Effect of Controlling Parameters on Heat Transfer during Jet Array Impingement Cooling of a Hot Steel Plate

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ABSTRACT:

This paper describes the experimental results on heat transfer characteristics of array of jet impingement cooling of a steel plate. The experiments were conducted on a stationary electrically heated steel plate. A commercially available shower was used to generate array of jets. The Time dependent temperature profiles were recorded by NI-cRIO DAS at the desired locations of the bottom surface of the plate embedded with K-type thermocouples. The controlling parameters considered in the experiments were water pressure, mass impingement density, mass flow rate, shower exit to surface distance respectively. Effects of these parameters on cooling rate were analysed through plots in the MS-EXCEL environments. The experimental results showed a dramatic improvement of heat transfer rate from the surface and the results established good optimal cooling strategies.

KEYWORDS: *Array of Jets, Heat transfer coefficient, Heat transfer enhancement, Jet Impingement Cooling, Optimal cooling, Patternator, Statistics*

Nomenclature:

ΔT	Measured temperature difference
ΔT^*	Non-dimensional temperature difference
Tc	Temperature of cooling water
T	Time
t^*	Non-dimensional time
l	Length of the steel plate
α	Thermal Diffusivity
CR	Cooling rate
CR*	Non-dimensional cooling rate
HTC	Heat Transfer Coefficient
D	Shower exit to surface distance
lt	Liter
min	Minute
m	Meter
s	Second
Pw	Water Pressure

I. INTRODUCTION:

Heat transfer enhancement is one the major parameters required to improve the performance of the thermal systems in many industries such as electronics, aerospace, automotive and steel manufacturing. Jet impingement cooling and spray impingement cooling are two of the most effective ways to improve the rate of heat transfer from the hot metal surface. Impingement cooling helps to achieve desired cooling rates from the surface by appropriate parametric control during the cooling process. Hence this process finds its use in many cooling application in particular to metal processing industry So far a great deal of experimental and computational work has been done to study these effects using single jet water impingement [1 – 4]. Lytle and Webb [5] have studied the effect of very low nozzle to plate spacing ($z/d < 1$) on local heat transfer distribution on a flat plate impinged by a circular jet issued by a long pipe nozzle which allows for fully developed flow at the nozzle exit. Gardon and Cobonpue [6] have reported the heat transfer distribution between circular jet and flat plate for the nozzle plate spacing greater than the two times the diameter of the jet, both for single jet and array of jets. Owen and Pulling [10] presented a model for the transient film boiling of water jets impinging on a hot metal surface of stainless steel and nimonic alloy. In their study, wetting of the surface was assumed to occur when the temperature of the surface falls to the Leidenfrost temperature.. Kumagai et al. [11] conducted an experimental investigation of cooling a hot thick copper plate by impinging a plane water jet to clarify the transient behavior of boiling heat transfer performance along the surface and the temperature profile inside the body as well as on the surface. This experimental result indicated a time delay of approximately 100 s before the movement of the wetting front for a saturated jet with velocity 3.5 m/s and an initial solid temperature of 400 ^{0}C. One of the cooling means of achieving higher rates of heat transfer is using water jet impingement. It has been proven an effective means and widely applied in steel industries. Compared with the other cooling methods, it definitely is a rapid steel cooling method and reveals an outstanding advantage in improving heat transfer efficiency in cooling process of high temperature steel. According to Wolf, et al. [12], for single-phase convection, the heat transfer coefficient for water impingement cooling system exceeds 10 KW/m^2.

