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A REVIEW ON COOLING OF DISCRETE HEATED MODULES USING LIQUID JET IMPINGEMENT

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ABSTRACT

The manuscript deals with the critical review for cooling of discrete heated electronic components using liquid jet impingement. Cooling of electronic components has been a lead area of research in recent years. Due to the rapid growth of electronic industries, there is an enormous rise in the system power consumption, and the reduction in the size of electronic components has led to a rapid increase in the heat dissipation rate per unit volume of components. The present paper deals with the role of liquid jet impingement (heat flux removal rate 200 - 600 W/cm^2) for cooling of electronic components. The type of working fluids (Water / Fluorocarbon liquids / Dielectric fluids / Nanofluids) used for cooling, mode of heat transfer (Natural / Forced / Mixed) from electronic components, and the method of analysis (Experimental / Numerical / Combination of both) greatly influence the cooling mechanism. The electronic components considered in the present study are limited to microelectronic chips, VLSI circuit chips, integrated circuits (IC) chips and resistors. Most of the literature is pertinent to cooling of square heat sources, and many of the researchers have also focused on the comparative studies using different working fluids. Results suggest that Fluorocarbon liquids can be used for higher heat flux removal due to their high boiling point. The temperature drop obtained from the electronic components using liquid jet impingement was found to be in the range of 80 - 85ºC.

Keywords: *Discrete heat source, Electronic component, Heat transfer enhancement, Liquid jet impingement, Review, Thermal management*

1. INTRODUCTION

The growth of electronic industries along with the miniaturization of electronic components has led to an enormous increase in the power density for integrated circuit (IC) chips. The key challenge for the researchers is to remove the increasing heat flux demand rate (300 W/cm^2) and to control the highly non-uniform power dissipation from the components. The various factors responsible for the failure of electronic components (Reynell, 1990) are humidity (16%), vibration (24%), dust (6%), and temperature (54%). It confirms that temperature leads the chart for the failure of electronic equipment, and must have to be controlled with great interest. The electronic industries are facing a stiff challenge for maintaining the component temperature below 85ºC (Joshi and Paje, 1991), failing which, the system reliability may decrease by 50%. The integrated circuit chips mounted on the printed circuit board (PCB) are made of Silicon, which is very sensitive to temperature due to strong energy band gaps. Hence, thermal management is critical and inevitable for electronic applications.

1.1 Different Cooling Techniques

Several cooling techniques are used for the electronic components; the choice of technique depends on the application. Active and passive are the two important cooling methods among them. Passive cooling methods like natural convection air cooling, thermoelectric cooling, heat pipes, and phase change based cooling do not need any external energy for heat removal from the electronic components and are used for low heat flux removal rate. However, active cooling offers high cooling capacity and requires the application of external energy in terms of fan or blower for heat removal from the electronic components. Forced convection air cooling, liquid cooling, spray cooling, jet impingement cooling, refrigeration cooling etc., fall into this category. Among this, air cooling technique is used for small heat flux levels (37.5 W/cm^2) and is not effective and sufficient to deal with the increasing heat flux demand from the electronic components. Hence, the industries are in search of better techniques in the form of liquid cooling (used high heat flux level, 200-600 W/cm^2) (Schafer *et al*., 1991).

1.2 Jet Impingement Cooling

Jet impingement (Cho *et al*., 2011) is one of the most important liquid cooling techniques used for different industrial applications like paper drying, textiles, annealing of metal, tempering of glass, cooling of electronic equipment etc. Here high-velocity fluid is ejected in the form of a jet from a slot or small hole that is imparted on target surfaces of different geometries like circular, concave, etc. For size and space optimization, the jets are kept normal to the target surface.

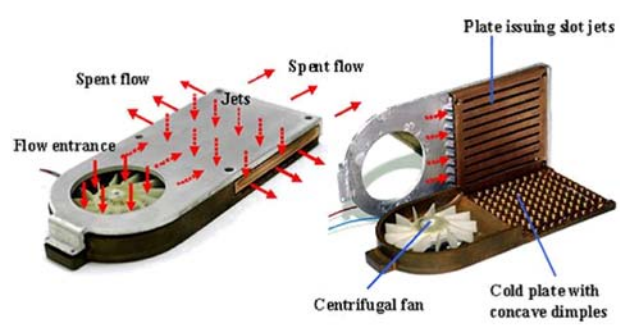

Fig. 1: Schematic diagram of jet impinging cooling in the central processing unit (CPU) (Chang *et al*., 2007)

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Jets are categorized into submerged and non-submerged on the basis of the medium on which they act; when the jet medium is same as that of surrounding medium, it is known as submerged jet, and if jet medium and surrounding mediums are different, then it is a non-submerged jet (Karwa, 2012). The jet impingement phenomenon in the central processing unit (CPU) of a computer (Chang *et al*., 2007) is shown in Fig. 1.

2. EFFECT OF WORKING FLUIDS ON COOLING OF ELECTRONIC MODULES USING LIQUID JET IMPINGEMENT

Numerous work has been reported for the cooling of electronic modules using different working fluids like Water, Fluorocarbon liquids (FC-72, FC-75, FC-77, FC-87), Dielectric fluids (R-113, HFE-7200), Nano-fluids (Al_2O_3, CuO, TiO_2) etc. The working fluids were chosen on the basis of their boiling point (Lee *et al*., 1988) that helps for better heat removal rate from the electronic components, and for maintaining their cooling level at optimal. The liquids used in the cooling of discrete heated modulus must meet several requirements depending on the specific applications. For better understanding, the present review has been categorized under different working fluids that are considered for the study.

2.1 Water as Working Fluid

Water is having high specific heat that leads to the requirement of smaller mass flow rate. It has a higher value of the latent heat of vaporization due to low freezing point and high boiling point value. Water is also non-toxic and low viscous. However, water is highly corrosive as compared to other fluids.

