Experimental study of water droplets impinging upon a hot surface

Cong Tran

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Experimental Study of Water Droplets Impinging upon a Hot Surface

By

Cong Tran

A Thesis Submitted in Partial Fulfillment of the Requirements for the

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

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DEPARTMENT OF MECHANICAL ENGINEERING
ROCHESTER INSTITUTE OF TECHNOLOGY
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Experimental Study of Water Droplets Impinging upon a Hot Surface

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FORWARD

I would like to take this opportunity to say thank you to my mother, father, and everyone in the family for supporting me and thank you for being there whenever I needed you. My mother is the one who would give everything up for my success. Thank you very much mommy.

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ABSTRACT

The objective of the presence investigation is to study the droplet impingement characteristics on heated and unheated surfaces with different surface roughness. The purpose is to show clear photographs of the impinging droplets from beneath the solid surface. Atmospheric pressure (101kpa), surface materials (glass and copper), impinging droplet temperature ($T_w = 24^\circ C$), original droplet diameter (4.7mm), and testing liquid ($H_2O$) were fixed. A MotionScope PCI8000S high-speed camera was placed beneath the heated glass surface. Droplets of water were dropped on the test surface, which is located 25 mm to 50 mm under the tip of a burette. For the unheated surfaces, the droplet was positioned above the surface between 23mm and 229mm. Thus, the primary parameter was the Weber number, which ranged from 30 to 60 for heated surface and 29 to 290 for unheated surfaces.

Furthermore, the effects of unheated copper surfaces with different surface roughness and droplet characteristic were experimentally studied. Surface temperature was fixed at $T_w = 24^\circ C$ whereas Weber number varied from 53 to 266. Impinging of water droplets upon unheated glass surface was also tested at
fixed surface temperature of $T_w = 24^\circ$C. However, Weber number was varied from 29 to 290 for unheated glass surface.

Finally, a theoretical study was conducted to compare the experimental results with the theoretical results. As a result, surface temperature was found to have very little effect on the spreading process of the impinging droplet upon both heated and unheated glass surface. Moreover, the results from impinging droplets upon unheated copper and glass surface were also analyzed. It was found that surface roughness exhibited no significant effect on the spreading process. The measurement values of maximum spreading diameter collected in the present investigation compare well with the predictions model provided by previous investigators. However, the maximum spreading time of the impinging droplets upon both heated and unheated surface did not correlate well with the previous models.
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NOMENCLATURE

\( a = \) Acceleration \( (m/s^2) \)

\( D_d = \) droplet diameter, prior to impact \( (m) \)

\( D_{\text{max}} = \) Maximum spreading diameter \( (m) \)

\( E_D = \) Dissipation Energy \( (J) \)

\( E_K = \) Kinetic Energy \( (J) \)

\( E_P = \) Potential Energy \( (J) \)

\( E_S = \) Surface Energy \( (J) \)

\( g = \) gravitational acceleration \( (m/s^2) \)

\( H = \) Height of the droplet at maximum diameter \( (m) \)

\( h_{lg} = \) heat transfer coefficient \( (J/kg) \)

\( k = \) thermal conductivity \( (W/mK) \)

\( Q'' = \) heat flux \( (W/m^2) \)

\( R_s = \) Surface roughness \( (m) \)

\( t = \) time \( (s) \)

\( T_{\text{crit}} = \) Critical temperature \( (K) \)

\( T_{\text{Leid}} = \) Leidenfrost temperature \( (K) \)

\( T_{\text{sat}} = \) Saturated temperature of water

\( T_w = \) Surface temperature \( (K) \)

\( V = \) Velocity \( (m/s) \)

\( V_o = \) Pre-impact velocity of the droplet

\( V_{\text{Vol}} = \) Volume of the droplet \( (m^3) \)
\[ y = \text{Distance (m)} \]

**Dimensionless Parameters**

\[ Bo = \text{Bond number, } Bo = \frac{D_d^2 \times \rho \times g}{\sigma}, \text{ defined in Eq. (3.4)} \]

\[ Oh = \text{Ohnesorge number, } Oh = \frac{\mu}{\sqrt[3]{\rho \times \sigma \times D_d}}, \text{ defined in Eq. (3.3)} \]

\[ Re = \text{Reynolds number, } Re = \frac{V_d \times D_d}{\nu_d}, \text{ defined in Eq. (2.2)} \]

\[ S_t = \text{Ratio of } R_s / D_d, \text{ defined in Eq. (3.5)} \]

\[ t^* = \text{Ratio of } (t / (D_d / V_d)) \]

\[ We = \text{Weber number, } We = \frac{\rho_d \times V_0^2 \times D_d}{\sigma_d}, \text{ defined in Eq. (2.1)} \]

**Subscripts**

0 = initial

1 = Prior to impact

2 = After impacted

\( d \) = Droplet

\( D \) = Dissipation

\( f \) = final

\( \text{max} \) = Maximum

\( \text{res} \) = waiting before rebound from surface

\( s \) = Surface

\( \text{sat} \) = Saturated
\( w = \text{Surface} \)

**Greek Letters**

\( \beta = \text{Spreading diameter} \)

\( \mu = \text{Viscosity} \)

\( \sigma = \text{Surface tension} \)

\( \rho = \text{Density} \)

\( \theta = \text{contact angle} \)

\( \nu = \text{Kinematic viscosity} \)

\( \pi = \text{Pi (3.14562...)} \)

\( \Phi = \text{Dissipation per unit mass} \)
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1. INTRODUCTION

Droplet impingement on a solid heated surface has been studied by many researchers for several decades. Yet, further investigation of this subject is still needed because little is known about the behavior of the droplets impacting on the hot surface. In 1756, Leidenfrost discovered a strange phenomenon in the behavior of water droplets on a heated surface; however, little light was shed on this subject. In the past few decades, interest in this subject has re-emerged. More information is needed to know about the behavior droplets impinging upon a heated surface because it is being used in a variety of applications. For instance, the automotive industries need this information in the design of fuel injectors in an IC engine. Furthermore, the use of the theory of droplet impingement is relevant in the area of nuclear technology, cooling of electronic devices, and steam engines.

Concurrent with the experimental work of Naber and Farrell (1993), Fujimoto and Hatta (1996), and Norbert (1999), Chandra and Avedisian (1991), Fukai et al. (1995), Wachters and Westerling (1966), and Wachters et al. (1966), this study is an attempt to understand some of the concepts involved with the
droplet impinging on a solid flat heated surface. The present investigation deals with pure liquid, H2O, droplets impacting on a surface heated from 24 °C to 260 °C. Specifically, distilled water was contained in the burette located on the top of the observation window (see fig. 4.3). Three sets of experiments were conducted for this investigation, distilled water droplets impinging upon heated glass surface, distilled water droplets impinging upon unheated glass surface, and distilled water droplets impinging upon unheated copper surfaces whose surfaces roughness were 1μm, 300-micron meter, and 600-micron meter. For unheated glass and copper surfaces, the Weber number was varied from 29 to 290. However, for heated glass surface, Weber number was fixed at 30, 50, and 60.

An extensive study of the droplet impingement upon a solid heated surface is needed to understand the complexity of the hydrodynamics of the impinging droplet such as the expanding and contracting phenomena, heat transfer between the droplet and the heated surface, momentum loss, surface tension, the wetting effect, vapor production, and contacting angle, etc. Fukai and Miyatake (1997) had concluded that the study of the droplet impingement needs more attention because
not much is yet known about the expansion of the process of the droplet.

The objective of the three different sets of experiments conducted in the present investigation is to study the spreading characteristics of water droplet impinging upon heated and unheated surfaces. Furthermore, different surface materials and surfaces roughness were also investigated. The spreading phenomenon of water droplet impinging upon heated and unheated glass surface was also studied.

