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Research Article

# Temperature analysis for the horizontal target cooling with non-confined and inclined air jet

**Sunil INGOLE**

*Department of Mechanical Engineering, Indira College of Engineering and Management, Pune, 410506, India*

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## ABSTRACT

In jet impingement cooling applications, the inclined jet in non-confined condition; also called as submerged jet is experimentally investigated. The objective is to analyze for hot surface cooling applications. Air is used as the working fluid, by using placement of jet on the leading edge of a horizontal rectangular target plate at height H, and examined for downhill side comprehensive cooling performance approach. The jet Reynolds number in the range of $2000 \leq Re \leq 20000$ is investigated with circular jet for inclination of $15° \leq \theta a \leq 75°$. The effect of jet to target distance (H) is also investigated in the range $0.5 \leq H/D \leq 6.8$. The temperature variation at the center line of target is studied with analysis of temperature profile. Its variation with respective to horizontal distance of jet from leading edge (X) and counters are plotted for jet diameter (D) of 16mm. The location of minimum temperature during cooling by jet impingement, goes to downhill side for jet impingement with an angle of 75, 60, 45, 30 and 15°. Cooling is observed to be increase up to $X/D = 5$, and then it declines. The cold spot is seen at ($X/D$) of around 5 to 7 except at high Reynolds number. The impact of jet inclination is more on temperature variation of flat target, compared to other parameters.

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## INTRODUCTION

Thermal cooling management is one of the most engrossed and significant region in various applications due to requirement of massive cooling. Cooling systems are integral part of all applications in electronics, machining, metals forming, etc. All such and similar uses of cooling requirements are having prominent importance as the overheating may cause the entire system to fail with major damage and non-achievement of objectives. The hardware failure of systems will result in damaging components and may even lead to burning of system due to excessive temperature, by creating severe effects on entire plant and operations.

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

***Corresponding author.**
*E-mail address: sbingole1@rediffmail.com

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1. Making compact cooling solution with high heat dissipation capacity system is required as space is constraint for many applications such as space, electronics, etc.
2. Making lower cost effective solutions are always desirable as manufacturing and operative costs will effect on economics in overall working of systems.
3. Making cooling systems which will not fail during operation this indicates with high reliability. For this typically active and passive cooling systems are used in combination.
4. Inventing low cost, high conductive adhesive material by composites or such methods as to use in components hardware. By these improvements in hardware will take place and it improves material properties related to thermal performance.
5. Use of hybrid system, which combines more cooling techniques, as sometimes use of one system and its failure may be dangerous.
6. Application of direct liquid cooling which might be effective but for typical electronics applications it is an important challenge.
7. Investigating and manufacturing high performance air cooling / air movers with higher heat carrying capacity.
8. Study and implementation of acoustic issues for high speed air movers / fans / jets.
9. Minimize impact on environment by using minimum power or use of solar power for cooling equipment.

Jet cooling technique review is conducted. This includes confined jet impingement [1], jets by impinging normally upward on the target surface [2], multi air jet array [3], staggered arrays [4], are explored experimentally for jet cooling analysis. Jets can be classified based on different factors associated with jet generating system, fluid used, position of jet placement, number of jets used, jet geometry, etc. Also inclination and orientation of jet will effect on its performance [5] Twisted tapes are used for making swirling jet [6] flow to make more turbulence. A jet in jet, called coaxial jet mixing with swirled inner jet [7] is also used. A jet can be rotated instead of fluid rotation, called rotating jet [8]. As reported, jet geometry plays vital role in flow pattern generation. In this line, slot jet of air [9], spent air exits [10], have proved variations in physical structure / method of jet used for improving effectiveness.

Various types of fluids are used to carry heat from hot surface. De-ionized water [11], air and water jets [12], mist jet impingement cooling using air-liquid mist [13], fluids with nanoparticles [14], electrically charged micro droplets [15] are the variations detected in jet fluid. Even, oil is also [16] observed to be one of the fluid experimented.

If also fluid is one of the important selection parameter for jet, for economic production of jet, the method of producing jets is also considered to be the important. Synthetic jet [17], synthetic pulsating jet [18], high formation frequency synthetic jets [19], micro-jet [20], verified and found as improved effective.

The physical exit paths in a compact system gives diverse flow patterns of jet fluid. Accordingly, elliptical shape [21], cusped elliptical [22], typical variations in inlet and outlet geometries of liquid jet [23], straight, chamfer inlet, chamfer outlet, chamfer in and outlet, countered inlet, and countered in and outlet, are studied. Triangular, square, pentagonal, and hexagonal shapes [24] are testified but slot jet and circular jets are used frequently due to their easiness in making and installation and application.

Frequency of jet indicates magnitude of pulsation of jet and such pulsating jets are analyzed [25]. Flow currents, eddies and ultimately heat transfer also depends on the surface on which jet is to be impinged. Jet on a pin fin heat sink [26], jet on and around a central pedestal [27], jet on micro channel heat sink [28], jet on single spherical cavities [29], are considered. The cooling effectiveness of jet depends on criterions like method used for jet production, fluid used in jet, orientation of jet, application specific, direction of jet impingement, physical structure like shape, size, of jet etc.

By seeing detailed study under all such type of vast jet configurations from literature, it can be concluded that; there is no specific diameter, shape, fluid, and Reynolds number are used for the best recommended jet cooling applications, but it differs from case to case – application to application. Air is used as main fluid for jet cooling. Slot jets, circular jets, elliptical jets are investigated by many ways. Essentially, hydraulic diameter is the leading factor for altogether study. To practice a circular jet will help to make system easily, with compactness, which is one of the prime requirement.

To make compact systems, compact jets are to be thought, inclined jet is one of the promising area for analysis. Heat transfer analysis is investigated for understanding effect of exit air, in which the target plate is inclined at an angle to base reference [30]. Inclined vertical surface characteristics by using horizontal air jet [31], are observed in literature. Jets are to be used for heating as well as cooling applications [32]. As stated earlier, cross-section of jet in inclined jet also plays role and variations are observed in literature [33]. Local convective heat transfers from a vertical heated surface to an inclination (90 to 45°) of circular free-surface jet is investigated [34]. Two inclined jets for different geometry [35] and four jets [36] numerical analysis is presented to increase effective cooling. Jet Correlations are available in the form of summarized table, which are represented by various authors [37].

The heat transfer characteristics for an inclined jet with cross flow [38], is given and even 2D jets [39] are also considered for analysis for simplicity. A spray cooling effect on cooling performance for electronics applications with (0, 20, 40, 50, and 60°) are analyzed [40]. Convection between a downward facing inclined wall [41], the hot object which is to be cooled is placed in moving position [42], and it is impinged with inclined jet, such compound techniques are also used. By compared with perpendicular jet, inclined jet is significantly neglected area, because of which probably perpendicular jet arrangements and applications for cooling are recognized generally [43]. The review of experimental jet study is presented [44] [45]and the inclined jet compressive review in table form is summarized as in Table 1.

In spite of all above challenges, research takes place for many equipment, applications and used many methods. In overall, the heat produced by individual component can be dissipated by using spot cooling methods. But challenge can be to dissipate it for bigger volume or surface. This requisite can be focused and called as 'comprehensive cooling'. This can be attained by inclined jet impingement methods, which moves its fluid flow volume with high velocity impact on target surface, and inclination gives overall cooling solution. The clear temperature variation analysis of inclined jet cooling is not being observed. Also its position and analysis of cooling spots with reference to inclinations are required to study for cooling solution design.