Now a days researchers are concentrating more on jet array impingement cooling rather than on single impinging jet, because array of jets maintains more consistent surface temperature and cools larger areas. Enhancement of heat transfer on an impinged surface by impinging an array of jets by minimizing a cross flow effect was studied by Nuntadusit et al. [13]. In his study conventional round orifices (of aspect ratio AR = 1) was substituted with elongated orifice (AR = 4 and 8). An experimental investigation of single phase and flow boiling heat transfer of submerged micro jet array was conducted with R134a by Eric A. Browne et al. [14]. Boiling experiments were performed with liquid subcooling of 10, 20 and 30^{0}C for jet velocities of 4, 7 and 10 m/s. It was found that boiling enhances heat transfer with a maximum heat flux of 590 W/cm^2. Shyy Woei Chang et al. [15] presented heat transfer measurements by impingement of array of jets on surface roughened by concave dimples. They experimentally revealed the isolative and interactive influences of surface topology on local and spatially averaged heat transfers. S. Caliskan and S. Baskaya [16] presented heat transfer measurements over surface having V – shaped ribs (V - SR) and convergent – divergent ribs (CD - SR) by circular impinging jet array using thermal infrared camera. The effect of nozzle geometry in liquid jet impingement cooling was detailed by Brian P. Whelan and Antony J. Robinson [17].In this paper effect of various controlling parameters on impingement cooling of a hot steel plate by an array of jets has been experimentally investigated. Commercially available water showers were used to generate array of jets and impinged on electrically heated square steel plate of side 120mm and thickness 4mm. The local temperatures are measured by using embedded K-type thermocouples. The temperature data were accessed by NI CRIO-DAS and used to investigate the heat transfer characteristics of jet cooling and characterize the showers to achieve the optimum cooling effect.

II. EXPERIMENTAL SET UP:

In the current paper the experimental set up is concentrated on rapid cooling of hot flat steel plate as shown in figure 1. The experimental set consists of heating arrangement, jet array impingement system and data acquisition system. Electrical coil heater of 2.5 KW, bounded over asbestos plate was used to heat up the selected test piece. To ensure uniform heating a proper gap was maintained between the lower surface of the test plate and the upper heater surface. For generating jet arrays, a commercially available shower having 80 holes on 50mm diameter periphery was used. The flow rate was regulated by changing the pressure at which the water was being delivered to the shower. The test piece was a square plate of side 120mm and 4mm thickness. It was embedded by four K – type thermocouples at suitable locations to record the temperature of the steel plate. The bed was designed in such a manner that the distance between the test piece and the shower can be varied by means of a hand wheel. A mechanical patternator was used to measure the impingement density. The patternator consists of an array of small collecting tubes arranged parallel to the main jet axis. NI CRIO – DAS aided with LABVIEW software was employed for acquiring the raw data, analyzing the data and presenting the results.

III. EXPERIMENTAL PROCEDURE:

The steel plate was heated to a temperature slightly higher than the test temperature to compensate for the heat loss during transfer of the steel plate from the heater to test bed (underneath the jet array system). When the temperature of the steel plate reached the required temperature the jet array was impinged on the hot steel surface and temperature - time data was generated with aid of NI - CRIO. The initial temperature of the steel plate was varied between 750^{0}C to 950^{0}C and the jet to surface distance was taken as 70mm, 135mm and 255mm.The mass flow rate was taken for different values between 0.5 to 9.56 lt./min. The mass flux density for different shower exit to surface gap was measured by means of a mechanical patternator. These were the same locations where the heat transfer experiments were subsequently conducted.

