International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:7, No:6, 2013

Wetting Front Propagation during Quenching of Aluminum Plate by Water Spray

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Abstract**—**This study presents a systematic analysis of wetted region due to cooling of aluminum plate by water spray impingement with respect to different water flow rates, spray nozzle heights, and subcooling. Unlike jet impingement, the wetting is not commenced upon spray impingement and there is a delay in wetness of hot test surface. After initiation, the wetting (black zone) progresses gradually to cover all test plate and provides efficient cooling in nucleate boiling regime. Generally, spray cooling is found function of spray flow rate, spray-to-surface distance and water subcooling. Wetting delay is decreasing by increasing of spray flow rate until spray impact area is not become bigger that test surface. Otherwise, higher spray flow rate is not practically accelerated start of wetting. Very fast wetting due to spray cooling can be obtained by dense spray (high floe rate) discharged from adjacent nozzle to the test surface. Highly subcooling water spray also triggers earlier wetting of hot aluminum plate.

Keywords**—**Water spray, wetting, aluminum plate, flow rate.

I. INTRODUCTION

MANY industrial processes such as electronic packages cooling, metal making such as steel, copper and aluminum making, etc require huge amount of heat dissipation by impingement of a coolant (e.g. water) on a flat high temperature surface. Microchannel flow, jet and spray impingements are common practices in these types of cooling which usually are associated with phase change heat transfer [1]. Spray cooling by droplet dispersion has surpassed jet cooling due to higher heat flux removal capacity, uniform surface temperature, cooling large surface area with a single nozzle, and resistance to localized dryout and delay critical heat flux (CHF) [2]. However, spray cooling is suffering from poor understanding of many underlying mechanisms of droplet breakup, impact, and boiling due to large number of parameters that influence spray performance. In fact, many parameters are involved in spray cooling that make spray modeling the hard task, compared to other cooling schemes. Influential parameters in spray cooling are geometrical and physical parameters [3]-[7]. Geometrical parameters include nozzle type and size, cone angle, nozzle-to-surface distance, heated surface condition, shape, material, and size, nozzle inclination angle, etc. For a given spray angle, the nozzle-to-surface distance determines the diameter of spray impact area. Physical parameters include coolant thermophysical properties, pressure drop, ambient conditions, and subcooling, etc. These parameters affect flow rate, mean droplet diameter and velocity, and volumetric flux. Mean droplet diameter (or droplet velocity) and volumetric flux and their spatial distributions are key hydrodynamic parameters that impact spray cooling performance [8]. Volumetric flux (flow rate per unit area) has dominant effect on spray heat flux extraction but the others are secondary parameters. If volumetric spray flux decreases due to larger nozzle distance or smaller supply pressure then heat flux is also decreased [5]-[9]. Droplet velocity consistently shown has strong influence on spray heat transfer and droplet diameter has shown some effects on spray cooling but is still under debate [10]. For normal and inclined sprays, highest CHF is achieved when the spray impacts area just inscribes the square surface of the heater [10]. Either smaller or larger impact area yield smaller CHF. CHF is spray cooling is enhanced in three ways: higher spray flow flux, more subcooling, and finer droplets.

Aluminum and copper small plates and pressure nozzles (only-liquid) rather than gas-assisted ones (atomizers) have been usually worked in the spray metal cooling researches. Cooling curves (temperature-time) or boiling curves (heat flux-temperature) have been used for deriving correlations for single phase and two-phase heat transfer for different boiling regimes. For example, Mudawar and his coworkers have conducted many studies for understanding of spray performance in cooling of aluminum parts and determined the local boiling curve at single phase, nucleate boiling and transition boiling regimes. They proposed the correlations of local heat transfer coefficients for each regime based on local distributions of hydrodynamic parameters of sprays at impingement surface; see e.g. [2]-[4], [8]. The derived correlations in spray researches are typically based on local hydrodynamics spray parameters upon impingement instead of upstream conditions such as nozzle pressure, nozzle flow rate, nozzle exit velocity and nozzle stand-off. But, nozzle and coolant parameters are relevant to industries. The study of these parameters in industrial scale is the aim of this research. Nozzle height, spray flow rate and water subcooling were systematically changed to examine their effects on cooling aluminum plates by water spray. Moreover, surface wetting which is associated with efficient surface cooling is also noted here and compared with surface wetting by water jet impingement that studied previously in ROT UBC group [11], [12].