The consideration of cooling of entire object surface, called as comprehensive / collective cooling approach the experiment is designed. In such configuration, jet is not impinged at the center of the target object, but it is located at the vertical plane, which is in line with edge of the target plate i.e. on leading edge. It is also called as 'offset cooling', and same is used in current study. To examine and understand effect of offset jet impingement cooling on typically temperature by use of inclined air jet, at Reynolds numbers up to 20000 is the objective. If careful analysis is performed,

**Table 1**. Inclined jet review

| Author | Jet size | number of jet / configuration | Re | Angle (°) | Other |
|---|---|---|---|---|---|
| Albert Y. Tong [43] | 2mm | Circular and parabolic | 2500, 5000, 10000 Water | 45-90 | Numerical sol. |
| Ali A. Al Mubarak, Syed M. Shaahid, Luai M. Al-Hadhrami [30] | 5mm | single array, equally spaced, 13 Circular jets | 9300, 14400, and 18800 Air | 1.5 | - |
| Sunil B. Ingole., Sundaram K. K. [46], [47] | H/D as 0.5 to 6.8 | Single circular | 2000-20000, Air | 15-75 | - |
| Hakan F. Oztop a,b, Yasin Varol, Ahmet Koca, Mujdat Firat, Betul Turan, Ilhan Metin [48] | 4mm | One jet, Circular | 2800, 9000, and 36,000 | 90 to 150 | - |
| Haydar Eren, Nevin Celik [49] | 30 mm × 2 mm | One slot jet | Air, 11800, 8800, 5800 | 30, 45, 60, 90 | Wind tunnel |
| Sunil B Ingole [50] | 5 mm | 4 | Up to 2000 | 60, 120 | Mixing jets |
| Jiwoon Song, Jang Woo Lee,Man Sun Yu,Sangwoo Shin,Beom Seok Kim, Hyung Hee Cho [32] | 10 mm | One circular jet | Compressed Air | 0 to 30 | Hot air on plate |
| Kyosung Choo, Tae Yeob Kang, Sung Jin Kim [33] | 2 × 20mm | slot | Air, 3000 to 25000 | 0 to 40 | - |
| C. F. Ma, Q. Zheng, K. Wu [34] | 0.987mm × 35 mm | Circular jet | Oil, 235 and 1745 | 90 to 45 | Oil used |
| Mizuki Kito [51] | 5 × 50mm | Slot | Air, 5000 | 0 to 60 | Twin jets |
| Ramezanpour A., Shirvani H., Mirzaee I [39] | NA | Slot | 4000-16000 | 40-90 | CFD |
| Soon Hyun Yoon, Moon Kyung Kim, Dae Hee Lee [52] | 350 × 26.5mm | slot | 10000-35000 | 60-90 | - |
| Victor Adrian Chiriac, Jorge Luis Rosales [53] | 10 mm wide | Slot, two jets | 300-600 | 30 | - |
| Sunil B. Ingole [54] | 10mm | 4 jets, 9 jets, pitch 15-30 mm | 2000, air | 90 | - |
| Yue-Tzu Yang, Yong-Xun Wang [38] | 6mm | Circular | 5000 | 45 | Cross flow |
| M. Zunaid, Afzal Husain, Bhupendra Singh Chauhan, Rohit Sahu [55] | 0.1 to 0.2mm | 4,5,9,13,16 jets | Fixed mass flow | 45 | Micro jets |
| Kuldeep Baghel, Arunkumar Sridharan, Janani Srree Murallidharan [56] | 6mm | circular | 17000-42000 | 15, 30, 45 | on convex surface |

**Table 2.** Parameters considered for study

| Parameter | Range | | | | |
|---|---|---|---|---|---|
| **D (mm)** | | | 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 |

common jets are using jet diameters in the range of 5 to 30 mm and choice of jet diameter is to be governed by the manufacturing capacity of designers and machines used. In general, only one diameter is investigated, (D = 16mm in presented case) as Reynolds number is function of hydraulic diameter of jet. The diameter of 16mm is selected as to acquire Reynolds number range, necessary for analysis. To understand behavior of heat-transfer and temperature ranges, wide range of Reynolds number are used. The parameters of interest and levels are of : diameter of jet (D), angle of jet impingement (Θ) , object to jet height (H) and velocity of air impingent (V) selected and used to calculate Reynolds number in Table 2. As per literature and results represented in that, the diameter of jet used to impinge the fluid is considered as characteristics length for all calculations and analysis. Same is considered in present study and related with jet outlet, as it will decide the flow pattern and contour currents.

## EXPERIMENTATION

Experimental work is proposed for investigation as per parameters decided. The setup has the air jet impingement arrangement with required inclination on object to be cooled. The object target plate is to be heated by providing electrical supply and supply is recorded by measuring Voltage and Current. This energy is supplied to the target plate for heating, which is to be dissipated out by fluid flow of impinged jet.

Following assumptions are made during calculations and experimentation.

1. The supply of heat is fixed – As the target plate is heated by using electric supply to simulate the heating condition, constant supply is assumed to be given to plate in spite of minor variations, as it does not affect majorly on heating system.
2. Insignificant heat loss by heat conduction through the object is assumed as thickness of plate is very small and lower side is insulated for radiation heat loss by applying color. Convective heat loss is neglected as air flow is prevented from bottom side of the plate.
3. The plate material used is consistent as it is taken from one bigger size plate, and minor material variations can be neglected.
4. Air is used as a working fluid that will lead to assume constant Pr with value 1. As we change air Pr, it will majorly add multiplying factor to equations. If fluid is changed for cooling applications, then Pr is to be considered as it effects strongly on heat transfer.

The heated object will dissipate heat by both surfaces. The heat transfer takes place by majority by convection, and partly by conduction and radiation. The heat transfer through conduction by thin object is very minor and hence to be neglected. The radiation heat loss by the thin foiled target from bottom is neglected as it is coated with black color and from top surface it is neglected. Heat transfer by natural convection from bottom side is minor and neglected.

The energy coming out of plate is written as:

$$E_{out} = Q_{conv.jet} + Q_{conv.bottom} + Q_{rad(both\ surface)} + Q_{cond} \quad (1)$$

The experimental setup is as shown in Figure 1 , the blower is used to supply air (Powerica Ltd., Centrifugal Type, Rated RPM 1500, 500 CFM, with motor 0.5 HP) with the arrangement of generation of air jet and its impingement on the target is made. The initial temperature of target is room temperature. The object target surface is placed horizontally [47].

The test object is hot flat surface. It is manufactured by thin foil of stainless steel 0.05mm thick and heated by Joule's effect. The one side surface area of target plate is 264mm x 108mm. The flat plate is fixed in between two copper bus bars in close-fitting plane position. The housing is made ready with the purpose of placing the target plate as per essential location. Also it is easy to adjustment height distance of jet from target (H). This height 'H' is verified with use of height blocks of standard sizes. Copper bus bars are fixed in combination with heater plate foil [57]. The supply of 230V, 5Amp is given to a transformer (Make – Super transformers, input 440/230V, Max DC voltage 60 V, 50 Hz, Insulation class – A, Max Current 300Aand converted to required ratings) and the supply given to target surface is of 3V and 50Amp AC. This heated target plate is dissipating heat by impinging air by circular cross-section jet. The width of target plate (shorter side) is considered as the reference Y axis for tracing the jet position. The jet is placed at the center location along the width of target surface. The longer side of target plate (length) is considered as X reference axis. For cooling of target plate, air is used as a fluid in present study. This will also satisfy requirements of air at Reynolds number varying from 2000 to 20000. The jet to target plate distance is one of the significant parameter to examine. To understand the effect of change in height H, it is wide-ranging from 10 mm to 55 mm. The axis of jet can make an angle of 0 to 90° with horizontal target plate as shown in block diagram. The angle of impinged jet is measured by angle measuring unit which is placed at the exit end of the jet. An infrared thermometer (Kusam-Meco