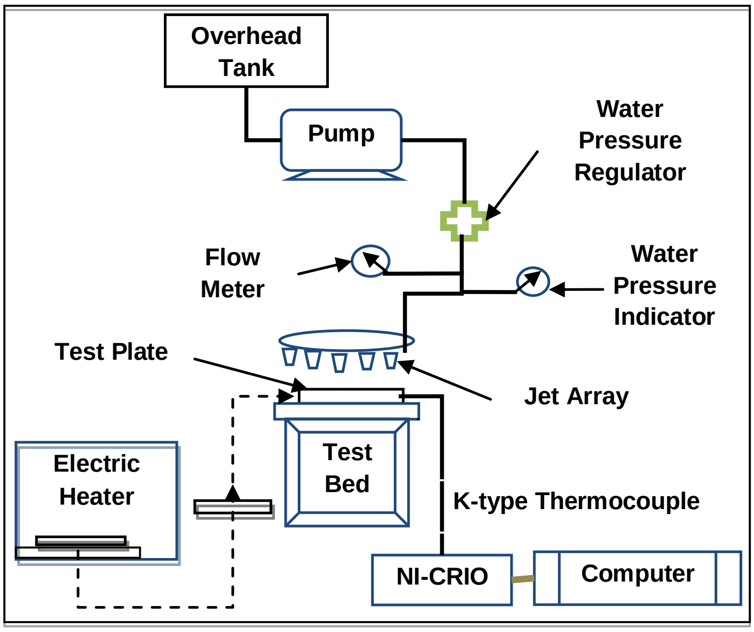

Figure 1. Schematic of experimental set up

IV. RESULTS AND DISCUSSION:

The variations of temperature with respect to time were measured at various key locations on the steel plate. From these data the rate of heat transfer from the plate were calculated. This paper mainly illustrates the relationships between the rate of heat transfer and the primary parameters: water pressure, mass flow rate, mass impingement density and shower exit to surface distance as well as cooling time.

4.1. Temperature – Time history:

Figure 2 shows the non-dimensional temperature difference against non-dimensional time for water pressure range of 2 - 4 bar. The non-dimensional temperature difference is taken as the ratio of the measured temperature difference to the cooling water temperature as shown in equation 1. The non-dimensional cooling time is calculated by using equation 2.

$$\Delta T^{*} = \Delta T / Tc \qquad (1)$$

$$t^{*} = (l^{2}/\alpha) * t \qquad (2)$$

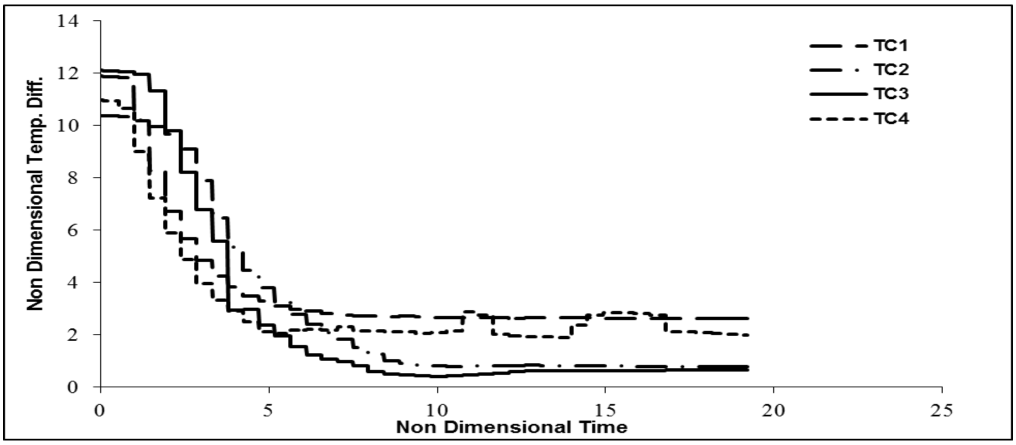

Figure 2. Non dimensional temperature difference vs non dimensional time for various thermocouple location

The temperature difference profile for different thermocouple locations in figure 2 indicates fairly uniform trend over the entire impinging surface.From the figure 3 shown below it is seen that as we increase the pressure, the fall in non-dimensional temperature difference becomes steep. But when the pressure is increased from 3.5 bar to 4 bar, we observe the steepness reduces. This might be due to the fact that as we increase the pressure, the atomization of water particles increases and blow off occurs there by not contributing significantly to the cooling process.