The details of an experimental setup and procedure are presented in Section Four. This experiment is set up in a way that the high-speed camera can see through the glass from underneath. Photographs of the impinging droplet on the heated surface were taken and clear details of the deformation process of the droplets were also carefully studied and analyzed.
2. LITERATURE REVIEW

2.1 Droplet Impingement on a Heated Surface

Background

In a past few decades, the subject of droplet impingement on a heated surface has been studied extensively by many researchers. A few researchers such as Wachter et al. (1966), Wachters and Westerling (1966), and Avedisian and Fatehi (1988), conducted the theoretical work to improve their understanding of the subject. In addition, other researchers such as Chandra and Avedisian (1991), Chandra and Avedisian (1992), Xiong and Yuen (1991), and Bernardin et al. (1997), used photographic techniques to prove their findings. Yet, more study is needed to comprehend the complexity of the subject. Fukai et al. (1996), once stated that it is essential to know all aspects of the impinging droplet on the heated surface because it is being used widely in variety of industrial applications.

Miyatake et al. (1996), Bernardin et al. (1997), and Zhou and Yao (1991) noted that the deformation of the impinging droplet on the heated surface is dependent upon a few factors such as impact velocity, surface tension, fluid properties, and
droplet diameter. In other words, the qualities mentioned above affect the impact energy of the impinging droplet. The impact energy is expressed in a form of a Weber number. In turn, the Weber number can be express as:

\[ We = \frac{\rho_d \times V_0^2 \times D_d}{\sigma_d} \]  

where

\[ \rho_d \] is the density of the impinging droplet

\[ V_0 \] is the impact velocity

\[ D_d \] is the droplet diameter prior to impact

\[ \sigma \] is the surface tension of the impinging droplet

It should be noted that the density and the surface tension are temperature dependent. The physical meaning of the Weber number is simply expressed as the inertia force over the surface tension force. It should be understood that Weber number is one of the main dimensionless groups responsible for the deformation and the hydrodynamics effect of the droplet impinging on a hot surface.
Weber number plays a paramount role in the subject of droplet impingement on a heated surface. Many investigators reported that the entire motion of the droplet depends critically on the Weber number. Some researchers even stated that the critical Weber number lies between 35 and 40. According to Hatta et al. (1998), the critical Weber number was found to be 50. However, the Weber number depends upon a number of factors such as fluid properties, testing temperature, droplet diameter, and of course, the impinging velocity. Therefore, it is understandable that different values of critical Weber number were obtained from different investigators. It is generally understood that when the Weber number is below a critical value, the impinging droplet does not break after impinging on the surface. As the Weber number rises near the critical value, the impinging droplet is expected to break partially into smaller droplet at its periphery. Furthermore, when the Weber number is gone beyond the critical one, the impinging droplet is postulated to disintegrate completely after it impacted the heated surface. Consequently, this critical Weber number has yet to be absolutely defined.
Fig. 2.1 The deformation process. This model is generated for the heated surface. Furthermore, this model could be used for heated surface with surface temperature vary from $24^\circ C$ to $500^\circ C$. 
Figure (2.1) shows the deformation process proposed by Hatta et al. (1997) to illustrate a general hydrodynamic process of the droplet impinging on a heated surface. It should be interpreted that as a droplet impinges upon the heated surface, (a), it begins to spread, (b). The impinging droplet continues to spread and accumulates its mass at its periphery until it reaches its maximum spreading diameter, (c). It is believed that the internal pressure in the periphery is greater than that of the central region and the radius of curvature at the periphery is smaller than the central region, causing the liquid in the droplet at the periphery to flow toward the center, (d). At the end, the droplet forms an elongated bar flowing upward. If the surface temperature is below the Leidenfrost temperature (Leidenfrost temperature for H$_2$O is 546.16°K or 273°C, it occurs at the point when the impinging liquid enters the film boiling region) then the droplet collapses and starts its motion from (a) until it is completely evaporated. Otherwise, if the surface temperature is equal or greater than the Leidenfrost temperature then the droplet rebound from the heated surface, (e). However, Wruck, and Renz (1999) generated a more complete model. This model is presented in the following figure.
$T_W >$ Leidenfrost temperature:
$10 < We < 100$

$We < 10$
$We > 100$

$\dot{Q}$

bouncing
regulary disintegration
splashing

$T_W \ll$ Leidenfrost temperature:
(wetting regime)

$\dot{Q}$

no splashing
splashing

Fig. 2.2 The deformation process
According to the Figure (2.2) presented above, one could notice that as the droplet impinges upon the heated surface, it either stays on the surface, departs from the surface, or breaks up into smaller droplets and floats on a thin film of vapor on a heated surface. The conditions described cover the entire phenomena of droplets impacting on the hot surface. Moreover, it was known to previous investigators that under a certain critical Weber number, the droplet remains intact after colliding with the surface and then rebounds from the surface. As the Weber number approaches near the critical value, the droplet disintegrates partially into smaller droplets and also rebound from the surface. Furthermore, when the Weber number increases beyond the critical one, the droplet completely breaks up into smaller droplets and does not rebound from the surface. However, these tiny droplets are floating on a thin film of vapor on the top of the heated surface.

In a later study, Hatta, et al. (1998) focused their work mainly on the effect of the Reynolds number on the collision of droplets on the heated surface. In this case, the Reynolds number has the following expression:
\[ \text{Re} = \frac{V_d \times D_d}{v_d} \]  \hspace{1cm} (2.2)

Where

- \( V_d \) is the impact velocity
- \( D_d \) is the droplet diameter
- \( v \) is the kinematic viscosity of the impinging droplet at the testing temperature (°K).

Hatta, et al. (1998) used the expression above (Eq. 2.2) to investigate the hydrodynamics of the droplet. In the beginning, they suspected that the Reynolds number should provide some information about the motion of the droplet after impinging on the surface. In doing so, they imposed different Reynolds numbers into the plots of spreading diameter of the droplet after impacting the surface versus the time require to reach the maximum diameter to see if any relationship between the dynamics of the droplets and the Reynolds number were existed. The graphs in figure (2.2) show the correlations.
Fig. 2.3 Correlation between the spreading diameter, $W$, droplet height, $H_1$, and the rebound distance, $H_2$ against dimensionless time, $T$ for water droplets impinging upon a heated surface above Leidenfrost temperature with different Reynolds numbers.
As a result, Hatta et al. (1998) found that the effect of the Reynolds number on the impinging droplet on a heated surface is relatively small at the beginning stage, after impacting the surface. However, they noticed that effect of the Reynolds number on the impinging droplet was significantly large at the later stage when the droplet departs from the hot surface.

It is generally believed that deformation and the hydrodynamics of impinging droplets are influenced by the surface temperature and the impact energy. However, the hydrodynamics of the droplet such as rebounding, breaking-up, and spreading process are not explicitly known to researchers. Furthermore, Andreani et al. (1997) noted that full details of the hydrodynamics are still unanswered because of the complicated physics involved.

As mentioned above, the surface temperature plays a very critical role in the hydrodynamics of the droplet impingement on a hot surface. It was reported by Sobolev et al (1997) and Takano et al (1991) that when the surface temperature increases, the time it takes for the droplet to rebound from the surface decreases. In simple words, the hotter the surface the shorter
the droplet tends to stick to the wall. However, Hatta et al. (1998) argued that this phenomenon depends mainly on the Weber number. Furthermore, they presented in their study that for the case of low Weber number (We<50), the time it takes for the droplet to depart from the heated surface is a function of the Weber number. The correlation below was used to estimate the time it takes for the droplet to rebound from the heated surface starts right at the point when the droplet collides with the surface.

\[ t_{res}^* = 1.25*W e^{0.37} \] (2.3)

Where

- \( t_{res}^* \) is the time it takes for a droplet to depart from the surface. It was non-dimensionalized by dividing time by \( D_d/V_d \).
- \( We \) is the Weber number.

Equation (2.3) was correlated by Hatta et al. (1998) for water droplets impinging upon the stainless steel surface heated above Leidenfrost temperature. This correlation will not be plotted and compared with experimental data collected in this investigation because no rebound effect was observed due to low surface temperature. However, Hatta et al. (1998) compared the
predicted result using equation (2.3) with their experimental results and reported that the two results exhibited the same behaviors. In further investigation, they stated that the Reynolds number indicated no effect on $t^*_\text{res}$.

