EFFECTS OF THE MOMENTUM OF WATER DROPLET ON ITS EVAPORATION ON HEATED SURFACES

M. Abu-Zaid

Mechanical Engineering Department, Faculty of Engineering
Mu'tah University Al-Karak, Jordan

ABSTRACT

This paper presents the results of an experimental investigation of the evaporation of a 3.46 mm diameter water droplet having a velocity in the range of 0.44-1.83 m/s on hot surfaces of aluminum, brass, and stainless steel. Measurements of droplet diameter upon impact on the hot surface, evaporation time, and surface temperature during droplet evaporation, under atmospheric pressure were performed. The results show that as the droplet velocity increases, the evaporation time decreases while the cooling effect increases at the same initial surface temperature. The surface temperature corresponding to minimum evaporation time was determined and found to be independent of droplet velocity in the temperatures ranges studied.

Keywords: Droplet evaporation, momentum effects, evaporation time, water.

INTRODUCTION

Practical applications of droplet evaporation include cooling of a turbine blade, cooling rolling steel plates, cooling during continuous casting, quenching, tempering, and emergency spray cooling of reactors in the nuclear power industries. In these applications, water is commonly used as the cooling agent. Thus, understanding the characteristics associated with the evaporation of water droplet is important for effective cooling in such applications.

When a single pure droplet is settled on a hot surface, heat is transferred to the droplet from the surface directly beneath it, causing the droplet to evaporate. The total evaporation time of the droplet depends mainly on the initial solid surface temperature, condition on the surface, and droplet momentum at impact.

Numerous studies on the droplet evaporation process on hot porous and non-porous surfaces have been reported in the literature. The evaporation process of droplets below leidenfrost temperature has been studied but not to the same extent as leiden frost phenomenon. Michiyoshi and Makino [1] studied the heat transfer characteristics of evaporation of a single droplet of pure water, deposited softly on several metal surfaces, at temperatures ranging from 80 to 450 °C. Makino and Michiyoshi [2] studied the effect of initial size of water droplet on its evaporation time. They presented a wide range of the so called boiling curve (q vs ΔT_{sat}), Thus establishing the thermal behavior of droplets during evaporation process.

Seki *et al.* [3] measured the transient temperature profile of a hot surface upon droplet impingement, dropped from a height of 20 mm, using a thin-film thermometer. Lee *et al.* [4] employed micro thermocouple surface probe to obtain direct measurements of liquid-solid contact in transition boiling and film boiling of water at atmospheric pressure.

Renken *et al.* [5] investigated the effects of vapor velocity on film condensation along an isothermal surface embedded in a porous medium. They found that the free stream vapor flow and the effective Prandtl number have a significant ramification on the heat transfer rate as compared to open space forced convection condensation.

Tio and Sadhal [6] studied the heat transfer aspects of droplet spray evaporation from a heated solid surface by employing a theoretical model for the low superheat regime. In this regime impinging droplets stick onto the solid without bubble nucleations. They assumed that the spray consists of droplets of the same size. They calculated Nusselt number and examined the effect of droplet contact angle, solid coductivity, and droplet concentration on heat transfer. Rizza [7] presented a numerical solution for spray evaporation on hot surface for temperatures below the leidenfrost temperature. He computed a dimensionless evaporation time, and from this he developed a flooding index. He showed that the flooding index is related exponentially to the droplet diameter and wetting ratio.

Pedersen [8] presented heat transfer data for individual water droplets impinging upon a heated surface. He studied the effect of surface temperature variation from the saturation temperature to 1800° F. He concluded that the heat transfer data show that the approach velocity is the dominant variable affecting droplet heat transfer, and the surface temperature has a little effect on heat transfer in the non-wetting regime.

Abu-Zaid and Atreya [9] studied the effect of water as externally applied on hot porous and non-porous ceramic solid for surface temperature ranging from 25 to 200°C. Both solids were instrumented with several surfaces and in-depth thermocouples. They concluded that the evaporation time is longer for the non-porous solid than for the porous solid for the same droplet size and under identical conditions. Also, they concluded that smaller droplets are more effective for cooling non-porous solid at or below 100 °C.

The aim of the present work is to investigate experimentally the effect of water droplet momentum on its evaporation on various heated surfaces (aluminum, stainless steel, and brass) in the evaporation and nucleate boiling regimes. The droplet diameter was 3.46 mm and the approach velocities ranged from 0.44 to 1.83 m/s.