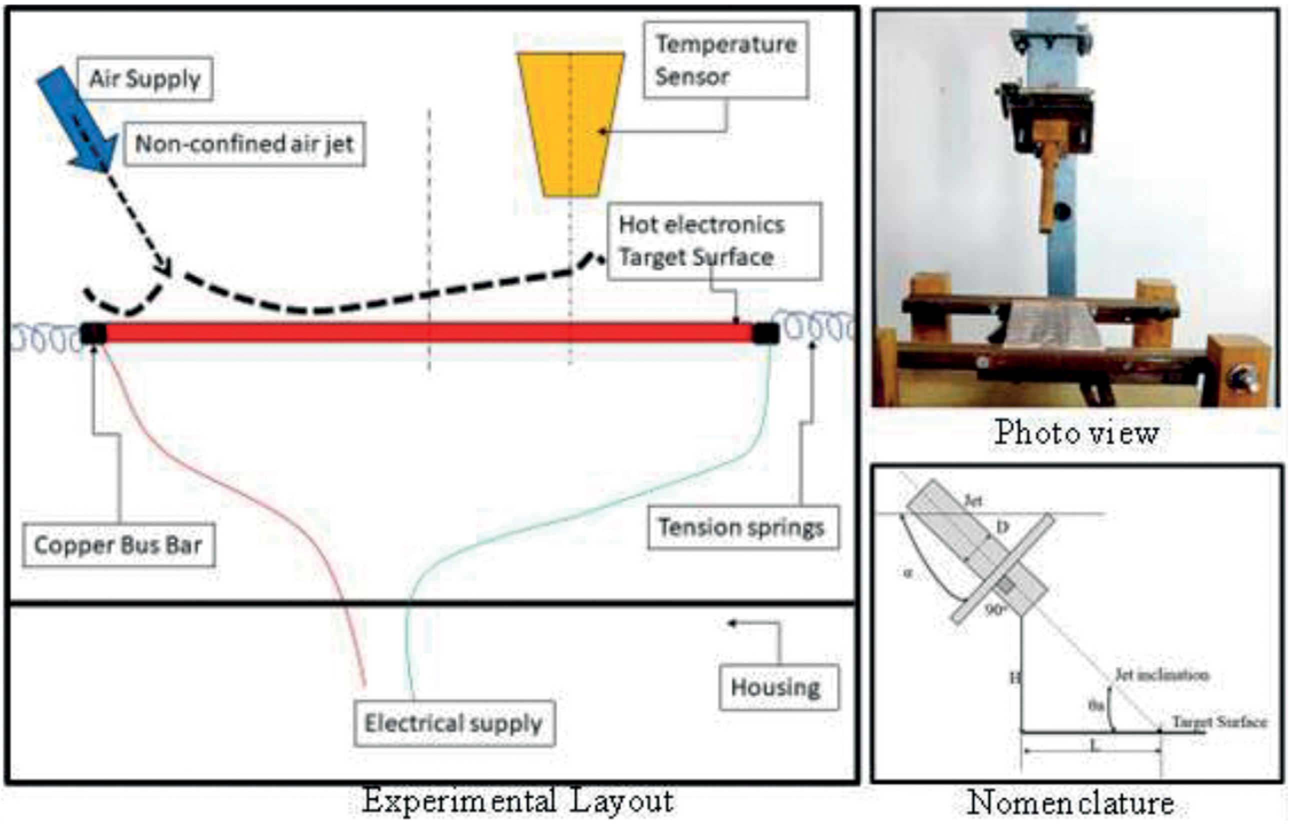



**Figure 1.** Experimental setup and nomenclature.

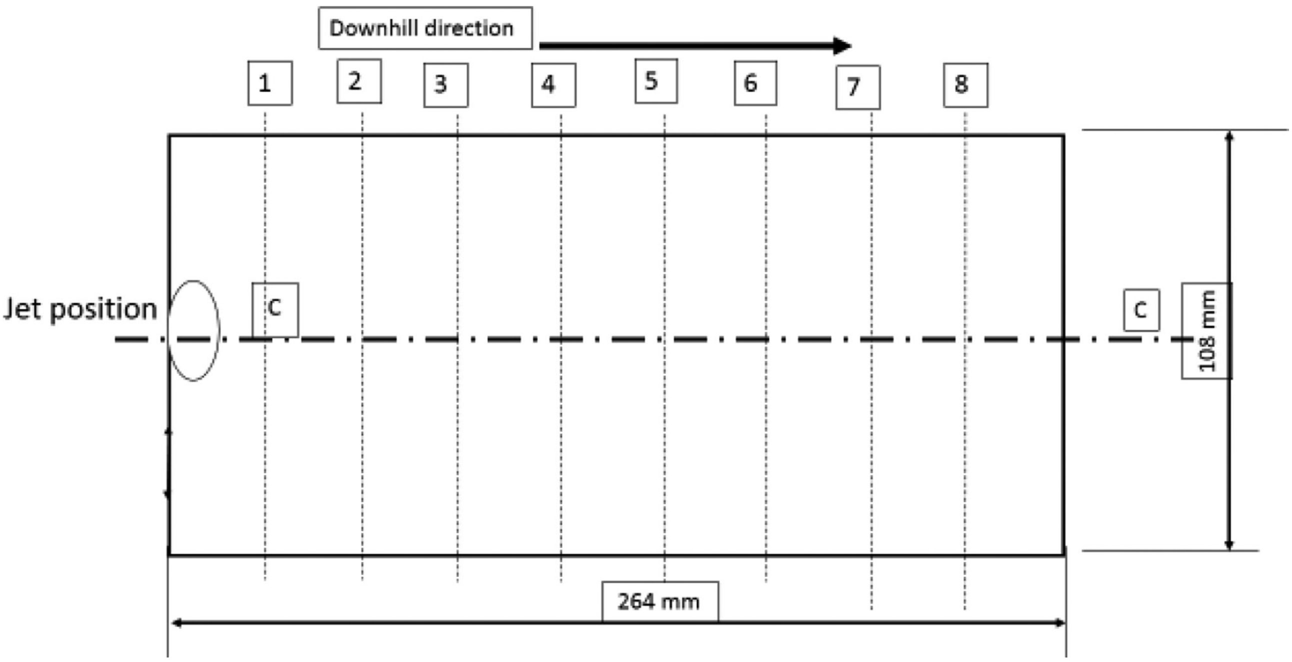



**Figure 2.** Target plate to be cooled.

**Table 3.** Uncertainty analysis

| S. No | Parameter | Symbol | Uncertainty |
|---|---|---|---|
| 1 | Jet air velocity | V | 0.49 to 2.3 % |
| 2 | Current supplied to heater | I | 5 % |
| 3 | Voltage applied to heater | V | 0.18 % |
| 4 | Temperature of target plate | T | 0.6 - 2.5 % |
| 5 | Reynolds number | Re | 4.4 to 6.6 % |
| 6 | Heat supplied | Q | 5 % |
| 7 | Nusselt number | Nu | 5.76 to 8.79 % |

IRL900, range – -30 to 550°C, Accuracy +/- 0.02 C for up to 100⁰C and 1% for greater than 100°C, 0.1 to 1 adjustment) is used to take temperature readings of the target plate. Total forty points are denoted to measure temperature on target plate. The velocity of air jet is measured (and then formulated in Reynolds number) by using anemometer. (TES Electrical Electronic Corp., Triple Display, 4 Digit LCD, 0 – 30 m/s range with 0.01 m/s resolution. Accuracy +/– 3%, Response Time 2 seconds). All readings are taken at steady state conditions, which is tried initially by using normal heating and cooling recordings, and takes place after +22 minutes. It will be considered as jet exit velocity, and used as governing parameter to calculate Reynolds number.

The experimental setup is validated by using available equations for perpendicular circular jet [58]. It is observed that stagnation Nusselt number is matching with results from equations and experiments in ± 10 %. The uncertainty analysis for various parameters are presented in Table 3.