Furthermore, in the process of analyzing the effect of Reynolds number on the dynamics of the impinging droplet on a heated surface, Hatta et al. (1998) also obtained the correlations for the maximum spreading diameter of the droplet after impacting the hot surface and the time when the droplet reaches its maximum diameter. In turn, the maximum diameter and the corresponding time were also proposed as functions of the Weber number. The correlation for the maximum diameter, $\beta_{\text{max}}$, was expressed as:

$$\beta_{\text{max}} = 1 + 0.093 \times W_e^{0.74} \quad (2.4)$$

in which the maximum spreading diameter ($\beta_{\text{max}}$) of the droplet is a dimensionless quantity which is non-dimensionalized by the initial droplet diameter $D_d$. Hatta et al. (1998) given the correlation presented in equation (2.4) for water droplet impinging upon the heated stainless steel surface heated below the Leidenfrost temperature. This correlation will further be
plotted and compared with experiment data collected during this investigation. See section five for the comparison and details discussion. The corresponding time, $t^*_\text{max}$, for the maximum diameter was express as:

$$t^*_\text{max} = 0.27 \times We^{0.46}$$  \hspace{1cm} (2.5)

$t^*_\text{max}$ is the non-dimensionalized by dividing it by $D_d/V_d$. Equation (2.5) was correlated by Hatta et al. (1998) for water droplets impinging upon the stainless steel surface heated below Leidenfrost temperature. Strictly speaking, they further elaborated that they found almost no effect of the Reynolds number on the either $D_{\text{max}}$ or $t_{\text{max}}$. Additionally, they commented that they found no significant effect of the surface temperature on the maximum spreading diameter.

Furthermore, in the investigation of Bernardin et al. (1997), three different Weber number were used. As a result, they suggested that the spreading process of the droplet is critically depends on both the surface temperature and Weber number. No correlation was derived by Bernardin et al. (1997). However, their data was plotted and compared with other correlations given in the table below.
Table (2.1). Correlations of $D_{\text{max}}$ and $t_{\text{max}}$, reported by Bernardin et al. (1997)

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<td></td>
<td>- Fluid: water, ethanol, and acetic acid</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Surface: copper</td>
</tr>
<tr>
<td>Takeuchi et al. [17]</td>
<td>Time corresponding to maximum extent of film spread: $t_{\text{max}} = \left(1 - \frac{\phi^2 + 1}{3\phi^2} \right) \frac{d_0}{u_s}$</td>
<td>- Experimental correlation</td>
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<td></td>
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<td>- Fluid: water</td>
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<td></td>
<td>- Surface: chrome-plated copper</td>
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<td>- Constants</td>
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<td>$T_r$ ($^\circ$C)</td>
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<td>$1.442$</td>
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<td>$1.557$</td>
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<td></td>
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<td>$2.53$</td>
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<tr>
<td>Makino and Michiyoshi [16]</td>
<td>Contact period (for transition and film boiling): $\tau_v = 1.51 \times 10^{17} \left( \frac{\rho_s \rho_f \mu_s \mu_f}{\pi} \right)^{-1.18} \cdot \Delta T_w^{-3.81}$ (s)</td>
<td>- Experimental correlation</td>
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<td>- Fluid: water</td>
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<td>- Drop impact velocity not given but determined</td>
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<td>from knowledge of syringe height given in</td>
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<td>photograph</td>
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<td>- Surfaces: copper, brass, carbon steel, stainless steel</td>
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<td></td>
<td></td>
<td>- Estimated $We$ range:</td>
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<td></td>
<td></td>
<td>$3.1 \leq We \leq 5.6$</td>
</tr>
<tr>
<td>Kurokawa and Toda [13]</td>
<td>Contact radius of film: $R = 3.16 \times 10^{-2.8} \cdot \phi^3$ (m) $0 \leq t \leq t_1$</td>
<td>- Experimental and numerical study</td>
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<td></td>
<td>- Fluid: water, ethyl alcohol and mercury</td>
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<td>- Surface: glass</td>
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<td></td>
<td></td>
<td></td>
<td>- $Re = \rho \omega d_0^2$</td>
</tr>
</tbody>
</table>

Units in correlations: $[T] = ^\circ$C, $[d_0, r_s] = m$, $[u_s] = m \cdot s^{-1}$, $[\rho] = kg \cdot m^{-3}$, $[\phi] = J \cdot kg^{-1} \cdot K^{-1}$, $[\mu] = W \cdot m^{-1} \cdot K^{-1}$, $[\mu_s, \mu_f] = N \cdot s^{-1} \cdot m^{-2}$, $[\tau] = s$. 


Figure (12) of Bernardin et al. (1997) showed no agreement between their experimental data and the correlations in table (2.1). However, the same trend was found between their experimental data and the correlations listed above. Furthermore, correlation given by Kurokawa and Toda (1991) presented in table (2.1) for the water impinging upon glass surface at room temperature \((T_w = 42^\circ C)\) will be plotted and compared with the measurement data collected in this investigation. Full details discussion is presented in section five.

2.2 Boiling and Formation of Bubbles in the Droplet

Boiling occurs when the temperature of the heated surface is higher than the saturation temperature of the impinging liquid. Thus, heat is transferred from the hot surface to the bulk liquid. In return, the temperature in the liquid becomes higher and higher until the liquid temperature goes beyond its boiling temperature. Once this condition is reached, the liquid on top of the heated surface starts to boil. When water is boiled at normal condition (atmospheric pressure), we can observe that the bubbles are moved away from the heated surface. This phenomenon occurs because the bubbles are carried away from
the heated surface by pressure, and buoyancy. In simple words, the mass of the vapor in the bubbles is lighter than the surrounding liquid, so the bubbles rise. Bubbles only occur when there are contacts between the heated surface and liquid surface. It is well known that water boils at its saturated temperature of 100°C. Newton had derived the law of cooling as

\[ Q'' = h(T_w - T_{sat}) \]  

(2.6)

Where

- **Q''** is the heat flux
- **h** is the heat transfer coefficient
- **T_w** is the wall temperature, and
- **T_{sat}** is the saturated temperature

For the impinging droplets, as reported by Wang et al (1997) that boiling takes place through four clarified regions, convective heat transfer, nucleate boiling, transition boiling, and film boiling. However, bubbles are formed drastically during the nucleate regime and the transition boiling regime. Explicitly, Chandra and Avedisian (1991) stated in their study that bubbles form over the mouths of the cavities on the heated surface. They generated the model below.
Figure (2.4) Bubbles generated in the cavity (Chandra and Avedisian (1991))
Figure (2.4) shows the formation of bubbles over the mouth of a cavity. As previously mentioned, bubbles only occur when there is a contact between the liquid and the heated surfaces. For impinging droplets, no homogeneous boiling was observed. Thus, bubbles only form at the liquid-solid interface. Figure (2.4) illustrates that bubbles would depart from the cavity and rise into the bulk droplet if the liquid temperature \( T_L \) is greater than saturation temperature \( T_s \) of the impinging droplets. In addition, bubbles would collapse on the mouth of the cavity if the \( T_L \) is less than \( T_s \). Furthermore, the figure below exhibited the steps at which bubbles are grown. It was modeled by Carey (1992) and reported by Ryan Fogarty in his Masters thesis (1999).
Figure (2.5). Progression of bubbles (Casey (1992))
Furthermore, these bubbles leave the heated surface and rise into the droplet. As the heat transfer rate increases, the rate at which bubbles form also increases. Thus, numerous bubbles are trying to form at once. In this situation, the heated surface is crowded with bubbles. As a result, no liquid is touching the heated surface; therefore, the liquid droplet is floating on top of a thin vapor film. This phenomenon is called film boiling. In simple words, once film boiling takes place, there is no bubble generation because there is not direct contact made between the droplet and the heated surface.

