The effects of spray characteristic on heat transfer during spray quenching of aluminum alloy 2024

Ruichao Guo, Jianjun Wu*, He Fan, Xuepeng Zhan

School of Mechanical Engineering, Northwestern Polytechnical University, Xi'an 710072, PR China

ABSTRACT

A spray quenching apparatus was performed and hot aluminum alloy 2024 thin sheets were spray quenched by two symmetrically arranged nozzles. The influence of spray nozzle distance on heat transfer was experimentally investigated. The results show that there is no film boiling regime and Leidenfrost point at different nozzle distance. Both critical heat flux (CHF) value and surface temperature at which CHF occurs first decrease to the minimum value with increased nozzle distance, and then increase until reach the maximum value. Finally, CHF value and surface temperature decrease with further increase of nozzle distance. However, the maximum CHF value is observed when nozzle distance is 70 mm, and the highest surface temperature at which CHF occurs is obtained at nozzle distance of 80 mm. A nozzle distance of 80 mm is better since there exists a longer nucleate boiling regime and a relatively higher CHF value. This phenomenon may have guiding significance for industrial production.

Keywords: Heat transfer; Spray quenching; Critical heat flux; Aluminum alloy

1. Introduction

With the development of the aviation industry and in order to satisfy weight requirements of large size aircraft parts, more and more metal honeycomb bonding composites have been applied to the design of aircraft structures, such as aircraft radome, spoiler, aileron, rudder, side wall and hatch door. The aluminum alloy 2024 thin sheets (0.30 mm—0.50 mm thickness), because of their good forming ability and machinability [1, 2], are widely used as preferred materials for aircraft metal honeycomb panels.

In order to obtain the required mechanical properties of structures, the aluminum alloy 2024 thin sheets, after heated above the solution temperature (approximately 500°C), are usually quenched by water, oil or other liquids [3]. The spraying quenching, compared with other quenching techniques, has been extensively used in aluminum alloy quenching due to its ability of higher removal of heat flux [4, 5]. However, a significant amount of residual stresses will be produced by the thermal gradients which occur during spray quenching. And the existence of residual stresses can have a significant impact on structures properties. The magnitude of residual stresses mainly depends on the quenching rate which is directly related to the spray quenching factors [6].

* Corresponding author at: Northwestern Polytechnical University, 127 West Youyi Road, Xi'an Shaanxi, 710072, PR China

Tel: +86 02988493101

E-mail address: wujj@nwpu.edu.cn (Jianjun Wu)

In spray quenching process, the primary spray parameters, which have the significant influence on heat transfer performance, are volumetric flux, Sauter mean diameter and mean droplet velocity [7]. The volumetric flux, compared with other parameters, is the most important parameter which has the strongest effects on the determination of Leidenfrost point, critical heat flux and its temperature [8]. Wendelstorf et al. [9] studied the heat transfer at different mass fluxes during spray quenching. They indicated that the heat transfer coefficient increased with the increasing of mass flux in film boiling regime, and also they found that the temperature may have an influence on heat transfer coefficient (HTC). A similar result, where heat transfer coefficient increased with volumetric flux, was found by Puschmann et al. [10]. Estes and Mudawar [11] found that low volumetric flux had a significant increase in the slope of the boiling curve between the single-phase and nucleate boiling regime. However, this influence was not pronounced at high volumetric flux. Lin and Ponnappan [12] studied different liquids (FC-87, FC-72, methanol and water) for the cooling of high heat flux heat sources. They presented that for a given surface superheat, the heat flux increased with the volumetric flux and critical heat flux increased with the volumetric flux. Rybicki and Mudawar [13] also indicated that volumetric flux and Sauter mean diameter were the key parameters that influenced spray quenching performance.

The spray quenching of aluminum alloys were widely investigated in previous literatures. However, many research results were focused on the spray quenching of aluminum alloy castings and plates. Few research was studied on spray quenching of thin sheets. Mascarenhas and Mudawar [14] studied quenching aluminum alloy 2024 cylinder using full-cone pressure sprays. They indicated that increasing nozzle pressure drop or decreasing orifice-to-surface distance may increase the heat transfer performance. Xu et al. [15] focused on 6082 aluminum alloy. The influence of spray pressure and surface roughness on heat transfer was investigated. They found that both the heat flux and heat transfer coefficient increased with spray pressure. Golovko et al. [16] examined quenching EN AW-6082 aluminum alloy by lumped heat capacitance method. The influence of spraying distance, inclination angle and flow rate on the heat transfer coefficients was discussed. They indicated that neither spraying distance nor inclination angle had significant influence on heat transfer coefficient. Mascarenhas and Mudawar [17] experimentally studied the parametric influence of spray quenching for thick-walled aluminum alloy 2024 tube. Three parameters including spray pressure, orifice-to-surface distance and thermal properties on temperature response during spray quenching were investigated. The results showed that increasing spray pressure or decreasing orifice-to-surface distance hastened the onset of rapid cooling stages of quench as well as improved overall cooling effectiveness.