EXPERIMENTAL APPARATUS AND PROCEDURE

A detailed description of the experimental apparatus shown in Figure 1 is reported elsewhere [10]. Briefly, however, a three heating solid elements namely aluminum, stainless steel, and brass were used. The upper surface was carefully machined and polished, and instrumented with a surface thermocouple (chromel-alumel) with a bead size of 150 μ m. and a time constant of one second. The two ends of the thermocouple were connected to a multi-meter to read the temperature of the tested surface. In addition they were connected to a high response BBC Goerz metrawatt chart recorder, with a 0.5 s. response time, and an accuracy of ± 0.5% of full scale value, to plot the temperature profile during droplet evaporation. To measure the diameter of the droplet upon impact on the heated surface, a fine scale was marked on the tested area of the surface from the thermocouple bead. The solids were heated from below by an electric heater, and its temperature was controlled by a variac.

A distilled water droplet of diameter 3.46 mm, with an average deviation of ±4.6%, was generated by a droplet generating system which consists of a stainless steel needle, a high quality syringe, and a Razel syringe pump [10].

The procedure consists of depositing gently a known size of water droplet, at about 20 °C from different release heights, free of transverse air current movement, on the heated surface over a range of initial surface temperature. The test area was allowed to reach a steady temperature before starting the measurements. The specific heights selected were 0.01, 0.05, 0.09, 0.13, and 0.17 m. The time duration until the droplet disappears after it touches the surface, i.e. the evaporation time was measured using Irwin crystal timer with a resolution of 0.01s. The chart recorder provides the transient surface temperature during the droplet evaporation time. The chart speed used in the experiments was in the range 0.0005 - 0.01 m/s.

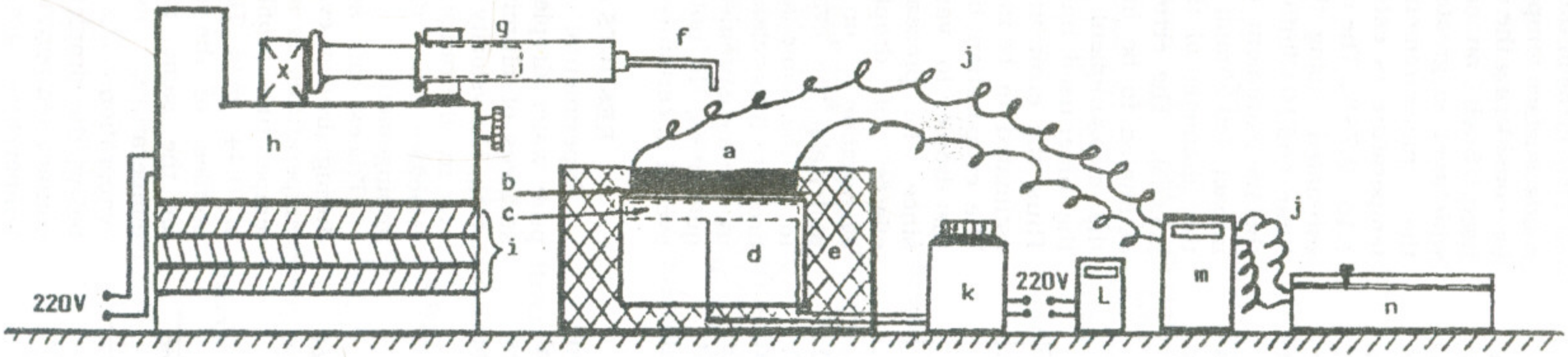

Figure 1 Experimental set-up: (a) heat surface; (b) mica sheet; (c) heater; (d) ceramica block; (e) insulation; 9f0 stainless-steel; (g) syringe; (h) pump; (I) wooden blocks each 4 cm height; (j) 0.076 mm thermocouple; (k) variac; (L) timer; (m) multimeter; (n) chart recorder.

ANALYSIS

Experimental data were obtained with droplet of 3.46 mm diameter. The droplet was deposited on the heated solids from different release heights. The velocity of the droplet at impact was calculated from the free fall equation, and a boundary conditions; droplet initial velocity = 0 at z =h, and droplet velocity at impact = V at z = 0, the droplet velocity at impact is given by: $V = (2\ g\ h)^{1/2}$, then the change of droplet momentum = mV.

Table 1 shows the specific release heights used, and the corresponding droplet velocity at impact and the change of momentum.