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II. EXPERIMENTAL SETUP AND PROCEDURE

The spray experiments were conducted on an industrial scoped facility (Fig. 1) which has the following sections: furnace, acceleration zone, spray zone and deceleration zone. The main components that were used for conducting the experiments included: a hydraulic torque motor to displace the test bed by chain conveyor to the spray section, series of water nozzles (jet and sprays) above the spray zone, and a water pipe system with upper tank, lower tank, headers, flowmeters, globe valves, etc to deliver the water from the upper storage tank to the nozzles. The water was supplied from the city line and was accumulated in the upper storage tank which mounted on a rigid 6.5*m* high tower. The water temperature is adjusted inside the tank by electrical coil heaters. After releasing water unto the test plate, the water was collected in the lower water storage tank to be recirculated with a centrifugal pump rated to deliver 170 *US GPM* at 185 *FT* of head within the water pipe system. The water can exit each nozzle at rate of up to 90*L/min*. Flow rates of the water nozzles were controlled by individual globe valves. Two tracks provide bed to the chain conveyor. A carrier attached to the chain conveyor allows the test plate to be put it in and take it out from the furnace. Further information on experimental setup was previously reported [13].

The aluminum test plates were 16×16×0.75 *in* square plate that made of 6061 T6 AL alloy. Each plate was instrumented with 16 Y-type thermocouples (TC) measured temperature at 1 mm below the surface. The TCs were arranged at rays from the plate center where one was at the stagnation point and others were implanted at 0.5, 1 and 2*in* increments at different angular directions. The sampling rate was 52*Hz*. The TCs were connected to a computer that operated data acquisition system. The flow rates and TC temperatures were monitored and recorded using Data Acquisition System Laboratory (DASYLab) software. A high definition camcorder was used to record the experiments at 120 frames per second. The liquid water flow rate was discharged from a 1*in* full cone spray nozzle (72° *FullJet* nozzle from Spraying Systems Company which delivers 8gpm flow rate at 8psi pressure and beyond). *Full cone* spray is commonly used for uniform distribution of impinging drops and, in turn, uniform cooling in continuous casting operations in steel and aluminum industries. In *full cone* nozzle, the spray impinges on a round area that has maximum volumetric flow rate at the center and it reduces radially toward the outer edge. This nozzle size and type was selected for its broad range of flow rate necessary for our tests to examine the effect of desire industrial spray parameters [4]. The circular impact area upon the test surface depends to nozzle flow rate and nozzle-to-plate distance [10]. The produced impingement regions in the present experiments inscribed the test plate surface or were smaller or larger than the square plate surface. No air stream was used to produce the full cone spray.

The aluminum test plate was heated inside the furnace up to 530°C. The specimen temperature was assumed uniform when all TCs readings were not different more than 3°C. The heated plate removed from the furnace and carrier-plate assembly was moved along the tracks and sit below the spray nozzle. Ten minutes before, water spray was issued at desired flow rate from the nozzle to maintain steady flow at wanted subcooling temperature. A diverting pipe is employed to bypass water from the nozzle before running the experiment. By turning the test diverting pipe, water spray allows dispersing over the heated plate and the experiments started. The test plate temperature was about 500°C at the beginning the experiments. The experiments were continued until all TC readings were below 50°C. The digital videos recorded from the experiments were saved by Sony's Picture Motion Browser software and were assessed frame-by-frame using Matrox Inspector image processing software for studying wetting zone during the tests. The experimental parameters are summarized in Table I where the effect of spray volumetric flow rate, water subcooling and nozzle height were explored. At the experiments, spray flow rates (*Q*) were 20, 25, 35, 45, 55 and 75*L/min*. The water temperature was set at 25°C except for subcooling series of experiments which it was changed to 10, 45, 65 and 80°C. The vertical distance between the spray nozzle and the test plates was also varied (4. 1875, 8.5, 10.5, 12.5 and 14.5 *in*). All present experiments were conducted with single identical full cone nozzle.

