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EXPERIMENTAL STUDY ON THE OVERLAPPING SPRAYS COOLING OF HOT SURFACES ABOVE LEIDENFROST POINT USING INDUSTRIAL ATOMIZERS

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ABSTRACT

It is known that volume flux density of the coolant has a major impact on the heat transfer rate in the film boiling regime. Hall and Mudawar [4] in their experimental study on quenching aluminum parts have reported correlations for heat transfer coefficient in all the regimes of spray cooling, namely: film boiling, film wetting, transition boiling nucleate boiling and, finally, single phase heat transfer regime together with correlations for points of transition between them. For the film boiling regime, which is a subject of the present study, the dependence of the local heat transfer coefficient on the volume flux density was found to be to the power of 0.264. In some other studies this power is reported to be even higher, e.g. 0.556 or 0.76 (see [5-7]). When an irregularly shaped part is to be quenched by sprays with a uniform cooling rates a question of coolant volume flux density distribution arises. Spray overlapping should be taken into account. The present study reports an experimental results on mass flux density 2D measurements for sprays from industrial FullCone pressure-swirl atomizers. A number of differently constructed nozzles were tested in order to verify whether these nozzles are appropriate for using in arrays in water spray quenching. Measured optimal nozzle-to-nozzle distance was found to be different from that predicted by ignoring the effect of droplet interaction on the resulting mass flux density distribution.

INTRODUCTION

Spray quenching is used to optimize heat transfer from a part to allow the capture of a metastable structure with the required physical properties, while simultaneously developing the desired distribution and level of residual stress. Therefore, the time-temperature history of the part must be accurately controlled during the quench [1]. Spray quenching provides a wide range of cooling rates due to its easily controllable quenchant flow rate.

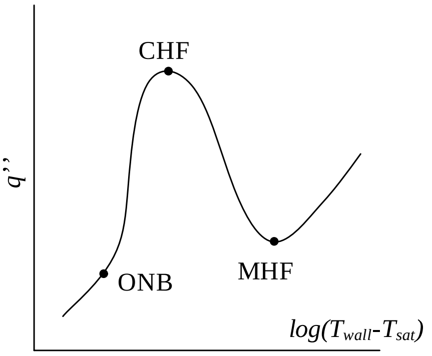

Figure 1. Boiling curve.

The usual quenching process begins at temperatures well above the saturation temperature of the liquid. During the spray quenching, the heat transfer changes its rate passing through various regimes. Figures 1 and 2 present the schematics of part surface heat flux and its temperature during all the phases of spray quenching respectively.

The process starts with film boiling where the part temperature is high enough to evaporate liquid droplets before they could reach the hot surface. Cooling is relatively slow during this phase. This regime ends within the point of a minimum heat flux (MHF). Then, passing through the transitional boiling, a point of maximum heat flux (CHF) is reached. The cooling rate has a maximum in the regime of transitional boiling. With the beginning of the nucleate boiling regime, the cooling rate starts to fall. The rate gets further smaller passing the point of the onset of nucleate boiling (ONB). The last regime is that of single phase convection.

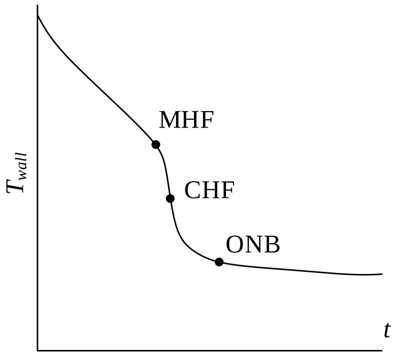

Figure 2. Temperature-time curve for cooling

There are a number of parameters affecting the heat transfer rate obtainable with spray quenching system during the above described regimes: water mass flux density, mean droplet size, droplet velocity, angle of impingement and the wetting effect. A decisive parameter of whether the water droplet will penetrate the vapour blanket established in the regime of film boiling is its momentum. This in turn is related to the droplet size and velocity. After the droplet have succeeded to penetrate the vapour blanket and reached the surface of the hot part, wetting characteristics and the impingement angle of the droplet will influence the heat transfer rate.

Mudawar and Valentine [2] conducted an experimental study of heat transfer from hot metallic surfaces to water sprays in the single-phase, nucleate boiling, and transition boiling regimes of the quench curve for surface temperatures below 400°C. It was demonstrated that heat transfer to water sprays depends on the local values of the spray hydrodynamic parameters such as volumetric spray flux, mass mean drop diameter, and mean drop velocity.