Table 1 Droplet velocity at impact and change of momentum

Release height(cm)	Droplet velocity(m/s)	Change in momentum (N.s)
1	0.44	$9.53X10^{-6}$
5	1.00	$21.65X10^{-6}$
9	1.33	$28.79X10^{-6}$
13	1.60	$34.64X10^{-6}$
17	1.83	$39.62X10^{-6}$

The radius of wetted area is a very important parameter as recognized by Bonicina [12]. The non-dimensionlized parameter β is normally expressed as the ratio of radius of the droplet wetted area at impact (r_2) to the radius of the spherical droplet of 1equivalent volume (r_1). Thus:

$$\beta = r_2/r_1 \quad (1)$$

The theoretical contact temperature of two semi-infinite slabs with constant thermal properties, initially at different temperatures brought into contact is calculated using the following equation given in Reference 3:

$$T_i = \frac{T_s + T_d[(pck)_d / (pck)_s]^{1/2}}{1+[pck)_d / (pck)_s]^{1/2}} \quad (2)$$

Table 2 lists the thermal properties of water and the heated surfaces used in the experiments given in Reference 13.

Table 2 Thermal properties of water and heated surfaces at 300 K

Substance	Density (kg/m³)	Specific heat (J/kg.K)	Conductivity (W/m.K)	Diffusivity (m²/s.)
Water	998	4181	0.606	$0.145X10^{-6}$
Aluminum	2702	903	237	$97.1X10^{-6}$
Brass	8800	420	52	$14.0X10^{-6}$
Steel	8055	480	15.1	$3.91X10^{-6}$

EXPERIMENTAL ERRORS

The error in the measurement of heated solids surface temperature may be estimated by considering the error in the thermocouple used. Such an error is 2.2 °C or 0.75% whichever is greater [16]. Thus the error in the measurement of solids surface temperature is estimated to be in the range 1.16 -2.75 %. The error in the parameter β is estimated using the method presented by Kline and McClintock [17]. Using the error in the measurement of droplet diameter upon impact (±0.25mm), and the uncertainty in the diameter of the droplet before impact (±4.6%). The error in the parameter B is estimated to be in the range 5.54-7 %. For the measurement of the evaporation time, the timer used has a resolution of 0.01 sec. Thus the error in the evaporation time is estimated to be in the range 0.006 - 1.43 %. The evaporation time is the time taken for the droplet to vanish from the surface. and since the present work, investigate the effects of droplet momentum on its evaporation on various non-porous materials, the evaporation time is cosidered to be the same as the residence time of the droplet. It is clear that the estimated errors in the measurement of the basic and derived quantities, do not significantly influence the overall uncertainty in the final results.

RESULTS AND DISCUSSION

Experimental data were obtained with pure water droplet on three hot horizontal surfaces of aluminum, brass, and stainless-steel. The velocity of the droplet upon impact was in the range 0.44 - 1.83 m/s. At higher velocities the droplet breaks up upon impingement.

Traces of solid surface temperature during droplet evaporation at three different temperatures is shown in Figure 2. These temperature profiles were for droplet velocity of 0.44 m/s. They have similar trend to profiles of the remaining droplet velocities for the same material and at the same temperature, except for the time of evaporation. The surface temperature just below the droplet falls immediately to the contact temperature upon impact, then this temperature gradually increases until it reaches the equilibrium temperature: the interface temperature during evaporation process. At the last stage of evaporation, as the droplet thickness on the surface becomes smaller, higher heat flux will pass through this thin droplet. This causes a rapid decrease in the solid surface temperature until the droplet is completely evaporated. Subsequently, the surface temperature increases rapidly to recover to its initial value.