TABLE I
EXPERIMENTS PARAMETERS

Q L/min	Subcooling °*C*	*H in*
20 - 75	10 - 80	4.1875- 14.5

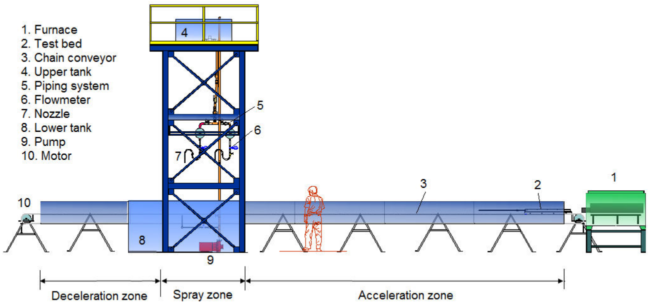

Fig. 1 Schematic of pilot scale apparatus

III. RESULTS AND DISCUSSION

Fig. 2 shows typical variation of temperature 1mm below plate surface during a water spray transient cooling experiment reading by the thermocouples at different positions around the center. The spray flow rate is 35*L/min* and the nozzle distance is 10.5*in*. The test plate starts cooling from 500°C temperatures after spray impingement. The temperature steadily decreased to around 300°C until sudden drop in temperature is occurred in coincidence of wetting initiation which observed from the video film. The sharp fall of plate temperature is not happened simultaneously all over the plate surface. The wetting front detected around the center (as illustrated in Fig. 3) and the plate is cooled at lower rate at distant points from the center (larger *r*). Indeed, the spray circular impingement area was not covered all square plate surface in this experiments and also lower water volumetric flux from the spray hit distant region from the center. The temperature is quickly fall to 100°C and below which demonstrate efficient cooling inside the wetting zone and suggests nucleate boiling regime. These cooling curves in Fig. 2 are similar to cooling curves from jet impingement which reported before [14].

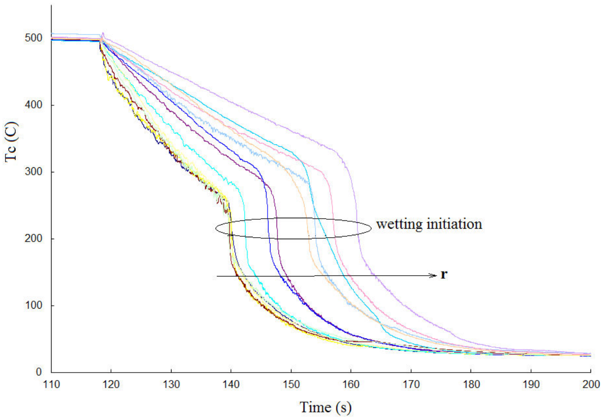

Fig. 2 Cooling curve for a water spray test (*H* =10.5*in, Q* =35*L/min, Tw* =25°C, *Ts* = 500°C), *r* is distance from the center