In an earlier investigation [18] we demonstrated that the water temperature and nozzle pressure had a significant influence on heat transfer of aluminum 2024. However, in industrial production, the two parameters are difficult to perform and may need higher cost. The volumetric flux is the ratio of volume flow rate and it can be changed by spray nozzle distance or spray pressures for identical spray nozzles. Unlike nozzle pressure or water temperature, nozzle distance is easier to operate in industry. Therefore, the present study is concerned with the influences of practical spray parameter (nozzle distance) on heat transfer during spray quenching. These influences are used to predict residual stresses during practical spray quenching in future work. In this paper, a spray quenching apparatus is performed to obtain time-temperature data. The surface temperatures and surface heat fluxes of thin sheets are inversely determined from smoothing time-temperature curves by B-spline approximation.

2. Experimental procedure

2.1. Spray quenching system and specimens

Schematic diagrams and the photo of the spray quenching experimental system are shown in Fig. 1 and it has been described in detail elsewhere [18]. Basically, the system consists of four sections: the tank system, the spray quenching system, the furnace system and the data acquisition system. The water is adjusted inside the tank and then, water at room temperature (approximately 25°C) is pumped from the tank to the spray nozzles. Nozzle pressure (P_N), varying from 1 bar to 5 bar, can be regulated by the inverter. And the nozzle pressure is to be set at 3 bar in present condition. Two commercial full-cone spray nozzles (Spraying Systems, Co., Ltd) are used at nozzle distance (D_N) ranging from 50 mm to 90 mm. In this work, the spray angle is 45° and nozzle orifice diameter (d_0) is 2.4 mm. The Sauter mean diameter (d_{32}) is approximately 0.3 mm obtained from the manufacture. Locations of nozzles are shown in Fig. 2. The dimensions of specimens are 60 mm×60 mm, and all the specimens have a normal thickness of 0.508 mm. The materials of the specimens are 2024-O aluminum sheets from Kaiser Aluminum, Co., Ltd, USA. And chemical composition of aluminum alloy 2024 are listed in Table 1. The density of aluminum alloy 2024 is assumed to be constant (2780 kg/m³). The thermal conductivity and specific heat capacity of aluminum alloy 2024 obey the following temperature dependent equations, respectively [19]:

$$\lambda = 167.7 + 0.108 \times T(^{\circ}\text{C}) \quad \text{unit : W/(m} \cdot ^{\circ}\text{C)} \quad (1)$$

$$c = 856.7 + 0.891 \times T(^{\circ}\text{C}) \quad \text{unit : J/(kg} \cdot ^{\circ}\text{C)} \quad (2)$$

Eqs. (1) and (2) are effective for the temperature varied from 0°C to 500°C.

Fig. 1. (a) Schematic diagrams of experiment; (b) photo of spray quenching apparatus.

Table 1

Aluminum alloy 2024 limits (wt %).

Chemistry	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	V	Zr	Al
Min	0.00	0.00	3.80	0.30	1.20	0.00	0.00	0.00	0.00	0.00	Balance
Max	0.50	0.50	4.90	0.90	1.80	0.10	0.25	0.15	0.05	0.05

Fig. 2. (a) Photo of nozzles' locations; (b) schematic diagram of experimental characteristics (unit: mm).

2.2. Heat transfer procedure

Characteristics of spray quenching are listed in Table 2. The method of investigation is based on the measurement in the middle of two specimens. A CHROMEPA®-ALOMEGA® thermocouple (CO2-K, OMEGA, USA) is sandwiched between the two specimens. And high temperature air set cement (OMEGABOND® 400) is applied to thermocouples to ensure good contact between surface of specimens and thermocouples (see Fig. 3). The thermocouple is about 0.013 mm in diameter. After installing the specimens in the furnace, they are heated to 495°C by resistive heaters and retained for 30 minutes when reaching the test temperature. Then the specimens are quickly moved from furnace to the spraying position. In this position, two surfaces of specimens are symmetrically quenched with sprays when two valves are simultaneously opened on water circuit. Supported by the evaluation of heat flux, there are minor differences (about 3.2%-8.9% when nozzle distance is 50 mm and 1.3%-3.5% for nozzle distance of 90 mm) between non-uniform and uniform volumetric flux distribution. Therefore, radial heat transport can be neglected. And the volumetric spray flux (Q''_{sp}) is assumed uniform over spray impact area which can be varied by applying spray flow rate (Q), nozzle distance (D_N) and spray angle (θ), as shown in Eq. (3),

$$Q''_{sp} = \frac{Q}{\pi (D_N \tan(\theta/2))^2} \quad (3)$$

The data from Table 2 are used in Eq. (3) to determine volumetric spray flux. And initial temperatures are recorded by a data acquisition instrument (OM-DAQ-USB-2401, USA) at high rate of 100 Hz when specimens are transferred to the spraying position.

Fig. 3. Locations of the thermocouple (unit: mm).

Table 2

Characteristics of spray quenching examined in present study.

