CONTACT ANGLES OF DROPLETS DURING SPREAD AND RECOIL AFTER IMPINGING ON A HEATED SURFACE

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The contact angle of a droplet impinging upon a hot surface undergoes changes as the drop spreads and recoils. The motion of the liquid and the effect of evaporation from the edges of the drop affect the contact angle. The changes in the contact angle during spreading affect the spreading characteristics of the droplet upon impact. However, the models available in literature for the maximum spreading ratio (maximum spread diameter divided by the initial droplet diameter) do not include this effect. In addition, the actual area of contact of a droplet is needed in the heat transfer studies. The present work reports an experimental study conducted to characterize the contact angle variation as a function of the heater surface finish, heater material, and heater surface temperature prior to impact. It is seen that the dynamic advancing contact angle extends beyond the equilibrium advancing and receding contact angles during the motion of the interface. Since the droplet spreading is influenced by the dynamic advancing contact angle, it is proposed to use the dynamic contact angle measurements in the available models for maximum spreading ratio. The experimental results obtained on the maximum spreading diameter indicate the validity of this approach.

Keywords: contact angle; drop impingement; maximum spreading ratio.

INTRODUCTION

The spread and recoil of a drop as it impinges on a hot surface provides an insight into the forces governing the motion of the liquid-vapour-solid triple line. The problem is of practical importance in fuel sprays on combustion chamber walls, fire retardant sprays, spray cooling of nuclear rods during accident conditions, and coating processes. Also, knowing the mechanisms responsible for the motion of the triple line will help us to improve our understanding of nucleate boiling phenomena and mechanisms leading to critical heat flux condition.

As a drop impinges a hot surface, it spreads on the surface under the influence of the momentum of the liquid and the gravitational force. As the liquid spreads, surface tension and viscous forces retard the advancing motion of the interface. As a result of these forces, the liquid vapour interface comes to a stop while the drop assumes its maximum spread diameter. During the spreading process, the surface tension force opposes the interface motion under the influence of the dynamic advancing angle. As the interface comes to a rest, the surface tension force pulls the interface back inward and the liquid starts its motion during the recoil process. The contact angle changes from the dynamic advancing angle to the dynamic receding angle. The droplet assumes a new shape under the receding contact angle at the triple line. The relaxation of the dynamic advancing and receding contact angles sets up an oscillatory motion of the drop as it finally comes to rest on the surface. The final contact angle that it assumes is between the equilibrium values of the advancing and receding contact angles.

The maximum spreading ratio \( (d_{\text{max}}/D) \) is therefore expected to be a function of the dynamic contact angles.

However, the current models on the maximum spreading diameter ratio do not include the dynamic contact angles. The current study focuses on measuring the advancing and receding contact angles for various conditions and applying the contact angle information in the existing models to predict the maximum spreading ratio.

The experiments are aimed at generating information useful in practical industrial systems such as spray cooling of metal casting and extrusions and spray of fuel on the combustion chamber walls. The experiments are conducted with surfaces exposed to air. However, precautions are taken to ascertain that the surfaces are clean of any scale or deposit build-up.

LITERATURE REVIEW

Contact angle has been a focus of research in many disciplines. From the viewpoint of physics, the intermolecular forces among the three phases at the triple contact line are responsible for the ultimate shape assumed by the liquid-vapour interface. From a chemistry viewpoint, the absorption of liquid on a solid surface and its transport introduces a hysteresis effect. From a heat transfer viewpoint, the rapid movement of the interface during evaporation in the contact line region introduces inertia (recoil) forces that determine the shape of the interface. In addition, the capillary forces due to a rough heater surface affect the contact angle.

There are four well-accepted conditions for contact angles reported in literature:

1. dynamic advancing contact angle;
2. equilibrium advancing contact angle.
(3) equilibrium receding contact angle;
(4) dynamic receding contact angle.

An equilibrium contact angle lies in between the equilibrium advancing and equilibrium receding contact angles. The exact value of the equilibrium contact angle depends on the history of the interface. For example, contact angle for a sessile drop placed with a micro-syringe will be the advancing angle to the equilibrium advancing contact angle, while the contact angle for a drop from which some liquid has been withdrawn with a syringe will be closer to the equilibrium receding contact angle.

In addition, there are several factors that affect the four contact angles listed above:
(a) advancing and receding contact angles are affected by the velocity of the interface
(b) all contact angles are affected by the evaporation at the interface
(c) the contact angle depends on the drop radius, or the bubble base size for small diameter drops.

