2 LITERATURE REVIEW

2.1 Cooling methods used in practice

Heat dissipation at all the four level stated above can be performed by using various techniques which can be classified as Table 2.1.

Table 2.1: Classification of cooling systems

Main Type	I. Subtypes
Circulation	• Forced cooling • Natural cooling • Boiling and condensation
Device used- With energy	• VCC Refrigeration • Jet Impingement • Spray • Micro channel cooling • Active Heat Sink • Immersion with boiling • Thermoelectric cooling • Piezo fans / synthetic jets
Device used- Without energy	• Heat pipe • Passive Heat Sink • Heat spreaders • Immersion without boiling
Material bases	• Cold plates • Spreaders • TIM
Fluid used	• Air • Water • Other fluids • Phase change material • Liquid metal cooling

The challenge is to remove heat from electronics parts, of which cooling need may not be fulfilled due to the limitations of cooling techniques used. The heat transfer convection limits are of: Water boiling and condensation (3000-100000 W/m^2K), water circulation (100-10000 W/m^2K), air and air jet (20-1000 W/m^2K). [3]

If above methods shown in table are compared**, passive heat sinks** and **active heat sinks** are useful for their uses with no leakage and ducting problems, especially as compared with liquid cooling. Also they do not need extra energy, considering **passive techniques**. [4] To improve effectiveness **foam heat sink** [5] is also proposed during fluid flow conditions. Classical **vapour compression cycle** of refrigerator cooling has high effective cooling, with expenses of compressor energy, space for system, use of refrigerant, piping, and leakage problems.

Forced air cooling systems are always carrying their importance and will be in future because of Cost, consistency and expertise available. [4] Air cooling techniques report like **piezo fans** (solid state devices), **Synthetic Jets** (periodic micro jets), **Nano-lightning** (micro scale ion driven, using very high electric filed) [3] Air cooling systems are used in combination with heat sink. If air reaches heat sink at significantly high temperature, it will reduce its capacity to transfer heat, and **jet cooling** might be the option for same. [6] **Hybrid thermal management** solutions are becoming more popular in case of thermal management problems. [4] The examples can be listed like air – water, sink – air jet, sink – fan, sink - liquid jet, sink – thermoelectric, sink – spreaders, etc. [7] Also **cross flow systems** of same fluid are giving different flow conditions and heat transfer rates. Boundary layer breaking tabulators are also used in systems with twisted tapes, coli inserts, swirls.

Liquid cooling, specially using water, may be the most general solution. But even it has good thermal conductivity and higher heat of evaporation, its dielectric constant is prohibiting it from regular use. The substitute fluid used is FC-72 (Fluorocarbo), which has dielectric constant of about 2% than water. [4] [8]. During **micro channel cooling** higher heat densities can be removed. [9]

Liquid metal cooling is also used in which GA-Sn-In Eutectics are used which remain liquid and also having low CTE. These can cool systems up to 200W/cm2. [3]

Use of **thermo syphon** and **thermoelectric** system like heat pipe are costly affaires. The **boiling** and **liquid forced convection** has highest heat transfer rates, but then also air cooling is widely used in many applications due to its availability of fluid, simple systems, and cost effectiveness.

Materials used in development of electronics systems and components are also playing an important role in heat dissipation. **TIMs** and **thermal paste** with heat **spreaders, use of Nano-technology** in relation with PCBs are available. This can be considered as a separate area to understand related to material science in electronics cooling.

Following are the challenges in front of investigators of thermal management systems.

1. Design of low space – high heat dissipation systems
2. Producing low cost systems
3. Design cooling systems without failure
4. Developing low cost high conductive adhesive material, spreaders
5. Use of advanced techniques like heat pipe, vapour chambers, thermoelectric cooling, in combination as hybrid system, etc
6. Application of direct liquid cooling
7. Developing high performance air cooling / air movers
8. Minimize impact on environment by proper cooling system design

The component generating heat is generally taken care by spot cooling systems. But comprehensive cooling can also be achieved by jet impingement methods. By considering this issues and with aim of addressing (7), the presented study is dealing with prominent techniques of air jet cooling. The jet impingement technique and its basic is explained in next section.

2.2 Jet cooling Techniques

Definition - Jets are defined as impingement of high velocity fluid on the target surface to be cooled through opening / pipe / nozzle.

Jet impingement fluids mostly used are air or high heat transfer coefficient liquids. Basically jets are classified as shown in Fig. 2.1. The criterion and types are as below.

1. Based on fluid flow a) Free jet, b) Submerged Jet, c) Confined jet [2]

2. Based on inclination of jet d) Perpendicular jet, e) Inclined jet, f) Projectile jet

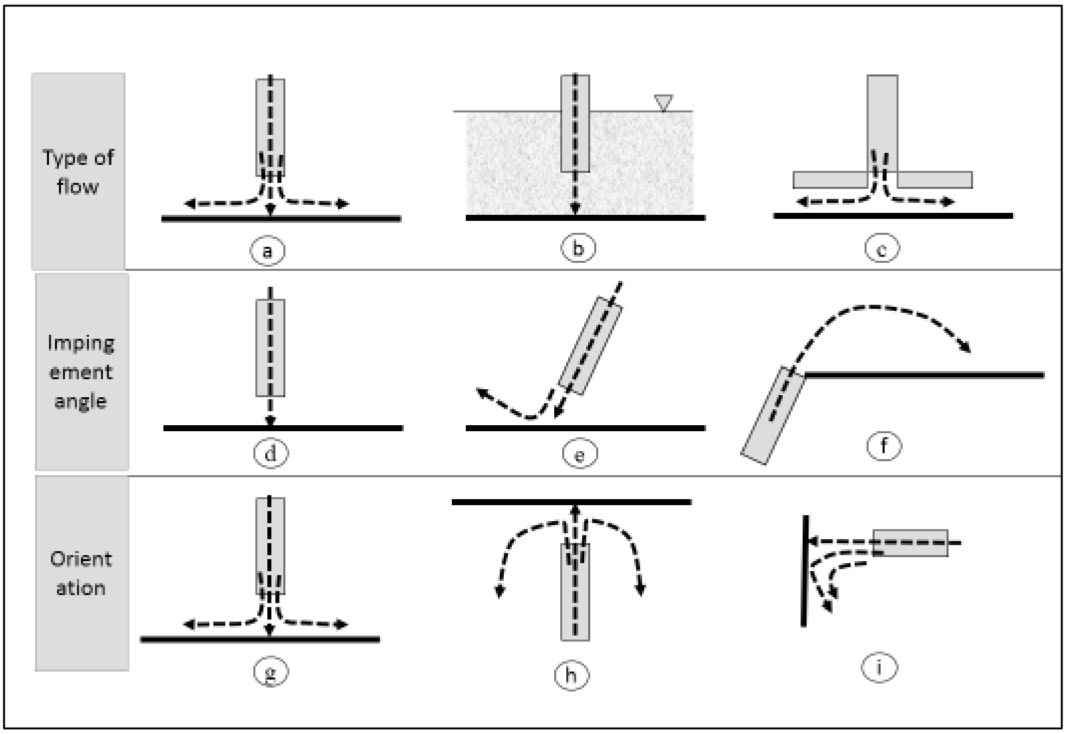


Fig. 2.1 : Types of jet a) Free jet, b) Submerged Jet, c) Confined jet, d) Perpendicular jet, e) Inclined jet, f) Projectile jet, g) Downward jet h) Upward jet, i) Horizontal jet

3. Based on orientation of jet g) Downward jet h) Upward jet, i) Horizontal jet

Air jets are having capability to dissipate high heat flux and they can also care about hot spots, basically for even cooling solutions. **Micro-air jet cooling** can reach up to 900 W / m^2K, but noise intensity generated during process is to be controlled. [4] Whereas liquid jets can cool up to 90W/cm^2 with 100^0C temperature hick with 8 ml/min as volume flow rate. [3] Following are the advantages and disadvantages of jet impingement system.