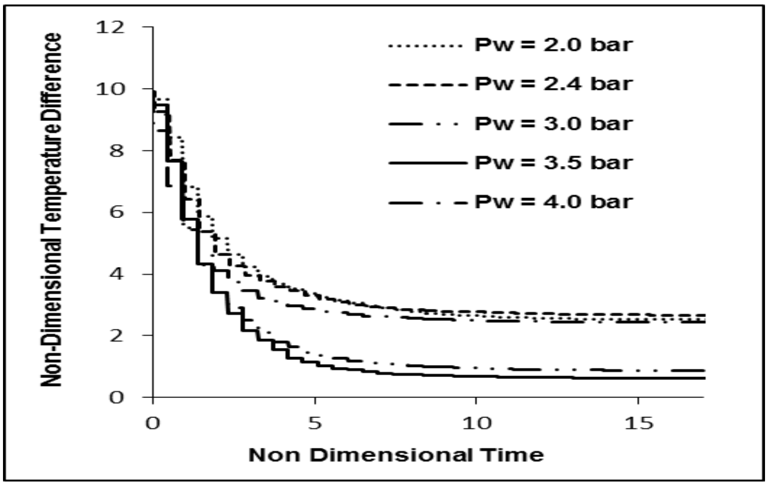

Figure 3. Non-dimensional temperature difference vs. non-dimensional time for different water pressure (pw)

4.2. Cooling rate:

The cooling rate is defined as the rate of change of temperature. The cooling rate is represented by equation 3.

$$CR = \Delta T / t \tag{3}$$

Figure 4 represents the variation of water flow rate with water pressure. Here we find that water flow rate varies directly with water pressure. Figure 5 plots the variation in non-dimensional cooling rate to that of water pressure for different jet exit to surface distance. The non-dimensional cooling rate is given by equation 4.

$$CR^* = \Delta T^* / t^* \tag{4}$$

Figure 5 clearly implies that as we increase the jet exit to surface distance the cooling rate reduces. This happens because when we increase the distance between the jet exit and the cooling surface, the cone angle increases and the amount of water impinging on the surface reduces.