## TEMPERATURE STUDY – CENTER LINE OF TARGET PLATE ANALYSIS

The jet cooling gives heat transfer enhancement [59], but in presented case only temperature as the parameter used for analysis. The average cooling is analyzed related to temperature profile after cooling steady state. After data collection and plotting, results are noted and presented. Center line of target temperature analysis, temperature ratio analysis, its variation related to height H, variation of temperature ratio with inclination, effect of Reynolds number, and minimum temperature are presented. Also to understand cold spots, temperature profiles of target at various experimental combinations are submitted with reference to jet impingement point. During initial study, it is observed that cooling takes place in negligible quantity for Re 2000 and for $(H/D)$ =6.8, hence not considered in this presentation.

The temperature at center line of target plate is noted. The temperature analysis gives entire view of cooling

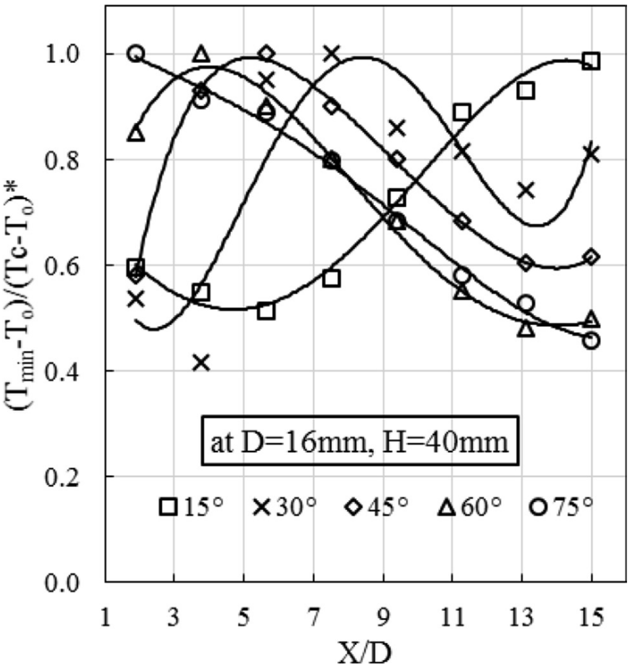



**Figure 3.** $(T_{min}-T_0) / (T_c-T_0)$, for different inclinations at H = 40mm.

analysis and pattern. Hence temperature at central line of the target plate (line C-C in Figure 2) is considered for analysis in this section. As cooling takes place symmetrically about this line, it is the best possible way to analyze data by investigations of non-dimensional temperature ratio $(T_{min}-T_0 / T_c-T_0)$. This nullifies room temperature effect on calculations and is frequently used in heat transfer analysis. The above stated ratio, in which $T_c$ indicates temperature at section C-C, can be understood by considering as $T_{min}$ equal to $T_c$. This indicates that ratio is 1, or the point where $T_c$ is measured is coolest point of section.

### Temperature Ratio for Different Jet Angles with H=40mm

Figure 3 shows the variation of $(T_{min}-T_0 / T_c-T_0)$, along X axis of target plate. It is plotted at target to jet height as 40mm. By this it is possible to locate the minimum temperature / cold spot conditions during cooling by jet impingement. Its location goes to downhill side for jet impingement with an angle of 75, 60, 45, 30 and 15°. The phenomenon of temperature jump is observed at 30° inclination at beyond $X/D$ of 13. It is because of fluid jump. 75 and 60° jet inclinations found to follow nearly same path after $X/D$ of 3 above. The cold spot location is going to change according to inclination changes. It can be observed that at 15° jet inclination, at $X/D$ 13 peak is observed indicating coolest point and it is related to geometrical inclination line (explained further). For 30°- angle trend line takes a deep at $X/D$ 13 as jet flow after impact will divert and mixes with surrounding as momentum force and does not have any more direction control after impact.

**Temperature Ratio for All Heights with respect to Jet Impingement Angles**

Also geometrically center line of jet intersects at the end of the target / downhill side end in case of jet of 15°, which is obviously as shown in Figure 4. Similarly, performance of analogous parameters for all target to jet heights from 10mm to 55mm are represented in Figure 5(a). It is strongly indicated that variations of temperatures are seen clearly as the function of impingement angle and angle is the predominant factor which influence on cooling. It is observed that trends are similar for 75, 60 and 45° of jet inclination, but it does show variations in pattern for 30 and 15° jet inclination. It is because of jet angle at 15 and 30° are making flow of air nearly parallel to plate and giving lesser cooling effectiveness. Further Fig 5 (b) shows normalized data indicating highest cold spot locations are at (*X* / *D*) of 2, 4, 6,8 and 15 for jet inclinations of 75, 60, 45, 30 and 15° inclination.

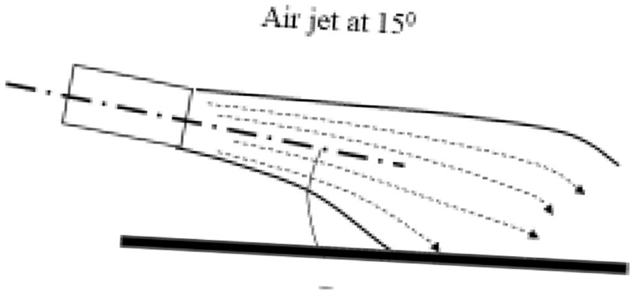
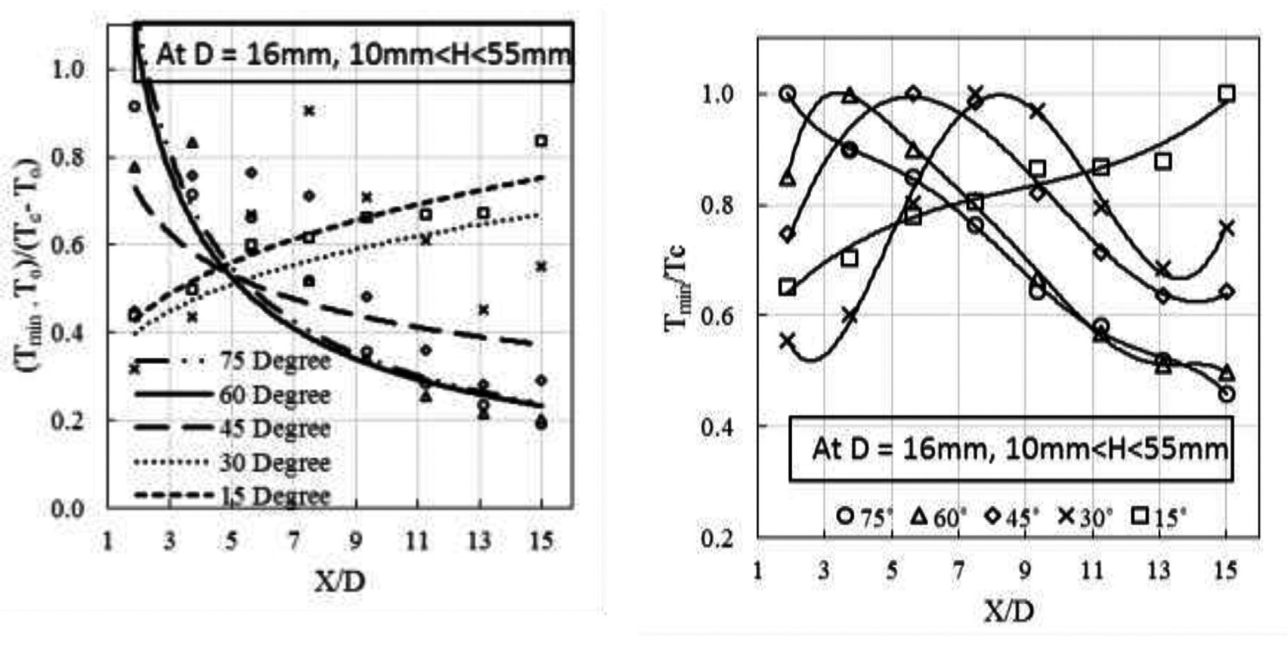