Advantages of jet

1. Can cool target up to 90 to 180 W/m^2.
2. Air and water are available at low cost and also available easily.
3. Hot spots can be cooled on the target.
4. Uniform cooling can be achieved.
5. Can be installed on an entire system directly.

Disadvantages of jet

1. Need of pump / micro pump / blower / compressor with extra power.
2. Blocking / chocking can be problem for micro jets with manufacturing difficulty.
3. Noise level of fluid impingement can be disturbing.

4. Difficult to install for portable electronics devices.

2.3 Jet impingement review

High heat flux removal problems can be handled by techniques of fluid impingement on electronic components, which is one of the passive technologies. The cooling performance of jet system is increased by impinging a fluid onto a surface locally breaking through the stationary boundary layer and thus increasing heat transfer. The jet is one of the effective and flexible and compact way to provide transfer of heat and as the effective boundary layer is thinner (in case of confined jet), it gives three times higher heat transfer compared to conventional cooling. [10] Also exit flow, after jet reaches to target, provides more turbulence in adjacent air. The parameters like jet hydraulic diameter, target to jet distance, properties of fluid used for jet, surrounding conditions are influencing on cooling performance.

The jet cooling / heating system uses laminar or turbulent jet with Reynolds Number as the base for analysis. [11] Critical Reynolds Number is defined as 3000. Below 3000, the viscous forces are greater as compared with inertia forces and jet disperses faster into surrounding. Laminar jet is having Reynolds Number up to 1000. From 1000 to 3000, the flow is transitional. However [11] refer that some researchers claim to be turbulent jet at Reynolds Number greater than 14000. This indicates that the claim of terms laminar or turbulent may not be important, but the flow patterns and stability of same will be playing vital role and this is interdependent on many factors.

2.3.1 Jets related to flow

Jets are classified depending on type of flow as free jet, confined jet and cross flow jets. In confined jet fluid flow with the restricted boundaries and in free flow it will flow in free, open space. Jung-Yang San et al. [12] examined stagnation Nusselt number for a **confined** circular air jet impinging on a flat surface. His experimental examination is related with effects of jet plate size and plate spacing (jet height). Jets are of diameter of 1.5, 3, 6 and 9 mm, with Reynolds number in the range of 10,000–30,000 and plate spacing-to-jet diameter ratio (H/d) is 1 to 6 was used. Stagnation Number depends on heating condition and flow arrangement of the jet after impingement. E. Baydar et al. [13] experimentally studied flow structures of air jets by **impinging normally upward** onto a flat target plate. The confinement plate is placed in parallel position below target plate. Comparisons of confined and unconfined conditions are made for the Reynolds numbers ranging from 30,000 to 50,000 and the nozzle-to-plate spacing in range of 0.2–6 are used. For confined jet, sub atmospheric regions occur on impingement and confinement surfaces at nozzle-to-plate spacing up to 2 for all Reynolds Number and they are nearly at the same radial location. It is observed that peaks in turbulence intensity and peaks in heat transfer coefficients on the impingement plate are having some relation between them. Chougule N.K et al. [14] used **multi air jet array** of nine jets (dia. 5mm and pitch 15mm, square) at (z/d 6-10, Re 7000 – 11000). *Multiple jets are used to cover larger area for cooling/heating.* It is suggested that value of nozzle pith should be in range of 3 to 5. This will allow better effect of individual jets by reducing adjacent jet interference. By increasing Z/d ratio from 6 to 10, Nu decreases from 50.1 to 36.41 at Re11000. By increasing Re from 7000 to 11000 average convective heat transfer coefficient was increased by 24%. For high Z/d ratio jets become vibrant and will not impinge at the desired target.

Jung-Yang San et al [15] also tested **staggered arrays of five air jets confined in a channel** using experiment technique for study. It is multi - jet system. The jet arrangement include one center jet and four neighboring jets (Reynolds Number 5000–15,000), the jet height-to-jet diameter ratio (H/d) is in the range 1-4; the jet spacing-to-jet diameter ratio (S/d) is in the range 4–8. For the center jet with a specific Reynolds number, its

Stagnation Nusselt number is linearly increased with the jet Reynolds number of the four neighboring jets. For all the five jets with the same Reynolds number, the correlation result shows that the stagnation Nusselt number of the center jet is proportional to the 0.7^{th} power of the Reynolds Number and the - 0.49 power of the W/d. The result also shows that the stagnation Nusselt number of the center jet considerably decreases with an increase of the jet plate width-to-jet diameter ratio (W/d).

Tadhg S. O'Donovan et al. [16] investigated fluid flow and heat transfer for an **axially symmetric** impinging free air jet. At low nozzle to impingement surface spacing the mean heat transfer distribution in the radial direction exhibits secondary peaks which have been recognized, in general, to an abrupt increase in turbulence. It is concluded that the magnitude of the secondary peak in the Nusselt number at r/D (at higher H/D) of about 1.7 to 2, distribution is influenced more by velocity fluctuations normal to the surface. Impinging jets provide a means of achieving high heat transfer coefficients both locally and on an area averaged basis.

The third jet cooling system in this category is of cross flow. D. Rundstrom et al. [17] studied thermal performance and pressure drops of a targeted cooling system with use of an impinging jet in blend with a low-velocity conduit flow on a heated wall-mounted cube, i. e. **cross flow condition**. A typical case of conduit with a hot source, one horizontal channel flow and one vertical jet is studied. It is one of the very complicated cases for flow visualization and understanding flow pattern for different Reynolds Number.

2.3.2 Jets related to physical structure of cooling system

It is possible to use various physical structures for jet cooling. Varieties of combinations are tested by researchers, by changing design of flow channel, swirl generation, exit vent provisions, vibrations, etc. Mao-Yu Wen et al. [18] used **twisted tapes for developing swirling jet** on a flat surface with micro-vibrations of frequency 0.3 to 10.9 Hz and amplitude 0.5 to 8.1mm. It is also understood to use two flow patterns of jet out of which one is swirling. P. A. Dellenback et al. [19] investigated **Coaxial Jet Mixing with Swirled Inner Jet** (Reynolds numbers of 30,000 and 100,000 and swirl number from 0 - 1) for heat transfer effect. Water is used as coolant. The annular jet is un-swirled. Local Nusselt numbers are minimum and maximum corresponding to the separation and reattachment linked with wall enclosed recirculation. Observed Local Nusselt numbers are up to 9.7 times fully developed values for experiment with high swirl with low annular flow rate. Local heat transfer rates is function of, Reynolds number, swirl numbers of the inner jet, and the annular-to-inner jet momentum flux ratios. Sung Kook Hong et al. [20] used **rotating jet** at 560RPM, impingement on concave surface. It is also concluded that local and averaged heat and mass transfer gets affected by surface geometry. Two jet orientation (front and trailing orientation) having Reynolds number of 5,000 are used. Heat transfer coefficients are measured with help of naphthalene sublimation method. The front orientation jet induces asymmetric

Sherwood number, and trailing orientation is giving shift heat/mass transfer feature because of rotation-induced flow behavior. Compared to flat surface, heat transfer on the concave surface gives more Sherwood Number, which indicates more heat transfer. This is because of increase in flow mixing by rotation.