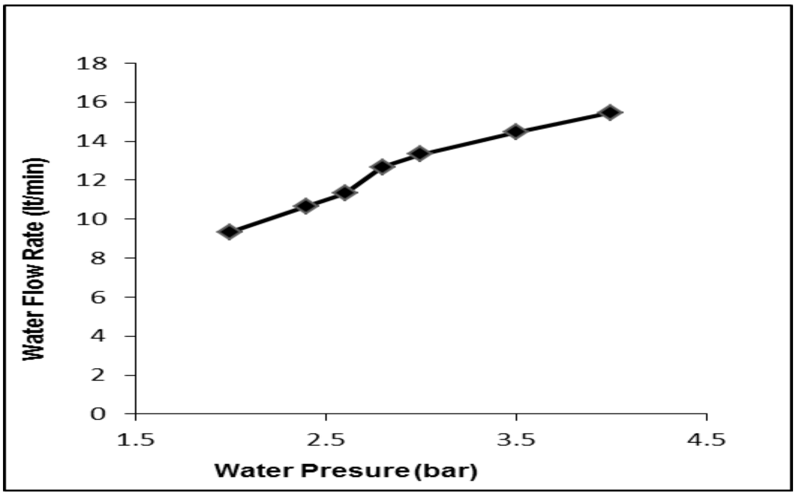

Figure 4. Water flow rate vs. water pressure

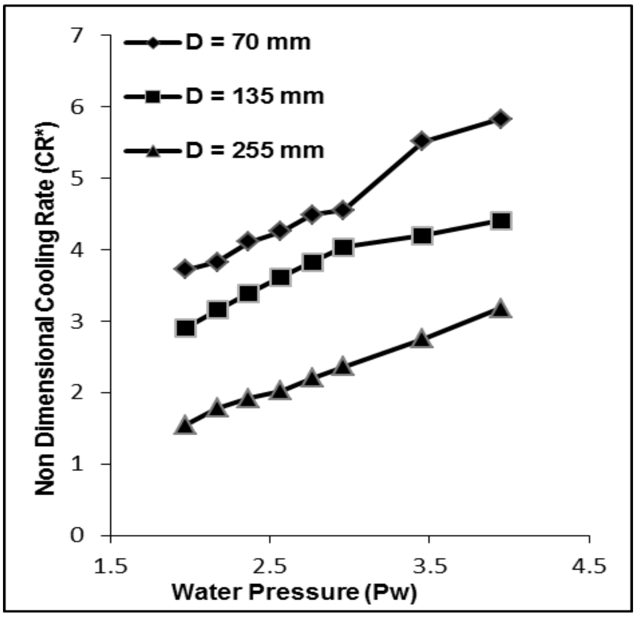

Figure 5. Non dimensional cooling rate vs. water pressure for d= 70mm, 135mm and 255mm

4.3. Mass Impingement Density:

A simple mechanical patternator was used to measure the mass impingement density. The behavior of cooling rate with respect to mass impingement is shown in figure 6.

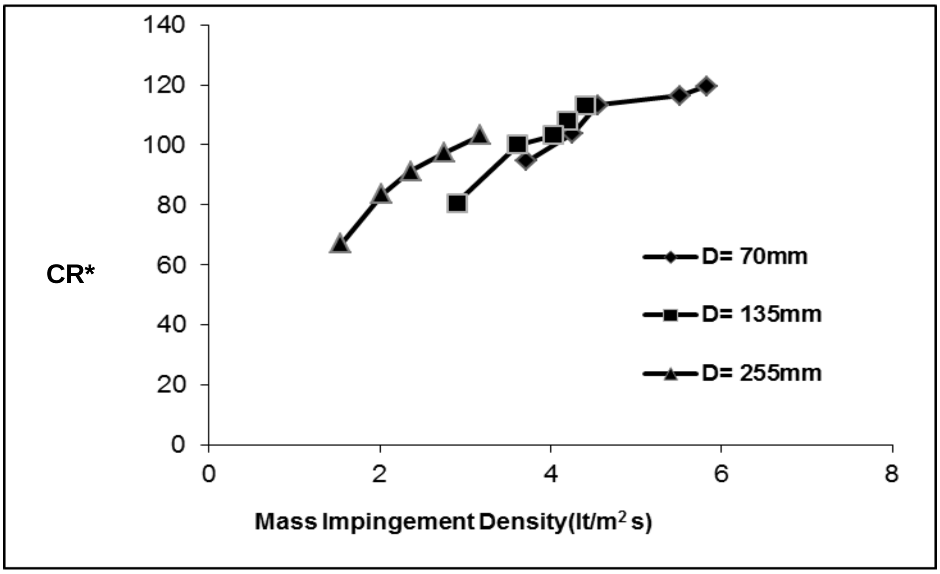

Figure 6. Non-dimensional cooling rate vs. mass impingement density for different shower exit to surface distance

From figure 6 it is pretty obvious that for D = 70mm the mass impingement density is more and hence the cooling rate increases.

