Multiple Jet Impingement: A Promising Method of Cooling

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Abstract - Convective heat transfer by jet impingement is a prominent method of cooling. The range of applications of jet impingement method being used is vast. It includes cooling of gas turbine components, cooling of fusion reactors, cooling of power electronics, annealing and quenching of metals, drying of paper and fabric as well as tempering of glass. These applications require large amount of removal of heat for better performance and jet impingement method provides better way of extracting large heat fluxes from high temperature components. This review oversees the theoretical and experimental developments in heat transfer by jet impingement method and the parameters related to this technique which affect heat transfer are studied. The main focus is on physics, correlations and outcomes of jet impingement in available literatures.

Keywords - Jet impingement, Heat transfer coefficient, Effect of parameters, Critical heat flux.

NOMENCLATURE

c_{pl}	Specific heat at constant pressure for liquid (KJ/kg K)
C	Constant
d	Diameter of jet orifice (mm)
G	Mass flux of liquid jet (Kg/m^{2}s)
h_{lv}	Latent heat of evaporation (J/kg)
q_c	Critical heat flux (W/m^2)
q_{co}	Critical heat flux for saturated liquid state (W/m^2)
ΔT_{sub}	Liquid subcooling at jet orifice exit (K)
ρ_l	Liquid density (kg/m^3)
ρ_v	Vapor density (kg/m^3)
σ	Surface tension (N/m)

I. INTRODUCTION

Jet impingement system provides efficient way of heat removal compared with conventional methods of cooling. It has been used for thermal management of wide variety of processes and applications. Jet of fluid is issued normal to the surface to be cooled through circular or slot orifice and impinged on surface with high velocity to remove the heat. The heat transfer coefficient is maximum in impingement region which is right below the orifice and decreases away from this region. For extracting large amount of heat and providing better thermal management of hot surfaces, arrays of jets are used. Multiple jets are used to increase temperature uniformity which gives higher average heat transfer coefficient.

Increasing heat transfer rate from higher temperature surfaces of various applications is a primary concern now days. So many methods are adopted for extracting heat form such applications which include pool boiling, detachable heat sinks, mini/microchannel heat sinks, heat pipes, sprays and jet impingement [1]. These schemes are adopted for cooling of electronic components, cooling of lasers, cooling of PV cells as well as for cooling of avionics. Processes such as cooling of gas turbine components, cooling of stock material during material forming processes, tempering of glass, drying of paper and textile, cooling of fusion reactor blanket and thermal management of high heat flux supercomputers, power devices and advanced military avionics requires a promising technique like jet impingement. With this technique, heat transfer coefficients that are up to three times higher than conventional cooling methods can be achieved at maximum flow speed and modest pressure drop, because boundary layers of impingement are much thinner and after impingement it serves as secondary cooling.

Jet impingement is one of the method of forced convection which is known to yield high local and average heat transfer coefficients. Compared to single phase jet impingement, jet impingement boiling achieves very high heat transfer coefficients. Most of the heat transfer literature incudes single phase jet impingement cooling in which coolant does not changes its phase. Two phase cooling is favored because of high heat transfer coefficients and nonlinear relationship between heat flux and surface to fluid temperature difference [2]. Multiple jet system can be used to provide uniform temperature reduction of larger surfaces. Numerous studies have been focused directly at electronics cooling. This study covers physics of jet impingement heat transfer, available correlations and results from experiments.

II. CONCEPT OF JET IMPINGEMENT HEAT TRANSFER

Single phase and two phase jet impingement cooling have been topics of interest for many decades. Impinging jets can be either air powered or can use form of liquid. Fluid stream is issued from nozzle or orifice at high velocity towards the surface of device to be cooled. Generally jets are issued normal to the hot surfaces through circular or slot orifices. As jet comes out from orifice, it thickens due to resistance from surrounding fluid and wall jet is formed along the impingement surface away from impingement region [3].

Fig. 1 shows the schematic of physics of free surface jet impingement. Basic four regions are observed in the flow field such as potential core, free jet region, stagnation region and wall jet region. Jet emerges from orifice and loses its axial velocity while approaching the hot surface. The velocity is higher in core. Downstream of stagnation zone, a wall jet forms and moves outwards parallel to the surface. Heat extraction is maximum in stagnation zone as well as at certain distance from stagnation zone due to wall jet. According to ranges of surface temperatures, heat transfer modes can be divided into forced convection, nucleate boiling, transition boiling and film boiling [4]. For liquid jet boiling on hot surface, the assessment of critical heat flux, which shows highest cooling capacity for the jet heat transfer, is very important to learn the burnout phenomenon in nucleate boiling [5].