**Figure 4**. Air jet at 15 degree- Physics.

**Temperature Ratio for All Angles with respect to Variation in Target to Jet Height (H)**

The average of the non-dimensional temperature ratio ($T_{min}-T_0 / T_c-T_0$) is plotted for all angles and all range of Reynolds number with respect to different target to height distances H in Figure 6(a). It is observed that all trend lines are giving similar trends. Cooling is better at leading edge for H=10mm up to $X / D = 5$, then it decreases. Cooling appears to be increasing up to $X / D = 5$, and then it declines. The cooling intensity depends upon turbulence intensity of fluctuations near wall [60]. Hence turbulence created due to impact of jet gives good cooling results, but it vanishes in lesser *X* / *D* distances. It may be because of lesser turbulence intensity after specific X. At H as 40 and 55mm, the trend line gives nearly parallel and overlying pattern, because jet might get stabilize till it reaches the target. In the view of observing all graph points together, a common configuration is considered. The plot for all variations of inclinations (Θa), and target to jet height (H) is shown in Figure 6(b). It shows that better cooling takes place at *X* / *D* distance of 5 to 7.

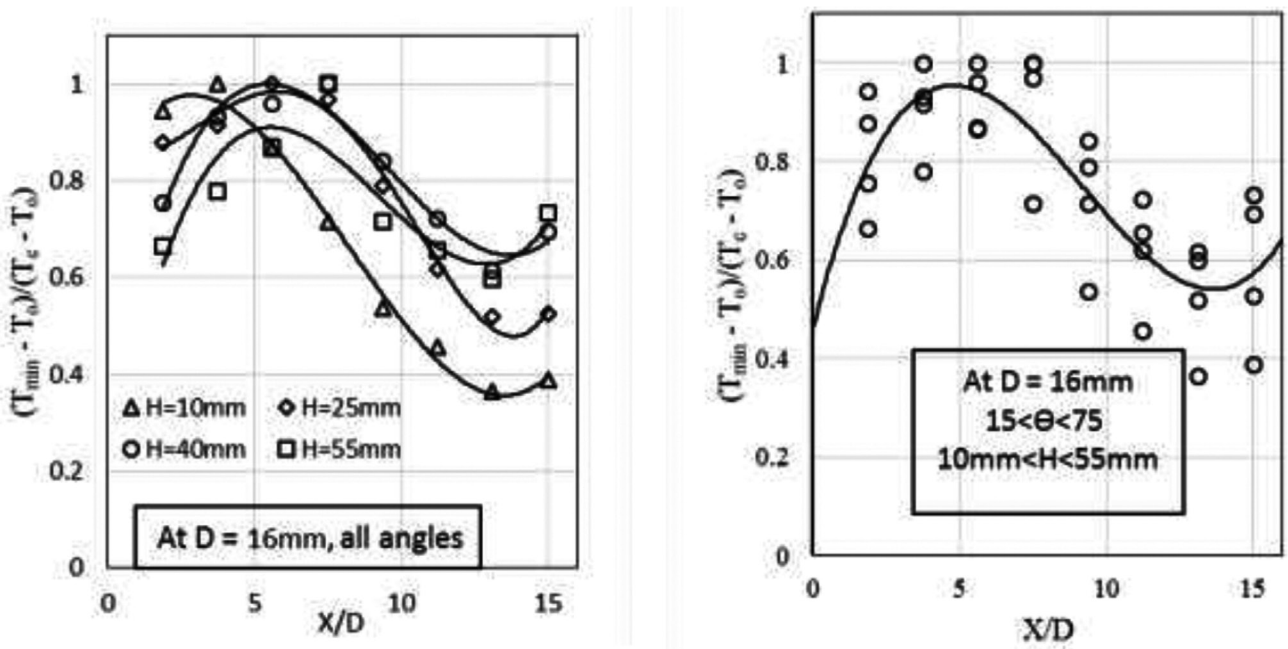



a) Temperature ratio b) Normalised data

**Figure 5.** Temperature ratio for different jet inclinations.

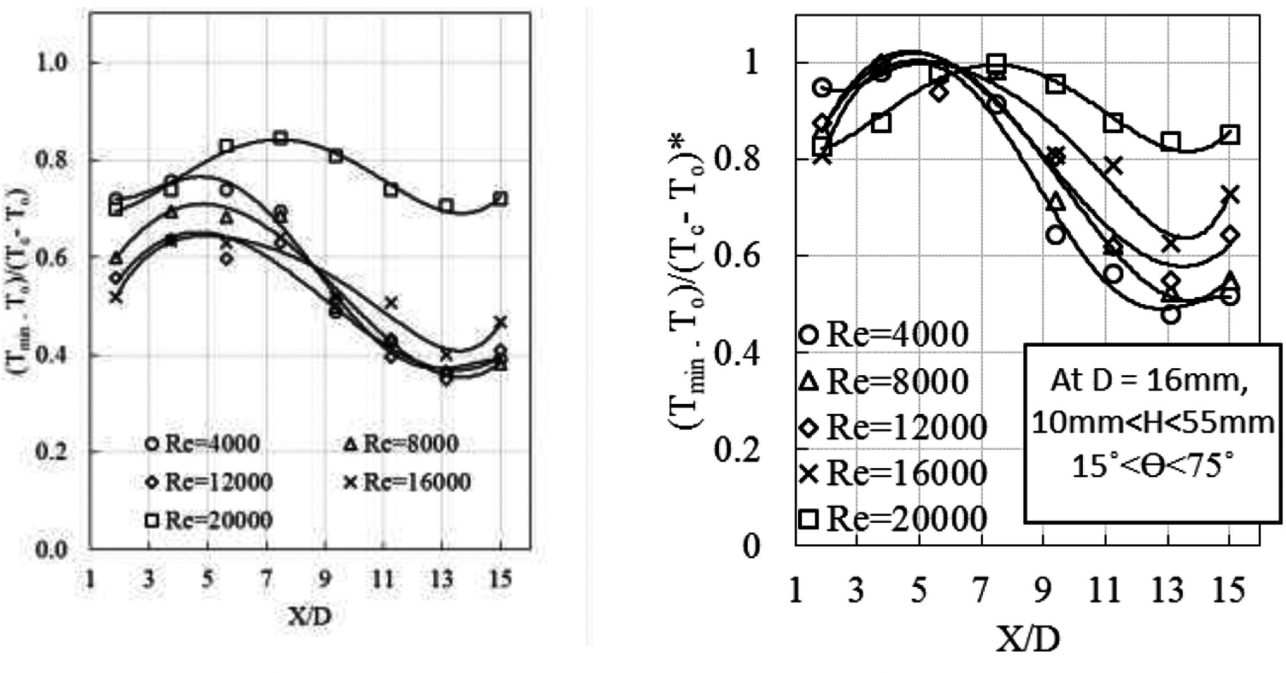
**($T_{min}$–$T_0$/$T_c$–$T_0$) Variation Related to Reynolds Number**