The channel flow indicates flow in a confined surface like duct for cooling particular components. F. Gori et al. [21] experimentally investigated similar flow. He compared **cooling of two smooth cylinders in row** by a slot jet of air with Reynolds Number = 11,000–22,200. Diameter of cylinder and slot jet height ratio is 1. It concludes that the first cylinder acts as a heat transfer promoter, as happens in uniform flow, only for Reynolds Number 22,200. It is important to know the pattern of cooling for various inline components, more than two in numbers, during a confined flow for PCB cooling applications.

The hot air exit from an electronics cooling system is a common problem in case of longer flow duct or rack cooling of a server. The solution came out with the help of exit vent systems, which can be also observed in case of cabinets. A. M. Iluber et al. [22] tested heat transfer with confined array of air jets with influence of **spent air exits**. Local heat transfer is calculated using confined 3x3 square arrays of axisymmetric air jets, normal to a hot source. The effect of small nozzle-to-plate spacing (0.25 and 1.0) considered. Average and local Nusselt number Nusselt numbers are presented for a Reynolds number range of 3500 to 20400. It is observed that at Reynolds Number of 17000, local Nu changes from 110 to 130 for r/D of 1. Even at high Reynolds Number of 20000, average Nusselt Number changes highest at r/D of 0.5 and 1.5. It is proved that spent air paths are equally important for uniform heat transfer in designing the cooling system for electronics components.

2.3.3 Jets based on fluid used for cooling

Different fluids are used to carry away heat from hot source. Type of fluid depends on various features of system to be designed for cooling; like specific application of cooling system, type of component to be cooled, size of component, temperature range of system, cooling requirements, heat generation rate, space availability for cooling system; energy required and permitted to use cooling system, etc. For electronics cooling systems, other than jet, phase change materials are also used. In this review we intent on single phase cooling fluid used for jet. Out of many such fluids, air and water are popular as their ease in use, availability and known properties for practice. Jemmy S. Bintoro et al. [23] tested cooling by using single phase impinging jet in a closed loop system. **De-ionized water is used as a fluid** in impinging jet, with two different nozzles (hydraulic diameters are 0.5 mm and 0.8 mm). The corresponding volume flow rates are 280 mL/min and 348 mL/min. Mini channels heat exchanger, mini diaphragm pump and a DC electric fan with the maximum power consumptions of 8.4 W and 0.96 W respectively, by satisfying need of low consumption of energy are used. The claim is water cooling system can be used in PCs directly, as it is of compact size. But care of leakage is to be taken care in practice.

B.P. Whelan et al. [24] also used liquid CPU cooler to achieve a cooling capacity of 200 W for a surface area of 8.24 cm^2, with an Intel Pentium 4 Processor. Low cost injection molding techniques are used which can significantly reduce the total system cost compared with conventional units. At maximum power the chip-to-air temperature difference is 45°C and it is up to typical design need. Drop in the system thermal resistance is observed for increasing the liquid volumetric flow rate between 2 L/min and 5.5 L/min of water.

Measurement and comparison of heat transfer to single, axisymmetric, submerged and **confined air and water jets** is reported by Colin Glynn et al. [25]. The experimental investigation for comparison of air and water is carried out. Jet diameter (0.5mm to 1.5mm), Reynolds number (1000 to 20000) and jet to target spacing (0.5D to 6D) and dimensionless jet-to-target spacing of 1to 4 are tested. It is observed that the average heat transfer increases with decreasing jet diameter. For the air jets, secondary peaks are present at low jet-to-target spacing and high Reynolds numbers. The water jets also exhibit secondary peaks, however these have only been observed at a low Reynolds number of 10000 and a low H/d of 1. The value of convective heat transfer coefficient is significantly higher in case of water. K. M. Graham et al [26] studied mist jet impingement cooling using **air-liquid mist** for small heat sources (6.35 mm, square). Jet used is using a coaxial jet atomizer, with a liquid jet of diameter 190 micron, located on the axis of an annular air jet (diameter 2 mm). The geometry of jet is of air nozzle (OD 25.4mm, ID 16.3mm), inserted with small size liquid nozzle (1.4mm).

Experiments are conducted using mists of both **methanol and water with air**. Surface averaged heat fluxes as high as 60 W/cm^2 could be dissipated with the methanol - air mist and target surface below 70°C, whereas for water/air mist target surface at 80°C. Similarly Cemil Y [27] used mist fluid on heated metal surfaces i.e. **water-air mist** (air velocity from 0 to 50 m/sec, liquid mass flux from 0 to 7.67 kg/m^2s). Experimental studies show that heat transfer coefficient increases not only with the air velocity but also with the liquid mass flux at the stagnation point. For weak (less percentage of water) spray, the mist heat transfer coefficient increases almost linear with the water mass flux. Injection of a small amount of water in the air jet, affects the heat transfer effectiveness positively. In case of weak fluid, the overall convective heat transfer coefficient is addition of: heat transfer coefficient of air and liquid, also the radial distribution of heat transfer coefficients of water mist is having similar trend to air jet.

Giuseppe Di Lorenzo et al. [28] suggests improving the thermal performances of confined slot jet (Reynolds number 100 to 400) by improvements in working **fluids with nanoparticles** (mixture of water and Al_2O_3 nanoparticles). The laminar flow and a uniform temperature of target with aim of improvement in local Nusselt number are considered. The conclusion of numerical study is the vortex intensity and size depend on the confinement, Reynolds number, and particle concentration values. The phenomenon of increase of fluid bulk temperature is noted because of the raised thermal conductivity of nano-fluids. A maximum increase of 32% in average heat transfer coefficients is observed at concentration of 5%, at the cost of pumping power; which increases as concentration increases. Experimental observations are not reported, as these all are numerical inferences. Similar cases are reported by Oronzio Manca et al. [29] in the range of Re as 5000-20000. The highest values of the average Nusselt numbers are observed for H/W = 10. A maximum increase of 18% is detected at concentration of 6%.

The efforts are made with **electrically charged jet fluid**. Weiwei Deng et al. [30] showed that electrically charged micro droplets can fully exploit the droplet cooling capacity that removed a heat flux of 96 W/cm^2 with a cooling efficiency up to 97%. An increase in the number of electro-spray sources per unit area will increase heat transfer further.

Roy J. Issa [31] uses **single oil jet** impinging on the bottom surface of the plate heated to temperatures ranging from around 115 to 630 °C for nozzle-to-plate surface distances of 0.6 and 1 cm. The application of jet for quenching parameters is tested. Tests results show the oil heat transfer effectiveness keeps increasing for increasing plate temperature, while the nozzle-to-plate surface distance is shown to have a lesser effect on cooling performance.

If also fluid is one of the important selection parameter for jet, for economic considerations, the method of producing jets is also considered to be important.

2.3.4 Synthetic jets

Synthetic jets are used typically for saving space, but has some limitations. Normally jets are developed by pressurizing of fluid. Air jet by compressed air, water jet by water pump, but synthetic jets are uses electromagnetic principles by which micro-jets are developed. These will significantly reduce the size of the cooling system. Jivtesh Garg et al [32] used **Synthetic jet** providing maximum air velocity of 90 m/s from a 0.85 mm hydraulic diameter rectangular orifice, used for cooling surface of 156 mm^2. In experimentation, jets with frequency of 3.4 to 5.4 kHz, used on two hot surfaces (50 and 80 °C) are tested. The **heat transfer enhancement factor** is defined as the ratio of Nusselt Number using jet to natural convection. The presented case shows it to be around 10 at jet distance of 8 mm or 9.3 jet orifice diameters., and COP (heat removed/consumed power) is 3.25 , because very less power is required for such jets.