Bubbles are not only formed at the boiling point of the liquid but they are also formed at temperature below its saturated temperature. Chandra and Avedisian (1991) stated that they found that some bubbles appeared in the droplet after impact at the room temperature. However, these bubbles are not formed under the influence of heat transfer. Chandra and Avedisian (1991) suspected that these bubbles formed by the air trapped inside the cavity just before the droplet impinges on the surface.
2.3 **Effect of Surface Temperature on the Droplet**

As previously mentioned, the Weber number is very critical to the behavior of the droplet impinging on a hot surface. However, the temperature of the heated surface also plays a significant place in affecting the dynamics of the droplet. Figure (2.6) below was proposed by Wruck and Renz (1999) to illustrate different boiling regimes, which is primary driven by the surface temperature.
The evaporation lifetime of droplets (Wruck and Renz (1999))

Fig. (2.6) The evaporation lifetime of droplets (Wruck and Renz (1999))
Figure (2.6) above shows the progression of the surface temperature in four different boiling regimes: convective heat transfer, nucleate boiling, transition boiling, and film boiling. It also presents the lifetime of the droplet. The lifetime of the droplet increases as the rate of evaporation decreases and vice versa. Thus, it is not erroneous to propose that the lifetime of the droplet on a heated surface is dependent primarily upon the surface temperature, denoted by $T_w$. From observation of Figure (2.6), it is reasonable to say that the lifetime of the droplet increases through the convective heat transfer region and continues to prolong its life through the nucleate boiling regime but at lower rates. As surface temperature increases from nucleate boiling region through the transition boiling region, the rate of evaporation increases. As a result, the lifetime of the droplet decreases. It is generally safe to say that beyond the boiling point of the impinging liquid, the lifetime of the droplet decreases continuously up to the transition boiling. Once the surface temperature reaches the Leidenfrost (critical) temperature, as presented in Figure (2.6), the droplet commences to evaporate at lower rates, which implies that the life of the droplet on the heated surface is extended. This phenomenon occurs through the film boiling regime. Through
this region, the droplet is literally floating on the top of the heated surface, which is suspended by a vapor cushion. The Leidenfrost temperature is postulated to be 200°C according to Wruck and Renz (1999). Furthermore, the photographs below were captured during an experiment with a high-speed camera at Leidenfrost temperature $T_w = 200^\circ$C.
Fig. (2.7) Droplet of liquid at $T_w = 200^\circ$C (Wruck and Renz (1999))
Leidenfrost temperature was defined by Baumeister and Simon (1973) and it could be expressed as:

\[ T_{\text{leid}} = \frac{27}{32} T_{\text{crit}} \]  

(2.7)

where

- \( T_{\text{leid}} \) is the Leidenfrost temperature, \(^\circ\)K
- \( T_{\text{crit}} \) is the critical temperature of the impinging liquid, \(^\circ\)K

Critical temperature of the impinging fluid was selected to use in equation (2.7) because at critical temperature there exists only single phase boiling. And that is film boiling. In other words, at critical temperature, the latent heat transfer coefficient, \( h_{lq} \), is zero. Equation (2.7) expressed the ideal Leidenfrost temperature. In reality, the Leidenfrost temperature is much higher than the ideal value. So far, the Leidenfrost temperature has yet to be determined because it depends on many parameters such as surface roughness, surface material, impinging liquid properties, etc. However, the predicted value of Leidenfrost temperature for water is \( T_{\text{leid}} = 546.16 \) \(^\circ\)K (or \( T_{\text{leid}} = 273 \) \(^\circ\)C).

In summary, the following observations can be made based on the available literature.
1. The deformations of the droplet impinging on a heated surface depend on the Weber number and the surface temperature.

2. The Reynolds number does not affect much on the deformation process of the droplet impinging on a heated surface at the earlier stage of impact. However, the Reynolds number influences significantly on the deformation of the droplet at the later stage when the droplet depart from the surface.

3. Bubbles are formed at the mouth of the cavity. Also, bubbles are only formed if there is contact between the liquid and the heated surface.

2.4 Objective of Current Work

The objective of the current work is to investigate the spreading and contracting processes of an impinging droplet on a flat heated surface. In the past few decades, the theory of droplet impingement on a hot surface was studied by many researchers both experimentally and theoretically; however, no one has yet tried to photograph the impinging droplet from beneath the heated surface. Therefore, an extended purpose of
the current study is to collect the photographs of the impacting droplets from beneath the heated surface and compare them with the results collected by other researchers. In doing so, more information may be obtained and a further understanding of the impinging droplet may be learned.

In addition, the hydrodynamics of the water droplets impinging upon unheated surfaces will also be investigated to study to effect of surface roughness on the maximum spreading diameter and spreading time. Comparison between the experimental results with the existing correlation will also be made.
3. THEORECTICAL WORK

The purpose of this section is to illustrate the theoretical study of the droplet impinging on a heated surface. It is well known that the deformation of the droplet impacting on a heated surface is primarily depended upon the impact energy. The impacting energy is expressed in the form of the Weber number, which can be showed as:

\[ \text{We} = \frac{\rho_d \times V_0^2 \times D_d}{\sigma_d} \]  

(3.1)

In addition, there are a few other dimensionless groups governing the subject of droplets impingement on a heated surface. The dimensionless groups are listed below.

Reynolds number:

\[ \text{Re} = \frac{\rho \times D_d \times V_d}{\mu} \]  

(3.2)

Ohnesorge number:

\[ \text{Oh} = \frac{\mu}{\sqrt{\rho \times \sigma \times D_d}} = \sqrt{\frac{3(1 - \cos(\theta)) \beta_{\text{max}}^2 - 12}{\text{Re}^2 - 4.5 \beta_{\text{max}}^4 \text{Re}}} \]  

(3.3)

Bond number:

\[ \text{Bo} = \frac{D_d^2 \times \rho \times g}{\sigma} \]  

(3.4)
The Bond number was defined as the ratio of the gravitational force over surface tension force. However, it is generally known that the gravitation force plays very little role in effecting the hydrodynamic of the droplet impinging upon a heated surface because the bond number is very small.

Furthermore, Mundo et al. (1995) suggested that the Ohnesorge number is responsible for the splashing phenomenon during droplet impact the heated surface. If the left side of the equation (3.3) is greater than the right side, then splashing should be expected. It should be noted that the right side of equation (3.3) equated with all parameters after impinging take place, whereas the left side of equation (3.3) was equated with all parameters before impinging take place. Furthermore, the splashing phenomenon was investigated in this experiment; however, no significant effect was found.

In addition, surface roughness was also an important parameter. However, it was normalized by the droplet diameter.

Surface roughness:

\[ S_r = \frac{R_s}{D_d} \]  

(3.5)

Where

\( R_s \) is the mean roughness height of the surface
Impinging of water droplets upon unheated copper surfaces was investigated to study the effect of surface roughness on the spreading process. However, little effect of surface roughness was found. Effect of surface roughness on the heated surface will be considered in future investigations.

In this investigation, only temperature ranges between 24°C and 260°C were considered. Droplets of distilled water impacted the heated surface and underwent processes such as spreading, recoiling, rebounding, and etc. However, the present study only concerned with the deformation process from impact to maximum spreading diameter.

It was suggested by previous investigators that the dynamics of the droplet impinging on a hot surface could be analyzed by the Navier-Stokes equations. However, in this investigation, an energy method was used to analyze the spreading process. The main improvement of this study is the incorporation of the potential energy term introduced after the droplet collided with the surface. Consequently, the surface roughness of the heated wall was embedded into the potential
energy term. Now, total energy of the system can be presented as:

$$E_k^1 + E_p^1 + E_s^1 = E_k^2 + E_p^2 + E_s^2 + E_d^2$$  \hspace{1cm} (3.6)

Where $E_k$, $E_p$, $E_s$, and $E_d$ represent kinetic, potential, surface, and dissipation energy, respectively. The superscripts (1) and (2) mean before and after impacting on a surface respectively. Equation (3.6) was modified from the model proposed by Chandra and Avedisian (1991). Just before impacting the heated surface, only kinetic and surface energy were considered. Potential energy is assumed to be zero. Furthermore, it was assumed that at final stage of deformation, the droplet obtained a shape of a disk. It was well known that when the droplet reaches its maximum spreading diameter, kinetic energy no longer existed. Armed with this information, the energy of the system when the droplet reaches its maximum spreading diameter consisted of potential, surface, and dissipation energy. Energy of the system can be expressed as:

Kinetic energy:

$$E_k = \frac{1}{2} m V_d^2 = \frac{\pi}{12} \rho_d D_d^3 V_d^2$$  \hspace{1cm} (3.7)

Potential energy:
$$E_p = mgR_s = \frac{\pi}{4} D_{max}^2 H \rho_d g R_s$$ (3.8)

Where \(R_s\) is the mean roughness height (see fig. (3.1)). In the present study, the surface roughness of the heated surface was .025\(\mu\)m. Calculating the potential energy for the droplet at its maximum spreading diameter, the result showed the value in the order of \(10^{-11}\)J. Thus, the surface roughness does not play an important roll in the spreading of the droplet. However, it must be taken into account when working with rougher surface.
Figure (3.1). Maximum spreading diameter.