Deiters and Mudawar [3] have shown how a spatial distribution of the surface heat transfer rate can be derived by combining the local heat transfer correlations with the spatial distribution equations of spray parameters. The authors have determined that the mass flux density of the sprays varies considerably throughout the spray field.

Typically, the spray quenching system involves either stationary parts or long extrusions moving through an array of spray nozzles. The more uniform the flux distribution of the overlapping sprays the less the differences in cooling rates of different regions of the quenched part. In order to eliminate undesired variations in cooling rate and to achieve uniform physical properties of the quenched part an optimal nozzle space size should be determined. Water mass flux density appears to be one of the major parameters controlling the spatial variations of heat transfer rate [4].

There are a number of studies on spray cooling in film boiling regime that point out that mass flux density is the major parameter affecting the heat flux from the hot surface [5, 6 and 7].

Although the impact of the mass flux density on the quenching process is well recognized, there are quite a few studies that took into consideration actual flux distributions. Further more, the mass flux density distributions of overlapping sprays from widely used for quenching pressure-swirl nozzles are scarcely studied. The goal of the present study is to determine the effect of pairs of overlapping sprays on heat transfer during the film boiling regime for quenching metallic parts.

EXPERIMENTAL

The experimental setup is presented schematically in Figure 3. Water mass flux density was determined with use of collection apparatus (6 in Figure 3). Spray water was collected by a square array of 20x20 glass measuring tubes. Each tube was capable of collecting 15cc. Tubes inner diameter was 14.6mm with about 0.7mm wall thickness.

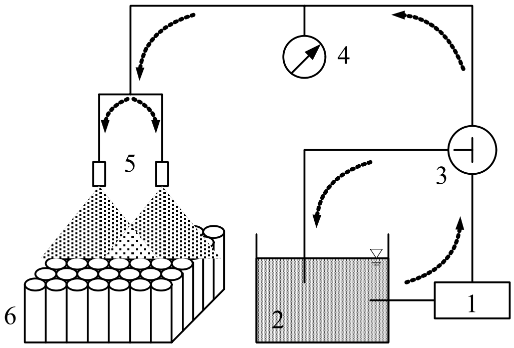

Figure 3. Experimental setup.

The filtered water was pumped from reservoir 2 using pump 1 through the regulating three-way valve 3 (served for bypassing the extra water flow) towards the nozzles 5. The operating pressure for all the experiments was 580 kPa registered by pressure gauge 4. The nozzles were mounted on X-Z device that allowed different height and nozzle-to-nozzle distances to be applied.

All the nozzles used in the present study were FullCone type pressure-swirl Spraying Systems Corp. produced bronze nozzles. The company supplied characteristics are summarized in Table 1.

Table 1. Spray nozzle characteristics

nozzle	orifice diameter, mm	flow rate, lit/min			spray angle*, deg
		4bar	5bar	6bar	
TG0.5	0.62	0.42	0.47	0.51	63
TG1	0.94	0.85	0.94	1.0	53
TG2	1.19	1.7	1.9	2.0	46
TG3	1.57	2.5	2.9	3.1	59

* at 6bar

It is worth noting that although all the nozzles used in the present study are marked as FullCone nozzles, there inside construction is not the same. Nozzles from TG0.3 to TG0.7 have the same screwable insert, while nozzles starting from TG1 and up to TG10 have a different one (although of various sizes). The two kinds of inserts are presented in Figure 4.

Figure 4. TG2 (left) and TG0.7 (right) internal geometry.

RESULTS AND DISCUSSION

Single nozzle tests

Typical mass flux density distributions from a single nozzle of type TG0.5 and TG2 are presented in Figure 4. The interpolation performed was checked against the previously measured mass flow rate and was found at least 2% accurate.

It is seen from Figure 5 that TG0.5 nozzle produces a horseshoe shape distribution, while the TG2 nozzle represents more uniformly spread mass flux distribution. The difference in mass flux distribution seen in Figure 4 can be a result of differences in the internal geometry presented in Figure 4. Horseshoe shape was also obtained for TG0.4, TG0.6 and TG0.7 nozzles for nozzle heights from 60 to 300mm (not reported here). Such nozzles can not be arranged in an array with uniform mass flux distribution.