The typical cooling process of aluminum test plate by water spray and progression of wetting front is illustrated in Fig. 3 by sequence of frames extracted from the video film during the same test condition of Fig. 2. The cooling start immediately after spray impingement but it takes time to initiate the wetting of the plate surface and the black zone to be appeared (No.3 in Fig. 3). In fact, water drops from the spray cannot survive at the surface after impingement due to high temperature of substrate and, in turn, cannot wet it which is evidence of film/transition boiling regimes. Thus, there is a delay in wetness of plate surface after impingement which is varied depends on the spray flow rate, nozzle height and subcooling during the present series of experiments. After initiation, the wetting zone spreads outward from small central region in radial direction and finally covers the whole plate surface. As shown, the propagation speed decreases with enlargement of black zone. In this dark region, the surface is wetted or is partially wetted that suggests the termination of film boiling inside the region where no stable vapor layers exist anymore. It was observed that water was deflected away from the surface at certain angle at the wetting front at border of the cooling zone. These observations are in line with research reports for jet impingement [15], [16] but they are reported here for spray water jets. There was also an audible boiling sound which was intensified when the movement of wetting front is originated. This is also reported for wetting of hot surface due to jet boiling impingement [15].

The experimentation with an industrial scale circular water jet performed previously at the same apparatus indicates a similar delay in start of wetting after jet impingement [11]. However, initial wetting was detected upon impingement which its size is changed according to jet flow rate and subcooling but the wetting progression was not begun immediately after impingement. The delay was found strong function of subcooling which is more pronounced in lower subcooling. After wetting propagation initiated, the sudden drops in temperatures were recorded due to occurrence of wetting front at the TCs location. In the present spray cooling experiments, though, the immediate wetting was not observed. The jet pressure may enforce wetting beneath the nozzle in stagnation zone and wetted and nonwetted zones are demarcated over the hot surface. But, the spray breaks liquid flow into fine droplets which spread over the plate surface and cannot impose localized cooling such as seen for the jet impingement. Similar to the jets cooling curves, sharp cooling is obtained at different locations at different times in spray cooling (as shown in the cooling curve in Fig. 2) which it is due to nonuniform spatial distribution of volumetric flow flux over the plate surface.

In these experiments, the delay in wetting initiation can be computed from TCs readings (Fig. 2) or from the video films (Fig. 3). The delay in wetting of plate surface due to different flow rates in range of *Q* =20-75*L/min* is shown in Fig. 4. Generally for a given nozzle standoff, less delay time is resulted by higher spray flow rate which displays better cooling. Higher spray flow rate, quicker wetting is initiated except for *H* =10.5*in* spray. At *H* =10.5*in*, the delay time is decreasing steadily by increasing spray *Q* until 45*L/min* and afterward it is flattened. The 45*L/min* spray was approximately inscribed the square test surface and higher spray flow rate does not change practically the delay time; the delays for 45 and 55*L/min* sprays are 18.5 and 18sec, respectively. The spray impact area at 55*L/min* is larger than plate surface and some water drops at the outer region of the spray did not hit the test surface. This demonstrates that for a given spray nozzle, the optimum cooling is resulted by a spray when the nozzle is mounted at a distance that impingement area just inscribed the heater surface. In other word, increasing spray flow rate is efficient until the spray impact area is not larger than test surface. Otherwise, it does not enhance the cooling rate accordingly. If spray flow rate is high enough and the nozzle is close to test surface (e.g. *Q* =75*L/min* and *H* = 4.1875*in*), then wetting starts almost upon impingement similar to the jet impingement but no delay was detected in wetting spreading.