The variations of ($T_{min}$–$T_0$ / $T_c$–$T_0$), dimensionless temperature ratio and dimensionless (*X/D*) is plotted for Reynolds number ranging from 4000 to 20000, i.e. turbulent inclined air jet as shown in Figure 7. It is giving almost similar profiles for all range of Reynolds number. This will be helpful to know temperature at a particular location. The ratio ($T_{min}$–$T_0$/ $T_c$–$T_0$)* is normalized data plotted in Figure 7(b). In this figure, 1 on Y axis is indicating location of minimum temperature, or can be also called as cold spot




a) Jet inclinationwise b) Common plot for all H and Θ

**Figure 6.** Temperature ratio for various H.




a) Variation trends b) Normalised data

**Figure 7.** Temperature ratio variation related to Reynolds number.

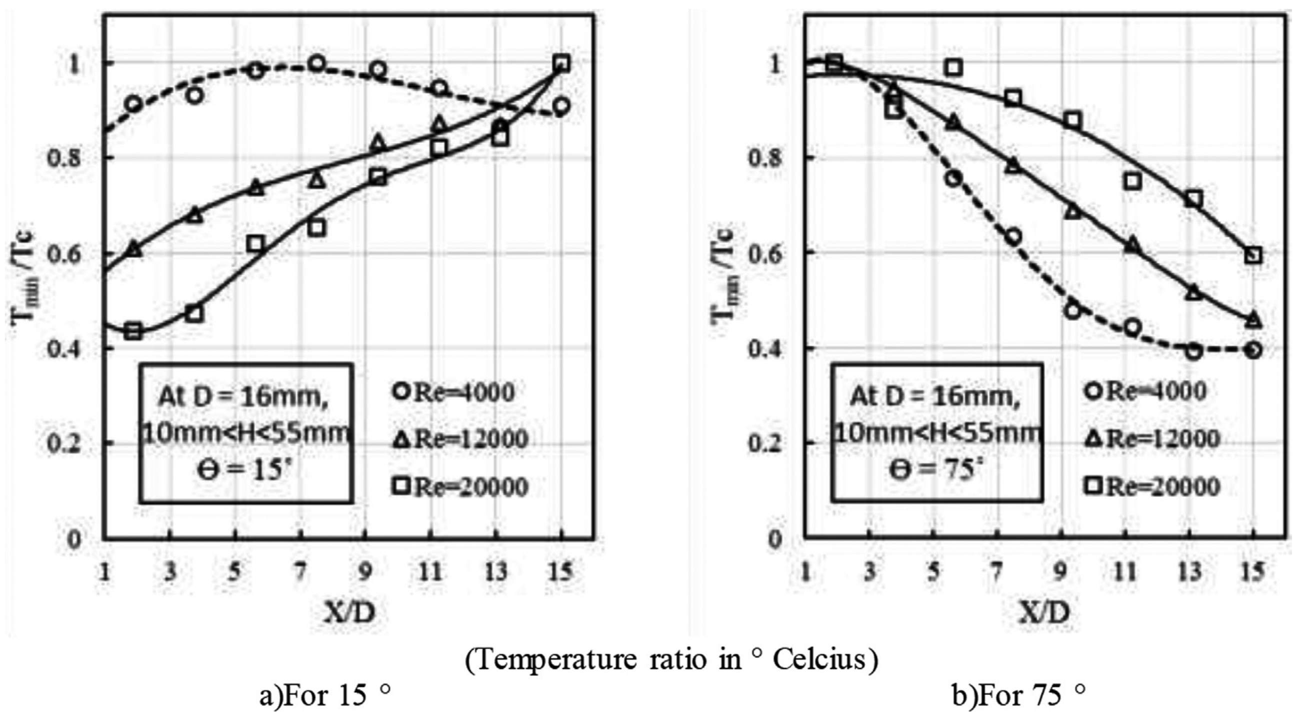



**Figure 8.** ($T_{min}/T_c$) for a specific angle of 15° and 75° and its effect at variation in Reynolds number a) 15°, b) 75°.

on target plate location. For jet diameter under study, best cooling is seen at ($X/D$) of 5 to 7. At higher Reynolds number better cooling is seen after cold spot. At the same time, lesser cooling is observed before cold spot. By this the trend on graph beyond $X/D$ as 6, are shifting upward / higher side with high Reynolds number giving ($T_{min}–T_0/T_c–T_0$)* higher.

This reverse change in direction of trendiness related to Reynolds number is called as 'Reversal cooing effect'. Also temperature jump is seen beyond $X/D$ of 13, giving hot spot at that location. The higher Reynolds number will produce massive scale vortex along the wall due to wall jet, and it sources difference in Nusselt number. The temperature jump may cause due to outer section turbulence by which thermal boundary layer gets disordered, particularly outside the impingement zone

**($T_{min}/T_c$) at Specific Jet Inclinations of 15, 45 and 75°**

The ($T_{min}/T_c$) is examined separately for a specific angle and its effect by variation in Reynolds number. Figure 8(a) shows the variations for jet inclination of 15°. It is seen that, after being exit at low Reynolds number, the jet flow change is direction due to lower momentum. By this cold spot is seen at ($X/D$) of around 5 to 7. But at high Reynolds number, because of high momentum of flow, cold spot is at extreme end of target plate ($X/D$ = 13 above). It is also observed that the cooling is uniform throughout the plate for 15°, shown by graph point locations in upper region on graph. Exactly reverse situation is seen for inclination of 75° as in Figure 8 (b). The cold spot is seen on / near leading

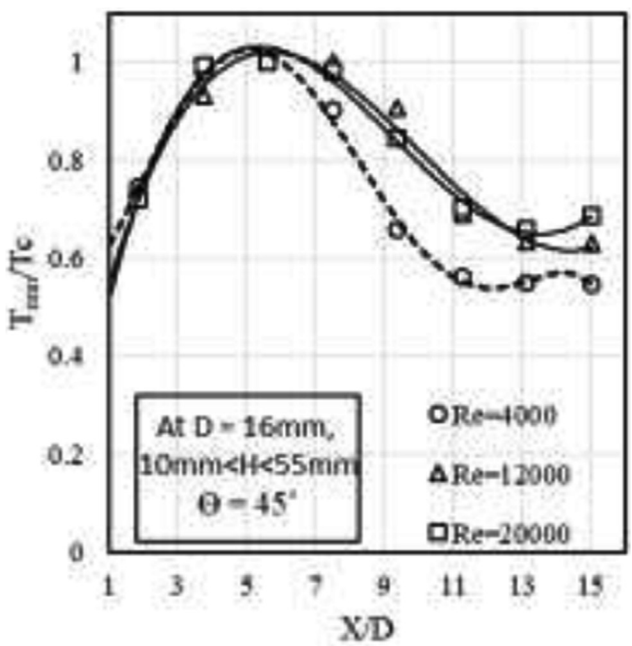



**Figure 9.** ($T_{min}$ / $T_c$) for a specific angle of 45° at variation in Reynolds number.

edge as expected. But in the downhill direction, the trend of increase in temperature is observed.

For the third case of 45°, it is seen that results are as expected and gets highest cooling at ($X/D$) of 5 as shown in