The cooling of ICs using water jets was carried out by (Maddox *et al*., 2016) that has resulted in a temperature drop of 45 - 60ºC from them. (Bhowmik *et al.,* 2003) has carried out cooling of four in-line square IC chips (10 mm x 10 mm) using 3 x 3 water jets with different flow rates. However (Whelan *et al*., 2012; Singh *et al*., 2016) predicted a temperature drop of 60ºC while carrying out experiments on CPU. (Singh *et al*., 2016) carried out numerical and experimental studies on cooling (heat flux removal rate of around 150 W/m^2) of CPU units using both Nano-fluid and water. Similarly, the microprocessor board (Sharma *et al*., 2012) was cooled to a temperature of 65ºC under water cooling medium (heat flux removal rate of 2 - 3 W/cm^2). The cooling of VLSI chips was carried out by (Kandilkar and Bapat, 2007; Heindel *et al*., 1995; Kiper, 1984) using water and FC-77, which is used for a heat flux removal of 500 – 1000 W/cm^2. The 3 x 3 array of flush mounted square VLSI chips under the same cooling medium (1200 W/cm^2) that has led to a temperature drop of 80ºC from the chips has been studied by (Heindel *et al*., 1995), while (Kiper, 1984) has considered square VLSI chips that has led to a heat flux reduction by as much as 28%. The experimental and numerical investigations of high power density electronic components under single-phase liquid cooling medium were studied by (Agbim, 2017). He found that the vertical cooling test sections generated a lower thermal resistance as compared to the horizontal one. (Chang, 1998) investigated numerically and experimentally the cooling of high heat flux (17 MW/m^2) electronic modules using high-velocity water jets. The boiling for these electronic modules is expected only for fluxes above 20 MW/m^2.

2.2 FC-72 as Working Fluid

The cooling of four chips has been carried out by (Bhowmik and Tou, 2005) using both FC-72 and water, and the comparison is shown in Fig. 2. The figure has shown the decrease in heat transfer coefficient (Nusselt number) by increasing the heating time of chips for both the working fluids; water and FC-72. It is found from the Fig. 2 that, the cooling is more effective using FC-72. It is seen that after 75 s, the Nusselt number of the four chips do not change significantly with time. However, during the entire power-on transient operation, the Nusselt number decreased continuously.

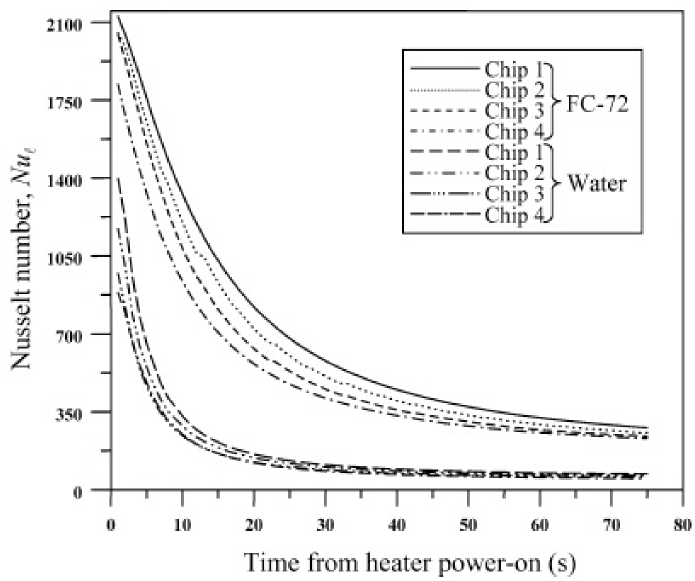

Fig. 2: Comparison of cooling of four chips using FC-72 and water (Bhowmik and Tou, 2005)

An empirical correlation between Nusselt number, Peclet number, and Fourier number was developed by (Bhowmik *et al*., 2003), and is given in Eq. 1. The equation predicted the transient behavior of electronic chips. The Eq. 1 has a regression coefficient of 0.96 with an RMS error of 6% on the estimate, and is valid for the following range of parameters, $1050 \leq Re_l \leq 2625$, $2 \leq q \leq 8$, $1 \leq t \leq 75$.

$$\frac{Nu_l}{Pe_l^{0.33}} = 26.61 F_0^{0.41} \quad (1)$$

The comparison of subcooling effects for different working fluids (Lee *et al*., 1988) is shown in Fig. 3.

It has been clear from the Fig. 3 that, FC-72 can be used for higher heat removal from the electronic components. FC-84 has the strongest sub-cooling effect as compared to R-113 and water, which are having progressively weaker effects. This is due to the different latent heat values among the fluids.

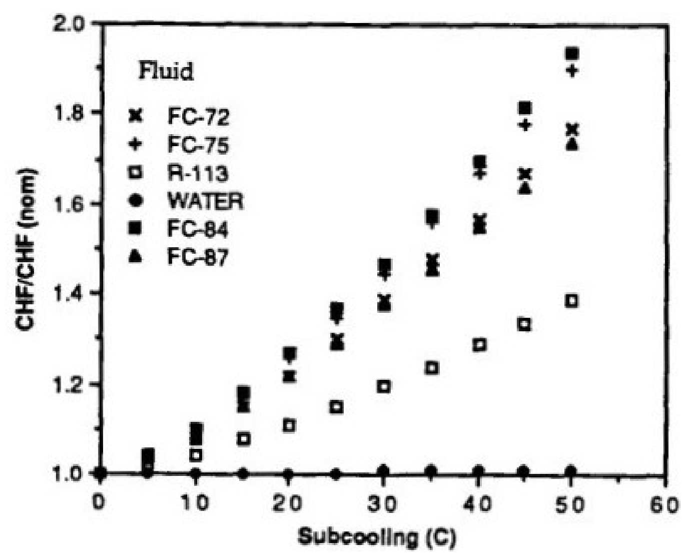

Fig. 3: Comparison of subcooling effect for different working fluids (Lee *et al*., 1988)

The cooling of resistors has been carried out by (Anwarulla, 2011; Cheng *et al*., 2001; Baker, 1972) using different working fluids like water, FC-72, Freon 113 and dielectric liquid. Cylindrical electric resistors (size 0.1 m diameter and 0.02 m thickness) (Anwarulla, 2011), film resistors (size 25.4 mm x 12.7 mm x 1 mm) (Cheng *et al*., 2001), and resistors of size (2 cm x 0.01 cm) (Baker, 1972) were considered for the study. In all the cases, it has been found that nozzle to target plate spacing, jet velocity, jet diameter, and inlet subcooling has a strong effect on the heat transfer rate from the resistors. Air cooling is very much effective during free convection for the resistors (Baker, 1972), while in case of forced convection; liquid cooling is preferred over air cooling, as the heat transfer is enhanced by a factor of 10 using liquid cooling. The cooling (heat flux removal of 310 W/cm^2) of high power electronics was carried out by (Fabbri and Dhir, 2005) using arrays of microjets using deionized water and FC-40. They also studied the effect of convective heat transfer on the Reynolds number, Prandtl number, and nozzle to plate distance on heat transfer rate. FC-72 was used as a coolant by (Mudawar and Maddox, 1990; Wang *et al*., 1999) for cooling of square electronic components (12.7 mm x 12.7 mm), and was seen that, the temperature of electronic components was dropped by 10% as compared to single phase cooling (Wang *et al*., 1999). However, the two-phase cooling effect was found to be more pronounced under natural convection mode as compared to the liquid jet impingement phenomenon.