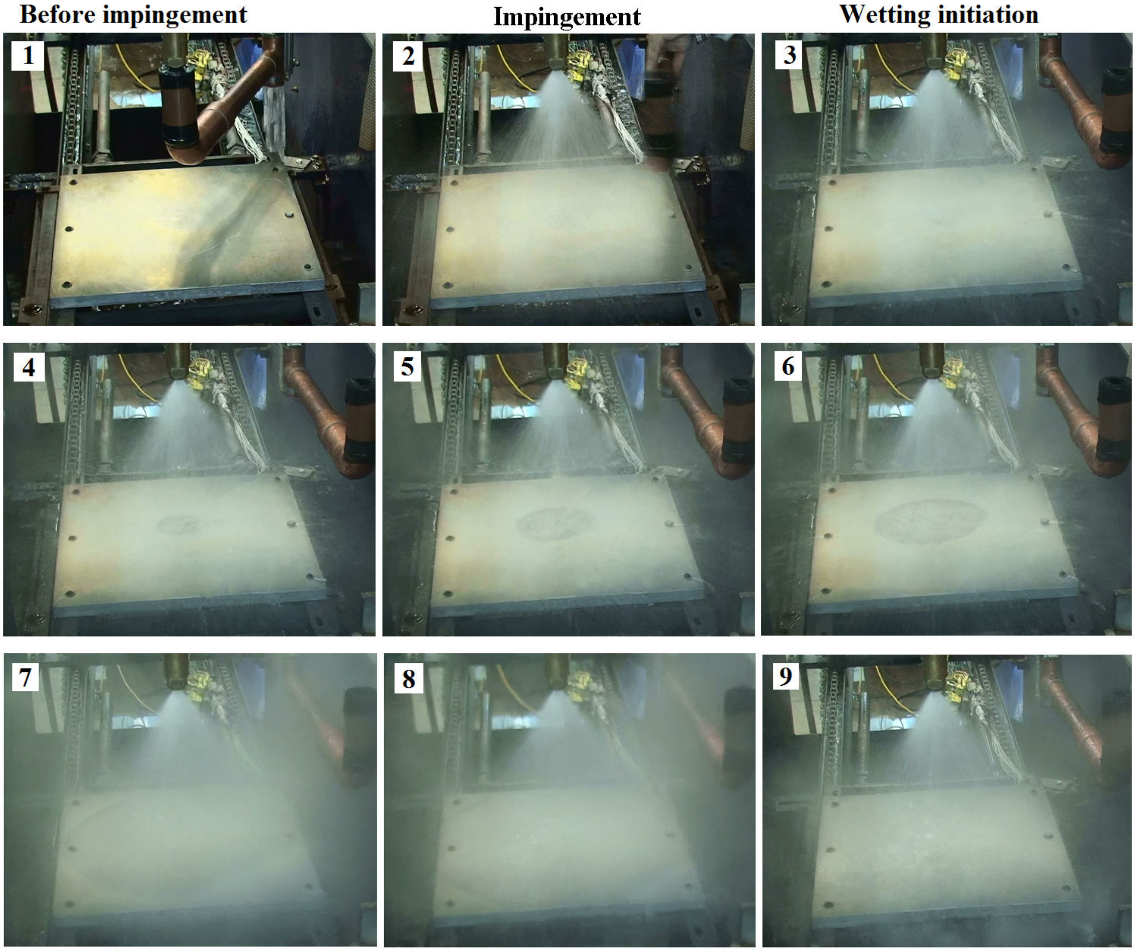

Fig. 3 Cooling of aluminum plate by water spray (*H* = 10.5 *in, Q* = 35 *L/min, Tw* = 25 *C, Ts* = 500 °C)

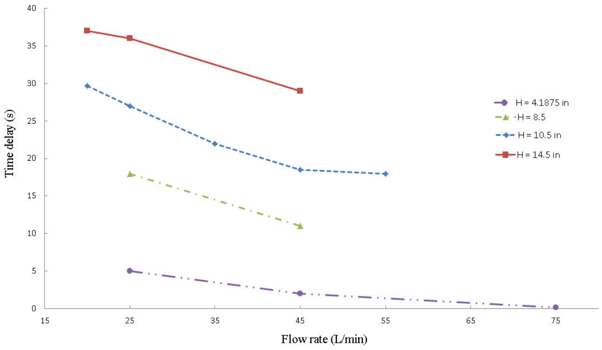

Fig. 4 Effect of spray flow rate on the delay of wetting start for various nozzle heights

The wetting time delay for spray cooling at different spray nozzle heights is illustrated in Fig. 5. Generally, wetting delay increases with elevation of spray nozzle. For a given spray flow rate, wetting takes longer time to start when the heated surface is cooled by more distant spray nozzle. Various circular impact areas from the spray were obtained by changing the nozzle heights. For all tested flow rates, the resulted impingement areas are smaller than square plate surface for $H < 10.5 in$ and they are larger for $H > 10.5 in$. Least delay is obtained by the lowest spray nozzle regardless of spray flow rate (see Figs. 4 and 5). Longest delay is measured for highest position of the nozzle ($H = 14.5 in$) of every tested flow rate because the spray impact areas were larger in all cases.