Figure (3.2). Liquid-solid interface of impinging droplet proposed by Mundo et al. (1995).
Where $\theta$ is the contact angle at the interface of gas/liquid, which located at the point where the meniscus begins (see fig. (3.2)).

Surface energy:

\[
E_s^1 = \sigma_d A = \pi D_d^2 \sigma_d \tag{3.9}
\]

\[
E_s^2 = \sigma_d A = \frac{\pi}{4} D_{max}^2 (1 - \cos(\theta)) \sigma_d \tag{3.10}
\]

In studying the literature, it was noted by many investigators that, so far, no one have yet tried to determine the velocity profile inside the deforming droplet because the physics is extremely complicated. Kukai et al. (1995) even commented that it is impossible to determine the velocity distribution of the internal flow of the droplet after impinging on a hot wall by experiment. Since the dissipated energy depends primarily on the velocity distribution, Chandra and Avedisian (1991) proposed that the dissipated energy could be examined as

\[
E_d = \int_0^t \Phi \, dV \, dt = \Phi V \tau \tag{3.11}
\]
Where $t_e$ is the time of deformation, $t_e = D_d / V_d$, $\Phi$ is the dissipation per unit mass of the experimental fluid, and $V$ is the volume of the droplet.

$$\Phi = \mu \left( \frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial y} \right) \left( \frac{\partial u_x}{\partial y} \right) = \mu \left( \frac{V_d}{H} \right)^2$$  \hspace{1cm} (3.12)

Where

$H$ is the height of the droplet showed in fig. (3.1)

Since the time period between impact and spread to maximum diameter was very short, the volume of the droplet was assumed to be constant. Furthermore, the droplet before impinging on the surface was also assumed to have a shape of a sphere and after impinging have a shape of a disk (see fig.3.1). The volume of the droplet before and after impinging was denoted as $Vol_1$ and $Vol_2$, respectively. They can be expressed as:

$$Vol_1 = \frac{\pi}{6} D_d^3$$  \hspace{1cm} (3.13, 3.14)

$$Vol_2 = \pi D_{\text{max}}^2 \times H$$

Setting equation (3.13) equal to equation (3.14), yield the expression below

$$H = \frac{D_d^3}{6D_{\text{max}}^2}$$  \hspace{1cm} (3.15)
Now, join equation (3.12-3.16), the dissipated energy can be calculated as:

$$E_d = \frac{2}{3} \pi \times \mu \times V_d \left( \frac{D_{\text{max}}^4}{D_d^2} \right)$$  \hspace{1cm} (3.16)

Combining equations (3.7) to equations (3.16), the total energy of the system can be expressed as:

$$\frac{1}{6} \rho_d V_d^2 D_d^3 + 2D_d^2 \sigma = \frac{1}{2} D_{\text{max}}^2 \sigma (1 - \cos(\theta)) +$$

$$3 \mu_d V_d \left( \frac{D_{\text{max}}^4}{D_d^2} \right) + \frac{1}{12} D_d^3 \rho_d g R_s$$  \hspace{1cm} (3.17)

Now, is it clear that the maximum spreading diameter of the droplet impinging upon a heated surface depends on the contact angle, the diameter of the droplet, the pre-impact velocity, and the surface roughness. However, $R_s$ is every small in this experiment. According to Marks’ Standard Handbook for Mechanical Engineers that the roughness on the surface for glass is 0.025 $\mu$m ($R_s = 0.025 \mu$m). Thus, the value of the potential energy could be neglected. However, for rougher surfaces the last term in equation (3.17) must be taken into consideration because it may affect the spreading process. For this notion, divide each term in equation (3.17) by $\sigma D_d^2$ obtained the following
\[
\frac{1}{3} \rho_d V_d^2 D_d + 4 = (1 - \cos(\theta)) \left( \frac{D_{\text{max}}}{D_d} \right)^2 + \frac{3}{2} \mu_d V_d \left( \frac{D_{\text{max}}}{D_d} \right)^4
\] (3.18)

Since \[ \frac{We}{Re} = \frac{\mu_d V_d}{\sigma_d} \] and \[ We = \frac{\rho_d V_d^2 D_d}{\sigma_d} \] and letting

\[ \beta_{\text{max}} = \left( \frac{D_{\text{max}}}{D_d} \right) \] equation (3.18) can be expressed as

\[
\frac{3}{2} \frac{We}{Re} (\beta_{\text{max}})^4 + (1 - \cos(\theta))(\beta_{\text{max}})^2 - \frac{1}{3} We - 4 = 0
\] (3.19)

Rearranging the terms in equation (3.19) to obtain the Weber number as a function of the maximum spreading diameter, yielded the following expression:

\[
We = \frac{4 - (1 - \cos(\theta))(\beta_{\text{max}})^2}{\frac{3}{2} \cdot Re (\beta_{\text{max}})^4 - \frac{1}{3}}
\] (3.20)

Different values of \( \beta_{\text{max}} \) were used to calculate the values of the Weber number. However, in deriving equation (3.20), it was assumed that Reynolds number and the contact angles were constant. The result will be presented in section (5.1).
4. EXPERIMENTAL SETUP AND PROCEDURE

4.1 Experimental setup

A pictorial representation of the experimental setup is show in fig. (4.1, 4.2 and 4.3). This experimental setup was very much like the experimental setup used by Wruck and Renz (1999), Hatta et al. (1997), Hatta and Fujimoto (1996), Chandra and Avedisian (1992 and 1991), and Naber and Farrel (1993). This experimental setup was oriented in a way that the liquid droplets impinge upon the hot surface at an impacting velocity ranging from 0.701 m/s to .99 m/s. A high temperature resistance glass was placed between two ring-heaters. The ring-heaters would allow the surface temperature of the glass to reach as high as 600°C. However, for the safety of the equipments, the maximum surface temperature in this experiment was set at 260°C. The ring-heaters were connected to a TCR POWER SUPPLY where the amount of voltage and current to the heaters could be regulated. Since the amount of voltage and current were being controlled, the temperature of the heaters is also being controlled. The multiple ring-heaters allowed for more precise control of the glass surface temperature distribution.
Figure (4.1) shows the base and whole experimental apparatus. The high-speed camera was mounted to a tri-pot at the bottom of the heated glass surface. The test section (glass surface and ring-heaters) was mounted on the table. A further detail of the experimental setup is shows in Figure (4.2).
Fig. (4.1) Experimental setup
Figure (4.2) Experimental circuit.
Figure (4.3). Blow up of the test section.
Figure (4.3) shows the test section. The important part of this experiment is the test section. The test section consists of the test surface (glass) and the ring-heaters. As previously mentioned, the ring-heaters were mounted side by side against the glass surface. This was high temperature resistant glass. It can withstand up to 900 °C while introducing cold liquid on top of it. The glass is called Firelite and it was produced by Technical Glass.

There are two light sources being used in this experiment. Instead of using flash units as described by Fujimoto and Hatta (1996) and Hatta et al. (1997), this experiment used a constant light source in the background. The purpose of these particular light sources was to give the camera the right lighting.

A piece of glass was heated by the two ring-heaters. One ring-heater was placed on the top of a glass surface and the other ring-heater was placed in the bottom of the glass. After the heaters and the glass were correctly secured in place, they were insulated by Fiberfrax insulations. Fiberfrax insulation is manufacture by UniFrax Corporation. It can handle the temperature up to 1482°C. These particular insulations were
chosen because they offer low thermal conductivity, high temperature stability, uniform density, and excellent resistance to thermal shock and chemical attack.