Evaporation affects the contact angles in two different ways. For equilibrium sessile drops placed on a surface with a micro-syringe, the initial contact angle observed is closer to the advancing contact angle. However, as the evaporation takes place, the effect is similar due to the removal of liquid from the drop with a resultant reduction in the contact angle. The other effect is seen at high evaporation rates where the momentum change induced by the evaporated vapour near the triple line reduces the contact angle.

Bernardin et al. studied the effect of the heater surface temperature on the advancing contact angles for practical aluminum surfaces in an attempt to understand the cooling behaviour of aluminum products during the quenching process. They found that the advancing contact angle of a spreading drop remains almost constant for temperatures below 120°C, but decreases for higher surface temperatures.

The receding contact angle has not received as much attention, but is important from a boiling heat transfer viewpoint. During bubble growth, liquid is pushed backwards, and the interface experiences the dynamic receding contact angle. As suggested by Kandlikar, the rapid evaporation occurring at the interface is responsible for the initiation of the critical heat flux condition.

The dynamic receding contact angle plays an important role in the meniscus region heat transfer. A number of studies have been conducted that focus on the liquid flow and heat transfer in the thin film region of the meniscus. For example, Wayne studied the effect of a change in the contact angle from its equilibrium value on the velocity of the liquid in the film and the associated heat flux during evaporation.

**OBJECTIVES OF THE PRESENT WORK**

In an effort to gain further understanding of various phenomena associated with advancing and receding contact angles of a liquid-vapour interface, the present work focuses on experimentally measuring the contact angles at various stages as a liquid drop impinges on a flat heated surface. The effects of surface roughness, surface material, and surface temperature on dynamic advancing and receding contact angles are studied. The experimental values of the advancing contact angle are used in the existing theoretical models to predict the maximum spreading ratio for water droplets impinging on a hot surface over a Weber number range from 10 to 58.

**EXPERIMENTAL SET-UP**

The experimental apparatus consists of five main components: the heated surface, cartridge heater, drop delivery system, constant light source, and high speed digital camera. A schematic of the system is shown in Figure 1.

The present study is conducted with water impinging on hot surfaces representative of the commercial surfaces employed in industrial applications such as spray cooling of metal castings and extrusions and fuel sprays on hot combustion wall chambers. Copper and stainless steel surfaces are polished to the desired roughness and then cleaned several times using de-ionized distilled water. The samples are then cleaned using an Acetone wash. In addition, experiments are also performed on a commercially available non-stick coating of SilverStone®. The surfaces are heated to the desired temperature and allowed to achieve steady state conditions before conducting the experiments. All experiments are conducted in air.

The heated surfaces are constructed using electrolytic tough pitch copper C110 (99.9% copper, 0.04% oxygen), 316 stainless steel, and SilverStone® (E. I. du Pont de Nemours and Company) non-stick surface. The copper and stainless steel heated surfaces are constructed from a 1-3/8 inch diameter rod of 4 inch (102 mm) length. A 3/8 inch (9.53 mm) hole is drilled into the bottom of the cylinder to receive the cartridge heater. The surfaces are polished to the desired surface roughness. The SilverStone® heated surface is constructed from a commercial clothes iron. The iron is stripped of all unnecessary components and is fitted with thermocouples for investigation. In each case, the heated surface is well insulated. Only the upper, exposed surface of the heater is exposed directly.

**Figure 1.** Experimental set-up for droplet impingement studies: (1) heated surface; (2) cartridge heater; (3) droplet delivery system; (4) light source; (5) high-speed camera; (6) light diffuser; (7) insulation.
The cartridge heater has a capacity of 400 watts at 120 volts. It is powered by a 120 volt DC power supply. Regulating the voltage of the DC power supply controls the heater surface temperature.

The droplet delivery system is constructed using a 100 ml burette (Kimax model 17027F-100 manual burette). It is used to deliver the de-ionized water manually on a drop-wise basis. The burette is suspended using pipe stands and clamps. The height for the burette tip is variable from the heated surface.

A 600 Watt floodlight provides the constant light source. The light remained turned on for the experiments to provide back lighting for the subject droplet. Light diffusers are utilized to minimize direct light rays from entering the camera and to provide even background illumination.

A MotionScope model 8000sPCI high-speed digital camera is used to record the droplet dynamics. The camera is capable of recording at 8,000 frames per second for 1.5 second duration. The frame rate and the shutter speed are adjusted to allow for the best possible images. For the majority of these experiments, the frame rate is set to 1,000 frames per second with a shutter speed of 1/20,000 seconds. The images are digitally captured and stored. The camera is placed 0.5 metres from the test section. The sample is adjusted to ensure that the test piece is level.