Characteristics	Value
Spray angle θ (°)	45
Nozzle orifice diameter d_0 (mm)	2.4
Nozzle pressure P_N (bar)	3
Sauter mean diameter d_{32} (mm)	0.3
Spray flow rate Q (L/min)	4.8
Water temperature T_w (°C)	25
Volumetric spray flux Q''_{sp} ($m^3/(s \cdot m^2)$)	$D_N = 50mm$ 5.943×10^{-2}
	$D_N = 60mm$ 4.124×10^{-2}
	$D_N = 70mm$ 3.029×10^{-2}
	$D_N = 80mm$ 2.319×10^{-2}
	$D_N = 90mm$ 1.832×10^{-2}

2.3. Experiment accuracy

The uncertainty of temperature measurement is approximately $\pm 1.2^\circ\text{C}$ for K-type thermocouples. And type CO2-K thermocouple has an absolute accuracy of about $\pm 0.75\%$ according to manufacture. The error of nozzle distance is about ± 0.5 mm. The uncertainty of nozzle pressure is ± 0.05 bar by pressure controller. The percentage of conductivity and heat capacity error is about $\pm 5\%$. The accuracy of the heated temperature is estimated to be $\pm 1^\circ\text{C}$ based on performance data of digital temperature controller in furnace. Because of the heat loss of natural and radiation convection during transformation, the uncertainty of initial temperature of specimens when beginning quenching is estimated as -5% . Possible sources of accuracy, almost all of which are first-level error in this experiment, are listed in Table 3.

Table 3

Sources of the accuracy.

Sources	Accuracy
Nozzle pressure	± 0.05 bar
Heated temperature	$\pm 1^\circ\text{C}$
Nozzle distance	± 0.5 mm
CO2-K thermocouples	$\pm 0.75\%$
Temperature measurement	$\pm 1.2^\circ\text{C}$
The conductivity and specific heat capacity	$\pm 5\%$
Initial temperature of specimens	-5%

3. Inverse analysis of heat transfer

3.1. Data smoothing

Once the mid-plane temperatures of the specimens during spray quenching are recorded, there exists considerably true random noise which can cause convergence problem for inverse heat transfer,

especially for the calculation of third or second derivatives. According to Vorster et al. [20], if the temperature data of aluminum alloy during spray quenching can be represented by a continuous and smooth function of time, temporal data smoothing is a reasonable approximation.

Therefore, in this study, truly random noise is reduced by fitting a B-spline of order three smoothing function to the temperature data points $[s_i, T_i]$, $i = 1, \dots, n$ with objective function [21],

$$\text{Min } J = k \int_{t_0}^{t_m} (y^{(2)}(t))^2 dt + \sum_{i=1}^n (y(s_i) - T_i)^2, \quad (4)$$

where k is smoothing parameter; $y(t)$ is B-type spline in the interval $D \in [t_0, t_m]$, and it can be presented as

$$y(t) = \mathbf{B}\boldsymbol{\tau}, \quad (5)$$

where

$$\mathbf{B} = \begin{bmatrix} N_{0,3}(u_0) & N_{1,3}(u_0) & N_{2,3}(u_0) & N_{3,3}(u_0) & & & \\ & N_{0,3}(u_1) & N_{1,3}(u_1) & N_{2,3}(u_1) & N_{3,3}(u_1) & & \\ & & \ddots & \ddots & \ddots & \ddots & \\ & & & N_{0,3}(u_i) & N_{1,3}(u_i) & N_{2,3}(u_i) & N_{3,3}(u_i) \\ & & & & \ddots & \ddots & \ddots \\ & & & & & N_{0,3}(u_{m-1}) & N_{1,3}(u_{m-1}) & N_{2,3}(u_{m-1}) & N_{3,3}(u_{m-1}) \end{bmatrix}. \quad (6)$$

And $\boldsymbol{\tau} = [\tau_{-3}, \tau_{-2}, \tau_{-1}, \tau_0, \dots, \tau_{m-1}]^T$ is the control point vector which needs to be calculated. The

elements $N_{j,3}(u_i)$ in Eq. (6) are basis functions of normalized uniform B-spline, where $u_i = (t - t_i)/(t_{i+1} - t_i)$.

To minimize the effects of fluctuations of experimental conditions on results, a particular distance ($D_N = 50\text{mm}$) is selected for spray quenching at the same condition ($P_N = 3\text{bar}$, $T_w = 25^\circ\text{C}$). This experiment is repeated three times, as is shown in Fig. 4. The comparisons among the three quenching curves show that the fluctuation can be controlled within 3%. Therefore, repetitions will be done for every group of experimental plan. It should be noted that these time-temperature curves are smoothed by seeking the solution of Eq. (4) with a smoothing parameter of $1e-3$. Our previous study [18] indicates that the curves tend to neither depart excessively from measured temperature points nor smooth away physically meaningful features of curves when smoothing parameter is $1e-3$.

Fig. 4. B-spline smoothed curve repeated three times when smoothing parameter is $1e-3$.

3.2. Solution procedure of inverse problem

According to the first law of thermodynamics, heat loss during the transformation includes natural and radiation convection. And these effects cause the temperature of specimens decreasing. However, during spray quenching, the influence of natural and radiation convection can be negligible because the heat loss is less than 5% that of spray quenching [22].

In the present case, the geometry of the thin sheets is simple enough. Thus, we can treat the problem as one-dimensional heat transfer, and heat conduction equation is shown as follows

$$\lambda \frac{\partial^2 T}{\partial x^2} = \rho c \frac{\partial T}{\partial t}, \quad (7)$$

where λ is the thermal conductivity of sheet, $\lambda = \lambda(T)$ in Eq. (1) and c is the specific heat capacity, $c = c(T)$ in Eq. (2). ρ is the density; t is the time; $T(x, t)$ is the object temperature.