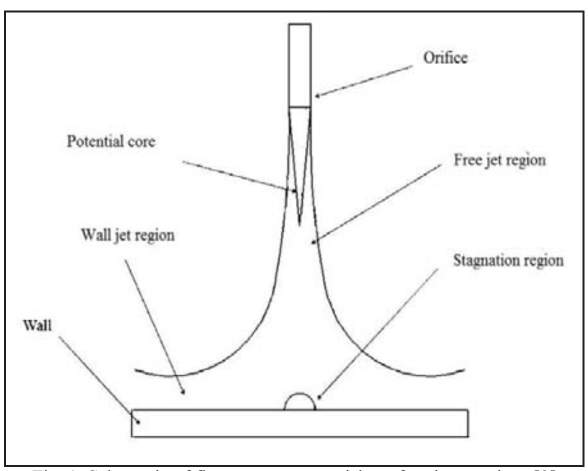

Fig. 1. Schematic of flow pattern comprising of various regions [3]

Jet impingement method can be incorporated with three basic forms like free surface jet, submerged jet and confined jet. A jet of fluid issued from nozzle or orifice into space containing different fluid having less density is depicted as a free surface jet and if space contains same fluid then it can be named as submerged jet. If radial spread of jet is restricted in narrow channel generally between impingement surface and orifice plate, then it is said to be confined jet.

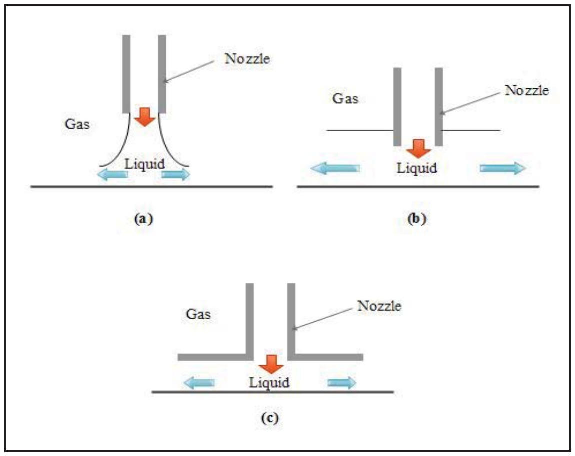

Fig. 2. Jet configuration : (a) Free surface jet (b) Submerged jet (c) Confined jet [6]

III. JET IMPINGEMENT BOILING HEAT TRANSFER

Boiling heat transfer with jet impingement has been used to satisfy the demand of high heat transfer rate. It is the most efficient way of heat extraction among all the steady state heat transfer methods. In the fully developed boiling regime, heat transfer occurs due to releasing of latent heat of vaporization and flow mixing due to bubbles departure. Main objective of most of the studies was to find out critical heat flux of jet impingement boiling on the various surfaces by varying the parameters such as jet exit velocity, jet geometry, fluid type and fluid subcooling etc.

Li et al. [7] experimentally studied steady boiling heat transfer for high velocity slot jet impingement and provided correlation to predict CHF under subcooled boiling condition for water as follows,

$$\frac{q_c}{q_{c,o}} = 1 + 0.26 \left(\frac{\rho_v}{\rho_l}\right)^{0.55} \left(\frac{c_{p,l}\Delta T_{sub}}{h_{lv}}\right)^{0.64} \qquad (1)$$

It was concluded that subcooled jet impingement can break through the bubble layer on heater surface resulting in better solid-liquid contact and would increase the CHF.

Thermal management of electrical and electronic component is one of the greatest need today. Jet impingement boiling can fulfill the need of maintaining the surface temperature by using various coolants. Cardenas and Narayanan [8] experimentally studied the thermal performance of dielectric water and FC-72 as coolant at one saturation temperature. They found that heat transfer using water is 3 to 5 times larger than FC-72.