**EXPERIMENTAL PROCEDURE**

The surface temperatures reported in this paper are the steady state surface temperatures taken just prior to droplet impingement. The transient effects of the impingement dynamic on the heater surface temperature are not studied.

The heated surface is polished using a buffing wheel and a one-micron slurry of aluminum oxide in water. The surface roughness is measured with a profile metre. The profile metre reports a Roughness Average Value, \( R_a \), from a continuous averaging of surface roughness heights. The profile metre has an accuracy of \( \pm 0.005 \mu \text{m} \) for the full range of measurements. The reported surface roughness values are an average of several independent measurements. The average value is within 5% of the range of measured values. For example, for a 320 grit finish on the copper surface the measured values were; 0.64, 0.62, 0.63, 0.64, and 0.64. The one-micron slurry produced a \( R_a \) value of 0.02 \( \mu \text{m} \). This procedure is used to prepare the copper and stainless steel surfaces. The SilverStone® surface is tested using the factory delivered surface finish. The SilverStone® surface roughness was measured to be 1.35 \( \mu \text{m} \). The copper surface is prepared with surface roughness values of 0.63 \( \mu \text{m} \), 0.32 \( \mu \text{m} \), 0.25 \( \mu \text{m} \), and 0.02 \( \mu \text{m} \). The stainless steel surface is prepared with surface roughness values of 0.13 \( \mu \text{m} \), 0.07 \( \mu \text{m} \), 0.04 \( \mu \text{m} \), and 0.01 \( \mu \text{m} \).

A 100 ml burette is varied from a height of 13 to 76 mm above the heated surface. The height remained constant for all experiments to eliminate the effects of a changing Weber number, \( W_e \). The water flow rate is set to a low value to allow a droplet to form on the end of the burette and fall under its own weight. The droplets produced in this manner had diameters that ranged from 2.779 mm to 2.881 mm. The average droplet diameter is 2.816 mm.

A K-type thermocouple with a thermocouple reader is used to monitor the surface temperature of the heated surface. The temperature has an accuracy of \( \pm 0.05 \degree \text{C} \). The voltage of the DC power supply is controlled to regulate the surface temperature and allow the heated surface to reach a steady state temperature. The camera is then set to record at the specified frame rate. After several minutes of steady state surface temperature, the droplet is allowed to impinge upon the surface and the video and temperatures are recorded.

The experiments where carried out using a clean sample. The sample was polished and rinsed using de-ionized distilled water. The sample is then rinsed with an Acetone bath. As previously mentioned, the sample was allowed to reach a steady state surface temperature. One thermocouple is located 3.2 mm from the surface and the second thermocouple is located 6.35 mm from surface. The steady state condition is achieved when the two thermocouples do not change for a period of ten minutes.

The contact angle \( \theta \) is measured using a secondary AutoCAD® program. The contact angle is measured within the droplet as shown in Figure 2. Single frames at desired time intervals after the impact are captured from the recorded video. The frames are then imported into AutoCAD®. Figure 3 depicts a typical frame and angle measurement technique followed. The angle that is included in the vapour medium is actually measured. The required contact angle is the complimentary angle of the measured angle.

**RESULTS**

The present work is concerned with the surface temperature and surface material effects upon the droplet's advancing and receding contact angles and characteristic behaviour. As such, it was mentioned that the height of the droplet delivery system was fixed for this set of experiments.

![Figure 3. Contact angle measurement: typical measurement of the contacting angle in a captured image frame.](image-url)
to minimize the effect of Weber Number on the data. Only the initial steady state temperatures are reported. No transient analysis of the droplet impingement was performed.

The analysis of the droplet impingement was broken down into two different cases. The first case is an equilibrium state. The second case is the dynamic state.

**Case One**

Equilibrium state measurements: The droplet is allowed to impact and come to equilibrium with the unheated surface at room temperature (22°C). Figure 4 shows the effect of surface roughness on the droplet shape on horizontal copper surfaces. The pictures are taken within several seconds after the droplet comes to an equilibrium state.

Figure 5 represents the equilibrium contact angles for individual droplets over copper and stainless steel surfaces. The reported contact angles are the average of several independent measurements. As the surface roughness decreases, the contact angles for copper decrease and then increase for the smoothest surface. However, the stainless steel surface exhibits a different behaviour. As the surface roughness increases, the contact angle decreases. This can be explained by comparing copper and stainless steel.