With boundary condition

$$\left. \frac{\partial T}{\partial x} \right|_{x=0} = 0, \quad (8)$$

and

$$T(x, 0) = T_1, \quad (9)$$

$$T(0, t) = y(t) \quad (10)$$

where T_1 is the initial temperature and $y(t)$ the smoothing B-spline curve in Eq. (5).

The heat transfer condition between the outer surface of sheet and liquid temperature belongs to the third boundary condition

$$\begin{aligned} -\lambda \left. \frac{\partial T}{\partial x} \right|_{x=\delta} &= h(T_s - T_w) \\ \lambda \left. \frac{\partial T}{\partial x} \right|_{x=-\delta} &= h(T_s - T_w) \end{aligned}, \quad (11)$$

where T_w is the temperature of water (assumed uniform, 25°C); T_s is surface temperature; δ is the thickness of sheet and h is the heat transfer coefficient.

An analytical method is derived to obtain the surface temperature and heat flux based on the temperature of a thermocouple positioned in the middle of two specimens, and the general solution of inverse heat conduction problem (IHCP) was given by Burggraf [23]. For present configuration, acceptable accurate can be approximated after second derivative yields [24, 25]. Therefore, solution reduces to

$$T(x, t) = \mathbf{B}\boldsymbol{\tau} + \frac{1}{2} \frac{x^2}{\alpha} \frac{d\mathbf{B}}{dt} \boldsymbol{\tau} + \frac{1}{24} \frac{x^4}{\alpha^2} \frac{d^2\mathbf{B}}{dt^2} \boldsymbol{\tau}, \quad (12)$$

$$q(t) = -\lambda x \frac{1}{\alpha} \frac{d\mathbf{B}}{dt} \boldsymbol{\tau} - \lambda \frac{x^3}{6} \frac{1}{\alpha^2} \frac{d^2\mathbf{B}}{dt^2} \boldsymbol{\tau}, \quad (13)$$

where α is thermal diffusivity, $\alpha = \lambda/(\rho c)$. The heat transfer coefficient can be obtained by Eqs. (11) and (13),

$$h = \left(-\lambda x \frac{1}{\alpha} \frac{d\mathbf{B}}{dt} \boldsymbol{\tau} - \lambda \frac{x^3}{6} \frac{1}{\alpha^2} \frac{d^2\mathbf{B}}{dt^2} \boldsymbol{\tau} \right) / (T_s - T_w). \quad (14)$$

The uncertainties of surface temperature, heat flux and heat transfer coefficient are calculated by a root summary square method of partial derivatives [26], following the equations respectively

$$\delta T = \sqrt{\left(\left(\frac{\partial T}{\partial t}\right) \cdot \delta t\right)^2 + \left(\left(\frac{\partial T}{\partial \lambda}\right) \cdot \delta \lambda\right)^2 + \left(\left(\frac{\partial T}{\partial c}\right) \cdot \delta c\right)^2}, \quad (15)$$

$$\delta q = \sqrt{\left(\left(\frac{\partial q}{\partial t}\right) \cdot \delta t\right)^2 + \left(\left(\frac{\partial q}{\partial \lambda}\right) \cdot \delta \lambda\right)^2 + \left(\left(\frac{\partial q}{\partial c}\right) \cdot \delta c\right)^2}, \quad (16)$$

$$\delta h = \sqrt{\left(\left(\frac{\partial h}{\partial t}\right) \cdot \delta t\right)^2 + \left(\left(\frac{\partial h}{\partial \lambda}\right) \cdot \delta \lambda\right)^2 + \left(\left(\frac{\partial h}{\partial c}\right) \cdot \delta c\right)^2 + \left(\left(\frac{\partial h}{\partial (T_s - T_w)}\right) \cdot \delta (T_s - T_w)\right)^2}, \quad (17)$$

where the data of partial derivatives are obtained from Table 3.

And according to the above error analysis, the results are $\pm 1.17\%$, $\pm 3.02\%$ and $\pm 4\%$, respectively.

4. Results and discussion

4.1. Time-temperature and heat flux profiles

Spraying quenching curves obtained at different nozzle distance are shown in Fig. 5. All curves are obtained by inverse heat conduction calculation and also they are smoothed and filtered by B-spline approximation. As shown in Fig. 5, initial temperatures at different nozzle distance are lower than the heated temperature (495°C) and they are slightly inconsistent. The main reason is that when specimens are transferred from heated position to spray quenching, the transported time cannot keep uniform and surface temperature drops about 20°C due to air and radiation convection heat transfer.

As spray quenching begins, the temperatures at different nozzle distance drop immediately and the duration is around 0.5 s when surface temperature varies from 470°C to 100°C. The whole spray quenching stage is approximately 3 s. Comparisons among the five quenching curves in Fig. 5 reveal that the surface temperature drops fastest when nozzle distance is 80 mm. It takes about 0.8 s to reach 100°C when nozzle distance is 60 mm as opposed to about 0.5 s for nozzle distance of 80 mm. Also Fig. 5 reveals that the two curves (C3 and C4) have nearly identical trend for temperature ranging from 470°C to 100°C. The reason behind this phenomenon is the influence of nozzle distance on heat flux. And this will be discussed in next section.