It has been recognized that addition of surface enhancements can greatly improve phase change heat transfer performance. The use of extended surfaces is to increase the surface area of heat transfer. Nucleation sites can be increased by creating voids on the surface to trap the vapor and promote bubble nucleation [9]. By providing surface roughness, pin fins, coatings and porous surfaces showed enhancements in heat transfer. Li et al. [10] investigated jet impingement boiling on nano-characteristic surface of stagnation zone with different surface wettability. The effect of impingement velocity, subcooling and solid-liquid contact angle on CHF were examined. They proposed semi-theoretical and semi-empirical correlation for saturated jet boiling as,

$$\frac{q_c}{Gh_{lv}} = C \left(1 + \frac{\rho_v}{\rho_l}\right)^{1/3} \left(\frac{\sigma\rho_v}{G^2 d}\right)^{1/3} \left(\frac{\rho_v}{\rho_l}\right)^{1/3} \qquad (2)$$

Flow boiling jet impingement on enhanced surfaces was studied by Ndao et al. [11] and showed that subcooled nucleate boiling is dominant heat transfer mechanism for enhanced surfaces compared to smooth surfaces. Fig 3 shows a comparison of the various micro pin fins. The circular pin fin gave better thermal performance for R134a as coolant. Two phase heat transfer coefficients up to 150,000 W/m²K were noticed at jet velocity of 2.2 m/s using R134a.

Liquid jet impingement cooling is used to extract high heat fluxes from metal parts which is called as quenching. The ability of liquid impingement to quench the metals with temperatures up to 800-1000 ºC at moderate flow rates is well known. Karwa and Stephen [12] carried an experiment to study thermo-hydrodynamic phenomenon occurring during quenching of hot stainless steel plate.

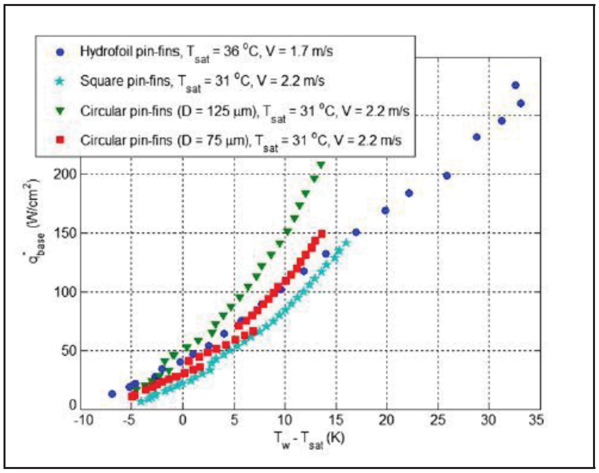

Fig 3. Boiling curve based on base area – effects of pin fins geometry [11]

IV. MULTIPLE JET IMPINGEMENT HEAT TRANSFER

An impingement using an array of multiple jets presented advantages over single jet by enhancing convective heat transfer form hot surfaces. The system of multiple jets is obvious for providing better area averaged uniform heat transfer coefficient. This method can be utilized for cooling of hot metals, plastics, glass sheets as well as for drying of paper and textile. It is greatly used to cool gas turbine applications and removing high amount of heat transfer from nuclear power processes. Impinging jets with microscale applications are commonly used in electronic components.

In multiple jet configuration, individual jets can be affected by the various parameters such as geometry adopted, jet to jet interaction spacing, flow field along the target surface, distance between orifice and target surface etc. Multiple jet configuration becomes more complicated due to above parameters. These parameters with the effects upon heat transfer are summarized here.

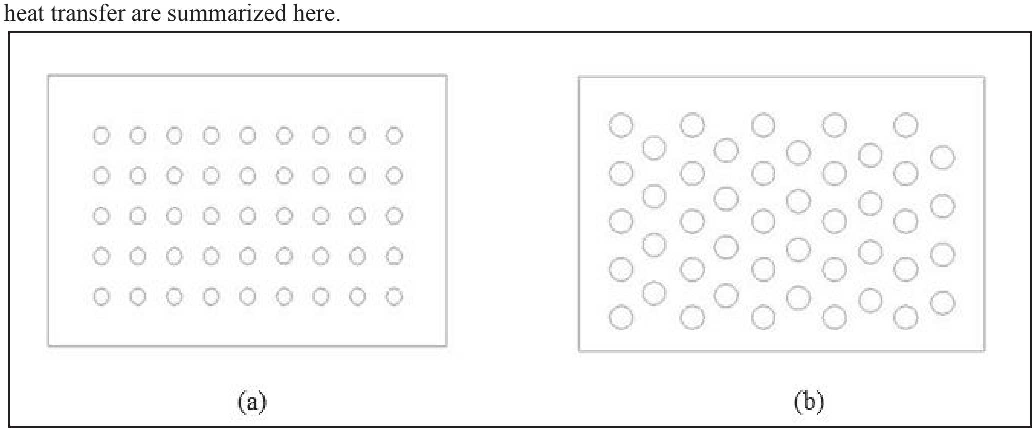

Fig 4. Arrangement of jets in array (a) Inline arrangement (b) Staggered arrangement [13]

4.1 Effect of coolants used on heat transfer

Suitable coolants for boiling heat transfer used were water, ethylene glycol, R-11, R-13, R-134a, FC-72, FC-77, FC-87, PF-5052, HFE-7100 etc. The properties of coolants mostly affected heat transfer performance. Cardenas and Narayanan [8] compared the cooling performance by water and FC-72 for jet impingement boiling.