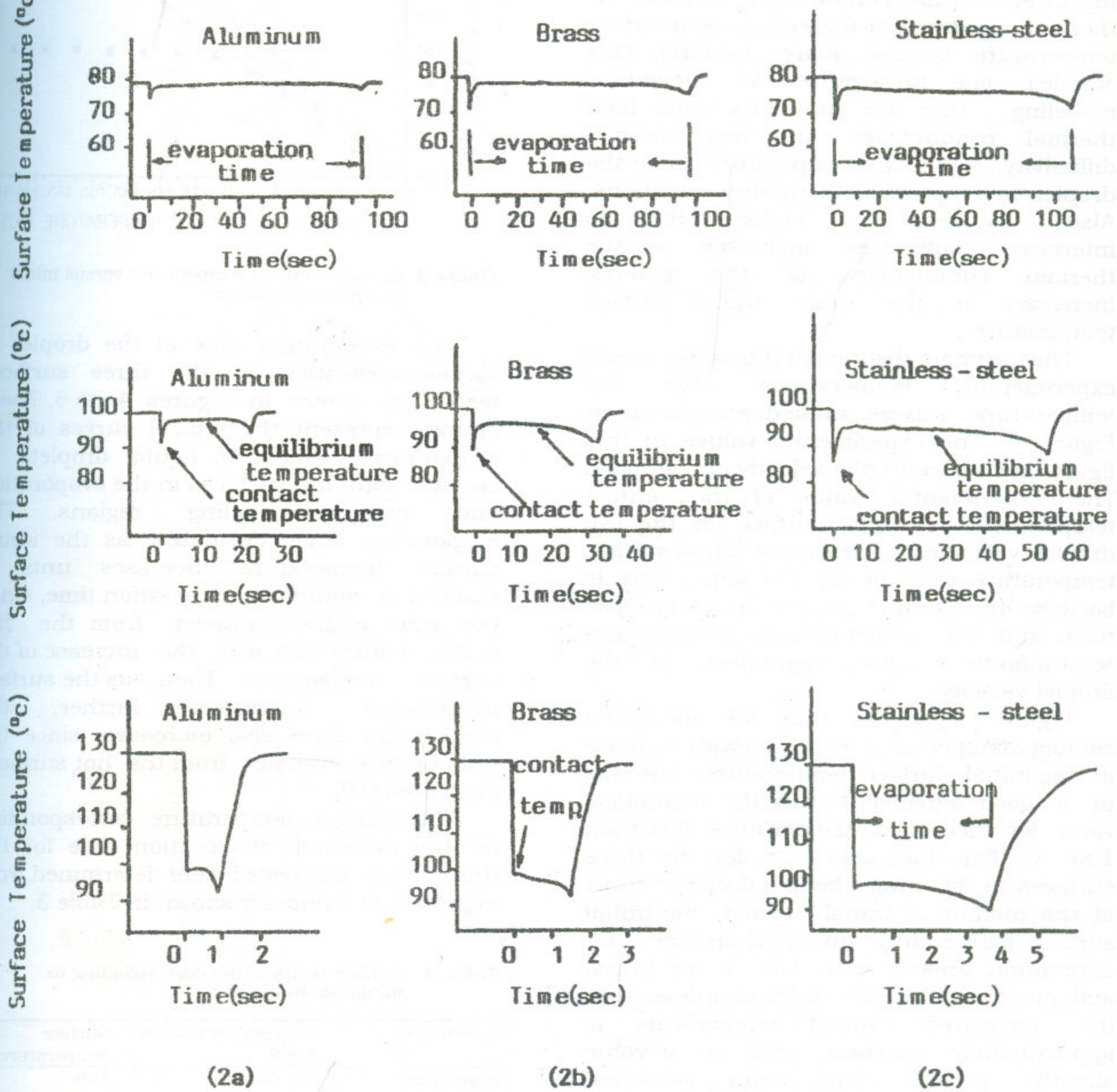

Figure 2 Traces of surface temperature of aluminum (2a), brass (2b), and stainless-steel (2c), at various initial surface temperatures. and droplet velocity of 0.44 m/sec.

It is clear from Figure 2 that the interface temperature for aluminum is nearly constant, while for stainless steel is decreasing more steeply than brass with time. This indicates that the droplet on stainless steel exhibits lower temperatures in its proximity than aluminum and brass at the same initial surface temperature due to its lower thermal conductivity. Thus as the thermal conductivity increases, the interface temperature become more uniform. This enables one to assume, for theoretical modeling, that for materials with high thermal conductivity and high thermal diffusivity, a constant temperature under the droplet is a reasonable boundary conditions. Also it is clear from Figure 2 that the interface temperature increases as the thermal conductivity of the material increases at the same initial surface temperature.

The intimate theoretical (Equation 2) and experimental temperatures for the temperature ranges studied are shown in Figure 3. The experimental values in this figure are for a droplet velocity of 0.44 m/s. The experimental value of the contact temperature of each surface for the five droplet velocities at the same initial surface temperature were nearly the same. This is because the contact occurs in a very short time, and the droplet sees the surfaces as a semi-infinite bodies regardless of the droplet velocity.