2.3 Nano-fluid as Working Fluid

Nano-fluids can reduce the pumping power requirement as compared to other conventional fluids due to its lower viscosity value and lower specific heat. However, the fluid is very expensive.

The cooling of the central processing unit (CPU) of the personal computer is carried out by (Naphon and Wongwises, 2011) using microchannels impinged with Nano-fluids. The comparison between 3 types of Nano-fluids (TiO_2, CuO, Al_2O_3) under water medium was carried out by (Teamah and Khairat, 2015), and concluded that the rate of heat transfer is maximum for CuO/water Nano-fluids, and minimum for TiO_2/water Nano-fluids, which predicts the cooling of electronic components. (Roberts and Walker, 2010) carried out experimental studies to determine the convective heat transfer characteristics of water-based alumina Nano-fluid (particle size 20-30 nm) used for the cooling of CPU. They found an enhancement of up to 1.5% by volume in the convective heat transfer. (Sohel *et al*., 2014) performed experiments on minichannels to determine the heat transfer enhancement (up to 18%) using water-based alumina nanoparticles (volume fraction of 0.10 to 0.25%). (Chein and Chuang, 2007) studied the performance of heat sinks using Nano-fluids, and found that, nano-fluid cooled microchannel heat sinks (MCHS) absorb more energy than water-cooled MCHS at low flow rates. (Chen and Ding, 2011) studied the heat transfer characteristics and cooling performance of a microchannel heat sinks with water-based alumina Nano-fluids using different nanoparticle volume fraction. (Ijam and Saidur, 2012) investigated experimentally the cooling of the electronic device under Nano-fluids (Sic-water with the volume fraction of 4% and TiO_2-water with the volume fraction of 12.44%).

2.3 Dielectric Fluids (HFE) as Working Fluid

The dielectric fluid has a wide range of boiling point. It has also low density, low boiling point and easy to evaporate. However, the demerit is that it has low critical heat flux value. Hence, the rate of heat dissipation from the electronic components using dielectric fluids will be much lower as compared to other fluids.

The cooling (heat removal rate of 100 W/cm^2) of integrated square electronics chips using dielectric fluids, HEE-7200 and HFE-8401 and embedded droplet impingement technique (EDIFICE) was carried by (Amon *et al*., 2005; Lou *et al*., 2005). They made a comparison between water and dielectric HEE-7200 fluid and found that the dielectric fluid has low viscosity, low surface tension, and has better atmospheric performance, and can be used for higher heat removal and thus lead to better thermal management systems. The cooling of microelectronic equipment has been analyzed (Honnor and Thomas, 1969) to obtain their best optimal design. The researchers have used direct cooling methods like forced, laminar and mixed convection mode of heat transfer to predict the component temperature accurately. The experimental investigation was carried out by (Bhowmik and Tou, 2005) to study the single-phase transient heat transfer from square electronic chips (10 mm x 10 mm) under different protrusion heights. They observed that flow separation and vortex shedding due to protrusion leads to decrease in the average Nusselt number with time. The comparison between flush and protruded heat sources was carried out by (Bhowmik and Tou, 2005). An empirical correlation was proposed by (Bhowmik and Tou, 2005) for the electronic chips under the transient forced convection as given in Eq. 2. This equation is used to predict the transient heat transfer behavior of chips.

$$Nu_l = 0.776\,(Pe_l)^{0.33}\,(F_o\,)^{-0.744} \qquad (2)$$

The Eq. 2 has a regression coefficient of 0.992 with an RMS error of 3.5% on the estimate and is valid for the following range of parameters, $800 \leq Re_l \leq 2625$, $1 \leq q \leq 7$, $0 \leq t \leq 75$.

The cooling of Silicon substrates was experimentally investigated by (Jaeger *et al*., 1989) under direct immersion cooling using Freon-12. They have compared the results with liquid jet impingement cooling of the same substrate and found that liquid jet impingement technique can be useful for a heat flux removal rate of 200 W/cm^2 with a maximum temperature rise for chips of the order of 50ºC.

The temperature drop and amount of heat flux removal from different electronic components using different cooling fluids along with shape and size of components are given in Table 1. It is seen that most of the researchers have focused on cooling of electronic components under water medium, with maximum heat flux removal up to 200 - 300 W/cm^2, and temperature drop up to 40 - 65ºC.

3. EFFECT OF MODES OF HEAT TRANSFER ON COOLING OF ELECTRONIC MODULES USING LIQUID JET IMPINGEMENT

Convective heat transfer (Incropera, 1988) is a predominant mode of heat removal from the electronic components which are further categorized into natural, forced and mixed convection. The detailed explanation of different cooling techniques used for electronic components is reported under section (Bhowmik and Tou, 2005; Nayaki *et al*., 2017). For better understanding, the present review is further categorized under different modes of heat transfer, which are considered in the present study.

3.1 Natural Convection Mode of Cooling

The numerical and experimental investigation of natural convection heat transfer from four in-line square arrays of flush mounted and protruded microelectronic chips is carried out by (Nayaki *et al*., 2017). The computational study was based on four different working fluids, like, water (Pr = 5, BP = 100ºC), FC−72 (Pr = 9, BP = 56ºC), FC−77 (Pr = 25, BP = 97ºC) and ethylene glycol (Pr = 130, BP = 197.3ºC), and has resulted in a temperature drop of 20 - 30ºC from the chips.

3.1.1 Laminar jet

The experimental and numerical investigation of four in-line electronic chips under natural convection heat transfer was carried out by (Bhowmik and Tou, 2005; Tou *et al*., 1998), and found that the heat fluxes, coolant flow rate and other geometrical parameters greatly affect the heat transfer rate from the chips. (Bhowmik and Tou, 2005) have also proposed a correlation for each chip, as given in Eq. 3. The equation is used to predict the transient behavior of each chip.