4.2 Effect of jet velocity on heat transfer

The increase in the jet velocity increased the single phase HTC, broadened single phase region and delayed occurring of nucleate boiling. Meyer et al. [14] found out the effect of jet velocity on maximum heat flux for various jet widths and subcooling of FC-72. Fig 5 shows that increasing the subcooling by 10 ºC resulted in an 18 W/cm² increase in CHF and slight increase in jet velocity resulted in large improvement in CHF.

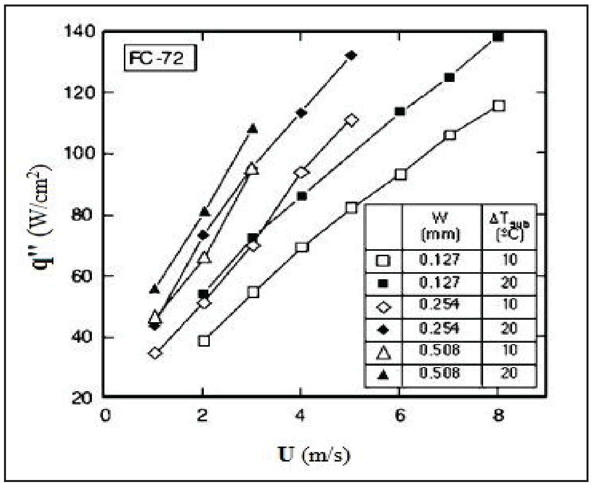

Fig 5. Variation of CHF for FC-72 with jet velocity [14]

4.3 Effect of orifice geometry on heat transfer

The heat transfer and pressure drop characteristics of both submerged and free-surface water jet arrays using different orifice geometries was investigated by Whelan and Robinson [15]. Geometries included were straight, contoured inlet, contoured inlet-outlet, chamfered inlet, chamfered outlet and chamfered inlet-outlet. It was found that addition of outlet modification had positive effect on heat transfer for free surface jets.

4.4 Effect of orifice dimension on heat transfer

The size of the orifice is critical parameter in the jet impingement heat transfer. Orifices used were having either circular, elliptical, square and slot configuration. The diameter of circular orifice and length-width of slot orifice measurly affected the heat removal process form hot surfaces. The measure conclusion was that as size of the orifice was decreased, heat transfer increased. Wang et al. [16] examined two-phase microjet cooling for removing heat from high-power VLSI chips. Almost 90 W heat was removed using four-jet array of 76μm diameter at the flow rate of 8 ml/min.

4.5 Effect of impact distance on heat transfer

The average heat transfer to an array of impinging jets is function of orifice to target spacing. A general observation was that decreasing orifice-target spacing increased heat transfer rate. Garimella and Schroeder [17] carried out the experiment of confined multiple air jet impingement by using array of nine and four jets. Fig 6 shows the experimental set-up used in the study. In both the cases, a decrease in the impact distance was found to increase the heat transfer coefficients, with effect being stronger at the higher Reynolds numbers.

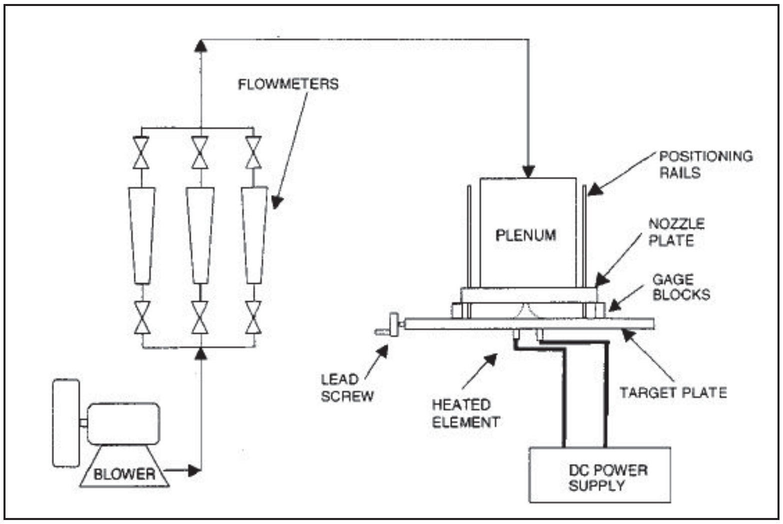

Fig 6. Schematic diagram of the air jet impingement experimental facility [17]