A MotionScope PCI 8000S high-speed camera was used to photograph the impinging droplet in the present study. The camera was manufactured by RedLake Imaging. Its record rates range from 60 through 8000 frames per second. However, this investigation only used the record rate of 1000 frames per second. The camera was placed underneath the experimental setup. The transparency of the glass allows the camera to see through and photograph the impinging on the top of the glass. For the past several decades, many researchers had photographed the impinging droplet on a heated surface from top view and side view; yet, no one has attempted to photograph the impinging droplet on a hot rigid surface from beneath. This study will attempt to clarify some of the issues that currently in controversial about the dynamics of the droplet impingement.
4.2 Experimental Procedure

The experiments were conducted with only one substance, pure water. Distilled water is poured into a burette located on the center but top of the observation window (see Fig. 4.3). Power to the system is turned on for a while to make sure that the surface is heated to the desired temperature. Once the surface reached a specific temperature, a manual, hand-operated valve located near the bottom of the burette is slowly opened. Water is released from the bottom of a burette at atmospheric pressure, $P_\infty = 101\text{kpa}$ and at room temperature, $T_\infty = 24 ^\circ\text{C} \pm 0.01^\circ\text{C}$. Because there was no specific device to measure the diameter of the droplet, so it was assumed that the droplet carried a shape of a sphere. Thus, the diameter of the droplet was estimated by the following expression

$$D_d = 3 \sqrt[3]{\frac{6 \times \text{Vol}}{\pi}} \quad (4.1)$$

where

$D_d$ is the diameter of the droplet

$\text{Vol}$ is the volume of the droplet
Since, the mass of the droplet can be measured by a scale, and the density of the liquid is also known, so from this information the volume of the droplet can be calculated directly through the correlation below.

\[
\rho = \frac{M}{Vol} \\
\text{or} \\
Vol = \frac{M}{\rho}
\]  \hspace{1cm} (4.2)

where

\( M \) is the mass of the droplet \((M = .057 \text{ grams})\)

\( \rho \) is the density of the fluid at standard temperature and pressure, \((\rho = 998 \text{ kg/m}^3)\)

The diameter of the droplet was calculated from equations (4.1-4.2) above. The mass of the droplet was experimentally measured by a very accurate scale \((\text{accuracy} = \pm .001 \text{g})\). A droplet of distilled water was dropped into a measuring cup. However, it was understood that the mass of each cup may vary; therefore, each cup was placed on the scale then the scale was zeroed while the cup was still on it. The cup was then held under the tip of the burette where the droplet will drop into the cup. After a series of drops were measured, an average mass of the droplet was calculated. It should be noted that the same method
was used to measure mass of the droplet as used in the actual experiment. The mass of the droplet was accumulated under the tip of the burette and it will depart the tip of the burette by its own weight. Fifty data points were collected. The droplet's mass ranged from 0.056g to 0.059g. Thus, an average of the collected mass was used to calculate the volume of the droplet. The diameter of the droplet was calculated to be 4.7mm. The table below shows the properties of the testing fluid and its pre-impact diameter and velocities.

<table>
<thead>
<tr>
<th>D_d (m)</th>
<th>( \rho_d ) (kg/m(^3))</th>
<th>V_d (m/s)</th>
<th>( h_0 ) (m)</th>
<th>( \mu_d ) (N.s/m(^2))</th>
<th>( \sigma_d ) (N/m)</th>
<th>( \nu_d ) (N.m.s/kg)</th>
<th>We</th>
<th>Re</th>
</tr>
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**Table (4.1) Parameters of the testing fluid.**

The mass of the droplet is accumulated at the tip of a buret then it dropped onto the heated surface under the influenced of its own weight.

At the moment when the droplet departed from the tip of the burette, the trigger was pressed to activate the camera. The trigger of the camera was off set by the proportion of 30% over
70%. In short, 30% was captured before the trigger was pressed and 70% was captured after the trigger was pressed. As a result, a MotionScope PCI software program operating under PC base recorded a photograph digitally. The photographs were studied and carefully analyzed. The results are discussed in the following chapter.
5. RESULT AND DISCUSSION

5.1 Results and Comparison

In this investigation, water droplets impinging upon the heated flat solid surface were divided into three sets of experiments.

1). Distilled water droplets impinging upon glass surface heated to below the Leidenfrost temperature

2). Distilled water droplets impinging upon unheated glass surface

3). Distilled water droplets impinging upon unheated copper surfaces with three different surface roughness, 1 μm, 300 micron meters, and 600 micron meters

The results were obtained and analyzed. Full details and discussion are presented below.

This experiment is associated with the effect of surface heat flux on the impinging droplets upon a solid glass heated surface. The purpose of this study is to use high-speed cameras to photograph the dynamics of the droplets impinging upon the heated surface. The liquid droplet is dropped from a buret onto a heated glass surface. The droplet has a diameter of about
4.7mm and pre-impact velocities of .701 m/s to 0.99 m/s. The impact velocities of the impinging droplet could be calculated by the following expression:

\[ V_d = \sqrt{2gh} \]  

(5.1)

Notice that the pre-impact velocities calculated above were very small. Consequently, the intention of this experiment is to use low impact energy, for the case of heated surface. The droplet is dropped from the height of 0.04 m to 0.025 m. For this height, the Weber number is below 50, (\( \text{We} \leq 50 \)).

Furthermore, water droplets impinging upon a solid unheated surface were investigated. For the case of unheated surface, higher impact energy was examined. The Weber number in this case varied from 29 to 290. In addition, different surface materials and surface roughness were also used.