Yogen Utturkar et al. [33] experimentally tested **synthetic pulsating jet**. Such jets impart a positive net momentum flux to the external Environment, and producing cooling effect. Heat removal is dependent on the location, orientation, strength, and shape of the jet. Out of these, jet location and orientation on the cooling performance are studied first time using experiment. Jet orientations of two types, namely, perpendicular and cross on the heater are used. David W. Gerlach et al [34] suggested a new design for Heat Removal using **solid spreaders** with high thermal conductivity and artificial jets. Heat sink is used with synthetic jet. The heat transfer coefficient, of peripheral surface, and the spreader parameters like thickness, thermal conductivity, and shape of holes are analyzed. It is observed that for 5W power dissipations, in each 27x38 mm layer, a 250 micron thick copper heat spreader can be used in better way.

Matrix of integrated synthetic jets is suggested for better performance in which cooling ambient air, flow along the fin height and originates from the base of the fins as induced jets.

Mangesh Chaudhari et al. [35] analyzed constructional feature of **synthetic jet by changing orifice shapes** (square, circular, and rectangular, Aspect ratio in the range of 1–20, and hydraulic diameter of 3.8–8 mm) for synthetic jet (Reynolds Number 950–4000) for various axial distances. It is concluded that the heat transfer is higher with a square orifice for (Axial distance/Hydraulic Diameter) greater than 5; and rectangular orifice (with aspect ratio between 3 and 5) shows highest performance for small (axial distances/Hydraulic Diameter).

Anna Pavlova et al. [36] tested **high formation frequency** of 1200 Hz for synthetic jets and found as better efficient system for small H/ d and low frequency jets are more effective at larger H/d. It is concluded that synthetic jets are about three times more effective in cooling than continuous jets at the same Reynolds number is stated. Similarly, Dan S. Kercher et al. [37] explained phenomenon of **micro-jet** cooling device, which can be used for pitch out of the fluid in which they are embedded. He analyzed geometrical parameters of the micro-jet cooling systems, and concluded that thermal resistance can be reduced for various locations of hot target surface. The average Nusselt Number is function of frequency of jet, Hydraulic Diameter of jet, Distance of target to jet, Reynolds Number of jet, and Pr of fluid.

Bong-Min Song et al. [38] developed hierarchical reliability model for predicting lifetime of down light – LED replacement bulb, with the **application of cooling using synthetic jets**. The application of synthetic jet technology proves that degradation rate is low and the junction temperature rise over the intended life (50,000 hrs) is negligible. Based on the proposed hierarchical model, the lumen maintenance is estimated to be 76% after 50,000 hrs operation.

2.3.5 Exit Jet shapes

The physical exit profile of jet gives diverse flow patterns of jet, which effect on cooling capability. It is also true that its practical use is dependent on simplicity in manufacturing of jet. S. C. Arjocu et al. [39] used jet array of three-by-three, in

elliptical shape at low Reynolds number conditions (300 to1500). Two different elliptic jet aspect ratios and impingement distance (1 to 6 jet hydraulic diameters). It is observed that average heat transfer is dependent inversely on elliptic jet aspect ratio. Bertrand P.E. Dano et al. [40] tested heat transfer performances of a **semi confined impinging array** of jets with reference to effect of nozzle geometry (**circular** and **cusped ellipse**), in cross flow condition. Cross-flow affects the heat transfer results based on the interaction with the jet at the surface. The overall heat transfer for the uniform heat flux condition is found to increase for the cusped ellipse jets particularly at high Reynolds Number conditions. Brian P et al. [41] tested a variety of inlet and outlet geometries of jet using liquid jet arrangement related with thermal-hydraulics heat transfer. The aim is to find out design in confined-submerged flow, with more heat transfer and less pumping power. It is observed that with a **square** array of 45 jets (1mm diameter) and fixed jet- jet spacing (5 mm), six different nozzle geometries viz. **straight, chamfer inlet , chamfer outlet, chamfer in and outlet, countered inlet, and countered in and outlet**, are studied. The arrays impose normally upon a heated circular copper surface (31.5 mm diameter) with constant heat flux. Reynolds number is in range of 800 to 10000 for which, confined-submerged jets are found to be give best results. Chamfering and contouring nozzle inlets showed reduction in pressure drop across Plate. Mangesh Chaudhari et al. [35] also analyzed synthetic jet orifice shape as different configurations. Slot jets and circular jets are equally appreciated for jet impingement cooling.

Azusa Kanamori et al [42] experimentally studied the effect of orifice configuration on flow behavior as well as impinging heat transfer characteristics of a jet. They tested and visualized (flow visualization with hydrogen bubbles) **triangular, square, pentagonal, and hexagonal shapes** (3 to 6 sides) with jet of Reynolds number is 5×10^4 The axis-switching phenomenon is observed in the free jet emitted from the various polygonal orifices. The number of polygonal sides' effects on the position where the contour line of the local wall pressure coefficient profile on the target plate approached a concentric circle shifted to the upstream side of the jet with increase in polygon sides. The process called "axis switching" for three-dimensional free jet has been stated. When numbers of jets are considered, ultimately, the polygonal /circular arrangement of jets, diameters of jet, pitch of jet are the considerable factors. Shape and size of jet exit, both are equally important factors. Yoonjin Won et al. [43] used **micro scale impingement jet** devices with diameter of 50 micron with very low Reynolds numbers (21 to 63), images are obtained and visualized to study flow physics.

With this **slot jet** and **circular jets** are used regularly due to their simplicity in manufacturing and use,

2.3.6 Jets with varied impingement frequency

Frequency of jet indicates magnitude of pulsation of jet. Against continuous jet, such jets are used. Pulsating flow increases mixing, that turbulence increases heat transfer. Such jets are functional with saving energy which is used for jet production and for its special flow patterns generated which creates turbulence and enhance heat transfer. Anna Pavlova et al. [36] tested high formation frequency of 1200 Hz for synthetic jets which is stated earlier. H. S. Sheriff et al. [44] studied flow pulsations effect on the cooling using water Jet. Pulsations are created using Sinusoidal and square-pulse waveforms. Pulse frequencies ranged from 5 to 280 Hz, which corresponded to Strouhal numbers (As describing oscillating flow mechanisms) based on jet width and velocity of 0.014 to 0.964 m/s. For pulsating jets with a square-pulse profile and an on/off incident flow, Nusselt numbers at the stagnation line are enhanced by as much as 33 percent. But it also depends upon diverse parameters of a typical case.