Table 1 Effect of cooling fluid on temperature drop or heat flux removal from electronic components using liquid jet impingement

Sl. no.	Author (s)	Cooling fluid	Temperature drop / Heat flux removal	Electronic Component (Size)
1	Maddox *et al*., 2016	Water	45 - 60ºC	Rectangular copper blocks (1.27 cm × 10.16 cm)
2	Whelan *et al*., 2012	Water	200 W, 65ºC	Square chips (8.24 cm × 8.24 cm)
3	Anwarulla , 2011	Water	45ºC	Resistor (100 mm diameter and 2 mm thick)
4	Cheng *et al*., 2001	FC-72	60ºC, 60 - 70 W/cm^2	Rectangular chips (12.7 mm × 8 mm)
5	Naphon and Wongwises, 2011	Water with TiO_2 suspended Nano-particles	5ºC	CPU unit
6	Fabbri and Dhir, 2005	Deionized water and FC-40	310 W/cm^2	Microelectronic chips (1.27 cm × 1.27 cm)
7	Bhowmik *et al*., 2003	Water	2 - 8 W/cm^2	Square IC chips (1 cm × 1 cm)
8	Bhowmik and Tou, 2005	FC-72	1 - 7 W/cm^2	Square chips (1 cm × 1 cm)
9	Amon *et al*., 2005	HFE 7200	45 W/cm^2	Square chip (2.54 cm × 2.54 cm)
10	Kiper, 1984	Water	500 W/cm^2	VLSI circuits (8 cm × 8 cm)
11	Honnor and Thomas, 1969	FC-72 and FC – 87	100 W/cm^2	Square chips (1.27 cm × 1.27 cm)
12	Teamah and Khairat, 2015	Water with 3 types of suspended Nano-particles TiO_2, CuO, Al_2O_3	75 W	Flat plate
13	Bhowmik and Tou, 2005	Water	1 - 7 W/cm^2	Square chips (1 cm × 1 cm)
14	Jaeger *et al*., 1989	Freon-12	150 W/cm^2	Silicon hybrid multiple chip packaging
15	Mudawar and Maddox, 1989	FC-72	106 W/m^2	Square chips (1.27 cm × 1.27 cm)
16	Sharma *et al*., 2012	Water	100 W, 40.7 - 50ºC	Microprocessor chips
17	Wang *et al*., 1999	Water and FC-72	1.3 - 5.4 W/cm^2	High performance electronic device (23.3 cm × 16 cm)
18	Agbim, 2017	Water	180-230 W/cm^2	Power electronic devices (MOSFETs, HEMTs, &IGBTs
19	Roberts and Walker, 2010	Aluminum - Water nanoparticles		Copper blocks
20	Sohel *et al*., 2014	Al_2O_3 - Water nanoparticles		Copper channel (5 cm x 5 cm x 1 cm)
21	Chein and Chuang, 2007	CuO-Water Nanofluid		Microchannel heat sink
22	Chen and Ding, 2011	Al_2O_3-Water nanoparticles		Microchannel heat sink (5 cm x 1.6 cm)
23	Ijam and Saidur, 2012	SiC-water and TiO_2-water Nanofluids		Mini channel heat sink (20 cm x 20 cm)

$$Nu_l = 0.31\ Fo^{-0.23}\ (Ra^*_l)^{0.25} \quad (3)$$

The Eq. 3 has a regression coefficient of 0.996 with an RMS error of 2% on the estimate and is valid for the following range of parameters, $800 \leq Re_l \leq 2625$, $1 \leq q \leq 7$, $0 \leq t \leq 75$.

The experimental determination of natural and forced convective heat transfer from small electronic devices was carried out by (Baker, 1972). They predicted that average convective heat transfer coefficient increased significantly, as the size of the heat source reduced. They used Freon 113 and silicon dielectric liquid for cooling the microelectronic devices, where, the average convective heat transfer rate was varied from 0.2 - 3 W/cm^2, and the heat flux was maintained at 100 W/cm^2. The experimental investigation of steady and transient heat transfer from eight in-line rectangular heated protrusions in a vertical channel under the natural convection was reported by (Joshi *et al*., 1989), using water, and concluded that, for smaller spacing, the component surface temperature increased significantly due to the reduction in fluid velocities.

3.2 Force Convection Mode of Cooling

3.2.1 Laminar jet

The cooling (heat flux removal of 310 W/cm^2) of high power electronics was carried out by (Fabbri and Dhir, 2005) using arrays of microjets with deionized water and FC-40. They also studied the effect of convective heat transfer on Reynolds number, Prandtl number, and nozzle to plate distance on heat transfer rate.

3.2.2 Turbulent jet

The experimental investigations on arrays of free and submerged jet cooling of electronic devices under water medium are carried out by (Robinson and Schnizler, 2007) under forced convection mode. The study has shown that the free jet configuration was found to behave thermally as a submerged jet within the range of $2 < H/d < 10$. Beyond this, a transition to entirely free-jet flow occurs, and the heat transfer coefficient has improved marginally with increasing the jet to target plate spacing. The spray cooling techniques can be used for multiple arrays of sprays to cool the ICs, by varying the heat flux from 50 - 150 W/cm^2, however for higher heat flux removal (500 - 1000 W/cm^2), microchannels were effective (Kandilkar and Bapat, 2007). The comparative study of the jet impingement, spray and microchannel cooling using water jets under forced convection was carried out by (Kandilkar and Bapat, 2007). (Leena *et al*., 2018) carried out experimental and numerical work on high power electronic components using multiple jet impingements. They varied the Reynolds number (4000-8000) and jet-to-jet spacing and found that at Reynolds number (Re = 5000) optimal cooling can be achieved. They have also proposed a correlation (given in Eq. 4) between the average Nusselt numbers in terms of Reynolds number. The equation suggests that the fluid-heater interactive surface would influence the boiling heat transfer more significantly. The Eq. 4 is valid for the following range of parameters, $4000 \le Re \le 8000$.

$$Nu_{avg} = 0.044Re^{0.58} \quad (4)$$

(Schafer et al., 1991) investigated experimentally the average heat transfer coefficient for multiple square discrete heat sources under FC - 72 medium. They observed that the Prandtl number is predominant to calculate the heat flux dissipation from the heated surfaces by maintaining the temperature difference between the heater surface and the liquid at 50°C. For water (Pr = 7) and FC-77 (Pr = 25), the heat flux dissipation from the heated surfaces is approximately 250 W/cm^2 and 40 W/cm^2 respectively. The experimental investigation of forced convection cooling for arrays of protruding discrete heat sources with definite heat input values is carried out by (Gupta and Jaluria, 1998). The test section consisted of four rows, each of three chips, and the chips were mounted at both top and bottom of the rectangular channel. The average heat transfer coefficient for different heat inputs did not show any appreciable change for arrays of heat sources (Gupta and Jaluria, 1998). The average Nusselt number value also decreased with increase in the channel height. The experimental study for cooling of simulated microelectronic chips of square size (12.7 mm x 12.7 mm) using water and flour carbon fluid is carried out by Mudawar and Maddox, 1990). It was seen that the Reynolds number was independent of heat transfer from the heat sources, and for turbulent jets, heat transfer was enhanced by approximately 25%.

