
<td>transient</td>
<td>400~950</td>
<td>0.1&lt;t&lt;0.14</td>
<td>15&lt;Q&lt;50</td>
<td></td>
</tr>
<tr>
<td>Muller and Jeschar</td>
<td>spray</td>
<td>stationary</td>
<td>100~350</td>
<td>t=0.45</td>
<td>100&lt;Q&lt;2500</td>
<td></td>
</tr>
<tr>
<td>Sasaki et al.</td>
<td>spray</td>
<td>transient</td>
<td>700~1200</td>
<td></td>
<td>5&lt;Q&lt;500</td>
<td></td>
</tr>
<tr>
<td>Mitsutaka and Fukuda</td>
<td>fog</td>
<td>transient</td>
<td>700~900</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Q in l/m²·min and N in drops/s.
The experimental conditions are summarized in Table 2.

### III. Theoretical Analysis

1. **Stationary Temperature Distribution of Thin Metal Disk upon Impingement of a Steady Stream of Uniform Droplets onto Its Central Zone**

A theoretical analysis was performed on the stationary temperature distribution of the thin metal disk observed in the experiment as detailed in the preceding chapter. It is supposed that a steady stream of uniform droplets of radius \( r_0 \) is impinged onto the central zone of the thin metal disk, which is \( R \) in radius and \( d \) in thickness, at an impinging rate of \( N \) drops per second. Without sacrificing usefulness of the analysis, the followings are assumed.

1. Heat removal rate by the droplet stream is uniform and constant on the average.
2. Heat transmitting area between the surface and a droplet is constant with time and represented as \( \pi R^2 \). The average radius \( R_a \) is estimated in such a manner that shall be seen.
3. Heat transfer across the disk thickness is neglected.
4. Heat transfer from the disk to atmosphere occurs only within the central region of radius \( R_a \) exposed to atmosphere excluding the covered region of the disk with an insulating brick.
5. No interaction between droplets in succession occurs.

Dimensionless form of the basic equations can be written as Eq. (1) or Eq. (2).

**[I] When \( R_a \geq R_b \)**

\[
\frac{d^2 T^*}{dr^*^2} + \frac{1}{r^*} \frac{d T^*}{dr^*} \left( \frac{h \nu \tau R^2}{k d} + \frac{h_c R^2}{k d} \right) T^* = - \frac{h_a R_c}{k d} T^*_a \quad \text{at } R_a < r^* < R_b, \]

\[
\frac{d^2 T^*}{dr^*^2} + \frac{1}{r^*} \frac{d T^*}{dr^*} - \frac{h_c R^2}{k d} (T^* - T^*_a) = 0 \quad \text{at } R_b < r^* < 1. \]

**[II] When \( R_a \leq R_b \)**

\[
\frac{d^2 T^*}{dr^*^2} + \frac{1}{r^*} \frac{d T^*}{dr^*} - \frac{h_c R^2}{k d} T^* = 0 \quad \text{at } R_b < r^* < 1. \]

The boundary conditions are the following:

- at \( r^* = 0 \), \( d T^*/dr^* = 0 \)
- at \( r^* = R_a \) and \( R_b \), \( T^* \) and \( d T^*/dr^* \) are continuous.

Equation (1) or Eq. (2) along with Eq. (3) were solved to give the close solutions of Eq. (4) or Eq. (5), respectively.

**[I] When \( R_a \geq R_b \)**

\[
T^* = (C_1/C_5) I_0(\sqrt{m+ma} r^*) + ma T^*_a/\{(C_5 (m+ma)) \}, \quad \text{at } 0 \leq r^* < R_b \]

\[
T^* = (C_1/C_5) I_0(\sqrt{m+ma} r^*) + (C_5/C_3) K_0(\sqrt{ma} r^*) + T^*_a/C_5, \quad \text{at } R_b \leq r^* < R_a \]

\[
T^* = 1 + (C_5/C_3) \ln r^* \quad \text{at } R_a \leq r^* \leq 1 \]

**[II] When \( R_a \leq R_b \)**

\[
T^* = (C_1/C_5) I_0(\sqrt{m+ma} r^*) + ma T^*_a/\{(C_5 (m+ma)) \}, \quad \text{at } 0 \leq r^* < R_a \]

\[
T^* = (C_1/C_5) I_0(\sqrt{m+ma} r^*) + (C_5/C_3) K_0(\sqrt{ma} r^*) + T^*_a/C_5, \quad \text{at } R_a \leq r^* < R_b \]

\[
T^* = 1 + (C_5/C_3) \ln r^* \quad \text{at } R_a \leq r^* \leq 1 \]

* In regard to the droplet velocity, its normal component is a determining factor on deformation behavior of the impinged droplet. 