Fig. 5. Spray quenching curves for aluminum alloy 2024 thin sheets with $P_N=3$ bar and $T_w = 25^\circ\text{C}$.

Generally, heat transfer undergoes four regimes during water quenching process of the heated aluminum alloy, as shown in Fig. 6. Quenching is initiated in film boiling regime. And in this regime a thin vapor film appears which can preclude direct contact between hot surface and water, leading to the poor heat transfer capacity during this regime. With surface temperature decreasing, this vapor film begins to collapse at Leidenfrost point (the minimum heat flux point). Collapsed area of vapor film increases with further decrease in surface temperature, causing the heat flux increasing in transition boiling regime. The collapsed area reaches a maximum value at critical heat flux point. And liquid gives a fully contact with hot surface at this point. Beyond critical heat flux point, in nucleate boiling regime, effectiveness of heat transfer is very high due to both bubbles growth and nucleation. Eventually, there exists low value in single convective cooling since heat is transferred directly into the liquid.

Fig. 6. A typical boiling curve [14].

When nozzle distance is 80 mm, variations of heat flux with surface temperature during spray quenching are shown in Fig. 7. The plot in Fig. 7 shows that as spray quenching beginning, the heat flux increases rapidly with surface temperature decreasing, and it reaches maximum heat flux (critical heat flux, CHF) of 1.87 MW/m^2 when surface temperature is 290°C . When surface temperature of thin

sheets ranges from 290°C to 100°C, heat flux has a fast decrease with the reduction of surface temperature and nucleate boiling appears to occur. Finally it enters single convective cooling regime when surface temperature is below 100°C, and boiling subsides in this regime.

Fig. 7. Spray quenching boiling curve for aluminum alloy 2024 thin sheets with $P_N=3$ bar, $T_w=25^\circ\text{C}$ and $D_N=80\text{mm}$.

Also we can find from Fig. 7 that there is no film boiling regime and Leidenfrost point. This phenomenon is mainly caused by low water temperature (25°C) used in present experiment. Kokado et al. [27] showed that there existed no film boiling at water temperature of 68°C. Liu and Wang [28] and Xu and Gadala [29] also indicated that no film boiling occurred at the beginning when water temperature was lower than 60°C. Compared with the higher temperature at which film boiling regime may exists, the formation of thin vapor film needs much more heat at lower water temperature. However, surface temperature drops rapidly as sprays impinge onto sheets (as shown in Fig. 5), and this limits the capacity of heating water to vaporization temperature, reversely. When water temperature is 25°C, there is a less area of thin vapor film than that at higher water temperature. Therefore, boiling curve enters transition boiling regime directly at water temperature of 25°C. Besides, the relatively lower heated temperature of specimens may also lead to this phenomenon.

4.2. Effect of nozzle distance on heat flux

In this section, the nozzle distance varies from 50 mm to 90 mm (other parameters are consistent, water temperature is 25°C and nozzle pressure is 3 bar) and its influence on heat transfer is discussed. Fig. 8 shows the effect of nozzle distance on spray quenching behavior for aluminum alloy 2024 thin sheets. It can be observed from Fig. 8 that for all the boiling curves at different nozzle distance, no film boiling regime occurs due to lower water temperature. These curves have similar trend with slight difference in values. The change in temperatures leads to the difference in heat flux which indirectly proves the sensitivity of B-spline approximation. In order to make a comparison of spray quenching performance for different boiling curves, the heat transfer efficiency is defined. And it is referred as

$$\eta = \frac{q_{regime} - q_{min}}{q_{min}} \times 100\% , \quad (18)$$

where q_{regime} is the heat flux for different boiling curves at different regimes, q_{min} is the minimum heat flux in the five boiling curves at different regimes in Fig. 8.

It is obvious that heat transfer efficiency is lowest for nozzle distance of 60 mm compared with other boiling curves from these comparisons. And it explains relatively long quenching time from 470°C to 100°C in Fig. 5.

Because of the high frequencies of data acquisition module, it is very sensitive to the temperature variation. To evaluate this influence on fluctuations, a typical quenching curve ($D_N = 50\text{mm}$) with discrete data is plotted in Fig. 9. The results in Fig. 9 display that there have large fluctuations when surface temperature approaches to the water temperature. The largest temperature difference is 20°C and a difference of 10°C - 15°C is shown for the rest of discrete data in this regime. These large fluctuations will have an effect on calculated heat flux at the end of spray quenching (see Fig. 8). However, heat transfer is subsided in this regime. Thus, we pay little attention to the end of spray quenching where relative magnitude of heat flux is small. Also it shows that there exist fluctuations at the beginning of spray quenching and a largest temperature difference of 10°C is found in this regime. However, relatively small fluctuations (about 3°C - 5°C) are shown for the rest of discrete data. Based on the objective function (Eq. 4), these fluctuations have an error of 0.8% on calculated results. Also the boiling curve ($D_N = 50\text{mm}$) in Fig. 8 shows that there has minor fluctuations in this regime. So the temperature fluctuations have little effect on transition boiling regime.