3.2.3 Phase change cooling phenomenon

(Cheng et al., 2001) carried out experiments to investigate the free jet impingement boiling phenomenon. The Jet velocity, jet diameter, and inlet sub-cooling clearly influenced the boiling heat transfer and critical heat flux. Higher velocity brought higher heat transfer coefficient in both single phase and boiling. The single-phase forced convection heat transfer from four in-line simulated flush mounted square electronic chips (10 mm x 10 mm) under water medium was carried out by (Tso *et al*., 1999). They suggested that the data from air-cooling may be used to predict the heat transfer characteristic of liquid cooling for similar geometry by considering the Prandtl number scaling. Experimental investigations were carried out by (Gersey and Muddawar, 1992) for different channel orientations to study the effect of critical heat flux (CHF) form nine in-line square microelectronic chips using FC-72. It was found that lowest CHF occurred when the bubbles stagnated on the chip surface. The forced convection boiling heat transfer regimes was studied experimentally by (Willingham and Muddwar, 1992) for nine in-line square microelectronic electronic chips (10 mm x 10 mm) which were flush mounted on a vertical channel filled with FC-72. They observed that the chips which were in the upstream had experienced a larger drop in temperature. Boiling incipience and critical heat flux (CHF) for all the chips were delayed to higher heat flux with increasing velocity or subcooling. Because of some unusual boiling activity on Chip 1, the authors believe that electronic cooling applications would benefit from the positioning of a heated plate upstream of the array of electronic chips in order to provide more uniform and predictable boiling on the surfaces of downstream chips.

The study has delineated three distinct heat transfer regions, laminar, the transition from laminar to turbulent, and turbulent, and concluded that Nusselt number of each chip is a strong function of Peclet number. The experimental analysis of IC chips was carried out by (Womac *et al*., 1994) under forced convection for both free and submerged jet configurations and for a wide range of velocities, nozzle diameters, and nozzle - to - heater separation distances using water and fluorocarbon liquid as coolants. They have proposed correlations for free surface and submerged surface jet impingement.

The experimental investigation of single-phase heat transfer from four in-line square electronic chip (both flush mounted and protruding) under forced convection with FC-72 as working fluid was carried by (Tou *et al*., 1998), and observed that, Nusselt number for all the chips have almost same value, and the heat transfer from the protruding chips is higher than the flush mounted chips. The Reynolds number has a great effect on the rate of heat transfer from the chips. The numerical investigation of two-phase jet impingement cooling of an electronic chip (Silicon) by boiling FC-72 dielectric liquid under forced convection cooling was carried out by (Wang *et al*., 1999) considering Eulerian two-fluid method for simulating the two-phase (liquid/vapor) flows with phase change boiling heat transfer, single phase jet impingement and natural convection two-phase cooling. They found that, the two-phase cooling results in 10% decrease in temperature of the ICs as compared to single phase cooling. The effect of forced convection cooling on microelectronic chips using FC-77 and water as cooling medium was considered by (Incropera *et al*., 1986; Gersey and Muddawar, 1992). The inline, four-rows of 12 flush mounted square discrete heat sources (12.7 mm x 12.7 mm) mounted on a horizontal rectangular channel filled with FC-77 and water was analyzed by (Incropera, *et al*., 1986), and found that, average convection coefficient for different rows of heat sources decreased by approximately 25% from the first to the second row, and by 5% from the third to fourth row. Again, the results of FC-77 were in strong agreement with water, for Reynolds number ranges of $5000 < Re < 14000$. The forced convection cooling of simulated microelectronic chips of square or rectangular size under water and Freon -12 cooling medium was studied by (Ali and Ramadhyani, 1992; Jaeger *et al*., 1989). The corrugated and parallel channels study was performed by (Ali and Ramadhyani, 1992), and they concluded that corrugated channels were much better than the parallel plate channels under the operating parameters like equal mass flow rate, equal pumping power, and equal pressure drop. The experimental investigation was carried out by (Tuckerman, 1984) to determine the heat transfer from the integrated circuits in water cooling medium. They observed that the heat flux removal from the IC chips was limited to 20 W//cm^2.

3.3. Mixed Convection Mode of Cooling

3.3.1 Turbulent jet

The experimental investigation of mixed convection heat transfer from 4 x 3 arrays of flush mounted IC chips of rectangular and circular geometry in a horizontal channel under FC-77 and water medium was carried out by (Mahaney *et al*., 1990), and found that laminar and transitional flow occurs at $Re_D < 4000$ ($Re_L < 2600$), and turbulent flow for larger

Reynolds numbers. The increase in Rayleigh number increases the Reynolds number that ultimately enhances the heat transfer rate from the chip.

The transient mixed convection heat transfer studies were carried out by (Flores *et al*., 2016) from two discrete flush-mounted heaters mounted in a rectangular channel of finite length. They studied the effect of buoyancy and inclination angle using water. The higher values of heat transfer rates were achieved for horizontal position of the channel, and the buoyancy and. The cooling of electronic chips using Ethylene glycol and FC-75 was carried out by (Caromona and Keyhani, 1989), and they observed the variation of Prandtl number has a negligible effect on the Nusselt number from FC-75 to Ethylene glycol. The liquid Immersion cooling of longitudinal array of discrete heat sources was carried out experimentally by (Heindel *et al*., 1992) under water and FC-77 medium. They observed flow regimes ranging from mixed convection to laminar and turbulent forced convection. They found that higher Prandtl number fluids enhance the heat transfer rate significantly due to their larger value of Reynolds number.

The temperature drop and amount of heat flux removal from the electronic components under different heat transfer modes along with type and size of components are given in Table 2. It is concluded that most of the researchers have focused on forced convection technique for cooling of electronic components. The maximum heat flux removal rate achieved is of the order of 50 - 2000 W/cm^2.

Table 2 Effect of Modes of Heat Transfer on Cooling of Electronic Modules using Liquid Jet Impingement