2.3.7 Jets depending on surface characteristics

It is also observed that different types of jets are having their own advantages and fluid flow patterns. But flow currents, eddies and ultimately heat transfer also depends on the surface on which jet is to be impinged. The target surface also directs and controls enhancement of heat transfer. There could be verities of types of jet by using this criterion. But jets **on cylindrical surface**, **on rectangular surface** are common examples. Luis A. Brignoni et al. [45] used, variety of confined air jet nozzle (Re 5000 to 20000) impingement configurations **on a pin fin heat sink**. The hybrid methods of cooling are used i.e. with active and passive cooling, in such cases. Four single nozzles of different diameters and two multiple-nozzle arrays studied at a fixed nozzle-to-target spacing. Enhancement factors are observed are of 2.8–9.7, with the largest value being obtained for the largest single nozzle (12.7 mm diameter). D. H. Lee et al. [46] checked fluid flow and heat transfer characteristics **on and around a central pedestal** and a secondary pedestal with an impinging jet mounted on a flat surface. Results with Surface Nusselt numbers, pressure coefficients and flow visualization are presented for jet Reynolds numbers of 23,000 and 2300, dimensionless nozzle-to-surface distance L/d is 2, and the non-dimensional height of the central pedestal H/D is 0.5. Averaged Nusselt numbers measured with secondary pedestals employed are 13% to 33% higher than values measured with no secondary pedestal. Seok Pil Jang et al. [47] studied jet **on micro channel heat sink,** impinged under condition of fixed pumping power, the pressure drop across the heat sink and temperature distributions at its base. It is observed that cooling of an optimized micro channel heat sink subject to an impinging jet is enhanced by 21% against parallel flow under the fixed-pumping-power condition. V.I. Terekhov et al [48] experimentally observed impact jet (Reynolds Number $1.2 \times 10^4 – 5.8 \times 10^4$) onto an obstacles in the form of **single spherical cavities**. Fields of pressure and heat-transfer coefficients inside the cavity are measured, and seen that at depth of the cavity, flow becomes unstable, large-scale vortex are generated and effects on the heat transfer. Cavities with (depth / diameter) greater than 0.26 generate a large-scale pulsing vortex. Soon Hyun Yoon et al. [49] tested **tilted plate** impinging using turbulent flow jet for heat transfer study. Measurement of local heat transfer coefficients is made using thermo-chromic liquid crystals. The jet Reynolds number (10,000 to 35,000) and the nozzle-to-plate non-dimensional distance (from 2 to 16), varied and measured for various oblique angles from 60 to 90 degree. The testing bring to a close that stagnation peak move in the direction of the minor flow section as the tilted angle reduces and the place of the stagnation position nearly agrees with that of the utmost turbulent concentration.

2.3.8 Inclined jets

To make electronics cooling systems compact, the cooling jets can be inclined. In the same line Haydar Eren et al. [50] tested **obliquely impinging slot jet**, with angle of the jet relative to the surface is used as 90°, 60°, 45° and 30°. Reynolds number of

5860, 8879, and 11606 of air flow are used and variation of local temperatures with respect to dimensionless length (W/L) is examined. The largest displacement observed in experiments is about 0.92 of Height of slot jet with 300mm width i. e. for tested case. Q. Li et al. [51] used spray atomizer for cooling of micro heat source using experimental measurements. The spray used is at different angle 0, 20, 40, 50, and 60 Degree at fixed distance of 1.4 cm from the heated surface. Temperature data inside the die is used to calculate the unknown spray cooling heat fluxes. It is observed that major decrease in cooling capability beyond a spray angle of 500 because of reduction in spray volumetric flux carry to the die. The cooling effectiveness is function of Reynolds number, characteristic length of plate to be cooled, point of jet impingement, and oblique angle of inclination of jet

2.3.9 Other cases of jets

Matteo Fabbri et al [52] tested cooling using **sprays** and micro-jets; and claim that criteria to decide good method between these is presented. Experiments conducted using nozzles for **droplet sprays** and orifice plates to create **arrays of micro jets**. The liquid jets with diameters ranging from 69 to 250 microns, total 4x6 arrays of micro-jets and jets pitches 1, 2, and 3 mm are used. The test fluid is deionized water and jet Reynolds number 43 to 3813. The micro-jet arrays proved better-quality to the sprays since they required less pumping power per unit of power removed. John C. Duda et al. [53] visualizes flow of development of vortex structures in a **round jet impinging on a flat plate** and a cylindrical pedestal using Smoke-wire flow visualization. Velocity and turbulence intensity at the jet exit are considerable parameters near the impingement surface. K. Oyakawa et al. [54] visualized flow pattern and heat transfer of impingement free jet at Reynolds Number = 9700. Reynolds number and the separation distance between nozzle exit and plate are parameters for study of Heat transfer with flow visualization images shows that a large scale vortex appear in the shear layer around the jet, after that the large scale vortices penetrate to the center of jet. M. Rahimi et al. [55] used under-expanded axisymmetric air jet for cooling heated surface. It is observed that radial distribution of the heat transfer coefficient is composite, whereas higher in impingement zone. Matteo Fabbri et al. [52] tested heat transfer using micro-jet (Reynolds Number 73 to 3813), jet diameters smaller than 69 and 250 microns, of water and FC 40 as tests liquids using experiments. The expression for average and local Nu is presented in terms of jet diameter at nozzle exit, and distance between the centers of two neighboring jets.

2.3.10 *Summary*

To fulfil the requirements of large scale integrated electronic cooling, depending on application and need of electronics system designers, variations in jet configurations are observed. More ways of designs has resulted in a large variation in jet impingement cooling techniques for which a broad classification is being presented. Broad methods of jet impingements are already shown Fig. 2.1, but based on sub-techniques used by researchers, Table 2.2 gives sub classification of jet impingement techniques. It is based upon criterions like method used, fluid used, orientation, application, direction, physical properties like shape, size, etc.

Table 2.2: Jet classification criterion

Criterion	Sub criterion
Flow	• Free jet • Confined jet • Cross flow jets
Physical structure	• Coaxial jet in jet • Swirling jet • Exit vent flow with jet • Channel flow jet
Fluid used	• Air jet • Water jet • Mist jet
Generation of jet	• Conventional jet • Synthetic jet

	• Micro jet
Geometry of jet	• Slot jet • Circular jet • Elliptical jet • Any other geometry
Frequency of jet	• Continuous jet • Pulsating jet
Surface to be cooled	• Jet on Pin-Fin(circular Cross section) • Jet on Heat sink (Rectangular cross section) • Jet on Cavity • Jet on nano particle surface • Jet on inclined surface • Jet on vibrating surface
Direction of jet	• Normal jet • Inclined jet

By changing various parameters, efforts are made to know physics of flow and variations in heat transfer using jets. These are: jet velocity, jet diameter, impact angle, number of jets, and jet to target spacing, jet to jet spacing, turbulence levels, jet shapes, jet length, jet confinement, target face enhancement, and fluid properties.

Forced convective heat transfer using impinging jets is known for providing high local and area averaged heat transfer coefficients. Impingement jets are of particular interest in the cooling of electronic components where advancement relies on the ability to dissipate extremely large heat fluxes because of physics of flow, turbulence generation, simplicity in controlling parameters, availability of verities of fluid, and typical range of convective heat transfer coefficient. Cooling systems are selected based upon designers requirements for convective heat transfer coefficients of forced air, jet of air, forced water, jet of water as 20-200, 200-900, 300-8000, 8000-50000 W/m^2.K respectively. [56]

In jet with air as a fluid is used, it has its own advantages, but then also need of design for improved cooling ability at the package level via optimized internal thermal conduction paths. Jet impingement cooling with proper hydraulic diameter overcomes the clogging constraints and is compatible with hot water also. Industries always call upon design for low cost thermal engineering systems with improved manufacturability. Some of the important cases in research of jet cooling are presented here, with their experimentations, and conclusions in brief, which will in turn help to further to understand research need in this area. For the general understanding of various heat transfer studies in jet cooling experiments. The jets are studied well but then also, by small change in any of the relevant parameter, it will influence on flow of physics as well heat transfer characteristics. The researchers used these techniques and hence it is required to study jets separately in detail, for each case. Instead of study of jets directly, let’s understand the main theme and sub theme under jets, by knowing what the results were in brief. Fig. 2.2 gives review in form of subthemes under jet impingement.