Figure 3 shows that the measured contact temperature increases with increase in the initial surface temperature, and was in a good agreement with the theoretical value for theoretical temperature less than 100 °C. This indicates that, for the three surfaces in this range, boiling does not occur at the instant of initial 1cotact. For initial surface temperature greater than 109 °C for aluminum, greater than 120 °C for brass, and greater than 120 °C for stainless steel, the measured contact temperature is approximately constant, and at a value slightly greater than water saturated temperature at atmospheric pressure, and lower than the theoretical contact temperature. This indicates that for this range, boiling starts at the instant of contact..

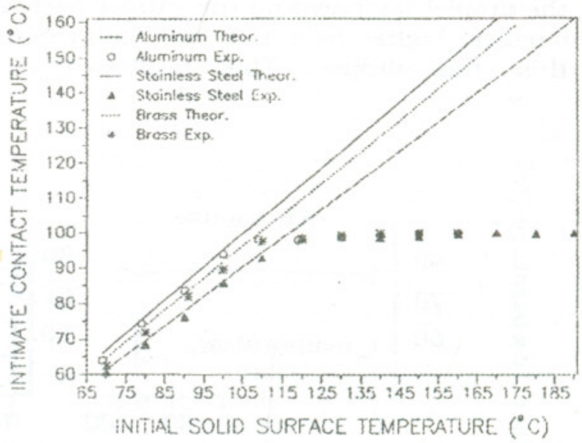

Figure 3 Intimate contact temperature versus initial surface temperature.

The evaporation time of the droplet at various velocities on the three surfaces tested are shown in Figures 4 to 6. These figures represent the typical curves of the evaporation times of liquid droplets in contact with hot surfaces in the evaporation and nucleate boiling regions. The evaporation time decreases as the initial surface temperature increases until it reaches a minimum evaporation time, since the rate of heat transfer from the hot surfaces increases with the increase of the surface temperature. Then, as the surface temperature increases further, the evaporation time also increases, since the rate of heat transfer from the hot surfaces decreases [10].

The surface temperature corresponding to the minimum evaporation time for the three materials tested were determined from Figures 4 to 6 and are shown in Table 3.

Table 3 Surface temperature corresponding to minimum evaporation

Substance	Thermal diffusivity m/s^2	Surface temperature °C
Aluminum	97.1×10^{-6}	130
Brass	14.0×10^{-6}	150
Stainless steel	3.91×10^{-6}	170

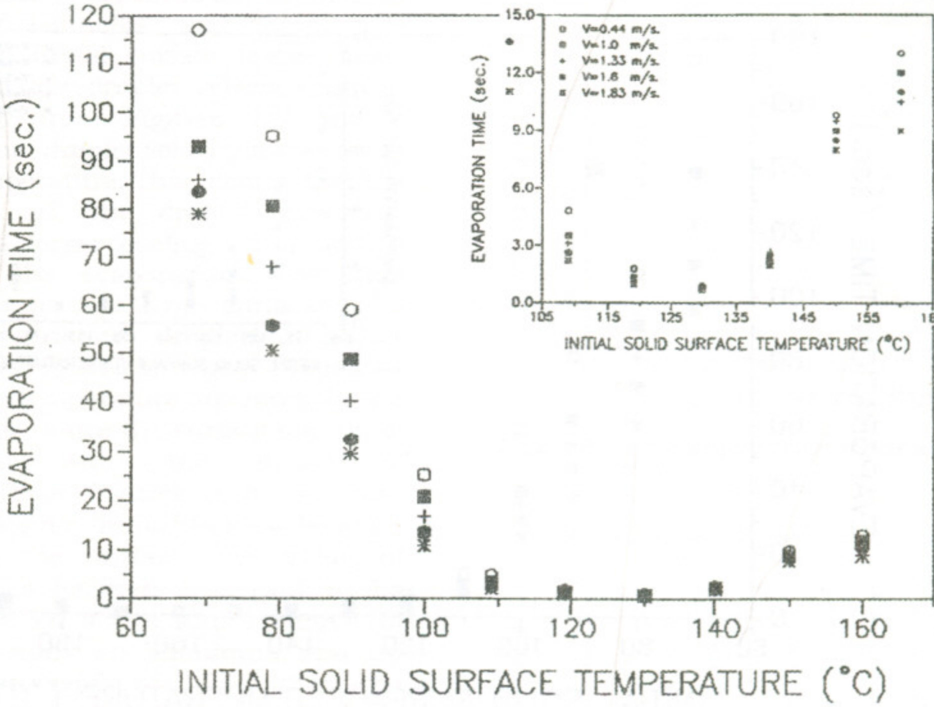

Figure 4 Evaporation time on aluminum versus initial surface temperature.