Sl. no.	**Author(s)**	**Mode of heat transfer**	**Temperature drop / Heat flux removal**	**Electronic Component (Size)**
1	Senthil *et al*., 2017	Free convection	20 - 30ºC	Square IC chips
2	Robinson and Schnitzler, 2007	Forced convection	35 - 40 W/m^2	Square stainless steel plate (7.8 cm × 7.8 cm)
3	Kadilkar and Bapat, 2007	Forced convection	80ºC, 500 - 10000 W/cm^2	VLSI chips (1.22 cm × 1.22 cm)
4	Gupta and Jaluria, 1998	Forced convection	60ºC, 60 - 70 W/cm^2	Square IC chips (1.27 cm × 1.27 cm)
5	Tso *et al*., 1999	Forced convection	5 - 20 W/cm^2	Square IC chips (1 cm × 1 cm)
6	Womac *et al*., 1994	Forced convection	50ºC	Square IC chips (1.27 cm × 1.27 cm)
7	Bhowmik *et al*., 2003	Free convection	1 - 7 W/cm^2	Square IC chips (1 cm × 1 cm)
8	Tou *et al*., 1998	Forced convection	100 - 200 W/cm^2	Square IC chips (1 cm × 1 cm)
9	Joshi *et al*., 1989	Free convection	45 W/cm^2	Rectangular chips (23.7 mm × 7.6 mm × 10.18 mm)
10	Flores *et al* ., 2016	Mixed convection	727 - 2970 W/m^2	Square heat source
11	Caromona and Keyhani, 1989	Free convection	11W	Heated protrusions
12	Mahaney *et al*., 1990	Mixed convection	50 - 200 W/cm^2	Square IC chips (1.27 cm × 1.27 cm)
13	Wang *et al*., 2004	Free convection	100^0 C and 90W	Square IC chips (1 cm × 1 cm)
15	Incropera *et al*., 1986	Forced convection	80 - 100 ºC	Square IC chips (1.27 cm × 1.27 cm)
16	Ali and Ramadhyani, 1992	Forced convection	50 W/cm^2	Square IC chips (7.6 cm × 7.6 cm)
17	Schafer *et al*., 1991	Forced convection	200 W/cm^2	Square IC chips (1.27 cm × 1.27 cm)
18	Tuckerman, 1984	Forced convection	20 W/cm^2	IC chips
19	Leena *et al*., 2018	Forced convection		Square copper block (7.4cm x7.4cm)
20	Heindel *et al*.,1992	Forced convection	2W	Square IC chips (2.54cm X2.54cm)

4. METHOD OF ANALYSIS FOR COOLING OF ELECTRONIC MODULES USING LIQUID JET IMPINGEMENT

Most of the work on cooling of electronic modules using liquid jet impingement was experimental and numerical in nature. However, few analytical and comparative studies were also carried out to predict the heat transfer behavior from the electronic chips. For better understanding, the present review has been categorized into different techniques used in the present study.

4.1 Experimental Techniques

The experimental study was carried out by (Overholt *et al*., 2005) to study the performance and usage of Microjet Cooling Jet Arrays (MCJA) in electronic components. It consists of jet arrays of small diameter (300 Microns) used for removal of higher heat fluxes from 300 – 1000 W/cm^2. The experimental investigation from a hot surface was carried out by (Karwa, 2012) using an array of jets under water medium. He had obtained a maximum heat flux of 8.5 W/cm^2 at the stagnation point, and the values decreased away from the stagnation point. The experimental

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study to enhance the convective heat transfer from the target surface was studied by (Agrawala *et al*., 2014), and the maximum heat flux was obtained at maximum Reynolds number and was seen that the axial dimension (nozzle to plate distance) had minimal effect on the surface heat flux. The experimental study for cooling of simulated microelectronic chips of square size (12.7 mm x 12.7 mm) using water and flour carbon fluid was carried out by (Besserman, *et al*., 1991; Mudawar and Maddox, 1990). It was seen that the Reynolds number was independent of heat transfer from the heat sources, and for turbulent jets, heat transfer was enhanced by approximately 25%. (Besserman, *et al*., 1991) have performed experiments to determine the average convection coefficient for a round heater using two liquids of different Prandtl number (Pr = 7 and 25). Data obtained for the two fluids are 'well correlated for multiple chips in terms of Nusselt number, Reynolds number, and Prandtl number, and is given in Eq. 5. The Eq. 5 is valid for the following range of parameters. $1000 \leq Re_d \leq 40000$, Pr = 7 (water) and 25 (dielectric fluorocarbon).

$$Nu_d = 0.39\, Re_d^{\,0.5}\, Pr^{0.4} \tag{5}$$

The experimental investigation of forced convection cooling from 3 x 3 square electronic chips using FC-72 was carried out by (Wadsworth and Mudawar, 1990). They observed that rectangular jets maintain nearly isothermal conditions at the chip surface, and the chip cooling rate was independent of channel height, and the average Nusselt number was strongly dependent on jet velocity and jet width. The analytical and experimental determination of natural and forced convective heat transfer from small electronic devices was carried out by (Baker, 1972). They predicted that average convective heat transfer coefficient increased significantly, as the size of the heat source reduced. They used Freon 113 and silicon dielectric liquid for cooling the microelectronic devices, where, the average convective heat transfer rate was varied from 0.2 - 3 W/cm^2, and the heat flux was maintained at 100 W/cm^2. The experimental investigation of different novel packaging methodologies for spray cooling techniques used in power semiconductor devices using dielectric liquids, FC-72 and FC-84 were carried out by (Vanam *et al*., 2005). They have mixed FC-72 and FC-84 to achieve maximum heat flux removal rate (100 W/cm^2), that gave the optimum design for semiconductors. The experimental investigation of Silicon microchannel coolers (having heat transfer coefficient of 130,000 W/cm^2 ºC) for high power chips was carried out by (Colgan *et al*., 2007), and found that microchannel was used for high heat flux removal rate in the range of 300 - 400 W/cm^2. They estimated the maximum power density for chips using the temperature difference between the chip and ambient as 63°C. The experimental investigation for the thermo-fluid design of single-phase submerged jet impingement cooling for electronic components was carried out by (Maddox and Bar-Cohen, 1994). They cooled 1 cm^2 square heat sources (dissipating power of 100 W) to 80ºC using FC-77 at 20ºC. They found that sub-cooling. The experimental investigation was carried by (Samant and Simon, Experimental studies (Sung and Muddwar, 2006) were performed to investigate the two-phase boiling characteristics of ICs with slot jets and microchannel flow, and dielectric PF-5052 fluid. The forced convection boiling heat transfer regimes was studied experimentally by (Willingham and Muddwar, 1992) for nine in-line square microelectronic electronic chips (10 mm x 10 mm) which were flush mounted on a vertical channel filled with FC-72. They observed that the chips which were in the upstream had experienced a larger drop in temperature. Boiling incipience and critical heat flux (CHF) for all the chips were delayed to higher heat flux with increasing velocity or subcooling. The experimental investigation was carried by (Samant and Simon, 1989) to determine the heat transfer from a small heated patch to a subcooled fully developed turbulent flow. They observed that using R-113, the maximum heat flux was limited by the thermal deposition temperature to 2.04 MW/m^2, for the velocity of 16.5 m/s. At a low velocity of 1.8 m/s, no boiling regimes were observed on surfaces at 80°C. They have developed a correlation between Nusselt number, Reynolds number and Prandtl number of chips that is given in Eq. 6.

$$Nu = 0.47 Re^{0.58}\, Pr^{0.50} \tag{6}$$

The effect of cooling performance on Titanium alloy plates using multiple jets with various nozzles was carried out experimentally by (He and Wen, 2017), and found that cross flow effect of multiple jets decreased the cooling effect over the plates. The experimental investigation of natural convection heat transfer enhancement from an 3 x 3 square (12.7 mm x 12.7 mm) IC chips was carried out by (Heindel *et al*., 1995), and found that, heat transfer was enhanced by 24 times in a vertical orientation and 15 times in horizontal orientations of heat sources, and the maximum heat flux for vertical orientation was found to be 23.6 W/cm^2 with a maximum temperature of 70ºC, and for horizontal orientation, it was 28.2 W/cm^2, having a maximum temperature of 65ºC.