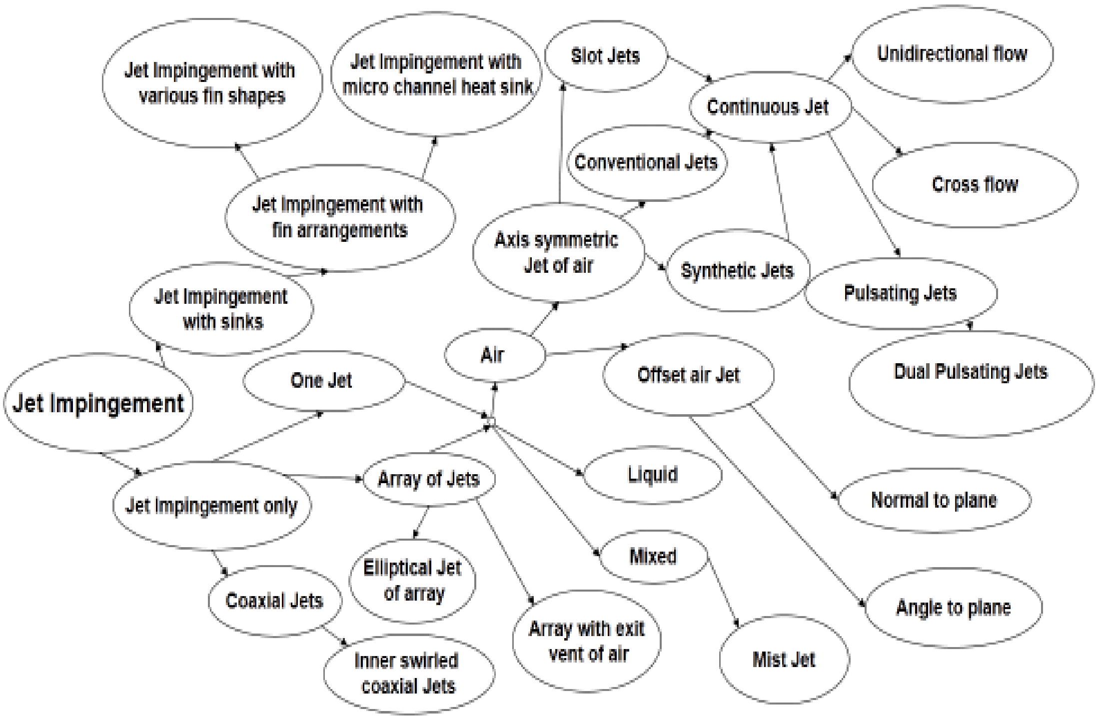


Fig. 2.2 : Classification of jets by available literature

By understanding and detailed study under all sub theme of jet configurations from literature, the following points are noted.

1. There is no specific diameter, Reynolds number used for Jet cooling applications, but it differs from case to case – application to application.
2. Air is used as major fluid for jet cooling.
3. Slot jets, circular jets, elliptical jets are investigated by many ways. Basically, hydraulic diameter is the governing parameter for altogether analysis. To use a circular jet will help to develop system easily, with less space requirement.

The area of interest to be identified as 'inclined jet cooling using air'. To fix the required parameters and design of experiments, specific review of inclined jet impingement is carried out and presented in next section.

2.4 Review on inclined Jet

2.4.1 Literature on inclined jet

The hydrodynamics and heat transfer of unequal geometry of the tilted plane jet (of liquid with uniform and parabolic cross section) is solved using the **Navier–Stokes equations** using a **finite-volume method**. [57] Nusselt number and pressure drop is studied. It is concluded that the maximum Nusselt number position and the maximum pressure position have been establish to move upstream from the geometrical impingement point of the jet with the degree of the displacements growing as the inclination increases. The conclusion of jet inlet velocity profile has a significant effect on the heat transfer. For uniform jets, the maximum Nusselt number increases as the inclination increases and for parabolic jet, it initially decreases and then increases (Fig. 2.3). Nusselt number is observed to be proportional to the square root of the Reynolds number.

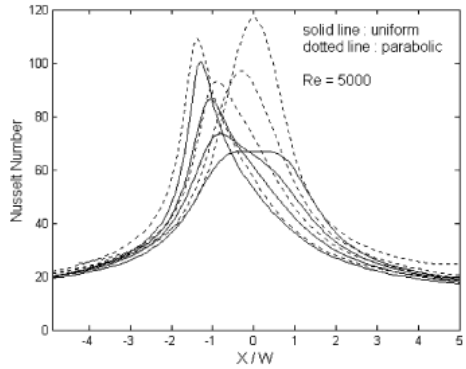


Fig. 2.3 : Comparison of uniform and parabolic jet [57]

Heat transfer characteristics **in a channel** is performed to understand effect of exit air from channel. [58] The Target plate is inclined at an angle to base reference.

An experimental and numerical study was carried out to describe the isothermal **laminar flow** of a **liquid jet** restricted by inclined plane walls which was originating from a rectangular duct. The rectangular duct has an aspect ratio of 13, the plane walls opposite to the impinging jet have an inclination of 12^0 and the nozzle-to-plate distance (D) is very small as 0.8. [59]

Experiment (Fig. 2.4) is performed for observing the heat transfer features of impinging circular jet at 90°≤φ≤150° **from bottom**. [60] Reynolds number, 2800, 9000, and 36,000 and jet-to-plate distance to jet diameter ratio H/D as 5, 10, and 15. It is observed that inclination was most effective parameter. With increasing jet to plate distance, for low Reynolds number, temperature of the stagnation point shows decrease for high Reynolds number. The position of the stagnation point changes with changing of inclination angle for high Reynolds number. Naresh R. et al [61] also investigated inclined vertical surface characteristics by using **horizontal air jet**.

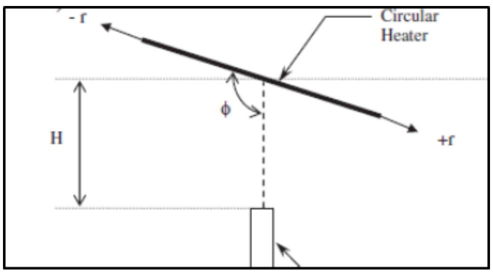


Fig. 2.4 : Jet impingement terminology on bottom of plate

Instead of experimentation in channel, it can tested **in wind tunnel** also. The investigation is carried for cooling applications with a single oblique (90°, 60°, 45° and 30°) air jet (with Re of 5860, 8879, and 11606). [50] By experimental study, a correlation is presented in terms of Temperature ratio as a function of Reynolds number, dimensionless distance, and oblique angle (Sin Ɵ). It is observed that the maximum heat transfer location shifts with increase in the inclination.

The jets can be used for cooling as well as heating. Jiwoon Song et al. [62] investigated the thermal features on an inclined (0 to 30 degree) plate for **heating application**. The jet impinged is an **under expanded sonic jet of hot fluid,** examined with effect of nozzle (D = 10mm) to space distance. It is concluded that the cooling effect is deteriorated generally as the inclination angle rises. The area covered by cooling, increases as angle increases in downward direction. The inclinations of jet defined by various authors are different, which may lead to confusion.

As perpendicular jet, in inclined jet also the cross section area of jet matters and variations are observed in literature. Kyosung Choo et al [63] verified **slot air jet with the inclined** (0 to 40 degree) experimentally. The dimensionless pumping power is considered for understanding effectiveness of cooling system. The smaller nozzle-to-plate spacing (equal to or less than one nozzle diameter) are showing that it is significantly different from those of large nozzle-to-plate spacing. Average Nusselt numbers at this condition increase as the inclination angle increases. But it decreases at higher spacing, due to momentum loss of the wall jet. Equation of ratios of Nusselt Number are presented.