**Case Two**

Dynamic behaviour: The second case considered is the dynamic behaviour of the droplet. In this study, the dynamic advancing and receding contact angles are measured.

The same technique is employed for determining the equilibrium advancing and receding contact angles. The surfaces are tilted at an angle of 28 degrees to the horizontal. Figure 6 represents a captured frame of the measurement of the equilibrium advancing and receding contact angles. The droplet is gently placed on the surface using the needle. The advancing contact angle was measured on the downhill or left hand side and the receding contact angle was measured on the up hill or right hand side. To check whether the angles are the true advancing and receding angles, the surface is tilted further to 45 degrees. The angles remained nearly constant indicating that these are representative of the advancing and receding contact angles respectively.

Again, the measurements are taken within several seconds after placing the droplet on the surface. Figure 5 also shows these contact angles for different surface roughness values for copper surface.
Three surface materials are used in this part of the study. The surfaces are; copper, stainless steel, and the SilverStone®. The copper and stainless steel are both polished using the one-micron slurry. They have a surface roughness of 0.02 μm for the copper surface and 0.01 μm for the stainless steel surface. The SilverStone® surface was tested using the factory finish with a surface roughness of 1.35 μm.

As stated before, the surface temperature was controlled to provide a steady state surface temperature. The surface temperatures ranged from 100°C to 220°C. De-ionized water at $T_{\text{water}} = 22°C$ is used as the test liquid in all experiments. The ambient temperature and pressure is recorded to be 22°C and 29.7 in Hg, respectively.

The dynamics on the droplet impingement is shown in Figures 7, 8, and 9. The Weber number for these three figures is fixed at 29.4. Figure 7 depicts the impact of a droplet on an unheated copper surface. The droplet behaviour is recorded to make the contact angle measurements. Once again, the reported contact angle is an average of several independent measurements. Figure 7(a) shows the droplet immediately following the impact. The spherical shape of the droplet is truncated by the surface. Figure 7(b) shows the droplet at 2 ms after the impact. The maximum spreading diameter is reached in Figure 7(d). Figures 7(e) and (f) are after 2 ms and 4 ms respectively following the instant when the maximum spreading diameter is reached.

Figure 8 shows the droplet impinging upon a copper surface with surface temperature of 120°C. The test piece has a slight 5-degree bevel around the edges. The bevel does not effect the droplet impingement area. The test piece was adjusted in the same manner to ensure a level surface. Figures 7 and 8 show very little difference. This is to be expected because the surface temperature is only 20° above the saturation temperature. However, the contact angles differ between the figures. Also, nucleation occurs much later and is not seen in the frames shown in Figure 8.

Figure 9 shows the droplet impinging upon a copper surface with a surface temperature of 200°C. The test piece has a slight 5-degree bevel around the edges. The bevel does not effect the droplet impingement area. The test piece was adjusted in the same manor to ensure a level surface. The surface temperature is well past the critical heat flux condition for the pool boiling case. In Figure 9(c), some tiny water droplets and vapour can be seen leaving the main droplet. Figure 9(e) shows the droplet behaving in a near film boiling manner (transition boiling). The droplet breaks down into smaller droplets as vapour is formed under the droplet. Figure 9(f) demonstrates this behaviour with increasing severity.

The copper surface material results coincided with the current literature. The dynamic advancing and receding angles are obtained using the AutoCAD program as described earlier. The reported contact angle is an average of several independent measurements. All of the contact angles are with in 5% of the average values. For example, the measured values of advancing contact angle for a copper surface at 128°C are; 129.4, 128.44, 132.15, 129.31, and 125.72 degrees. Figure 10 depicts the dynamic advancing and receding contact angles for the heated copper surface. The dynamic advancing contact angle begins at a value of approximately 130 degrees and remains nearly constant around 140 degrees at higher temperatures. The dynamic receding contact angle starts at around 80 degrees at 125°C.

Figure 10. Dynamic advancing and receding contact angles for a copper surface: 120°C < $T_s < 220°C$; $h = 1.5$ inches; $T_{\text{water}} = 22°C$; $R_s = 0.02$ μm; $We = 29.4$.
but sharply increases around 150°C to the same value as the dynamic advancing contact angle. This behaviour can be attributed to approaching the transition boiling condition.