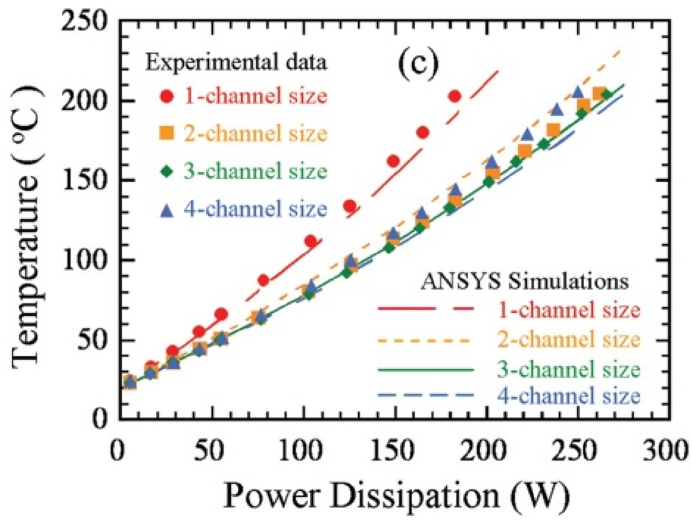

Fig. 4: Comparison between experimental and ANSYS data for the temperature of heat sources (Calame *et al*., 2009)

The experimental investigation was carried out by (Calame *et al*., 2009) for high heat flux removal from BeO ceramic and GaN-on-SiC semiconductor dies using hierarchically branched microchannels. They found that 1.5 kW/cm^2 was removed from the 3.6 mm x 4.7 mm resistive zone of the BeO-based die at a surface temperature of 203ºC. The BeO based die can be used instead of high thermal conductivity GaN-on-SiC die with a 12.5 mm x 5 mm resistive zone for a heat flux of 3.9 kW/cm^2. The comparison between experimental and ANSYS temperature data of different heat sources is shown in Fig. 4. The figure has shown a clear match between the experimental and numerical results. By increasing the power rating, the component temperature of chips has increased. Again, the chips in channel 1 have experienced higher temperature.

Experimental investigations were carried out by (Gersey and Muddawar, 1992) for different channel orientations to study the effect of critical heat flux (CHF) form nine in-line square microelectronic chips using FC-72. It was found that lowest CHF occurred when the bubbles stagnated on chip surface causing premature dry out, and highest CHF values were measured for up flow with the chips either upward or downward facing (θ = - 45º, 0º, 45º). The numerical and experimental investigation for cooling of electronic modulus for arrays of liquid jets was carried out by (Hosain *et al*., 2016). They found the impingement surface of rough concave dimples reduced the Nusselt number followed by an increase of S/D_j ratio, for arrays of discrete heat sources. The experimental and numerical investigation has been carried by (Mcglen *et al*., 2004) to examine the jet impingement cooling combined with micro finned surfaces to enhance the thermal management of power electronic devices (resistors, diodes, logical gates etc.), and found that, at low power (105 W) the thermal resistance was reduced between 5 - 13% with micro fins. The experiments were also carried out to evaluate the reliability of micro fins. The experimental investigation was carried out by (Anderson and Muddawar, 1989) to study the effect of pool boiling on simulated square electronic chips using dielectric fluorocarbon (FC-72) in a vertically filled cavity. They have observed that the maximum heat flux is a function of surface geometry and orientation but independent of surface roughness.

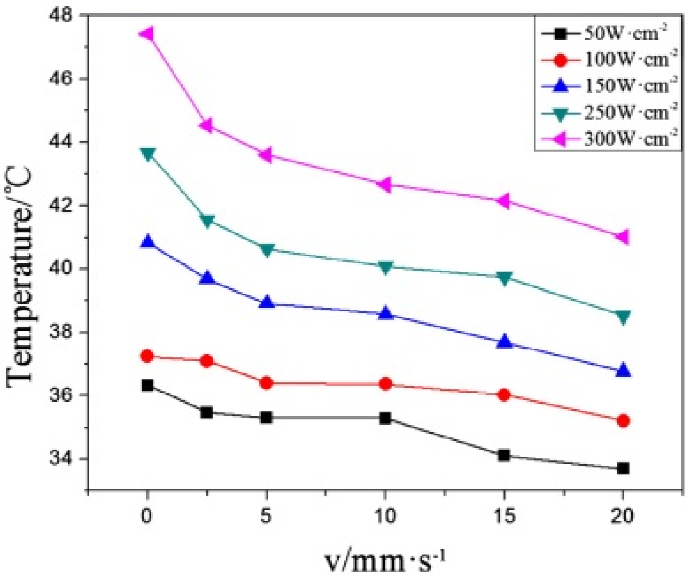

Fig. 5: Average Surface Temperature for different heat flux, Re = 10120 (Ai *et al*., 2017)

The experimental investigation of jet impingement using moving nozzles was studied by (Ai *et al*., 2017). They have also compared the heat transfer effect of fixed and moving nozzles. It was clear that moving nozzle performs better than a fixed nozzle for reducing the maximum temperature difference between the heating surface and the average liquid film thickness, which has resulted in better heat transfer rates and more uniform temperature, as shown in Fig. 5. The Fig. 5 has shown that the average substrate temperature and the Nusselt number has increased with increase in the nozzle velocity for different heat flux values. However, compared with a fixed nozzle, the effects of the moving nozzle are more significant at higher heat fluxes. The maximum average temperature difference was approximately 7°C and the Nusselt number has increased by 31% at the same heat flux.

