Characterization of The Heat Transfer in Film Boiling with Spray Quenching for Different Material Properties

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Abstract

A hot aluminum alloy AA6082 and nickel disc of 560 °C and 850 °C was cooled by a spray nozzle with the spray flux of 4.2, 10 and 13.7 kg/m^{2}s. The temperature history during the cooling process was recorded with use of an infrared camera. The energy balance equation is the basis for the numerical procedure of Heat Transfer Coefficient (HTC) calculation in the film-boiling regime. It is found that HTC is almost independent from kind of metals. HTC has a stronger function of surface temperature. With use of single droplet model in film boiling developed, vapor film thickness can be calculated to predict this trend.

Keywords: *Spray quenching*, *Heat Transfer Coefficient*, *Material Properties, Vapor Film Thickness*, *Film Boiling*

1. Introduction

For any quenching method, when liquid comes in contact with a sufficiently hot surface, immediately a vapor blanket will be formed in the interface between solid-liquid contacts. This vapor layer from heat transfer point of view has significantly reduced the heat transfer rate due to poor conduction through the vapor layer. In this stage, boiling process is called in the film boiling region. As the process is continued, then the surface cooled down until suddenly the vapor blanket collapsed. This point of condition remarked as the Leidenfrost transition. Then the liquid starts getting partially in contact with the hot surface. This is called the region of transition boiling. After Leidenfrost transition, the heat flux abruptly increases due to liquid contact and keep increasing until it reaches the maximum value called as departure from nucleate boiling (DNB) point. At this point, the value of maximum heat flux can be very high in comparison with the one in the film boiling. Subsequently, boiling continues to the nucleate boiling region identified by intensive bubble formation on the surface. Meanwhile the surface temperature keeps being drop until it reaches 100 °C (for water) and at this point downward, single-phase forced convection is started until it reaches the ambient temperature.

Temperature profile over the distance on the hot surface during quenching process with water spray is depicted in Fig. 1.

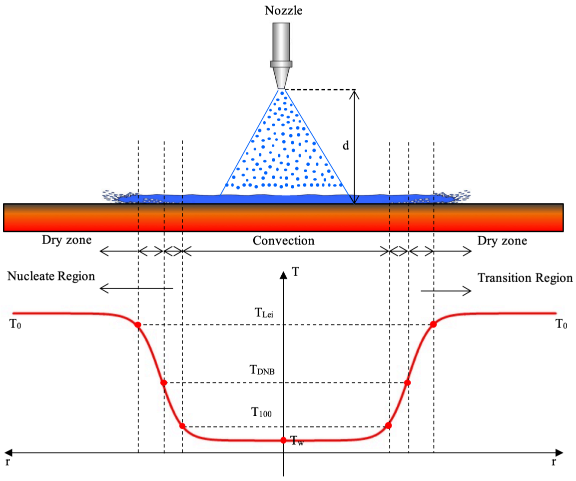

Fig. 1 Temperature profile over the hot surface in the spray cooling application

Many researchers have done extensive works on the parameters characterizing the boiling heat transfer in the film boiling regime. Müller [1,2] presented the change of the heat transfer coefficient (HTC) versus the surface temperature for Nickel. They investigated the HTC variation at different values of spray flux. Jeschar et al. [3] found that in the range of film boiling, HTC can only be influenced by the spray flux. Drop velocity, distance of nozzle to surface and nozzle type are considered as parts contained in the volumetric spray flux. However, the study of Wendelstorf et al. [4] and Puschmann et al. [5] shows that HTC in the film boiling depends not only on the spray flux but also on the temperature. In a similar result, Wang et al. [6] found that in the nonboiling regime, the heat transfer coefficient was a function of mass flux and wall temperature. Puschmann and Specht [7] also found that with a lower spray flux, the drop diameter exerts no influence on the HTC. However, when they doubled the droplet velocity, they obtained an increase of about 10% in the HTC.

This study focuses on the influence of kind of metals on the heat transfer performance in film boiling regime. Knowledge on the relation between HTC as a function of different material properties is estimated with use of energy balance equation. As for an explanation of HTC as a function of surface temperature, single droplet model is developed to predict the thickness of vapor film in order to explain the latter phenomenon.