Fig. 8. Variations of heat flux with nozzle distance for $P_N=3$ bar and $T_w = 25^\circ\text{C}$.

Fig. 9. The spray quenching curve with discrete data when nozzle distance is 50 mm.

For spray quenching technology, the CHF is an important parameter to estimate the heat transfer capacity. The volumetric spray flux and Sauter mean diameter (assumed uniform in this work) have a significant influence on CHF value [11]. The variations of CHF value and volumetric spray flux with nozzle distance are shown in Fig. 10. It is to be noted that the radial heat conduction from non-wetted regions to the regions covered by sprays is negligible when nozzle distance is less than 70 mm (see Fig. 11a). The calculations show that radial heat transport is about 3.7% of total heat flux and it just has minor influence on transition boiling regime (at the beginning of spray quenching). Therefore any observed difference of CHF value can be considered as the effect of sprays on heat transfer.

Fig. 10. CHF and volumetric spray flux of aluminum 2024 spray quenching at different nozzle distance.

Fig. 11. Half displayed schematic diagrams of spray quenching when (a) nozzle distance is 70 mm and (b) nozzle distance is 80 mm.

It may be concluded that CHF value firstly decreases with increased nozzle distance before reaching minimum CHF value at the point where nozzle distance is 60 mm, and then CHF value increases when nozzle distance ranges from 60 mm to 70 mm. Finally, CHF value decreases with

further increase of nozzle distance (as is shown in Fig. 10). The reason behind this phenomenon is the combined effects of increased spray quenching area and decreased volumetric spray flux with nozzle distance increasing. Heat transfer in spray quenching differs from that observed in pool boiling. The heat transfer is enhanced when the contact area between the droplets and surface of specimen increases. It is known that, near CHF point, thin vapor film is collapsed and a large number of bubbles exist on the quenching surface of heated sheets, carrying away tremendous amounts of heat. And also the form of bubble coalescence and the intermittent vapor film inhibit CHF value [30]. Fig. 12 shows the schematic diagram of spray quenching neat CHF point. Thus, any additive that can prevent the bubble coalescence will improve CHF value. In cavitation theory [31], it is hard to merge the bubbles with the increasing of distance between cavities. And when this distance goes beyond the bubble departure diameter, bubble coalescence does not happen. In this experiment condition, the increasing nozzle distance, which may improve the droplets' distance, will inhibit the bubble coalescence to some extent.

Fig. 12. Spray quenching scheme at CHF point.

When nozzle distance changes from 50 mm to 60 mm, the descent gradient of volumetric spray flux is relatively remarkable and the increases of impact area and inhibition of bubble coalescence is relatively smaller. And CHF will decrease. The gradient decreases slightly for nozzle distance varying from 60 mm to 70 mm (see Fig. 10). At the same time, the spray quenching area and distance between cavities increase with the increasing of nozzle distance (see Fig. 11(a)). Mudawar and Estes [32] indicated that the maximum CHF was obtained when the impact area just inscribed the square heated surface, following the subsequent equation

$$D_N = (L/2) / \tan(\theta/2), \quad (19)$$

where θ is spray angle and L is heated surface area relative to length.

According to Eq. (19), the largest CHF seems to occur when nozzle distance is 72 mm and this value has a good agreement with the result shown in Fig. 10 ($D_N=70\text{mm}$). But there has a surplus coverage for spray quenching area when nozzle distance is 80 mm (see Fig. 11(b)). In this condition, the contact area is larger than that at nozzle distance of 70 mm, but the value of volumetric spray flux at nozzle distance of 80 mm is less than that when nozzle distance is 70 mm. Moreover, bubble coalescence is inhibited with increased distance between cavities. Therefore, there exists a slight drop when nozzle distance changes from 70 mm to 80 mm. With nozzle distance further increasing, a larger number of sprays exceed the surface of specimen which will lead to the CHF reaching a lower value

since the volumetric spray flux also reaches the minimum value and the cavities' distance may be out of the bubble departure diameter.

The influence of nozzle distance on the surface temperature at which CHF occurs is shown in Fig. 13. It shows that, with the nozzle distance increasing, temperature firstly has a drop at nozzle distance of 60 mm and then increases until nozzle distance reaches to 80 mm. Finally, the temperature decreases when nozzle distance ranges from 80 mm to 90 mm.

Fig. 13. The influence of nozzle distance on surface temperature at which CHF occurs.

The rationale behind the changing trend for the surface temperature at which critical heat flux occurs is the result of increased nozzle distance and bubble coalescence. At lower nozzle distance (50 mm), it is known that volumetric spray flux is larger and the vapor film is broken easier which can increase direct liquid-solid contact area during transition boiling. Thereby CHF is occurred at a higher temperature. When nozzle distance varies from 50 mm to 60 mm, the volumetric spray flux has a quick drop. There exists a little inhibition of bubble coalescence since the increased spray quenching area is relatively smaller at the same time. This phenomenon promotes the transition boiling and the CHF is occurred at a lower temperature. When nozzle distance increases from 60 mm to 80 mm, bubble coalescence is prevented with the increases of distance between cavities. Therefore nucleate boiling is enhanced and leads to the CHF occurred at a higher temperature. With nozzle distance further increasing, the heat transfer subsides in nucleate boiling regime and there exists less bubble formation since more sprays exceed the surface of specimen. So the CHF occurs at lower temperature.