4.2. Numerical technique

The numerical simulations (using Response Surface Approximation (RSA) and Multi-Objective Genetic Algorithms (MOGA)) for flow distribution were carried out by (Lam and Prakash, 2016), where they described heat transfer enhancement from chips. They found minimal entropy generation for jet impingement with Al_2O_3/Water Nano-fluid. The numerical investigation to study the effect of geometrical parameters on the confined impinging jet heat transfer was studied by (Lou et al., 2005). They found that decrease of nozzle width and nozzle plate spacing resulted in an increase of heat transfer coefficient and ultimately Nusselt number. The numerical and experimental investigation of the effect of geometric and flow parameters on the Electronic cooling on square simulated electronic chips using free jets and sprays was made by (Estes and Mudawar, 1995), and suggested that the spray cooling is more effective for high heat flux removal from electronic components. They also found better single phase cooling performance and higher value of critical heat flux at the chip. The experimental and numerical investigation of natural convection heat transfer was carried out by (Gdhaidh, 2016) under liquid cooling medium using air and water. They carried out the simulations using ANSYS Icepack to study the heat transfer characteristics of unsteady and steady jets on high power electronics. (Leena et al., 2015) found that, heat transfer enhancement was due to construction and destruction of thermal and hydrodynamic boundary layer formation. They also proposed correlations for the Nusselt number in terms of Reynolds number for cooling of electronic chips. The numerical simulations with an axis-symmetric single and double jets using run out table cooling (ROT) technique (optimizes the use of water in the steel industry), and constant heat flux (2.5 W/cm^2), constant temperature boundary condition was carried out by (Hosain *et al*., 2016). The numerical investigation for cooling of four types of Nanoparticles Al_2O_3, CuO, ZnO, and SiO_2 with water with different volume fractions of 1 - 5% was carried out by (Yarmand *et al*., 2014), and found that SiO_2/Water Nanofluid generate highest Nusselt number followed by Al_2O_3, ZnO, CuO and pure water. SiO_2 has lower heat transfer coefficient because of small thermal conductivity value among all the tested Nanofluids. The internal heat sink plays an important role in the heat removal from electronic components that lead to a temperature drop of 64.28 ° C.

The temperature drop and amount of heat flux removal from electronic components along with type and size of components for a different type of analysis are given in Table 3. Many researchers have focused on experimental techniques by varying the channel orientation on which electronic components are mounted. The maximum heat flux removal rate obtained is of the order of 1 - 10000 W/cm^2, and the temperature drop is found to be 65 – 80ºC.

5. CONCLUSION

A detailed review was carried out for cooling of electronic components using liquid jet impingement. Most of the work was based on experimental and numerical analysis on single and arrays of square heat sources using water medium, under free and forced convection mode. A comparison study was also carried out using different working fluids for cooling of discrete heat sources. The broad summary of the review is given below.

(i) Electronic components under consideration: **Microelectronic Chips, VLSI circuit chips, Integrated circuit (IC) chips, Resistors**
(ii) Heat source size: **Square**
(iii) Heat source dimension: **10 mm^2 or 12.7 mm^2**
(iv) Heat source type: **Flush mounted or protruded**
(v) Cooling fluid used: **Water or Fluorocarbon liquid (FC-72, FC-75, FC-77, FC-87, and R-113) or Dielectric Fluid (HFE-7200) or Nanofluids (Al_2O_3, CuO, TiO_2 etc.)**
(vi) Mode of heat transfer: **Natural or Forced convection**
(vii) Method of analysis: **Numerical or Experimental**
(viii) Reynolds Number: **800 – 30000**
(ix) The temperature drop from the component surface: **65 - 85ºC**
(x) Heat flux removal from the component surface: **150 - 600 W/cm^2**

NOMENCLATURE

C_P	specific heat of the liquid at constant pressure, J/kgK
D	Duct Hydraulic diameter (4A/P)
Fo	Fourier number, $\alpha t/Hc^2$
H	height of the channel, m
Hc	height of the chip, m
H/d	Distance between the orifice plate and impingement surface (m)
h	heat transfer coefficient, W/m^{2}K

Table 3 Method of Analysis for Cooling of Electronic Modules using Liquid Jet impingement

Sl. no.	Author(s)	Method of analysis	Temperature drop / Heat flux removal	Electronic Component (Size)
1	Overholt, 2005	Experimental	300 - 1000 W/cm^2	Electronic components (1 cm × 1 cm)
2	Karwa, 2012	Experimental	8.5 W/cm^2	Steel industries
4	Besserman *et al.*, 1991	Experimental	248 W/cm^2	Electrical heater (1.27 cm × 1.27 cm)
5	Wadsworth and Mudawar, 1990	Experimental	100 W/cm^2	Square chips (1.27 cm × 1.27 cm)
6	Baker, 1972	Experimental and Analytical	500 - 10000 W/m^2	Small microelectronic chips, (2 cm × 2 cm) and Resistors
7	Vanam *et al.*, 2005	Experimental	140 W/cm^2	IGBT flip chips (1.5 cm × 1.5 cm)
8	Colgan *et al.*, 2007	Experimental	63ºC, 300 - 400 W/cm^2	High power Square IC chips (2 cm × 2 cm)
9	Leena *et al.*, 2015	Experimental and Numerical	12000 W/m^2	Target surface (12 cm × 12 cm × 1 cm)
10	Maddox and BarCohen, 1994	Experimental	80 ºC, 100 W/cm^2	Electronic chip (1 cm × 1 cm)
11	Willingham and Mudawar, 1992	Experimental	40 - 50 W/cm^2	Square IC chips (1 cm × 1 cm)
12	Heindel *et al.*, 1995	Experimental	65 - 80ºC, 0.35 - 28.2 W/cm^2	Square IC chips (1.27 cm × 1.27 cm)
13	Calme *et al.*, 2009	Experimental	1.5 - 3.9 kW/m^2	Chips
14	Gersey and Mudawar, 1992	Experimental	0.13 - 120 W/cm^2	Square IC chips (1 cm × 1 cm)
15	Mcglen *et al.*, 2004	Experimental and Numerical	17 - 20 MW/m^2	Square IC chips (1 cm × 1 cm)

k thermal conductivity of liquid, W/mK
l length of heat source, m
Nu_l Nusselt number based on heat source length, hl/k
Nu_d Average Nusselt number (hD/K_f)
Pe_l Peclet number based on heat source length, $Re_l Pr$
Pr Prandtl number of liquid
Q Volumetric flow rate, m^3/s
Re_l Reynolds number based on heat source length, Ul/ν
Re_D Reynolds number of the duct (WD/ν)
t time elapsed after the power ON, s
U flow velocity, Q/WH m/s
W width of the channel, m

Greek Symbols
α thermal diffusivity of liquid, $k/\rho C_p$
μ dynamic viscosity of the liquid, Ns/m^2
ν kinematic viscosity of the liquid, μ/ρ, m^2/ s
ρ density of liquid, kg/m^3

ABBREVIATIONS

CHF Critical Heat flux
IC Integrated chips
MCJA Microjet cooling arrays
MCHS Microchannel heat sink
MOGA Multi-objective genetic algorithm
ROT Run out Table Cooling
RSA Response surface method

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