2. Model of single droplet in film-boiling regime

For a general insight and for obtaining some qualitative knowledge on the spray cooling mechanism, a model has been developed using a single droplet. When a single droplet reaches the hot surface, a contact temperature will be established which is only slightly below the surface temperature of the metal. This contact temperature depends on the ratio of the heat penetration coefficient of the metal and the liquid. The heat penetration coefficient is the product of thermal conductivity (λ), density (ρ) and specific heat capacity (c). Since metal has a significantly higher value than water, the contact temperature is closer to the metal temperature. As the contact temperature is considerably higher than the boiling temperature, the water evaporates immediately. This is visible using the high-speed camera [8]. Therefore, the droplet can be considered to expand almost without friction on a vapor cushion. In Fig. 2 the temperature profile in a bounced droplet is shown in principle with the maximum expansion. The surface of the droplet to the metal side is assumed to be at boiling temperature. Therefore, the heat transfer in turn depends on the temperature gradient in the fluid.

For the maximum expansion the following equation is valid [9]:

$$d_{max} = (1.18)d.We^{0.24} = (1.18)d.\left(\frac{\rho.v^2.d}{\sigma}\right)^{0.24} \qquad (1)$$

Where We is the Weber number, d is the droplet diameter, v is the droplet velocity, ρ and σ is the density and the surface tension of the liquid, respectively.

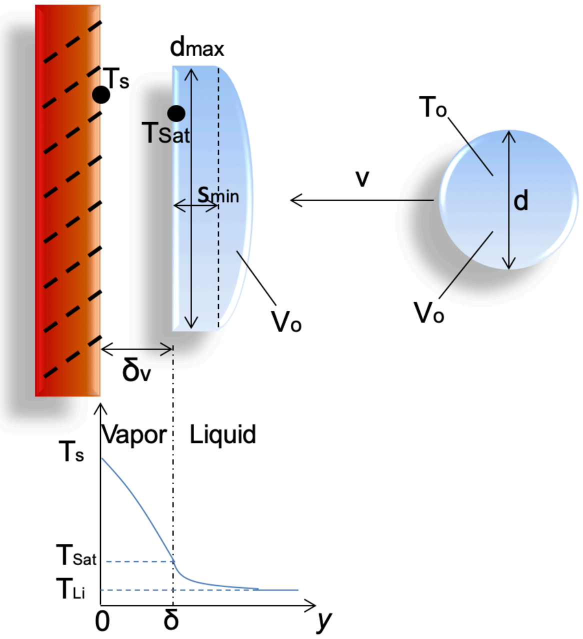

Fig. 2 Schematic temperature profile of an impacting droplet in film boiling regime

In this position the droplet is approximated as disc-shaped. Since the volume of the droplet remains constant during the deformation, the minimum thickness is:

$$s_{min}.\frac{\pi}{4}.d_{max}^2 = \frac{\pi}{6}.d^3 \qquad (2)$$

Due to the relatively short contact time, the droplet can thus be assumed to be a semi-infinite body for the heat conduction. Under this condition, the temperature distribution within the droplet can be defined according to the equation [10, 11]:

$$\frac{T - T_{Sat}}{T_{Sat} - T_{Li}} = erf(\eta) = erf\left(\frac{x}{2\sqrt{\alpha.t_{con}}}\right) \qquad (3)$$

where $\alpha = \frac{\lambda}{\rho.C}$ is the thermal diffusivity of the water. T_{sat} and T_{Li} are the saturated temperature and the initial temperature of the droplet, respectively. This yields the heat flux into the droplet as [12]:

$$\dot{q}_d = \sqrt{\frac{(\lambda.\rho.c)_{Li}}{\pi.t_{con}}}(T_{Sat} - T_{Li}) \qquad (4)$$

Labeish [13] determined the contact time as:

$$t_{con} = 2.\frac{d}{v} \tag{5}$$

This heat flux corresponds to that is discharged by the wall. By assuming that the heat flux constant over short contact time or equals to $\overline{\dot{q}_d}$, one can obtain a good approximation of the wall temperature profile as [14]:

$$T_w = T_{init} - \left[\overline{\dot{q}_d} \sqrt{\frac{\pi . t_{con}}{(\lambda . \rho . c)_w}} \right] \tag{6}$$

where λ, ρ, c is conductivity, density, and specific heat capacity of the sample respectively. Then the vapor film thickness on the basis of single droplet can be estimated:

$$\delta_v = \frac{\lambda_v}{\dot{q}} (T_w - T_{sat}) \tag{7}$$

3. Experimental Method

3.1 Experimental setup

The experimental setup is shown schematically in Fig.3.