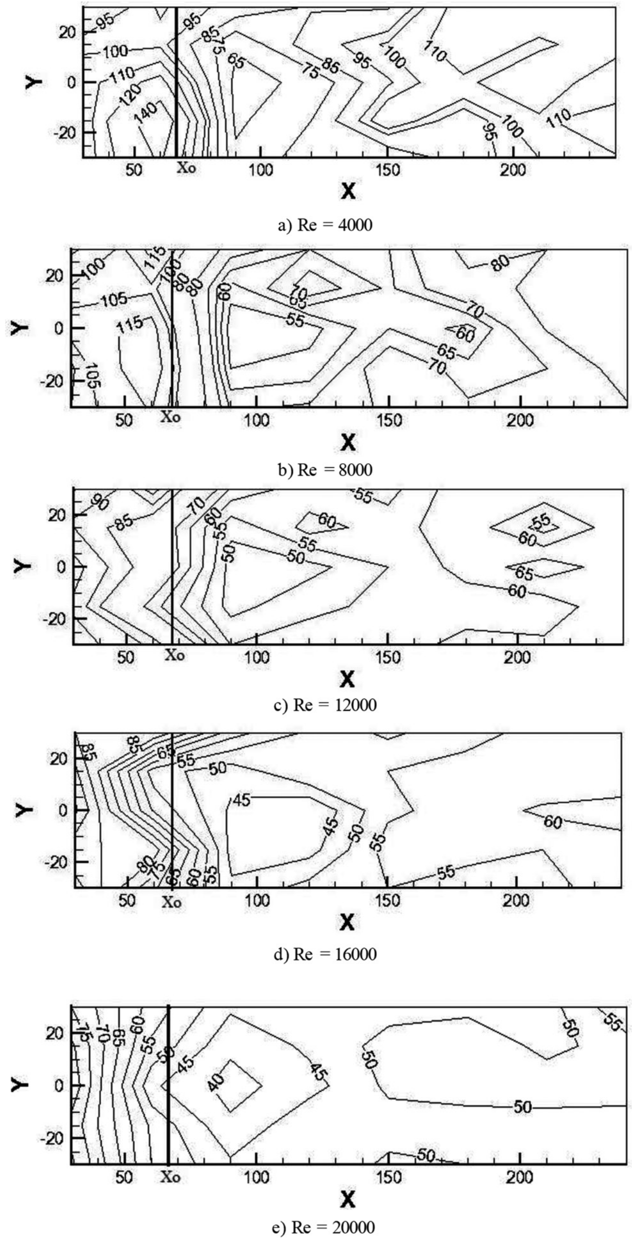



**Figure 10.** Temperature profile for Θa =45°, H/D=3.4 with a) Re = 4000, b) Re = 8000, c) Re = 12000, d) Re = 16000, e) Re = 20000**.**

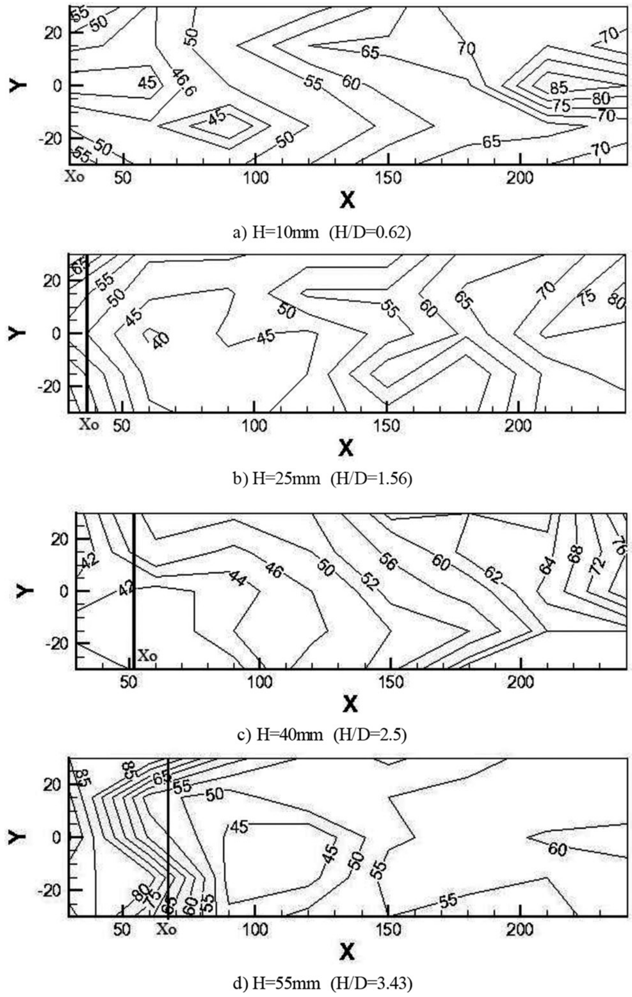



**Figure 11.** Temperature profile Θa =45°, Re = 16000 with a) H=10mm, b) H=25mm, c) H=40mm, d) H=55mm.

Figure 9. Reynolds number is having lesser impact on cooling performance compared with cooling performance due to inclination effect. For 45° of jet impingement, the temperature variation is nearly similar for both Reynolds number of 12000 and 20000. But at Reynolds number of 4000 only, the momentum of jet plays important role related to gravity, giving little diverted line. The temperature ratio gives the wavy nature indicates coolest point is surrounded by temperature isotherm contours.

## TEMPERATURE PROFILE AND COLD SPOTS

It is assumed for simplicity in analysis that the flow is of two dimensional. But as per understanding physics of flow, it is a complex and three dimensional phenomena [43]. Hence temperature variation on entire target surface is presented to understand the effect of inclined jet.

### Effect of Reynolds Number on Temperature Profile

The temperature profile at different Reynolds number ranging from 4000 to 20000 as plotted and shown in Figure 10. In the plot $X_0$ indicates position of jet. For understanding effect of jet cooling, and simplicity, target to jet height is kept constant as 55mm (H/D = 3.4) during the analysis in this section.

As known, highest Reynolds number is giving lowest temperature zone. But the position of cold spot remains same (almost around X distance of 100mm) as the effect of inclination dominates other factors. The $X_0$ is 66mm in this case, hence the uphill side flow in all the case is giving higher variation in temperature with smaller X distance, whereas for downhill side flow is showing lesser zones of temperature variation, as flow gets stabilize by creating boundary layer along surface.

**Influence of Target to Jet Height on Temperature Profile**

For understanding effect of variation in height on temperature profile of target, temperature contours are plotted. As H increases, cold zone gets shifted to downhill side, obviously the geometrical stagnation distance (the distance from leading edge, where axis of jet geometrically intersect on target surface) effects on location of cooling zone. In plot it can be observed that apart from geometrical stagnation distance (Xo) (shown by dark vertical line) and proximate area of that line, the temperature profile is showing large variations in temperature as in Figure 11. The Reynolds number is function of velocity and convective heat transfer coefficient increases as jet impinges on the surface [61], as a result of flow counters with velocity and momentum.

**Effect of Jet Inclination on Temperature Profile**

Temperature profile isotherms for 15°, 45° and 75° jet inclinations is shown in Figure 12 a), b), and c) respectively. The effect of temperature profile variation is to be seen during change in inclinations of jet. The location of minimum temperature during cooling by jet impingement, goes to downhill side (Figure 12) for jet impingement with an angle of 75, 60, 45, 30° and 15°, 75° and 60° jet inclinations found to follow nearly same path after *X*/*D* of 3 above and jet inclination angle is the predominant factor which influence on cooling. The variations of ($T_{min}$ / $T_c$), dimensionless temperature ratio and dimensionless (*X*/*D*) is giving almost similar trends for all range of Reynolds at ($T_{min}$/$T_c$) jet inclinations of 15, 45 and 75°. Reynolds number is having lesser impact on cooling performance related to location/place. During analysis of temperature profile of a target, it can be observed that apart from stagnation distance and surrounding region, the temperature profile is showing large variations in temperature.