Yule et al [8] have studied experimentally the spray characteristics of TG0.5, TG1, TG2 and TG3.5 nozzles. Spray mass flux distribution was measured along line crossing the spray axis. It should be noted that for TG0.5 nozzle used in Yule's [8] study a parabolic shaped distribution was obtained and almost flat distribution for TG3.5 nozzle. However, TG0.5 nozzle droplet size measurements have revealed the ring (although the measurements are along line) shape distribution with smaller droplets concentrated around the axis of the spray and larger at the periphery.

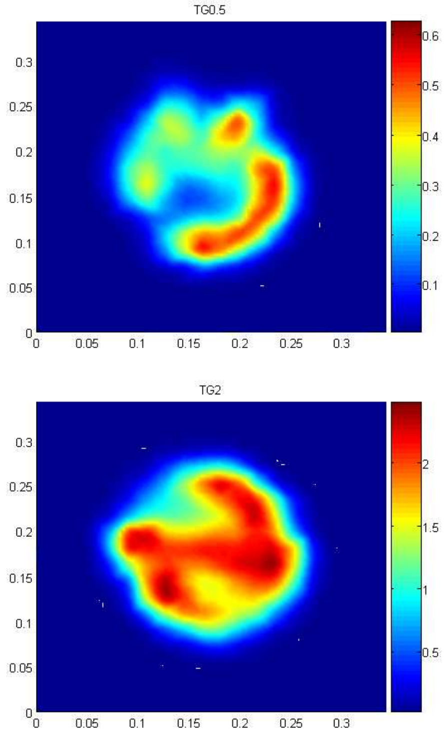

Figure 5. Typical mass flux density (kg/m^2-s) for TG0.5 and TG2, height 160mm.

Double nozzle tests

Depending on the nozzle type the degree of interaction between two sprays may vary for the same distance between the nozzles. The question in such situations is whether the resulting mass flux distribution of two overlapping sprays can be achieved by simply adding the two distributions measured with each spray working alone.

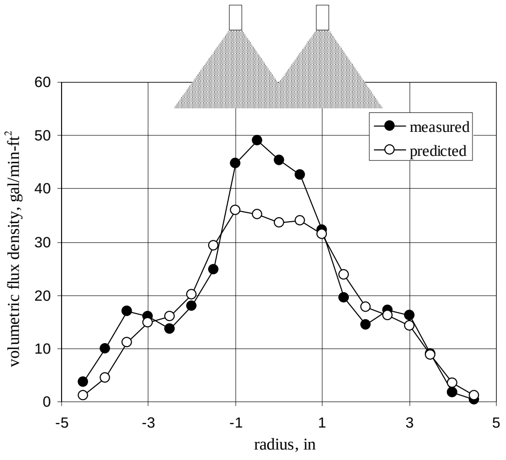

Figure 5. Volumetric flux density for two GG10 nozzles (adopted from Mizikar [9]).

A number of studies are available in the literature on this subject. Mizikar [9] have studied the effect of interaction between the two full cone narrow angle sprays of GG series of Spraying Systems Corp. Figure 6 presents the results of predicted (algebraic addition of two separate distribution) and the measured distribution of two overlapping 2 inch separated sprays. The difference between the predicted and the actual distributions is critical in the mid-section between the sprays where the interaction of droplets causes increased volumetric flux density. On the other hand, Hall and Mudawar [4] reported a relative insensitivity for two flat spray nozzles. Their predicted and measured flux distributions are almost identical. It can be suggested that the absence of considerable interaction between the droplets is due to a relatively dilute spray pattern in the overlapping region in their study.

For all the nozzles starting with TG1 the algebraic sum of two separately measured mass flux densities and the actual distribution obtained while both nozzles were operating was different – see Figure 6 for a typical comparison. The difference was similar to that obtained previously by Mizikar [9], namely high mass flux density in the midzone between the nozzles.

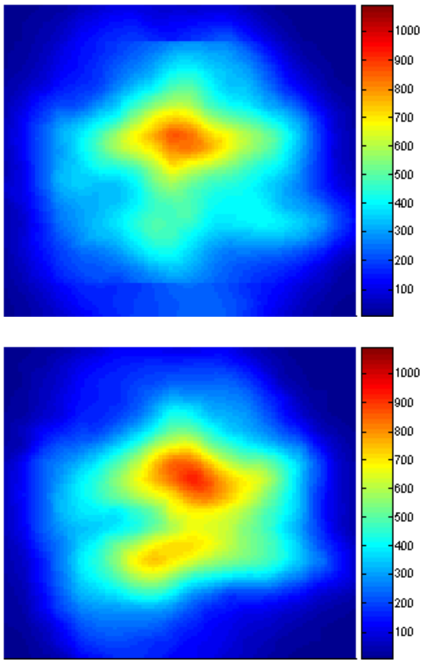

Figure 6. Mass flux density (mg/m^2-s) for two TG1 nozzles, algebraic sum (top) and actual distribution (bottom), h=330mm