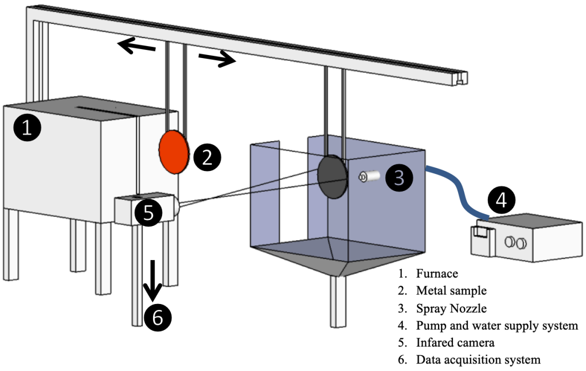

Fig.3 Schematic diagram of quenching experimental facility (top view)

In this work, all samples were heated up to 560 °C for AA6082 and 850 °C for Nickel. Once the sample reaches the designated temperature, then it is shifted freely from the furnace to the cooling unit direction. Detailed information on disc of AA6082 and nickel used in the experiments is summarized in Table 1.

Table 1 Geometry and material details

Parameter	Nickel	AA6082
Diameter of disc	140 mm	140 mm
Thickness	2 mm	3 mm
Density	8908 kg/m^3	2770 kg/m^3
Thermal cond.	91	170 W/m/K
Specific heat	440	1050 J/kg/K

A spray-cooling unit which consists of centrifugal pump supplying water at the certain level of flow rate is prepared to perform a quenching process at the right time. There is the data acquisition system that consists of an infrared (IR) camera connected to a computer system for the image recording during the quenching process. Prepared samples have to be painted black on the backside to ensure a better emissivity. The movement of the sample is verified not to cause a significant temperature drop. It is verified not more than 2° C temperature difference.

3.2 Determination of Emissivity

Calibration of emissivity of a graphite coating is performed with use of a small copper cylinder machined with an inside bore. A thermocouple is inserted inside the bore so that the temperature of the metal could be measured. This cylinder is painted black with the graphite coating and placed inside a horizontal cylindrical furnace. An IR Camera is then positioned in front of the outlet of this furnace from a distance of 80 cm. The temperature of the furnace is increased in steps of 50 °C from 50 to 700 °C. The temperature of the cylinder measured by thermocouple and that of the IR camera are aligned with each other by adjusting the emissivity value in the settings of the camera. It is found that emissivity of the coating changes from 0.92 to 0.94. However, the mode value of emissivity is found to be 0.92. Therefore, it can be inferred that a constant value of emissivity of 0.92 should be used for the optimum accurate measurement of the surface temperature.

3.3 Spray flux measurement

The water spray flux is measured by changing the targeted sample with a patternator. It consists of brass tubes with diameters of 10 mm connected to the plastic bottle into which the water drops will be collected. Water droplets are sprayed over the patternator tubes and then the mass of the water droplets m_d collected by the plastic glass is measured after a certain period of time Δt. A denotes the area of the opening of the tube. Then, the spray flux can be derived from $\dot{m} = m_d/(A.\Delta t)$. The measurement is estimated to be accurate within ±4% as several repeating measurements are fluctuating in this range.

3.4 Energy balance analysis and accuracy

In order to calculate the heat transfer coefficient for a specific position on the metal disc, an energy balance is performed as follows:

$$-\rho \times c \times s \times \frac{\Delta T}{\Delta t} = \dot{q}_{sp} + \dot{q}_{\lambda} + \dot{q}_R + \dot{q}_{\alpha}$$

where ρ, c, and s are the density, specific heat capacity, and the thickness of the metal disc, respectively. The change of the stored enthalpy in the disc caused by temperature decrease is equal to the sum of the heat transfer by the spray $\dot{q}_{sp}$, radial conduction $\dot{q}_{\lambda}$, radiation $\dot{q}_R$, and free convection $\dot{q}_{\alpha}$. The heat flux due to spray has the largest magnitude when compared to all other sources. It is defined as

$$\dot{q}_{sp} = \alpha_{sp} \times (T_s - T_{sp})$$

where $\dot{q}_{sp}$, α_{sp}, and T_s are the heat flux, heat transfer coefficient, and surface temperature of the metal disc, respectively. Radial conduction $\dot{q}_{\lambda}$ is calculated using the Fourier approach for cylindrical coordinates as

$$\dot{q}_{\lambda} = -s \times \lambda \times \frac{1}{r} \times \frac{\partial}{\partial r}\left(r \times \frac{\partial T}{\partial r}\right)$$

where s is the thickness of the disc, λ is the conductivity of material, and r is the radius. The gradient $\partial T / \partial r$ is known from the temperature measurement. Heat loss due to radiation and natural convection is less than 5% that of the spray and is therefore negligible. The repeatability was considered good as statistical fluctuation can be controlled within 5% as shown by Fig.4.