The dynamic advancing and receding contact angles for a stainless steel surface are represented in Figure 11. The surface temperatures ranged from 100°C to 250°C. The dynamic advancing contact angle begins at a value of around 130 degrees and increases to around 160 degrees for heater surface temperatures above 200°C. The dynamic receding contact angle begins at a value of around 60 degrees, and similar to the copper case, jumps to the same value as the dynamic advancing angle for temperatures above 150°C. The dynamic advancing and receding contact angles remain almost equal for temperatures above 150°C. At a surface temperature of 200°C, the advancing and receding contact angles begin to climb and approach 180 degrees indicating the film boiling region.

The SilverStone® surface tests are conducted in the same manner as for copper and stainless steel surfaces. Figure 12 shows the results of the dynamic contact angle measurements for the SilverStone® surface tested. The surface temperatures ranged from 60°C to 220°C. The advancing contact angle remains at a value of approximately 130 degrees. The receding contact angle remains close to 90 degrees. However, the advancing and receding contact angles do not merge at higher temperatures, although there is a slight increase in the dynamic receding contact angle at higher temperatures. This behaviour is distinctly different from the other two surfaces and can be attributed to the SilverStone® coating. This surface is specially prepared to provide a non-stick coating to prevent foods and sauces from sticking to the surface. This coating drastically alters the shape of the droplet and its behaviour at elevated temperatures.

**DISCUSSION ON CONTACT ANGLE RESULTS**

The effect of roughness is seen to be important for advancing contact angles near very low roughness values. As the surface becomes smoother, the advancing contact angle becomes higher. For higher roughness values, the contact angles seem to remain almost constant, although some increase is noted at higher roughness values. It is also noted from Figure 5 that the equilibrium contact angle lies somewhere between the advancing and receding contact angles. Since the equilibrium contact angle depends on the history of the interface, its utility in dynamic interface modelling seems to be limited.

The effect of temperature on dynamic advancing and receding contact angles is seen only around temperatures between 140–150°C. At this temperature, it is suspected that the rapid evaporation near the liquid-solid contact region influences the dynamic contact angles, and both dynamic advancing and receding contact angles become almost equal to each other.

The experimental results show that the dynamic advancing contact angles are significantly higher than the equilibrium contact angles. Furthermore, the equilibrium contact angle is not a unique measurement as it can vary between the static advancing and receding contact angles. Since the spreading phenomenon is affected by the actual dynamic contact angle, it is recommended that this value be used in the modelling of spreading characteristics of impinging droplets. Further study on this aspect is reported in the next section.

**APPLICATION OF ADVANCING CONTACT ANGLE IN PREDICTING MAXIMUM SPREADING RATIO**

The maximum diameter reached by a liquid droplet after impinging on a hot surface is of interest from a heat transfer viewpoint. Kandlikar et al. provide a summary of available literature in this area and provide experimental results on the maximum spreading ratio as a function of Weber number. The experimental data was compared to existing correlations using three models: Akao et al., Kurabayashi and Yang (referred to in Yang), and Healy et al. These available correlations predict the spreading ratio as a function of the surface temperature. The model by Akao et al. is a simple correlation between the spreading ratio and the Weber number given below:

\[
\frac{\ell_{\text{max}}}{D} = 0.613 \cdot W e^{0.39} 
\]

where \( \ell_{\text{max}} \) is the maximum spread diameter, \( D \) is the initial droplet diameter just prior to impact, and \( W e \) is the Weber number. Akao originally gave the ratio in terms of the initial droplet radius and the maximum spreading radius. The

comparison between the experimental data by Kandlikar et al.\textsuperscript{10} and Akao et al.\textsuperscript{11} model is shown in Figure 13. The symbols show experimental data points and the solid lines represent the model prediction for different Weber numbers. It can be seen that Akao et al.\textquoteright s model is able to predict the maximum spreading ratio quite well except for the highest Weber number case, $We = 58$.

The model by Kurabayashi and Yang\textsuperscript{12}, K-Y model, includes the Weber number and Reynolds number of the impacting droplet in predicting the maximum spreading ratio, $\beta_{\text{max}}$:

$$
\frac{We}{2} = \frac{3}{2} \beta_{\text{max}}^2 \left[ 1 + \frac{3We^*}{Re} \left( \beta_{\text{max}} \ln(\beta_{\text{max}}) - \frac{\beta_{\text{max}}^2 - 1}{2} \right)^{0.14} \right] - 6
$$

Figure 14 shows the comparison between the Kandlikar et al.\textsuperscript{10}’s experimental results and the K-Y model. The model significantly over predicts the results for all Weber number cases.