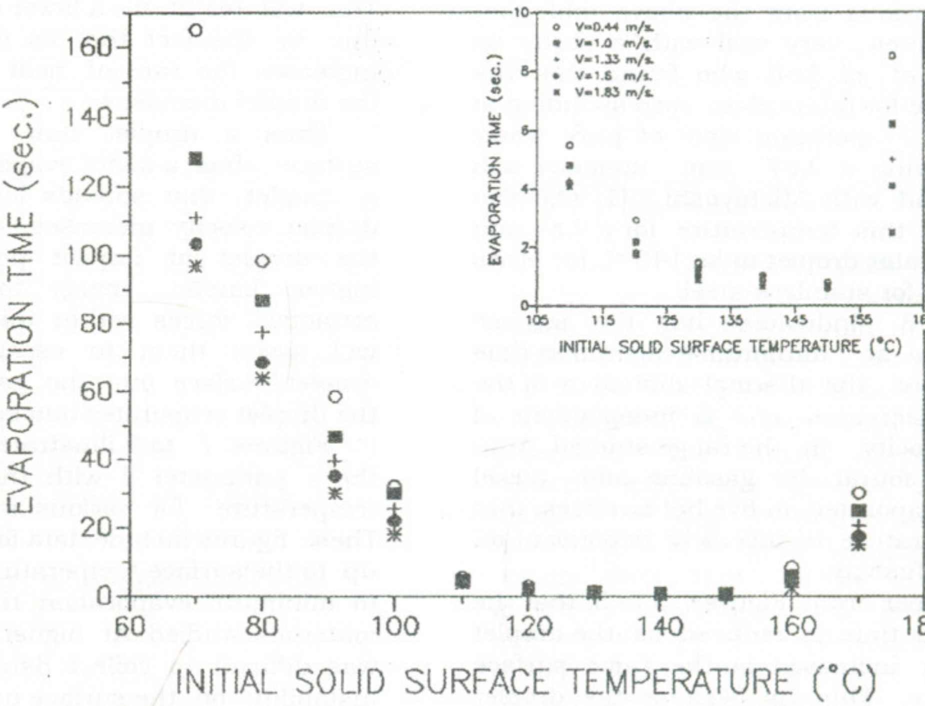

Figure 5 Evaporation time on brass versus initial surface temperature.