Figures 7a-7d presents the results of nozzle-to-nozzle distance optimization experiment for two TG2 sprays. It is seen that starting with small distance of 53mm between the nozzles the midzone maximum diminishes with increasing the distance. The distribution seems to be quite uniform for a distance of 100mm between the nozzles.

Similar optimization experiments for TG3 nozzle for the same nozzle height have revealed that the optimal distance between the nozzles is about 140mm. This is explained by a wider (59 against 63 degrees) spray angle for TG3.

From Figures 7(a-d) it can be concluded that non-uniformity in mass flux density from TG2 nozzles used in the present study even for a nozzle-to-nozzle distance of 100m is about 10-15% maximum to minimum ratio. In the film boiling regime the heat flux from the part is proportional to some power of mass flux density – 0.76 [5,6] and 0.556 [7]. The corresponding ratio of heat fluxes (resulting from 15% difference in mass flux density of water) would be about 10% for both correlations. This has to be taken into account while predicting the cooling rate of metallic parts by water spray quenching.

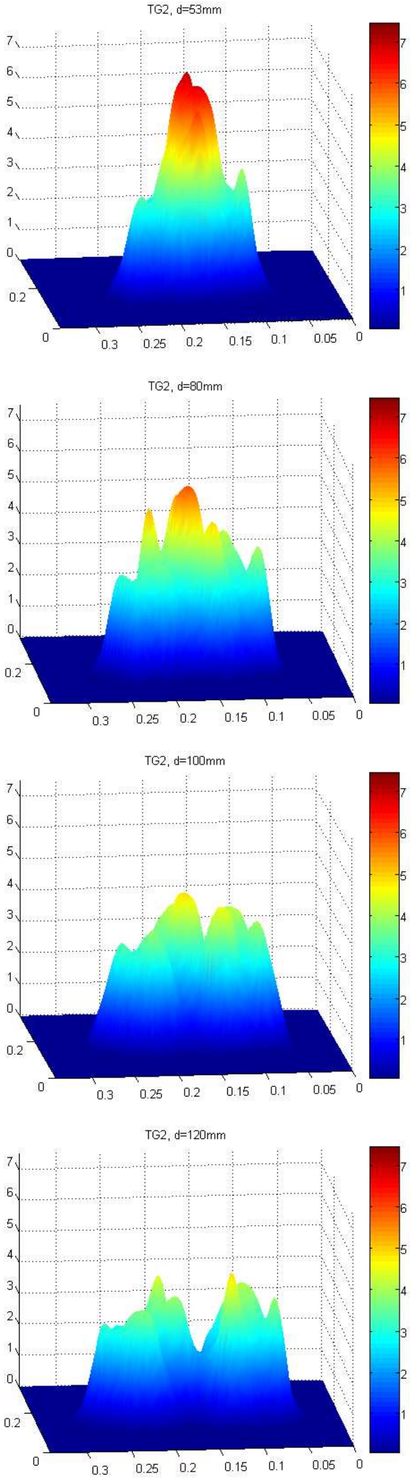

Figure 7(a-d). Mass flux density (kg/m2-s) for two TG2 nozzles, h=160mm.

SUMMARY

An experimental study on the interaction of industrial FullCone swirl-pressure atomizers is reported. The experimental setup allowed measuring a 2D mass flux density distribution of the sprayed water. A number of differently constructed nozzles were tested in order to verify whether these nozzles are appropriate for using in arrays in water spray quenching. Measured optimal nozzle-to-nozzle distance was found to be different from that predicted by ignoring the effect of droplet interaction on the resulting mass flux density distribution. The 2D spatial distributions of the mass flux density were found to have about 15% min-to-max difference. Such a difference is expected to affect the cooling uniformity in the quenching surface during film boiling regime.

ACKNOWLEDGMENT

You can place your acknowledgements here.

NOMENCLATURE

Symbol	Quantity	SI Unit
t	time	s
q’’	heat flux	W/m^2
T	temperature	K
d	nozzle-to-nozzle distance	mm
h	nozzle height	mm

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