In an attempt to improve the K-Y correlation, Healy et al.\textsuperscript{13} introduced a contact angle correction factor defined as follows.

$$
\beta_{\text{K-Y,corr}} = \beta_{\text{K-Y}} \left( \frac{45}{\theta} \right)^{0.241}
$$

Healy et al.\textsuperscript{13} suggested the use of the equilibrium contact angle, but did not provide the values of these angles. The advancing contact angle measurements for copper surface, from the present investigation, is used in the Healy K-Y correlation. The results of the comparison of Healy et al. and a contact angle of 130 degrees with the experimental data of Kandlikar et al.\textsuperscript{10} are plotted in Figure 15. The agreement has improved considerably as compared to the K-Y correlation. The model is able to predict the results better than the Akao et al.\textsuperscript{11} correlation for the highest Weber number case of $We = 58$.

In light of the present comparison, a slight modification to Healy et al.\textsuperscript{13} correlation is suggested as follows:

$$
\beta_{\text{K-Y,corr}} = \beta_{\text{K-Y}} \left( \frac{45}{\theta} \right)^{0.331}
$$

The advancing contact of 130 degrees is used. The new exponent for the Healy et al.\textsuperscript{13} K-Y Correction is found to be 0.331. This exponent corrects the Healy et al.\textsuperscript{13} K-Y Correction to show good agreement with the Weber Number greater than 30. Figure 16 shows the results using a value of 0.331 as the exponent.

However, it is suggested that additional data for the spreading ratio over different surfaces (and different contact angles) be obtained and compared with the above correlation before using it in practical applications. Larger Weber numbers should also be studied to see how the correlation will predict the behaviour.

**CONCLUSIONS**

The following conclusions are drawn from the present study:

1. The droplet shape under equilibrium conditions depends on the surface roughness. The equilibrium contact angle lies between the two limiting values given by static advancing and static receding contact angle
values. The contact angle depends on the surface and the history of the droplet.

(2) The dynamic advancing and receding contact angles are different for a droplet spreading and recoiling after impingement. For water at atmospheric temperature, the dynamic receding contact angle increases to the same value as the dynamic advancing contact angle at a temperature of around 140–150°C. At a temperature of around 200°C, both these angles further increase indicating the transition to the film boiling region. This behaviour is seen for copper and stainless steel surfaces.

(3) The dynamic receding contact angle for SilverStone® non-stick coating is relatively high, around 90 degrees, and is not affected as much as the copper or stainless steel surfaces at higher temperatures.

(4) The dynamic receding angle is indicative of the change from a liquid contact with the heater surface to transition boiling around 150°C, and to a fully established film boiling at around 200°C for water impinging on copper and stainless steel surfaces.

(5) Further studies are recommended to establish a firm connection between the dynamic receding contact angle changes to the establishment of transition and film boiling regions.

(6) The maximum spreading ratio for water droplet impinging on a hot surface is predicted reasonably well with a correlation given by Akao et al. for We ≤ 29. Further improvements are obtained for We = 58 case by introducing a modified Kurabayashi and Yang model, as suggested by Healy et al., and using the advancing contact angle instead of the equilibrium contact angle. The Kandlikar and Steinke exponent value of 0.331 provides a good prediction for higher Weber numbers using the Healy et al. correlation.

(7) It is suggested that the Akao correlation be used for Weber numbers less than 30 and the Healy et al. correlation with the Kandlikar and Steinke Exponent of 0.331 for Weber Numbers greater than about 50 (approximate value at this stage).

(8) Further studies are recommended to determine the validity of these correlations for higher Weber numbers (We > 59). The higher Weber number results are of great interest in practical industrial applications.

NOMENCLATURE

- \( d_{\text{max}} \): maximum spreading diameter, m
- \( D \): drop diameter prior to impact, m
- \( h \): height from heated surface, m
- \( R_s \): average roughness, m
- \( T_s \): surface temperature, °C
- \( T_{\text{sat}} \): saturation temperature, °C
- \( T_{\text{water}} \): water temperature, °C
- \( V \): drop velocity at the moment of impact, m s\(^{-1}\)
- \( \text{We} \): Weber number, \( = \rho V^2 D/\sigma \)

Greek Symbols

- \( \alpha \): surface inclination, degrees
- \( \beta_{\max} \): maximum spreading ratio, \( d_{\text{max}}/D \)
- \( \theta \): contact angle, degrees
- \( \rho \): density, kg m\(^{-3}\)
- \( \sigma \): surface tension, N m\(^{-1}\)
- \( \mu \): viscosity, kg m s\(^{-1}\)

REFERENCES


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