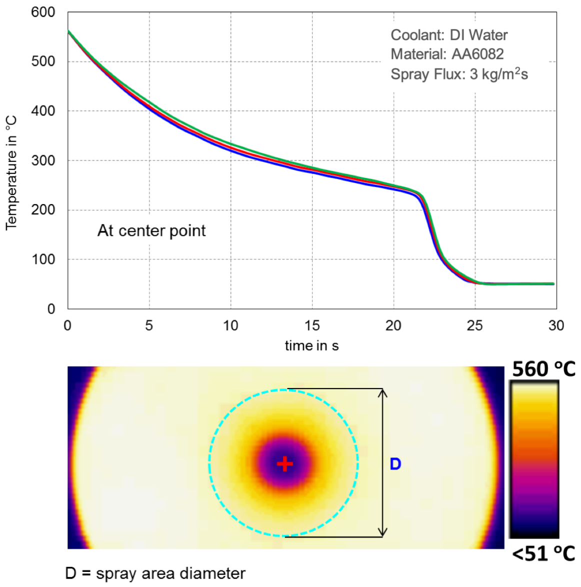

Fig.4 Cooling profile repeated three times using deionized water (DI Water)

4. Results and Discussion

In the film-boiling regime the vapor film created between the hot surface and the water droplet acts as insulation for the heat transfer. What is shown in Fig. 5 gives an inference that the heat transfer in the film-boiling regime is almost independent from kind of metals. However, it also gives another fact that the favor film thickness decreases with the decrease of the surface temperature. This fact agrees with the results summarized in Fig. 6 showing the HTC as a function of the surface temperature. The HTC increases with the decrease of the surface temperature. The reason for this is that the favor film thickness decreases with the decrease of the surface temperature. A reduction of the vapor film thickness will lead to the increase of the heat transfer performance.

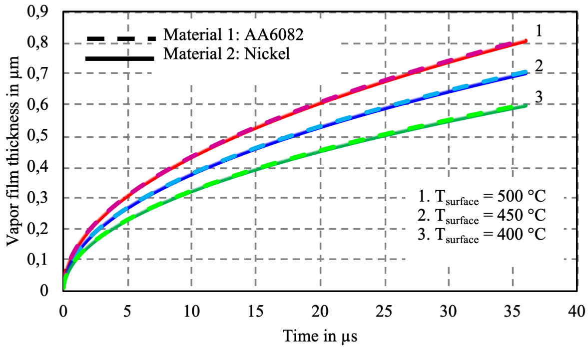

Fig. 5 Vapor film thickness of a single droplet in the film-boiling regime

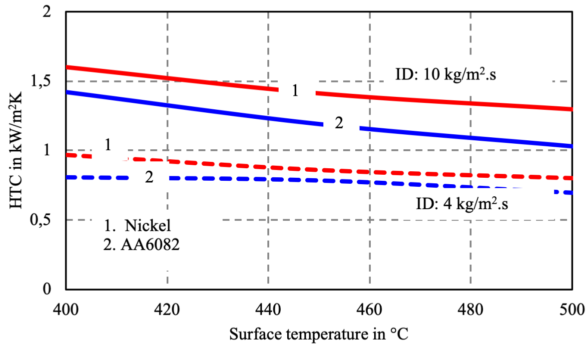

Fig. 6 HTC in the film-boiling regime from the experimental quenching of nickel and AA6082 sample

HTC versus surface temperature in the film-boiling regime from the quenching experiment of nickel and AA6082 sample is depicted in Fig. 7. It is obviously showing that first, impingement density is the dominant factor influencing the heat transfer coefficient in the film boiling region. Other than that, the surface temperature also plays a major role as the heat transfer coefficient increases with the decrease of the surface temperature. Furthermore, it can be observed that in the range of 400 - 500 °C by increasing the impingement density from 4 kg/m^2.s to 10 kg/m^2.s has increased HTC to a factor of 50 to 75 %. By reducing the surface temperature has increased HTC to a factor of 25 to 40 %. Changing material properties of the samples only results in the increase of HTC to a factor of 10 to 20 %. However, it is said in the literatures that material properties are still not yet proven to have an influence on the heat transfer process in film-boiling regime.

5. Concluding remarks

The experimental work for studying the influence of different material properties with use of spray cooling is established. A disc of AA6082 and nickel is heated up to 560 °C and 850 °C, respectively. Key characteristics parameters in every boiling regime are reviewed. This paper emphasizes some fundamental information by highlighting some facts as follows:

1. HTC in the film-boiling regime is almost independent from material properties as it is a weaker function compared to spray flux or surface temperature
2. HTC increases with the decrease of surface temperature
3. The thickness of vapor film decreases with the decrease of the surface temperatures
4. Point #2 is inferred due to point #3

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