4.6 Effect of jet to jet spacing on heat transfer

The primary advantage of multijet impingement over single jet impingement is the creation of multiple stagnation zone with greater heat transfer coefficients. The effect of interjet spacing was studied by Yong et al. [18]. Due to strong interjet interference, the flow in array jet impingement was like channel flow which gave uniform heat transfer on the surface. It was found that heat transfer performance for dense array of multiple jets was better.

4.7 Effect of target surface enhancement on heat transfer

Surface enhancement is one the method adopted for achieving higher heat transfer coefficients. Air jet impingement, using multiple jets in conjunction with surface enhancements, is an attractive option to remove high amount of heat. El-sheikh and Garimella [19] experimentally studied heat transfer using different pin-finned heat sinks with air as coolant and found that increase in heat transfer by increasing number of fins and fin height.

Crossflow in jet impingement arrays has a detrimental effect on heat transfer effectiveness. The surface averaged heat transfer coefficient and pressure drop characteristics of impinging free-surface and confined-submerged water jet arrays had been experimentally investigated by Esposito et al. [20].

Browne et al. [21] experimentally investigated single-phase and flow boiling heat transfer of submerged microjet array with R134a as a coolant. They used staggered array of seventeen jets of diameter 112µm. The effect of parameters such as subcooling, jet velocity on boiling curve was studied. The effect of dissolved nitrogen on temperature excursion was studied by Browne et al. [22]. It was confirmed nitrogen slightly reduced single-phase performance of heat extraction.

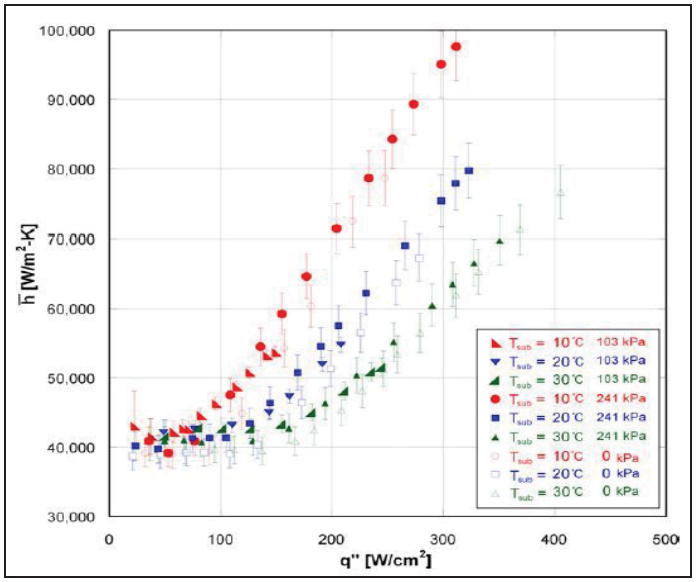

Fig 7. Area-averaged heat transfer coefficients for flow boiling curves with different partial pressures of nitrogen with a jet velocity of 4 m/s and subcoolings of 10, 20, and 30 ºC [22].

V. CONCLUSION

Jet impingement cooling used in various applications for dissipating intense heat was investigated. Single phase as well as two phase cooling with jet impingement method was found to be capable of removing large amount of heat flux using various coolants and surface enhancements. Critical heat flux was found to be increased by increasing jet velocity and inlet subcooling. For given flow rate, reducing jet area increased cooling performance. Two phase jet impingement cooling received more attention in recent years but correlations available are limited.

Compared with single jet impingement, multiple jet impingement achieved better thermal performance. The parameters affecting multiple jet impingement heat transfer were studied. Influencing parameters related to jet (impact velocity, subcooling, jet shape and size, impact distance etc.) and related to target surface (smooth, finned) onto the performance of heat transfer by impingement were studied.

The outcomes of multiple jet impingement experiments were reviewed carefully. It was found that use of multiple jets helped to provide uniform cooling.

REFERENCES

[1] I. Mudawar, Assessment of high-heat-flux thermal management schemes, IEEE Trans. Compo. Packag. Technol. 24 (2001) 122-141.