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Table 2. Experimental conditions.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature of hot metal disk, ( T_w ) (°C)</td>
<td>240~860</td>
</tr>
<tr>
<td>Droplet diameter, ( 2r_0 ) (mm)</td>
<td>2.7 and 3.0</td>
</tr>
<tr>
<td>Rate of droplet, ( N ) (drops/sec)</td>
<td>0.5, 1.0, 2.0 and 3.0</td>
</tr>
<tr>
<td>Normal impaction velocity of droplet*, ( v_0 ) (cm/sec)</td>
<td>150~400</td>
</tr>
<tr>
<td>Weber number, ( W_e ) (--)</td>
<td>100~800</td>
</tr>
</tbody>
</table>
When \( R_s \leq R \),
\[
T^* = (D_1/D_3)I_0(\sqrt{m + ma} \cdot r^*) + maT_2^*/(D_2(m + ma)) \text{ at } 0 \leq r^* \leq R_s
\]
\[
T^* = (D_1/D_3)I_0(\sqrt{m} \cdot r^*) + (D_2/D_3)K_0(\sqrt{m} \cdot r^*) \text{ at } R_s < r^* < R
\]
\[
T^* = 1 + (D_1/D_3)\ln r^* \text{ at } R \leq r^* \leq 1
\]
\[
\text{where,}
\]
\[
C_1 = 1 - maT^*(m + ma)
\]
\[
C_2 = [C_1(\sqrt{m + ma} R^*_b)K_1(\sqrt{ma} R^*_b)] + mT^*_b K_1(\sqrt{ma} R^*_b)\frac{\sqrt{ma} R^*_b}{(m + ma)}
\]
\[
C_3 = [C_1(\sqrt{m + ma} R^*_b)K_1(\sqrt{ma} R^*_b)] \frac{\sqrt{ma} R^*_b}{(m + ma)} + \frac{T^*_b}{(m + ma)}
\]
\[
C_4 = [C_1(\sqrt{m + ma} R^*_b)K_1(\sqrt{ma} R^*_b)] \frac{\sqrt{ma} R^*_b}{(m + ma)} + \frac{T^*_b}{(m + ma)}
\]
\[
D_1 = \frac{1}{2} \frac{(2 + \sqrt{3}) \exp (-\sqrt{3} t^*)}{1 + (2 - \sqrt{3}) \exp (-\sqrt{3} t^*)}
\]

The both parameters were evaluated so as to be in best agreement of the observed temperature distribution of the disk with the theoretical calculation from Eqs. (4) and (5). Then, the heat transfer coefficient \( h \) and heat transfer per droplet \( Q_o \) were determined with Eqs. (8) and (9), respectively.

\[
h = \frac{kd d}{R^2 \tau_x \cdot N} \text{ (8)}
\]
\[
Q_o = \frac{\pi kd (T_b - T_0) m}{N} \left( \frac{R_b}{R} \right)^2 \text{ (9)}
\]

All parameters included in Eqs. (8) and (9) can be specified corresponding to the experimental condition, except the average radius of the heat transmitting area \( R_b \) and the residence time on the hot metal surface \( \tau_x \) of the droplet, which will be estimated in the next section taking account of the impinged droplet behavior as discussed in previous papers.

2. Average Radius of Heat Transmitting Area \( R_b \) and Residence Time on Hot Metal Surface \( \tau_x \) of Droplet

When a liquid droplet impinges onto a sufficiently hot metal surface, it is deformed to undergo an outward radial thin-film flow at the bottom part of it and the radius of the heat transmitting base area \( R_b \) changes with time elapsed. Nevertheless the appropriately averaged radius \( R_b \) is included in this analysis, which is based on the assumption (2). It should be reasonable to define the average radius in Eq. (10), since in this situation the temperature differences as a driving force of heat transfer is held approximately constant.

\[
R_b = \left[ \frac{\int_0^t R_b dt}{\tau_x} \right]^{1/2}
\]

\( \tau_x \), the residence time of an impinging droplet on hot metal surfaces, can be calculated with Eq. (11), as detailed in a preceding paper.

\[
\tau_x = \frac{[2 + \sqrt{3}] (\sqrt{3} - \sqrt{\phi^*_x + 1})}{\sqrt{3} + \sqrt{\phi^*_x + 1}}
\]