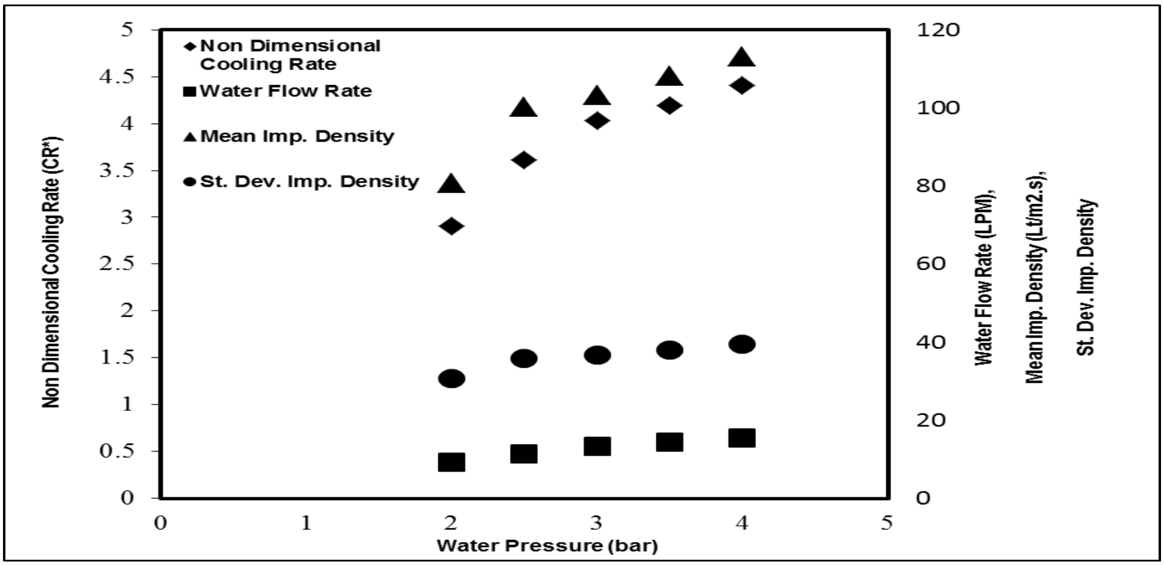

Figure 7. Variation of non-dimensional cooling rate with respect to water pressure, water flow rate, mean impingement density and standard deviation impingement density

It is observed from Figure 7 that with increase in water pressure, the water flow rate, impingement density and non-dimensional cooling rate increase monotonically.

4.4. Heat Transfer Coefficient:

The average heat transfer coefficient "h" was calculated using the cooling water temperature and the surface temperature of the hot steel plate. Figure 8 shows the variation of Heat transfer coefficient with non-dimensional temperature difference. The high value of Heat transfer coefficient indicates that the heat transfer taking place is predominantly convective heat transfer.

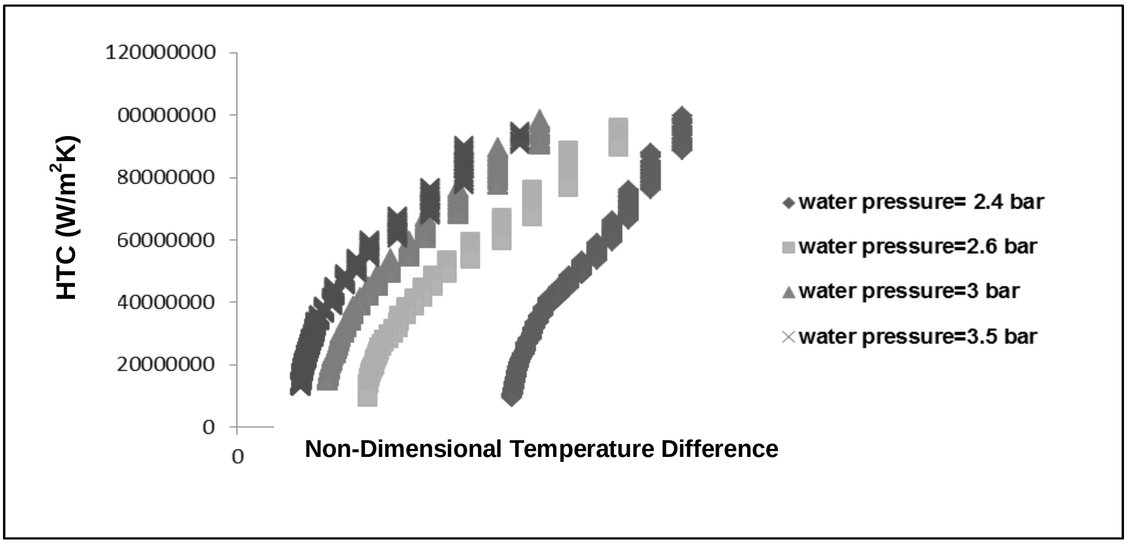

Figure 8. Heat transfer coefficient vs. non dimensional temperature difference for variations in water pressure.