[2] M. Sung, I. Mudawar, CHF determination for high-heat flux phase change cooling system incorporating both micro-channel flow and jet impingement, Int. J. Heat Mass Transfer 52 (2009) 610-619.

[3] I. Mudawar, 2013, Recent advances in high-flux two-phase thermal management, ASME J. Therm. Sci. Eng. Appl. 5 (2013) 021012 1-15.

[4] Y. Qiu, Z. Liu, Critical heat flux of steady boiling for saturated liquids jet impingement on the stagnation zone, Int. J. Heat Mass Transfer 48 (2005) 4590-4597.

[5] Z. Liu, Y. Qiu, Boiling heat transfer characteristics of nanofluids jet impingement on a plate surface, Heat Mass Transfer 43 (2007) 699–706.

[6] R. Cardenas, V. Narayanan, A generalized critical heat flux correlation for submerged and free surface jet impingement boiling, ASME J. Heat Transfer 136 (2014) 091501 1-9.

[7] Y. Li, Z. Liu, Q. Wang, Experimental study on critical heat flux of steady boiling for high-velocity slot jet impinging on the stagnation zone, Int. J. Heat Mass Transfer 70 (2014) 1–9.

[8] R. Cardenas, V. Narayanan, Comparison of deionized water and FC-72 in pool and jet impingement boiling thermal management, IEEE Trans. Comp. Packag. Manuf. Technol. 2 (2012) 2156-3950.

[9] M. Rau, S. Garimella, Confined jet impingement with boiling on a variety of enhanced surfaces, ASME J. Heat Transfer 136 (2014) 101503 1-12.

[10] Y. Li, Z. Liu, G. Wang, L. Pang, Experimental study on critical heat flux of high velocity circular jet impingement boiling on the nano-characteristic stagnation zone, Int. J. Heat Mass Transfer 67 (2013) 560–568.
[11] S. Ndao, Y. Peles, M. Jensen, Experimental investigation of flow boiling heat transfer of jet impingement on smooth and micro structured surfaces, Int. J. Heat Mass Transfer 55 (2012) 5093-5101.
[12] N. Karwa, P. Stephan, Experimental investigation of free-surface jet impingement quenching process, Int. J. Heat Mass Transfer 64 (2013) 1118-1126.
[13] J. Lee, Z. Ren, P. Ligrani, D. Lee, M. Fox, H. Moon, Cross-flow effects on impingement array heat transfer with varying jet-to-target plate distance and hole spacing, Int. J. Heat Mass Transfer 75 (2014) 534-544.
[14] M. Meyer, I. Mudawar, C. Boyack, C. Hale, Single-phase and two-phase cooling with an array of rectangular jets, Int. J. Heat Mass Transfer 49 (2006) 17-29.
[15] B. Whelan, A. Robinson, Nozzle geometry effects in liquid jet array impingement, Applied Thermal Eng. 29 (2009) 2211-2221.
[16] E.Wang, L.Zhang, L. Jiang, J. Koo, J. Maveety, E. Sanchez, K. Goodson, T. Kenny, Micromachined jets for liquid impingement cooling of VLSI chips, IEEE J. Microelectromech. Syst. 13 (2004) 833-842.
[17] S. Garimella, V. Schroeder, Local heat transfer distributions in confined multiple air jet impingement, ASME J. Electronic Packag. 123 (2001) 165-172.
[18] S. Yong, Z. Zhou, X. Nan, Convective heat transfer for multiple rows of impinging air jets with small jet-to-jet spacing in a semi-confined channel, Int. J. Heat Mass Transfer 86 (2015) 832-842.
[19] H. Sheikh, S. Garimella, Heat transfer from pin-fin heat sinks under multiple impinging jets, IEEE Trans. Adv. Packag. 23 (2000) 113-120.
[20] E. Esposito, S. Ekkad, Y. Kim, P. Dutta, Novel jet impingement cooling geometry for combustor liner backside cooling, ASME J. Therm. Sci. Eng. Appl. 1 (2009) 021001 1-8.
[21] E. Browne, G. Michna, M. Jensen, Y. Peles, Microjet array single-phase and flow boiling heat transfer with R134a, Int. J. Heat Mass Transfer 53 (2010) 5027–5034.
[22] E. Browne, M. Jensen, Y. Peles, Microjet array flow boiling with R134a and the effect of dissolved nitrogen, Int. J. Heat Mass Transfer 55 (2012) 825–833.