5. Conclusions

Heat transfer in spray quenching of aluminum alloy 2024 thin sheets has been experimentally investigated under different nozzle distance. The heat flux and surface temperatures are calculated by the inverse method from the mid-plane temperatures measured at center of two sheets. Repeatability and accuracy of measurement are verified in this study. All quench curves are smoothed and filtered by B-spline approximation with a smoothing parameter of $1e-3$. The major conclusions are shown as follows:

1. Heat transfer in spray quenching of aluminum alloy 2024 thin sheets consists of three regimes,

including transition boiling regime (470°C-about 290°C), nucleate boiling regime (about 290°C-100°C) and single convective cooling regime (less than 100°C). There is no film boiling regime and Leidenfrost point due to lower water temperature.

2. As nozzle distance increases, both CHF value and the temperature at which CHF occurs first decrease with increased nozzle distance to the minimum value, and then increase until reach the maximum value. Finally, the two parameters decrease with further increase of nozzle distance.
3. The maximum CHF value is observed when nozzle distance is 70 mm. However, the highest surface temperature at which CHF occurs is obtained at nozzle distance 80 mm.
4. Compared CHF value with surface temperature at which CHF occurs, a nozzle distance which is slightly larger than the optimized nozzle distance in Eq. (19) is better because there has a relatively longer nucleate boiling regime and a relatively higher CHF value. This phenomenon may have guiding significance for industrial production knowing only the size of target and the spray angle.

Nevertheless, this paper dealt only with one condition of parameters (such as nozzle pressure and spray angle). Future work will focus on the correlation of optimized nozzle distance and relatively length under different conditions.

Acknowledgements

The authors wish to thank Chuanmei Xie from Xi'an Suny Fine Chemical Co., Ltd for helpful discussions. This work is supported by National Science Foundation of China (Grant No. 51075332).

Nomenclatures

B	matrix of coefficient	T_w	water temperature, °C
c	specific heat capacity, $J/(kg \cdot ^\circ C)$	ΔT	difference between surface and water temperature, °C
CHF	critical heat flux, W/m^2	$y(t)$	B-spline smoothed temperature, °C
d_{32}	Sauter mean diameter, mm		
D	the interval		
d_0	nozzle orifice diameter, mm	Greek symbols	
D_N	nozzle distance, mm	α	thermal diffusivity, m^2/s
h	heat transfer coefficient, $W/(m^2 \cdot K)$	δ	thickness of sheets, mm
HTC	heat transfer coefficient, $W/(m^2 \cdot K)$	η	heat transfer efficiency
L	the heated surface area relative to length	λ	thermal conductivity, $W/(m \cdot ^\circ C)$
k	smoothing parameter	θ	spray angle, °
m	an integer which defines the length of interval D	ρ	density, kg/m^3

n	an integer which defines the number of time-temperature data	τ	control point vector
N	the normalized uniform B-spline elements		
P_N	nozzle pressure, bar		
q	heat flux, W/m^2		
Q	spray flow rate, L/min		
Q''_{sp}	volumetric spray flux, $m^3/(s \cdot m^2)$		
s_i	time fraction of discrete temperature data, s		
t	time, s		
T	temperature, $^{\circ}C$		
T_s	surface temperature of specimens, $^{\circ}C$		

References

- [1] J.T. Maximov, G.V. Duncheva, A.P. Anchev, M.D. Ichkova, Modeling of strain hardening and creep behavior of 2024-T3 aluminum alloy at room and high temperatures, Computational Materials Science 83(2014) 381-393.
- [2] J. Zhang, Y.L. Deng, W. Yang, S.S. Hu, X.M. Zhang, Design of the multi-stage quenching process for 7050 aluminum alloy, Materials and Design 56 (2014) 334-344.
- [3] L. Zhang, X. Feng, Z.G. Li, C.Y. Liu, FEM simulation and experimental study on the quenching residual stress of aluminum alloy 2024, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 227(7) (2013) 954-964.
- [4] Z. Zhang, P.X. Jiang, X.L. Ouyang, J.N. Chen, D.M. Christopher, Experimental investigation of spray cooling on smooth and micro-structured surfaces, International Journal of Heat and Mass Transfer 76 (2014) 366-375.
- [5] H.B. Xu, C.Q. Si, S.Q. Shao, C.Q. Tian, Experimental investigation on heat transfer of spray cooling with isobutane (R600a), International Journal of Thermal Science 86 (2014) 21-27.
- [6] B.W. Xiao, Q.G. Wang, P. Jadhav, K.Y. Li, An experimental study of heat transfer in aluminum castings during water quenching, Journal of Materials Processing Technology 210(14) (2010) 2023-2028.
- [7] D.D. Hall, I. Mudawar, Experimental and numerical study of quenching complex-shaped metallic alloys with multiple overlapping sprays, International Journal of Heat and Mass Transfer 38(7) (1995) 1201-1216.
- [8] H.M. Al-Ahmadi, S.C. Yao, Spray cooling of high temperature metals using high mass flux industrial nozzles, Experimental Heat Transfer 21(1) (2008) 38-54.
- [9] J. Wendelstorf, K.H. Spitzer, R. Wendelstorf, Spray water cooling heat transfer at high temperatures and liquid mass fluxes, International Journal of Heat and Mass Transfer 51(19-20) (2008) 4902-4910.