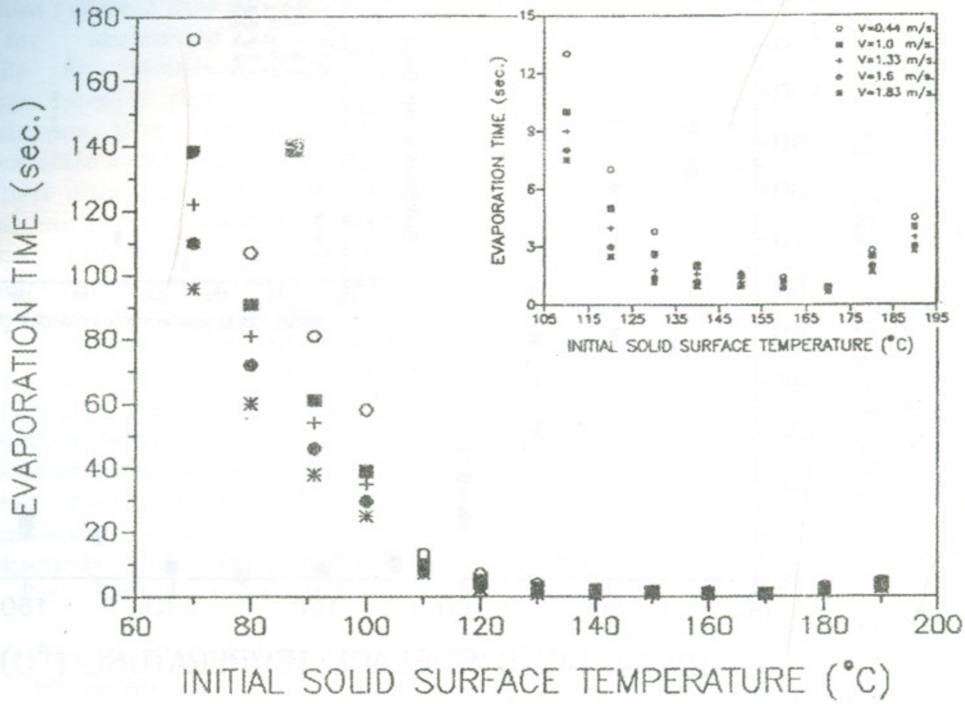

Figure 6 Evaporation time on stainless steel versus initial surface temperature.

It is obvious from the above table that results agrees very well with a study by Avedisian *et al.* [14] who found that the temperature for brass plate corresponding to minimum evaporation time of pure water droplet having a 2.67 mm diameter was 147 °C, and with Michiyoshi [1] who also found that this temperature for a 2.84 mm diameter water droplet to be 145 °C for brass and 174 °C for stainless-steel.

Table 3 indicates that the surface temperature at minimum evaporation time increases as the thermal diffusivity of the material decreases and is independent of droplet velocity in the range studied. Abu-Zaid [10] found for gasoline and diesel droplets evaporated on five hot surfaces, that this temperature is inversely dependent on thermal diffusivity.

It is clear from Figures 3 to 5, that the evaporation time is reduced as the droplet velocity is increased at the same surface temperature. This is because the droplet diameter upon impact increases i.e. the paramteter β increases as the droplet velocity increases as seen in Figures 7 to 9. This will result in a lower evaporation time due to the fact that as the contact area increases the rate of heat transfer through the droplet increases.

Thus a droplet that spreads on the surface has a faster evaporation time than a droplet that spreads less. Also, as the droplet velocity increases, the molecules of the droplet at impact possess relatively higher kinetic energy to overcome the attractive forces within the droplet, which will assist them to escape through the droplet surface into the gaseous state, and the droplet evaporates quicker.

Figures 7 to 9 illustrate the variation of the parameter β with the initial surface temperature for various droplet velocities. These figures include data for this parameter up to the surface temperature corresponding to minimum evaporation time for the three materials studied. At higher temperatures, it was difficult to collect data due to droplet instability on the surface upon impact. This parameter is of great importance in the study of evaporation phenomena since it determines the droplet evaporation time and its cooling effect. It accounts for the effect of a number of variables that characterize surface finish, initial surface temperature, surface tension, and droplet release height.

It is clear from Figures 7-9 that β increases as the droplet velocity increases at the same temperature. This means that the surface area of the droplet increases, resulting in a larger cooling effect, and a seduction in the evaporation time. This illustrates that to cool large surfaces, it is necessary to generate droplets at higher frequency. Also it is clear that β 1increases as the surface temperature increases for the three materials, since the surface tension of water decreases with the increase of temperature. These Figures point out that for gently deposited droplet (release height = 0.01 m) on the surface, the value of parameter β lies between 1.35-1.65 in the range studied. Di Marzo and Trehan [15] found in their study on aluminum, that up to droplet release height of (0.02-0.03 m), the value of this parameter is independent of the release height and lies between 1.2-1.5, and, it increases as the surface temperature increases.

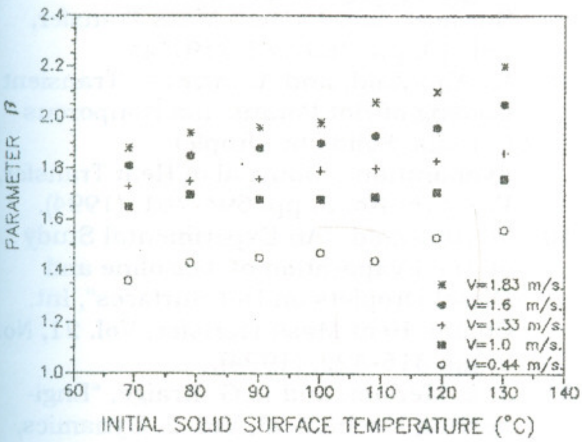

Figure 7 Parameter β for aluminum versus initial surface temperature.