Time integral involved in the numerator of Eq. (10) can be estimated with Eq. (12) on the dimensionless time integral of the heat transmitting area over the droplet residence time:

\[
I(R_b, \tau_x) = \frac{1}{2} \int_0^t R_b dt
\]

\[
\phi^*_x = (2.6 + 0.84 \sqrt{W}_d^{0.56} - 0.71 \sqrt{W}_d^{1.18} - 2.4 \sqrt{W}_d^{0.56} + 6.8) / 2
\]

Substituting Eqs. (11) and (12) into Eq. (10) and rearranging provide the following equation on \( R_b \).

\[
R_b = \left[ \frac{4H(R_b, \tau_x)}{\pi \tau_x^2} \right]^{1/2}
\]

Thus, parameters required in Eqs. (8) and (9) can be all evaluated.
Note that since the dimensionless $r^*_a$ and $I(R^*_b, z_G)$ are functions of $\phi^*_a$ which is a function of $We$ alone as shown in Eq. (13), they are functions of $We$ alone, too. The relation of $r^*_a$ vs. $We$ based on Eqs. (11) and (13) has been already illustrated elsewhere. In Fig. 3, calculated values of $R_b/R_b$ with Eqs. (13) and (15) are shown against the Weber number. The flow diagram for data-processing is shown in Fig. 4.

**IV. Results and Discussion**

1. **Stationary Temperature Distribution of Thin Metal Disk**

   When sufficient time had elapsed after an incipient impingement of the droplet, transient phenomena had diminished and stationary condition could be attained.\(^*\)

   Figure 5 illustrates a typical example of the observed stationary temperature distribution of the thin stainless steel disk, where $T_w=560^\circ C$, $We=570$, $N=0, 0.5, 1.0, 2.0$ and $3.0$ drops per second. Naturally, the temperature distribution becomes steeper with increased droplet rate. When $N=0$, the temperature over the thin stainless steel disk should be essentially constant, provided that the heat loss to atmosphere is negligibly small. However, this is not the case of the present study and the heat loss to atmosphere can not be neglected. Value of the heat loss term $m$ is so chosen that the sum of squares of the temperature difference between observations in the experiment and calculations from the exact solution of Eq. (1) with $R^*_b=0$ and $N=0$, which is of the same form as Eq. (4) with $m=0$, is the least. The solid line $A$ in Fig. 5 is thus obtained most probable curve. Predicted curves from the theory with $N=0$ and $R^*_b=0$ are generally in satisfactory agreement with observations, which may sustain the validity of the assumption (4).

2. **Average Radius of Heat Transmitting Area, $R_b$**

   When the best-fit calculations from Eq. (4) or Eq. (5) to the observation is to be sought with $N \approx 0$ using the known value of $m$, two kind of the adjustable parameters may be considered; that is $R^*_b$ and $m$. $R^*_b$, however, should be regarded as a characteristic dimension of the deformed droplet on the hot surface rather than as an adjustable parameter and it was calculated from Eq. (15). Actually, it is seen in Fig. 5 that the best-fit curve with single parameter $m$ obtained in comparisons of Eq. (4) or Eq. (5) with the

* Here, the ‘stationary’ state is oscillatory just as in frequency response, corresponding to the intermittent nature of contact between droplets and the surface. Virtually, the observed amplitude of the cyclic change of the temperature remained within 2% of the average value, which, as will be seen, provided only a minute effect on the estimated heat transfer coefficient.

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**Fig. 3.** Calculations of $R_b/\phi_a$ with Eq. (15).

**Fig. 4.** Flow diagram for data-processing.

**Fig. 5.** Comparison of the observed stationary temperature distributions of the metal disk with the best-fit calculations.
observed data is satisfactory and the standard deviation of the observation from the calculation is sufficiently small to be compared with the experimental accuracy. Thus, estimation of the average radius of the heat transmitting area $R_b$ from Eq. (15) is reasonable.

3. Stationary Temperature Distribution of Thin Metal Disk

When $N \neq 0$ the similar optimization problem as detailed in Section IV. 1. 1, for the most probable value of parameter $m$ with the determined values of $ma$ and $R_b$, is treated with the simple searching technique. The regression curve $B, C, D$ and $E$, solid lines drawn in Fig. 5, are in excellent coincidence to the observation. The averaged standard deviation of the observation from the calculated temperature distribution is $2.2 \cdot 10^{-4}$ for 102 runs in this experiments, which sustains the stationary technique of this paper.

2. Heat Transfer Coefficient $h$ between Hot Metal Surface and Droplets Impinging onto It

When the optimal values of the parameter $m$ as above obtained are put into Eq. (8), values of the heat transfer coefficient $h$ can be evaluated. The result has been shown in Fig. 6. Different tendency is apparent depending on whether it exceeds or not a critical surface temperature near 400 °C. It is supposed that the lower and the higher regions of temperature respectively correspond to the wetting and the non-wetting regime of heat transfer. The overall trend as seen in Fig. 6 is analogous to the relation hitherto reported, though data in the wetting regime is very scattered and this is due to differences in the drop rate $N$ as will be discussed in the next section.