- [10] F. Puschmann, E. Specht, J. Schmidt, Local Distribution of the Heat Transfer in Water Spray Quenching, International Conference on Continuous Casting of Non Ferrous Metals, Proceedings of the DGM Frankfurt (2000)101-107.
- [11] K.A. Estes, I. Mudawar, Correlation of Sauter mean diameter and critical heat flux for spray cooling of small surfaces, International Journal of Heat and Mass Transfer 38(16) (1995) 2985-2996.
- [12] L.C. Lin, R. Ponnappan, Heat transfer characteristics of spray cooling in a closed loop, International Journal of Heat and Mass Transfer 46(20) (2003) 3737-3746.
- [13] J.R. Rybicki, I. Mudawar, Single-phase and two-phase cooling characteristics of upward-facing and downward-facing sprays, International Journal of Heat and Mass Transfer 49(1-2) (2006) 5-16.
- [14] N. Mascarenhas, I. Mudawar, Analytical and computational methodology for modeling spray quenching of solid alloy cylinders, International Journal of Heat and Mass Transfer 53(25-26) (2010) 5871-5883.
- [15] R. Xu, L.X. Li, L.Q. Zhang, B.W. Zhu, X. Liu, X.B. Bu, Influence of pressure and surface roughness on heat transfer coefficient during water spray quenching of 6082 aluminum alloy, Journal of Materials Processing Technology 214(12) (2014) 2877-2883.
- [16] O. Golovko, I. Frolov, D. Rodman, F. Nurnberger, O. Grydin, M. Schaper, Spray cooling of extruded EN AW-6082 aluminum alloy sheets: spatial heat transfer coefficients, Forschung im Ingenieurwesen 78(3-4) (2014) 131-137.
- [17] N. Mascarenhas, I. Mudawar, Methodology for predicting spray quenching of thick-walled metal alloy tubes, International Journal of Heat and Mass Transfer 55(11) (2012) 2953-2964.
- [18] R.C. Guo, J.J. Wu, W.P. Liu, Z.K. Zhang, M.Z. Wang, S.C. Guo, Investigation of heat transfer on 2024 aluminum alloy thin sheets by water spray quenching, Experimental Thermal and Fluid Science 72 (2016) 249-257.
- [19] N. Zhao, Y.Q. Yang, M. Han, X. Luo, G.H. Feng, R.J. Zhang, Finite element analysis of pressure on aluminum alloy 2024 created during restricting expansion deformation heat treatment, Transactions of Nonferrous Metals Society of China 22(9) (2012) 2226-2232.
- [20] W.J.J. Vorster, S.A. Schwindt, J. Schupp, A.M. Korsunsky, Analysis of spray field development on a vertical surface during water spray-quenching using a flat spray nozzle, Applied Thermal Engineering 29(7) (2009)1406-1416.
- [21] C.H. Reinsch, Smoothing by spline functions II, Numerische Mathematik 16(5) (1971) 451-454.
- [22] K.H.M. Abdalrahman, Sabariman, E. Specht, Influence of salt mixture on the heat transfer during spray cooling of hot metals, International Journal of Heat and Mass Transfer 78 (2014) 76-83.
- [23] O.R. Burggraf, An exact solution of the inverse problem in heat conduction theory and applications, Journal of Heat Transfer 86(3) (1964) 373-382.
- [24] J. Taler, Theory of transient experimental techniques for surface heat transfer, International Journal of Heat and Mass Transfer 39(17) (1996) 3733-3748.
- [25] M. Ciofalo, I.D. Piazza, V. Brucato, Investigation of the cooling of hot walls by liquid water sprays, International Journal of Heat and Mass Transfer 42(7) (1999) 1157-1175.
- [26] R.J. Moffat, Describing the Uncertainties in Experimental Results, Experimental Thermal and Fluid Science 1(1988) 3-17.
- [27] J.I. Kokado, N. Hatta, H. Takuda, N. Harada, An analysis of film boiling phenomena of sub-cooled water spreading radially on a hot steel plate, Arch. Eisenhüttenwes 55(3) (1984) 113-118.
- [28] Z.H. Liu, J. Wang, Study on film boiling heat transfer for water jet impinging on high temperature flat plate, International Journal of Heat and Mass Transfer 44(13) (2001) 2475-2481.

- [29] F.C. Xu, M.S. Gadala, Heat transfer behavior in the impingement zone under circular water jet, *International Journal of Heat and Mass Transfer* 49(21-22) (2006) 3785-3799.
- [30] Z.H. Liu, Q.Z. Zhu, Prediction of critical heat flux for convective boiling of saturated water jet impinging on the stagnation zone, *Journal of heat transfer* 124 (6) (2002) 1125-1130.
- [31] C.E. Brennen, *Cavitation and bubble dynamics*, Oxford University Press, Oxford, 1995.
- [32] I. Mudawar, K.A. Estes, Optimizing and Predicting CHF in Spray Cooling of a Square Surface, *Journal of Heat Transfer* 118(3) (1996) 672-680.