V. CONCLUSION:

In the present study, the effects of various parameters such as water pressure, mass impingement density, mass flow rate and shower exit to surface distance on the heat transfer rate from a hot metal surface by impingement of an array of jets was experimentally studied. The major findings are as follows:-

- The cooling rate is uniform over the entire surface of the steel plate.

- The maximum drop in temperature difference with respect to time was recorded for a water pressure of 3.5 bar.
- At a shower exit to surface distance of 70mm the maximum cooling rate was obtained.
- With increase in mass impingement the cooling rate increased gradually.
- High value of heat transfer coefficient indicates active convective heat transfer.

From the above results it is can be said that to optimize the cooling rate the jet exit to surface distance and the water pressure are to be optimized.

REFERENCES

[1] J.N.B Livingood, P. Hrycak. Impingement heat transfer from turbulent air jets to flat plates – a literature survey NASA Technical Memorandum (NASA TM X-2778) 1970.

[2] H. Martin, Heat and mass transfer between impinging gas jets and solid surface. Adv. Heat transfer 13, 1-60. 1977.

[3] J.W. Baughn, S. Shimizu, Heat transfer from a surface from uniform heat flux and an impinging jet. J. Heat Transfer 111, 1096-1098, 1989.

[4] R. Gardon, C. Akfirat, The role of turbulence in determining heat transfer characteristics of impinging jet. Int. J. Heat Mass Transfer 8, 1261-1272, 1965.

[5] D. Lytle, B.W. Webb, Air jet impingement heat transfer at low nozzle plate spacings. Int. J. Heat Mass Transfer 37, 1687–1697, 1994.

[6] R. Gardon, J. Cabonpue, Heat transfer between a flat plate and jets of air impinging on it. Int. Develop. Heat Transfer, ASME, 454-460, 1962.

[7] R.G. Owen, D.J. Pulling, “Wetting delay: .lm boiling of water jets impinging hot .at metal surfaces”, in: T. Nejat Veziroglu (Ed.), Multiphase Transport Fundamentals, Reactor Safety, Applications, vol. 2, Clean Energy Research Institute, University of Miami, pp. 639–669, 1979.

[8] S. Kumagai, S. Suzuki, Y. Sano, M. Kawazoe, “Transient cooling of a hot metal slab by an impingement jet with boiling heat transfer”, ASME/JSME Thermal Eng. Conf. 2, 1995.

[9] D.H. Wolf, F.P. Incropera, R. Viskanta, Jet Impingement Boiling. Advances in Heat Transfer. Vol. 23, 1-131, 1993.

[10] C. Nuntadusit, M. Wae-hayee, P. Tekasakul, S. Eiamsa-ard, “Local heat transfer characteristics of array impinging jets from elongated orifices”. International Communications in Heat and Mass Transfer 39, June 18, 1154–1164, 2012.

[11] Eric A. Browne, Gregory J. Michna, Michael K. Jensen, Yoav. Peles,. “Microjet array single-phase and flow boiling heat transfer with R134a”. International Journal of Heat and Mass Transfer 53, March 15, 5027–5034, 2010.

[12] Shyy Woei. Chang, Shyr Fuu. Chiou, Shuen Fei. Chang, “Heat transfer of impinging jet array over concave-dimpled surface with applications to cooling of electronic chipsets”. Experimental Thermal and Fluid Science 31, June 17, 625–640, 2007.

[13] S. Caliskan, S. Baskaya, “Experimental investigation of impinging jet array heat transfer from a surface with V-shaped and convergent-divergent ribs”. International Journal of Thermal Sciences, May 18, 59 234-246, 2012.

[14] Brian P. Whelan, Anthony J. Robinson, “Nozzle geometry effects in liquid jet array impingement”. Applied Thermal Engineering 29 2211–2221 2009.