The following photographs were captured for water droplet impinged upon a heated glass surface. Analysis and detail of the photos will be discussed below.
Fig. (5.1). Impinging Water droplet on heated glass surface, $T_w = 150^\circ$C, $We = 30$. The time between each photo is 1ms, start from zero ms. The photos should be viewed from left to right.
As previously mentioned, these photos were taken from beneath the heating surface. However, there were a few sets of photos were taken with the camera oriented horizontally. Analyzing the photographs presented in figure (5.1), it was obvious that the droplet stayed intact the whole time it was on the solid heated surface. Bubbles formed during the deformation process. More bubbles appeared in the droplet at 7ms. The droplet reached it maximum spreading diameter at 9ms. At 10ms, the droplet started to disintegrate at its periphery. Further deformation was taking place at 11ms. At 12 ms big bubbles appeared in the droplet. The droplet in figure (5.1) is in the nucleate boiling regime. The droplet will further deform and evaporate completely after 56ms. More photos of the droplet are current presented below.
Fig. (5.2). Water droplet impinging upon heated glass surface, $T_w = 150^\circ C$, $We = 50$. The time between each photo was 1ms. Photos should be viewed from left to right.
Right from the beginning, at 3ms bubbles were formed inside the droplet. It is also obvious that breakup started at 3ms. Observing the photographs above in figure (5.2), one should recognize that at the periphery, small droplets were formed and leaving the original droplet. The droplet continued to expand and reached its maximum spreading diameter at 6ms. The droplet in figure (5.2) reached its maximum diameter faster than the droplet presented in figure (5.1). For higher Weber number, figure (5.2) exhibited a more energetic breakup than figure (5.1). Thus, it's erroneous to say that the higher the Weber number the sooner the droplet will disintegrate. Furthermore, the breaking up process continued. It is generally believed that disintegrate of the droplet was caused by the inertia forces. As previously stated, the Weber number was equated to the ratio of the inertia force over the surface tension force. Thus, the higher the Weber numbers the higher the inertia force. In addition, the surface tension force was weakened by the temperature of the heated surface. As a result, the impinging droplet could not recover its surface tension force, so it broke. Bubbles also play an important role in the breaking up process. The bubbles inside the droplet occasionally exploded due to the unbalance of pressure inside the bubbles and the surrounding area. When
bubble explodes, it breaks up the main droplet. Figure (5.2) exhibited this phenomenon at 7sm. The droplet in figure (5.2) disintegrated vigorously after 8ms. Furthermore, the droplet will evaporate completely in 70 ms. Additionally, more photographs of water droplet impinging upon a glass heated surface were captured in the figure below.
Fig. (5.3). Water droplet impacting upon the glass heated surface, $T_w = 120^\circ C$, $We = 30$. Photos should be viewed from left to right. The time increment between each photo was 1 ms.
Analyzing the photos in figure (5.3), noticing that at low Weber number and low temperature, the droplet impacted the surface calmly. No noticeable disintegration occurs during the deformation process. As noticed from the previous figures, mass of the droplet was accumulated at the periphery. Further, the droplet stayed in contact with the surface the whole until the droplet evaporated completely. Unlike figure (5.1) and (5.2), the droplet did not breakup into smaller droplets at the periphery. In this case, the photos exhibited more bubbles in the droplet as it’s spreading in comparison with those showed in figure (5.1 & 5.2). This phenomenon occurred because the droplet directly made contact with the heated surface. Many researchers prior to this study noted this scenario, and they called it the wetting effect. The wetting effect occurs more often at lower surface temperature because the droplet is physically wetting the surface. As the surface temperature increases, the wetting effect decreases. This wetting effect phenomenon exists through the nucleate boiling regime and transition boiling regime. Once the surface temperature reaches the Leidenfrost temperature wetting effect is no longer existed. Furthermore, film boiling takes place when surface temperature equals or greater than Leidenfrost temperature. In the film boiling regime, it is
preferred as the non-wetting state. The Leidenfrost temperature for this experiment was calculated to be 273°C. Unfortunately, the surface temperature in this experiment could not exceed 260°C. Otherwise, interesting photographs may be observed.
Figure (5.4). Impinging of water droplet upon heated glass surface, $T_w = 170^\circ C$, $We = 50$. The time between each photo is 1ms. Photos should be viewed from left to right.
Figure (5.4) exhibited more violent break up than any previous figures. Again, mass of the droplet was accumulated at its periphery. As soon as 3sm, disintegration of the droplet took place. The droplet reached its maximum spreading diameter at 6ms. However, the breakup process was much more severe at 10ms. Compare figure (5.4) with figure (5.1, 5.2, & 5.3), one could say that surface temperature place an extreme role in the deformation process of the droplet impinging upon that solid heated surface. Figure (5.2) had the same Weber number as figure (5.4); however, figure (5.4) had higher surface temperature than figure (5.2). As a result, the breakup process occurred more severely in the figure (5.4) in comparison with those in figure (5.2). Furthermore, the series of photos in the figure below had the same Weber number; however, different surface temperature was applied. Results were analyzed and discussed in explicit detail below.
Figure (5.5). The photos above were taken at $T_w=250^\circ C$ and $We = 50$. The photos should be viewed in order from left to right. The time increment between each photo is 1 ms.
Analyzing the figure (5.5) above, one could see that right from the beginning (1ms) vapor was formed at the moment the droplet came into contact with the surface. As time progressed, the droplet started to deform vigorously. It reached the maximum spreading diameter at about 5 ms after impinging upon the heated glass surface. More explicit than the previous photos showed in figure (5.1 to 5.4), the droplet in figure (5.5) exhibited the breaking up process right at the first millisecond when touched the heated surface. And then, on its way to reach its maximum spreading diameter, the droplet broke up into many smaller droplets. It was clear that the breakup process started at the periphery. The breakup process was more noticeable at 8 ms after the impact took place. Furthermore, it was more obvious than any previous photos presented in Figure (5.1 to 5.4) that after the droplet impacted the hot surface, its mass accumulated at the periphery. At 6ms, the droplet was severely broke up. At 11ms the droplet was almost completely disintegrated. Compare the photos in figure (5.5) with those presented in figure (5.2 & 5.4); one could say that the surface temperature helps deforming the droplet. It may not be true to say that the surface temperature helps in the expanding process;
however it is legitimate to say that the surface temperature helps in the disintegrating process. From the collected data, it is not erroneous to conclude that the spreading process is independent of the surface temperature. However, Weber number plays a paramount role in the spreading process.

The correlations given in equations (2.4, 2.5, 3.20 and Kurokawa and Toda (1991) in table (2.1)) were plotted and compared with the experimental data collected during the present investigation. The graphs below show the relationships between the calculated data and the experimental data.
Figure (5.6). Plot of predicted $\beta_{\text{max}}$ from the correlation given by Hatta et al. (1995) against $\beta_{\text{max}}$ collected from this investigation over Weber number ranges $\text{We} = 30, 50, 60$, and temperature ranges from $T_w = 180, 200, 240 \, ^\circ\text{C}$.
The figure (5.6) above is a plot of the Weber number against the spreading diameter of the droplet impinging on a heated surface. It exhibits some similarities between the experimental data collected during this investigation and the correlation given by Hatta et al. (1998). It is irrelevant to say that experiment data in the present study was inaccurate or the correlation given by Hatta et al. (1998) was fault because the experiment depends on many parameters. One significant different from the work of Hata et al. (1998) and the present experiment was the size of the droplet. Hatta et al. (1998) used the droplet diameter of 300 μm to 700 μm whereas the present study used the diameter size of 4.7 mm. Thus, the discrepancy may be caused by the difference in the size of the droplet. Furthermore, it is important to see that experimental data agrees with the data from the correlation.
Figure (5.7) Plot of measurement values of spreading diameter and predicted values of spreading diameter against Weber number.
Figure (5.7) shows the predicted values of the maximum spreading diameter according to the correlation derived by Chandra and Avedisian (1991) and the measurement values of $D_{\text{max}}$ collected in this experiment. It should be noted that the two data sets compare quite well. As it is generally believe that the higher that Weber the bigger the spreading diameter. For the heated surface, the measurement of $D_{\text{max}}$ collected in this experiment compare well with correlation of Chandra and Avedisian (1991) in figure (5.7). However, the same data were plotted in figure (5.6) with the correlation given by Hatta et al. (1998). It should be obvious that for heated surface, measurement values of $D_{\text{max}}$ in this investigation agreed more with correlation derived Chandra and Avedisian (1991) than with correlation derived by Hatta et al. (1998). Moreover, Fukai et al. (1998) recorded that they also found little resemblance between the spreading diameter in their study compared with the correlation derive by Hatta et al. (1998).