The surface to be cooled (its texture, convexity-concavity, position/placement) has equally importance, as it directly effects on flow pattern. C. F. Ma et al. [64] investigated the local convective heat transfer from a **vertical heated surface** to an inclination (90 to 45 degree) of circular free-surface jet (Reynolds number between 235 and 1745) **of transformer oil** is made. Maximum heat transfer coefficient was decreases with the increasing of jet angle and its position changes towards upstream direction. Local Nusselt number are calculated in both X and Y direction. Symmetrical pattern is observed in Y direction and asymmetric situation in X direction. The correlation is presented in terms of Reynolds Number, Prandtl Number for various angles.

MIzuki Kito et al [65] investigated heat Transfer characteristics for inclined (0~60°) jet (**Reynolds number 5000**) with H/D of 3 to 7. The maximum Nu decreases as θ increases and the Nu peak position shifts towards the uphill side until θ = 45° and shifts back for less than 45°. There is growth of maximum Nu by 19% with respect to normal jet. Even **twin impinging jets inclined** to face each other are also tested which shows that Nu peak was powerfully affected by jet positioning. The average Nu amended about 20% compared with that of a single jet. (Fig. 2.5)

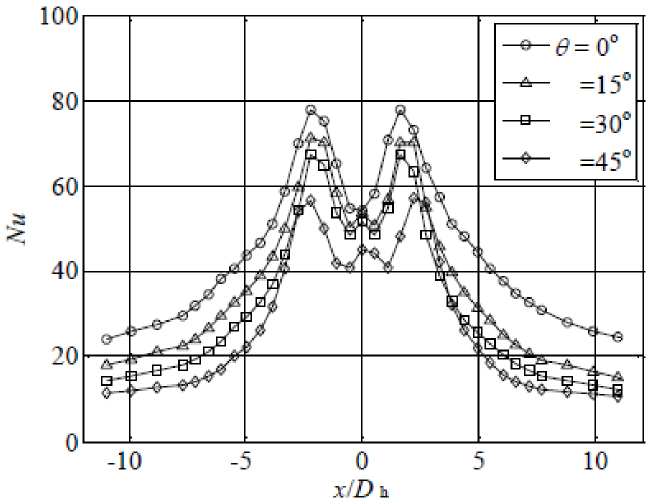


Fig. 2.5 : Performance of twin inclined jet

Kazuyoshi Nakabe et al [66] also investigated two inclined jets for different geometry. It is also concluded that two jets are inclined at different Reynolds Number , the resultant jet oscillate by which core of jet buckles and it acquires more turbulent intensity. This will help in sweep stagnation point back and forth which lead to increase effective cooling area.

Soon Hyun Yoon et al [49] during study of jet (Reynolds number of 10000 to 35000), the nozzle-to-plate distance (H/B) (2 to 16), and the oblique angle (60 to 90 degree), presented a correlation for maximum Nusselt Number. The local Nusselt numbers for minor flow area were greater, because of complex levels in turbulent intensity. The turbulent intensity can be increases by confined jet, which can be useful for electronics packaging. Victor Adrian Chiriac et al [67] studied **laminar flow** heat transfer with a pair of 1 cm wide inclined **confined impinging air jets** (Reynolds number of 300 and 600) at the center of a channel for the application of electronics PCB cooling. The behavior of jet unsteadiness largely governed by on the closeness of the jet inlets, the channel size and jet Reynolds number.

Being jets are complicated in flow behaviour and thus 3-D study is also performed by Yue-Tzu Yang et al [68]. They made a three-dimensional numerical simulation of heat transfer characteristics for an inclined jet with **cross flow** impingement. The cross flow can generate diverse flow counters. Velocity ratios of jet and cross flow are changed with Re = 5000 and angle of 45 Degree. The generation of a counter-rotating longitudinal vortices are seen after the numerical computations.

For simplicity, 2D jets are also considered by some of the authors. Ramezanpour A. et al [69] numerically studied (2D) jet to find heat transfer rate using **CFD**. Jet used is unconfined, and **submerged impinging** inclined (40-90 degree) jet (Reynolds in range of 4000-16000) discharged from a slot nozzle to flat and inclined plate for H/D spacing of 4-10.

The jet and spray has the small difference in definitions. Simply number of nozzles together can generate a reasonable better spray of fluid. Hence spray also can be considered as sub themes of jet. A **spray cooling** effect on cooling performance for electronics applications with different spray angles (0, 20, 40, 50, and 60 Degree) are analyzed, with distance between targets and spray as 1.4 cm. [51]

Carlo Bartoli [70] worked on natural convection between a **downward facing inclined wall**, heated by Joule effect, and air in the presence of small air pulsating jets is tested with and without pulsating jets. It is observed that, if jets are not used; in the closeness of the leading edge, the local heat transfer coefficient rises up. It happens up to an inclination angle of 22 Degree, after 22 Degree inclination heat transfer coefficient declines.

The hot object which is to be cooled is placed in moving position than stationary by D. Benmouhoub et al [71], and it is impinged with inclined jet. It is compound technique in which two methods are combined. The optimal jet inclination is found to be 0 to 25 Degree, and by using this compound techniques stagnation point can be changes as per requirements as well as heat transfer can be improved.

If also many researchers are identified who worked on inclined jet heat transfer, it is comparatively neglected area, because of which probably perpendicular jet systems and applications for cooling are established commonly. [57]

2.4.2 Summary

The inclined jet review is summarized as in Table 2.3

Table 2.3 : Inclined jet review

Author	Jet size	Number of jet / configuration	Re	Angle (Degree)	Other, Equation
[57]	2mm	Circular and parabolic	2500, 5000, 10000 Water	45 - 90	Numerical, FEV
[58]	5mm	single array of equally spaced centered, 13 Circular jets	9300, 14400, and 18800 Air	1.5	-
[70]	1.5mm	Circular	Air		Object heated by Joule effect
[72]	4mm	One jet, Circular	2800, 9000, and 36,000	90 to 150	-
[50]	30 mm x 2 mm	One slot jet	Air, 11800, 8800,5800	30,45,60,90	Wind tunnel used
[62]	10 mm	One circular jet	Compressed Air	0 to 30	Hot air on cooled plate
[63]	2x20mm	slot	Air, 3000 to 25000	0 to 40	-
[64]	0.987mm x 35 mm	Circular jet	Oil, 235 and 1745	90 to 45	Oil used

[65]	5x50mm	Slot	Air, 5000	0 to 60	Twin jets are tested
[69]	NA	Slot	4000-16000	40-90	Using numerical model of CFD
[49]	350x26.5 mm	slot	10000-35000	60-90	-
[67]	10 mm wide	Slot, two jets	300-600	30	-
[68]	6mm	Circular	5000	45	Cross flow

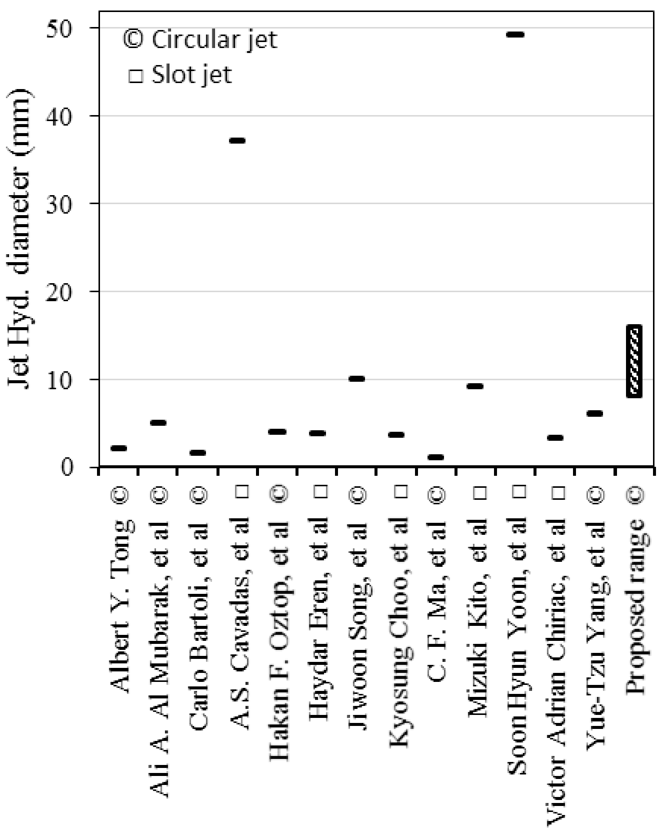


Fig. 2.6 : Jet hydraulic diameter used in literature

Following facts are noted.