3. Effect of Droplet Rate $N$ on Heat Transfer Coefficient $h$

Influence on the heat transfer coefficient $h$ exerted with the droplet rate $N$ at the surface temperature of 340 and 560 °C is represented in Fig. 7. Within $N = 3.0$, values of $h$ in the non-wetting regime at 560 °C are essentially independent of $N$, while in the wetting regime at 340 °C significantly decrease with an increasing $N$. Apparently, in the wetting regime the assumption (5) made in Section III. 1 is not necessarily satisfied at least within a few droplets per second and the foregoing droplets would affect on heat transfer process of the succeeding droplet. Perhaps any part of the water remaining on the surface after the main part of water has rebounded off is participating. Further investigation in this respect is required.

V. Conclusion

The stationary technique for measuring heat transfer coefficient from hot metal surfaces to an impinged droplet has been presented.

The stationary temperature distribution of the thin metal disk upon impingement of a steady stream of uniform droplets was measured. The results were analyzed by means of the theoretical equations (4) and (5).

The average radius of heat transmitting area $R_b$ was estimated from Eq. (15) as a characteristic dimension of the deformed droplet on the hot surface.

The optimal value of parameter $m$ in theoretical relation could be found with best accuracy in comparisons of theoretical solutions with the observed temperature distribution and the heat transfer coefficient in Eq. (6) was determined.

From values of heat transfer coefficient it was found that the wetting regime and the non-wetting regime were prevailing below 350 °C and above 400 °C of the surface temperature of the metal disk, respectively. In the non-wetting regime the heat transfer coefficient is independent of application rate of droplets to the surface within a few drops per second, while in the wetting regime it is dependent even on such a small rate of droplets.

Nomenclature

$d$: thickness of thin metal disk (cm)

$h$: heat transfer coefficient between hot metal surface and droplet impinged onto it (cal/cm²·sec·°C)

$ha$: heat transfer coefficient between hot metal surface and atmosphere (cal/cm²·sec·°C)

$I_i(x) (i=0, 1)$: $i$-th-order modified Bessel function of

![Fig. 6. Heat transfer coefficient $h$ against surface temperature $T_w$.](image)

![Fig. 7. Effect of the droplet rate $N$ on heat transfer coefficient $h$.](image)
first kind
\[ K_i(x) \quad (i=0, 1): \quad \text{i-th-order modified Bessel function of second kind} \]

\[ k: \quad \text{thermal conductivity of metal disk (cal/cm·sec·°C)} \]
\[ m = kN_1R^2/kf \quad (--) \]
\[ \alpha = \frac{haR^2}{kd} \quad (--) \]
\[ N: \quad \text{impinging rate of droplet (drops/sec)} \]
\[ Q_o: \quad \text{heat transfer per droplet (cal/drop)} \]
\[ R: \quad \text{radius of thin metal disk (cm)} \]
\[ R_h: \quad \text{radius of hole for introducing droplet (cm)} \]
\[ R_1: \quad \text{radius of heat transmitting base area (cm)} \]
\[ R_2: \quad \text{average radius of heat transmitting area (cm)} \]
\[ R_2^* = \frac{R_2}{R} \quad (-) \]
\[ r: \quad \text{radial position (cm)} \]
\[ r^* = \frac{r}{R} \quad (-) \]
\[ r_0: \quad \text{radius of droplet (cm)} \]
\[ T(R): \quad \text{disk temperature (°C)} \]
\[ T^* = \left( \frac{T(R) - T_b}{T(R) - T_0} \right) \quad (--) \]
\[ T_a: \quad \text{temperature of atmosphere (°C)} \]
\[ T_0: \quad \text{boiling temperature of liquid (°C)} \]
\[ T_w: \quad \text{temperature of central zone of thin metal disk (°C)} \]
\[ t: \quad \text{time (sec)} \]
\[ t^* = \frac{v_1r_0}{2} \quad (--) \]
\[ \Phi: \quad \text{impaction velocity of droplet (cm/sec)} \]
\[ W_e: \quad \text{Weber number} \quad (-) \]
\[ \tau_s: \quad \text{residence time on hot metal surface of droplet (sec)} \]
\[ \tau_t^* = \frac{v_1r_0}{2} \quad (--) \]
\[ \phi^*, \theta^*: \quad \text{see Eqs. (13) and (14), respectively} \]

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