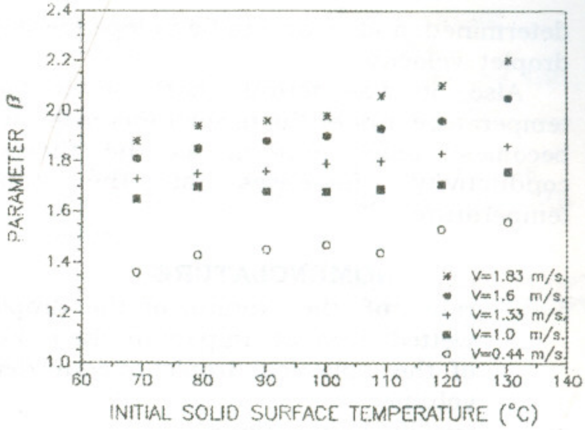

Figure 8 Parameter β for brass versus initial surface temperature.

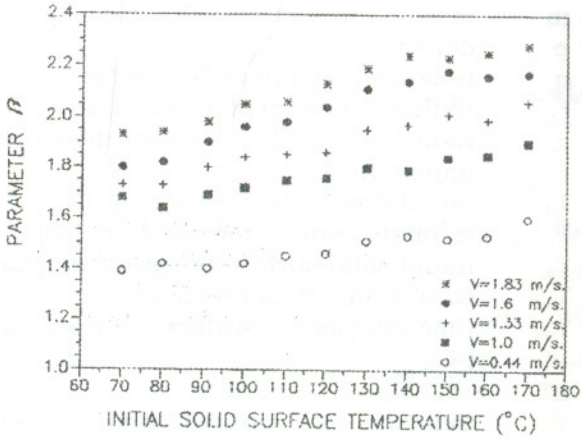

Figure 9 Parameter β for stainless steel versus initial surface temperature.

CONCLUSIONS

The results of the experimental investigation of the evaporation of a 3.46 mm diameter water droplet, having a velocity in the range 0.44-1.83 m/s on hot surfaces of aluminum, brass, and stainless steels are presented. The droplet diameter in the present study was chosen, because it is within the range of droplet sizes, usually found in actual spray applications. These results show, that as the droplet velocity increases, the evaporation time is reduced and the cooling effect increases at the same initial surface temperature. The surface temperature corresponding to minimum evaporation time for the materials tested was determined and found to be independent of droplet velocity.

Also it was found that the surface temperature under the droplet increases and becomes more uniform as the thermal conductivity increases at the same temperature.

NOMENCLATURE

β	ratio of the radius of the droplet wetted area at impact to the radius of the spherical droplet of equivalent volume.
c	specific heat (J/kg.K).
g	gravitational acceleration (m/s^2).
h	droplet release height (m).
k	thermal coductivity (W/m.K)
m	mass of droplet = 0.00002165 kg.
p	density (kg/m^3).
q	time-averaged heat flux (W/m^2).
r_1	radius of spherical droplet (m^2).
r_2	radius of droplet on the surface upon impact (m).
T_d	initial droplet temperature (°C).
T_i	intimate contact temperature (°C).
T_s	initial solid surface temperature (°C).
T_{sat}	saturation temperature (°C).
T_{ws}	time-averaged surface temperature (°C).
ΔT_{satv}	$= T_{ws} - T_{sat}$
V	Velocity of droplet upon impact (m/sec).
V_o	initial velocity of droplet (m/sec).

Subscripts

d	droplet
s	solid

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تأثير زخم قطرة ماء على تبخرها على أسطح ساخنة

محمود ابو زيد
قسم الهندسة الميكانيكية – جامعة مؤته

ملخص البحث

يعرض هذا البحث نتائج دراسة عملية لتبخر قطرة ماء ذات قطر ٣,٤٦ ملم وسرعة ضمن المجال ٠,٤٤ – ١,٨٣ متر / ثانية على ثلاثة أسطح ساخنة : ألمنيوم، نحاس أصفر، وفولاذ. لقد تم قياس قطر القطرة حال تلامسها مع السطح الساخن ، وقت التبخر، ودرجة حرارة السطح أثناء تبخر القطرة تحت ظروف الضغط الجوى. أظهرت النتائج أنه كلما ازدادت سرعة القطرة تناقص وقت التبخر وازداد تأثير التبريد على نفس درجة حرارة السطح الأولية. كما تم في هذا البحث تحديد درجة حرارة السطح المناظرة لأقل وقت للتبخر، ووجد أنها لا تعتمد على سرعة القطرة ضمن مجال السرعات التي تم دراستها.