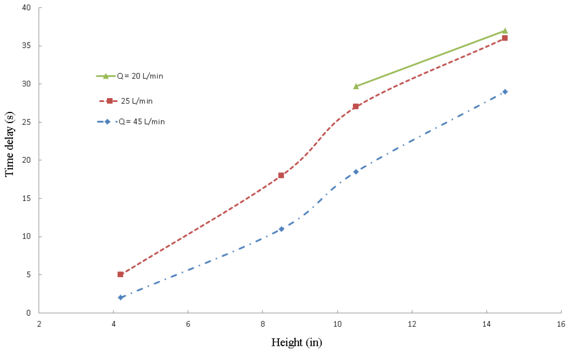

Fig. 5 Effect of spray nozzle heights on the delay of wetting start for various spray flow rates

Fig. 6 illustrates the time delay measured in spray experiments by different temperatures for water. The spray nozzle was mounted at H =10.5*in* and Q =45*L/min* for all these tests. The delay constantly reduced by higher subcooling. Longest delay (54sec) among all present spray tests was resulted when the water temperature was 80°C (or 20°C subcooling). As shown, subcooling could strongly postpone the wetting initiation and inhibit efficient cooling. Highly subcooled water can break earlier vapor layer beneath the water drops due to film/transition boiling regimes and wet the plate surface successfully. Therefore, it takes longer time for lower subcooled water to cool the plate.

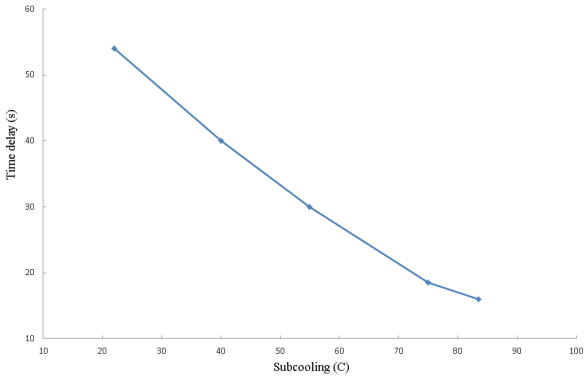

Fig. 6 Effect of water subcooling on wetting time delay in spray cooling (H = 10.5 *in*)

IV. SUMMARY AND CONCLUSION

A series of water spray experiments was conducted for cooling aluminum plates in industrial scale apparatus. The spray flow rate, spray nozzle height and water subcooling were varied systematically to examine their effects on efficient cooling which occurred by wetness of the hot test surface. 16 thermocouples in different radial and angular locations were used in every plate to map the plate temperature. The wetting was not start upon spray impingement and there was a delay is wetting initiation although instant wetting was observed in previous experiments with water circular jet performed at the same facility. In the spray tests, the wetting start in the center by sudden temperature drop and wetted (black) zone progressed radially outward to ultimately cover all test plate surface and provide nucleate boiling regime.

The delay in wetness of plate surface after spray impingement is found to depend on the spray flow rate, nozzle height and subcooling. Higher spray flow rate improves cooling by reducing the time delay in start of wetting provided that the round impact area is not larger than test plate surface. More increasing spray flow rate will waste water coolant that not hit the test plate and will not practically accelerate wetting. It was observed that if enough highly flow rate is issued from a spray nozzle close to test surface, then almost no delay in wetting initiation (similar to jet impingement) and consequently accelerated wetting propagation will be resulted. Subcooling also speeds wetness of test surface.

ACKNOWLEDGMENT

This research was supported by a grant fund NPRP 09 - 507 - 2 – 191 from the Qatar National Research Foundation (QNRF), Qatar.

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