Impinging of water droplet upon unheated glass surface and copper surface were also tested. Photographs of the impinging droplets were stored elsewhere. However, measurement values of $D_{\text{max}}$ was collected and incorporated the plot below.
Figure (5.8). Comparison of measurement data collected for water droplet impinging upon a solid copper surface at room temperature $T_w = 24^\circ C$ with three different surfaces roughness. Weber number was varied from 53 to 271.
Figure (5.8) was plotted with predicted values of $D_{\text{max}}$ from both Chandra and Avedisian (1991) and Hatta et al. (1998) correlations. It should be noted that the measurement values of $D_{\text{max}}$ was measured from photographs of water droplets impinging upon the unheated copper surfaces with three different surfaces roughness. Apparently, the measurement values of $D_{\text{max}}$ were not in agreement with either Chandra and Avedisian (1991) correlation or Hatta et al. (1998). These two correlations over predicted the values of $D_{\text{max}}$. Even though no agreement was accomplished between the previous correlations and the experimental data; however, the same patterns between the correlations and the measurement values of $D_{\text{max}}$ were observed. Technically speaking, from the figure (5.7) above one could notice that at lower Weber number ($We<100$), the experimental data exhibited little agreement with correlation given by Hatta et al. (1998). Furthermore, at higher Weber number ($We>100$), measurement values of $D_{\text{max}}$ showed some similarities in comparison with correlation derived by Chandra and Avedisian (1991). In further investigation, impinging of water droplets upon the unheated glass surface was tested. The results from this investigation were presented in the following figure.
Figure (5.9). Comparison of measurement data collected for water droplets impinging upon a solid glass surface at room temperature, $T_w = 24^\circ C$. Weber number was varied from 29 to 290.
Figure (5.9) presented the four different sets of data, experimental data of $D_{\text{max}}$, Hatta et al. (1998), Kurokawa and Toda (1991), and Chadra and Avedisian (1991) correlations. Kurokawa and Toda (1991) derived the correlation, which is valid for the impinging droplets upon the glass surface at room temperature ($T_w = 24^\circ\text{C}$). Photographs of water droplets impinging upon a solid glass surface at $T_w = 24^\circ\text{C}$ were taken and measurement values $D_{\text{max}}$ of was obtained directly from the photos. The results were plotted in figure (5.9) so that comparison between the experimental values of $D_{\text{max}}$ and predicted values of $D_{\text{max}}$ could be made. For impinging of water droplets upon a glass surface, measurement values of $D_{\text{max}}$ was compared with three different previous correlations. As a result, experimental data agreed well with correlation given by Kurokawa and Toda (1991), and Chadra and Avedisian (1991). As noted in figure (5.8) that at low Weber number ($We < 100$) the experimental data compare rather well with the Hatta et al. (1998). In turn, the same phenomenon was observed in figure (5.9) as well. In short, good agreement was capture in figure (5.9) at $T_w = 24^\circ\text{C}$ for water droplet impinging upon a glass surface.
The spreading diameters of water droplets impinging upon a heated glass surface were presented below. Figure (5.10) below captured the time histories of the droplets impinging upon heat surface different surface temperatures and different values Weber number.
Figure (5.10) Plot of measurement values of spreading diameter versus time it took to reach its maximum. Surface temperature and Weber number are indicated in the legend. $\beta_{\text{max}}$ is noted by $D_{\text{max}}/D_d$; thus $\beta_{\text{max}}$ is dimensionless.
The graphs in figure (5.10) were generated from measuring the spreading diameter of the droplet. It was assumed that at the beginning stage when the droplet just touch the surface, the height and the diameter of the droplet are equaled. As time progressed, the height of the droplet decreased from the original droplet diameter to a minimum value. Simultaneously, the diameter of the droplet increased until it reaches its maximum spreading. In general, it is believed that the height of the droplet after impinging upon the surface is inversely related to the spreading diameter of the droplet. In simple words, as the spreading diameter of the droplet becomes larger, the height of the droplet becomes smaller. When the spreading diameter is at its maximum, the height of the droplet is postulated to be at its minimum. Figure below shows the graphs of the height of the droplet after impinging upon the surface as a function of time.
Figure (5.11). Time histories of droplet deformation process after impinging upon the surface at which surface temperature and Weber number were indicated in the legend. \( \Psi_{\text{min}} \) is noted as the height of the droplet divided by the original droplet diameter. \( \Psi_{\text{min}} \) is a dimensionless number.
The graphs above in figure (5.10 & 5.11) was compare with previous studies by other researched such as Fujimoto and Hatta (1996), Hatta et al. (1998), Fukai et al. (1995), Fujimoto et al (1997) and etc. As a result, the experimental data presented in this experiment exhibits the same patterns as those presented papers by investigators whose name were mentioned above. It should be understood that the data collected from this experiment might not match those obtained by other researcher because the experiment depends upon variety of parameters. These parameters could be environmental conditions, properties of the testing fluid, experimental setup, droplet size, surface temperature, and etc. Again, it is important to note that the data collected during this investigation correlates with those presented from previous studies. In addition, the measurement data for the three sets of experiment were plotted in the figure below. Details discussion is yet to follow.
Figure (5.12). Measurement values of $\beta_{\text{max}}$ for three sets of experiments. For heated glass surface, surface temperature ranged from $T_w = 180^\circ\text{C}$ to $240^\circ\text{C}$. For unheated glass and copper surfaces, surface temperature was $T_w = 24^\circ\text{C}$. 
Figure (5.12) showed the measurement values of maximum spreading diameter with respect to Weber number. There is a direct relationship between maximum spreading diameter and the Weber number. In other words, as the Weber number increased, the maximum spreading diameter increased. Technically speaking, it was obvious that surface temperature exhibited no significant on the spreading process of water droplet impinging upon flat solid surface. Furthermore, surface roughness also showed little effect on the spreading phenomenon. Remarkably, at higher Weber numbers (\( \text{We} > 250 \)), surface roughness showed no effect on the spreading process. An explanation might be that at higher Weber numbers, the droplet possesses higher inertia forces, which in turn, overcomes the resistant between the liquid and the solid interface. That is why surface roughness has almost no impact on the spreading process. However, surface roughness may play a major role in effecting the deformation of the impinging droplet for heated surface. In addition, the maximum spreading time is presented in the figure below.
Figure (5.13). Maximum spreading time of water droplets impinging upon heated surface.
Figure (5.13) showed the graphs of correlation given by Hatta et al. (1998) for stainless steel heated surface and measurement maximum spreading time collected in the present investigation versus Weber number. The correlation suggested that as the Weber number increased, the maximum spreading also increased. However, opposite behavior was found for the measurement values of maximum spreading time. In short, the measurement values in this investigation suggested that as the Weber number increased, the maximum spreading time decreased. Thus, the collected data of maximum spreading time did not correlate well with the prediction values. Intuitively, it's made sense to see that when the Weber number increases, the maximum spreading time should decrease. Obviously, Hatta et al. (1998) did not see the issue from this point of view.

5.2 Experimental Error

Errors from measurement values of the droplet mass was calculated to be ± 2%. The temperature of the room at the time taking the data was fixed at 24°C, so the density of the fluid was assume to be constant. Thus, the uncertainty of the volume is also ± 2%. The droplet was assumed to have a shape of a sphere;
thus, the volume of the sphere was present in equation (4.1). The uncertainty of the diameter of the droplet was calculated to ± 0.6%.

The thermal couple used in the experiment has the diameter of 1.59 mm and the accuracy of ± 2 °C.

The meter used to measure the distant from the tip of the buret has the accuracy of ± 0.1 mm. Since the pre-impact velocity depends on the height of the droplet, so the uncertainty in the velocity was calculated to be ± 1.4%.
6. CONCLUSION AND FUTURE WORK

The effect of surface heat flux on the impingement droplet was evaluated by photographic of droplets of distilled water impinging on a heated surface. In addition, droplets of distilled water impinging upon unheated glass and copper surfaces were also investigated to study the effect of surface roughness on the spreading process. From the results, the following conclusions were drawn.

1. Initially, the droplet impacting on heated surface spreading out like a shape of a donut (annulus) until it approaches a maximum diameter. Because the internal pressure in the periphery is much stronger than that of the central region and because the radius of curvature in the periphery in much smaller than that of the central portion, the liquid in the droplet flows toward the center. At the end, the droplet forms an elongated bar flowing upward. And then, it breaks up due to bubbles explosions.

2. Surface tension plays an important role in the study of impingement droplet. For water droplets impinging upon a solid
surface at low Weber number, surface tension forces keep the droplet intact after impinging take place.

3. As the Weber number increases, the maximum spreading diameter also increases. Furthermore, it was learned that the surface temperature has almost no effect on the spreading process. As a result, the measurement values of maximum spreading diameter collected in the present investigation for both heated and unheated surfaces compared well with the predictions values calculated from correlations provided by previous investigators.

4. The measurement values of maximum spreading time did not correlated well with the prediction values. Experimental data suggested that as the Weber number increases, the maximum spreading time of the impinging droplet decreases. However, correlation given Hatta et al. (1998) exhibited opposite behavior in comparison with experimental data.

5. Water droplets impinging upon unheated copper surfaces with different surface roughness was analyzed. As a result, little effect of surface roughness on the spreading process was found for impinging droplets with lower Weber number. Furthermore, at higher Weber number (We > 250), surface roughness showed no effect on the spreading process.
Future work is essential to investigate the dynamic behavior of impinging droplets on a heated surface. Further investigation of the flow field inside the droplet is essential. In addition, future study should focus more on higher surface temperature with higher Weber number. It is also interesting to determine the critical Weber number. The Weber number depends upon varieties of parameters; thus, the critical Weber number may be equated as a function of fluid properties, droplet diameter, surface materials, etc.
7. REFERENCES


The following set of photos were produced under atmospheric pressure and at room temperature. The photos show in figures (5.1-5.5) were taken with the camera located beneath the heated surface. However, this set of photos was taken with the camera located horizontally.

Figure (A1). The impinging droplet of distilled water upon a heated surface at $T_s = 200^\circ$C and $We = 50$. 
Figure (A2). The impact of a distilled water droplet on a heated glass surface with the following conditions: $T_w = 180^\circ\text{C}$, $We = 30$. 
Figure (A3). The impinging droplet of distilled water upon a hot wall at $T_w = 240^\circ C$ and $We = 60$. 
Figure (A4). The impinging droplet of distilled water upon a heated surface with $T_\infty = 260^\circ C$ and $We = 60$. 