1. Every reference researcher worked with different view of analysis, hence it is quite difficult to compare all. Also their configurations and physical parameters are varying a lot.
2. Angle of impingement or range of angles for impingement, used in general is from 0 to 90 degrees.
3. Majority of inclined jets are investigated which impinge at the center of target plate.
4. Slot jets, circular jets, elliptical jets are studied. Basically, hydraulic diameter is the governing parameter for altogether analysis.
5. *Majority of industrial uses of jets are using jet diameters in the range of 5 to 30 mm* and selection of jet diameter depends on the development and hardware capacity of manufacturer. Only one diameter is investigated generally, as Reynolds Number is function of hydraulic diameter of jet.
6. To understand characteristics of heat transfer, wide range of Reynolds Number are used**.**

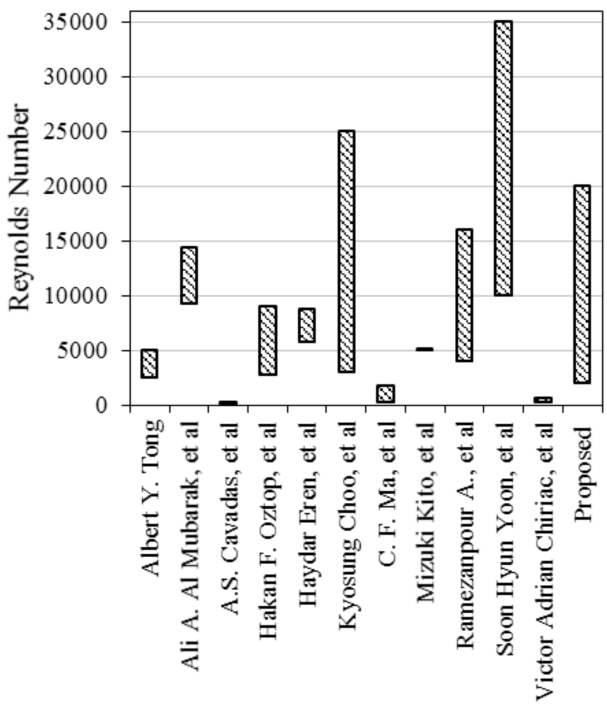
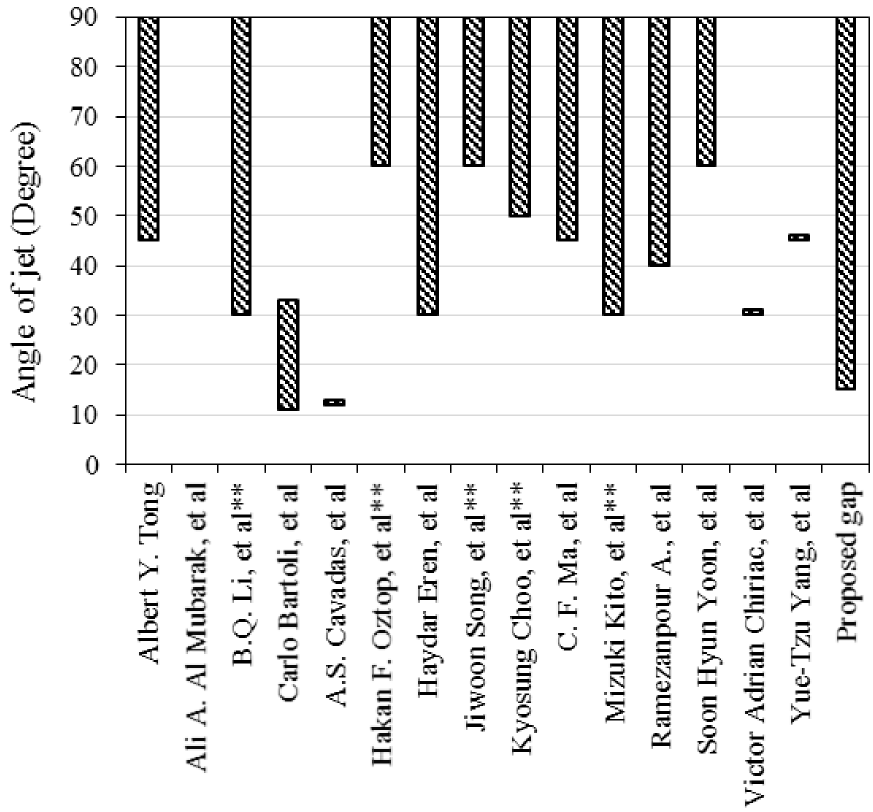


Fig. 2.7 : Jet Reynolds Number used in literature



** Convered angle as per present study as these are defined differently.

Fig. 2.8 : Angle of jet used in literature

During electronics cooling applications, space constraints deliberations will force to think on various oblique jet impingement. Hence the location selected is at leading edge. The inclined circular jet heat transfer analysis is actually three dimensional study, which is complex phenomenon. [57]

2.5 Gap analysis

Based on the literature available, following points are noted.

1. With the intention of cooling of entire target surface, with comprehensive / collective cooling approach of electronics devices, jet is not impinged at the center but placed at vertical plane, in line with edge of the target plate i.e. on leading edge, can also be called as offset cooling, is the gap found.
2. To cover broad area of study for general use of cooling of electronics system at moderate heating cases, diameter of 8, 12, 16 mm are used.
3. Little work is performed on jet inclination angle from 15 to 75 degree, is the gap recognized.

2.6 Objective and scope

1. To investigate and understand effect of offset jet impingement cooling by use of inclined air jet.
2. To predict effect of use of air jet using investigation at Reynolds numbers for the range of 2000 to 20000.
3. To integrate and propose correlations for Nusselt Number using inclined air jet for offset cooling.
4. To investigate effect of 'target to jet distance' with different angles on 'Nusselt Number distribution'
5. To investigate inclined jet enhancement factor.

The scope is limited to the range of the experiment for Diameter of Jet (D), Angle of impingement (Θ) , Target to Jet distance (H) and Velocity of fluid impingent (V) selected and shown in Table 2.4.

Table 2.4 : Range of experiments

Parameter	Steps considered				
D (mm)	8	12	16	---	---
Θ	15	30	45	60	75
H (mm)	10	25	40	55	--
V (m/s)	4.3	8.3	12.3	16.3	20.3

2.7 Conclusion

With comprehensive cooling approach of electronics devices, jet is to be placed at vertical plane, in line with edge of the target plate i.e. on leading edge, for offset cooling at different inclinations from 15 to 75 Degree is the gap found. The hypothesis of the physics of flow and problem with theoretical terms is to be defined specially for inclined jet with aim of understanding parameters to be considered during study.

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