It can be concluded that, for 15° inclined jet, it can be seen that lowest temperature zone is at the end of downstream boundary of target plate. For 45°, it shifts to center of X distance, whereas for 75° it is on the leading edge of the target plate. As stated in earlier sections, jet under study is considered as submerged jet of alike fluid. The aim in this article is investigate location of maximum cooling / heat transfer by identifying hot and cold spots. When air impingement jet angle increases, the three dimensional velocity gradient is decreased at the location of maximum cooling. [34] This happens because jet fluid entry near surface volume starts heat exchange between the jet and plate, typically on upstream side. This leads to growth in spread

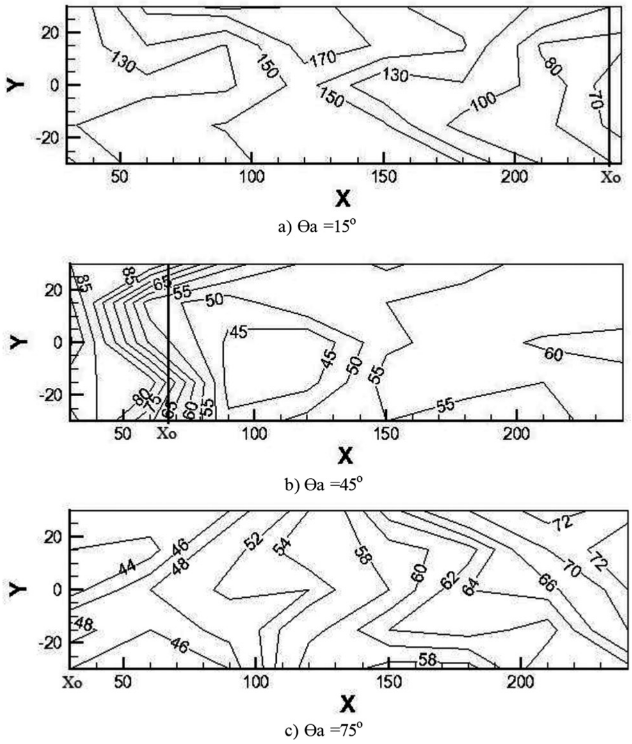



**Figure 12.** Temperature profile for H = 55mm, Re = 16000 with jet inclination of a) 15°, b) 45°, c) 75°**.**

in flow on opposite i.e. downstream side. Whereas, on the contrary the flow reduces in upstream side. This leads to crowded temperature profile lines in upstream side leading to poorer heat transfer.

## CONCLUSION

The inclined, non-confined jet of air is experimentally investigated for cooling the hot target plate. The conclusions are:

- The Center line temperature analysis shows that the location of minimum temperature during cooling by jet impingement, goes to downhill side for jet impingement with an angle of 75, 60, 45, 30 and 15°.
- The phenomenon of fluid jump is observed at 30° inclination at beyond of 13.
- Cooling is observed to be increase up to *X*/*D* = 5, and then it declines. The variations of dimensionless temperature ratio and dimensionless (*X*/*D*) is giving almost similar trends for all range of Reynolds number at jet inclinations of 15, 45 and 75°.
- Cold spot is seen at (*X*/*D*) of 5 to 7. But at high Reynolds number, because of high momentum of flow, cold spot is at extreme end of target plate (*X*/*D* = 13 above).

- It is also concluded that Reynolds number is having lesser impact on cooling performance related to cold spot analysis in inclined jet cooling.
- During analysis of temperature profile of a target, it is concluded that apart from geometrical stagnation distance and nearby region, the temperature profile is showing large variations in temperature, which is difficult to predict owing to boundary effects.

Analysis of combination of jet cooling or multiple inclined jet cooling, its variation with same and different inclination can be future scope for analysis for compact cooling devices.

## NOMENCLATURE

| | |
|---|---|
| A | Area ($m^2$) |
| D | Diameter / Hydraulic diameter of Jet (m) |
| H | Target to jet height (m) |
| h | Convective heat transfer coefficient ($W/m^2K$) |
| I | Current (Amp) |
| Lc | Characteristic length (m) |
| Q | Heat (W) |
| T | Temperature (°C or K) |
| V | Velocity (m/s) |
| X | Distance, along X Axis (m) |
| Xo | Geometrical Stagnation distance (m) |

**Symbols**

| | |
|---|---|
| θ | Angle (°) |
| ρ | Density ($kg/m^3$) |

**Non Dimensional terms**

| | |
|---|---|
| AR | Angle Ratio |
| EF | Enhancement Factor |
| Nu | Nusselt number |
| Pr | Prandtl number |
| Re | Reynolds number |

**Subscripts / Superscript**

| | |
|---|---|
| a, act | Actual |
| avg | Average |
| avg-y | Average along Y axis |
| c, c-c | Along Centerline |
| Conv | Convection |
| max | Maximum |
| min | Minimum |
| o | Ambient Condition |
| x,y,z | Directions |
| * | Normalized |

## DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

## CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

## ETHICS

There are no ethical issues with the publication of this manuscript.

## REFERENCES


[1] San JY, Shiao WZ. Effects of jet plate size and plate spacing on the stagnation Nusselt number for a confined circular air jet impinging on a flat surface. Int J Heat Mass Transf 2006;49:3477–3486. [CrossRef]

[2] Baydar E, Ozmen Y. An experimental investigation on flow structures of confined and unconfined impinging air jets. Heat Mass Transf 2006;42:338–346. [CrossRef]

[3] Chougule NK, Parishwad GV, Gore PR, Pagnis S, Sapali SN. CFD analysis of multi-jet air impingement on flat plate. In: Ao SI, Gelman L, Hukins DWL, Hunter A, Korsunsky AM, editors. Proceedings of the World Congress on Engineering; July 6-8; London, UK: Newswood Limited; 2011. pp. 2431–2435.

[4] San JY, Tsou YM, Chen ZC. Impingement heat transfer of staggered arrays of air jets confined in a channel. Int J Heat Mass Transf 2007;50:3718–3727. [CrossRef]

[5] Ingole S, Sundaram K. Investigation of maximum Nusselt number with inclined and non-confined offset jet impingement cooling. Int J Heat Technol 2018;36:869–876. [CrossRef]

[6] Wen MY. Flow structures and heat transfer of swirling jet impinging on a flat surface with micro-vibrations. Int J Heat Technol 2005;48:545–560. [CrossRef]

[7] Dellenback PA, Sanger JL. Heat transfer in coaxial jet mixing with swirled inner jet. J Heat Transf 1994;116:864–870. [CrossRef]

[8] Hong SK, Lee DH, Cho HH. Heat/Mass transfer measurement on concave surface in rotating jet impingement. J Mech Sci Technol 2008;22:1952–1958. [CrossRef]

[9] Gori F, Petracci I, Tedesco V. Cooling of two smooth cylinders in row by a slot jet of air with low turbulence. Appl Therm Eng 2007;27:2415–2425. [CrossRef]

[10] Huber AM, Viskanta R. Cornvective heat transfer to a confined impinging array of air jets with spent air exits. J Heat Transf 1994;116:570–576. [CrossRef]

[11] Bintoro JS, Akbarzadeh A, Mochizuki M. A closed-loop electronics cooling by implementing

single phase impinging jet and mini channels heat exchanger. Appl Therm Eng 2005;25:2740–2753. [CrossRef]
[12] Glynn C, O'Donovan, Murray DB. Jet impingement cooling. Proceedings of the 9th UK National Heat Transfer Conference. 2005:1–9.
[13] Graham KM, Ramadhyani S. Experimental and theoretical studies of mist jet impingement cooling. J Heat Transf 1996;118:343–349. [CrossRef]
[14] Di Lorenzo G, Manca O, Nardini S, Ricci D. Numerical study of laminar confined impinging slot jets with nanofluids. Adv Mech Eng 2012;4:248795. [CrossRef]
[15] Deng W, Gomez A. Electro spray cooling for microelectronics. Int J Heat Mass Transf 2011;54:2270–2275.
[16] Issa RS. Heat transfer performance of an oil jet impinging on a downward-facing stainless steel plate. Therm Sci 2011;15:397–408. [CrossRef]
[17] Garg J, Arik M, Weaver S. Meso scale pulsating jets for electronics cooling. J Electron Packag 205;127:503–511. [CrossRef]
[18] Utturkar Y, Arik M, Seeley CE, Gursoy M. An experimental and computational heat transfer study of pulsating jets. J Heat Transf 208;130:062201. [CrossRef]
[19] Pavlova A, Amitay M. Electronic cooling using synthetic jet impingement. J Heat Transf 2006;128:897–907. [CrossRef]
[20] Kercher DS, Lee JB, Brand O, Allen MG, Glezer A. Microjet cooling devices for thermal management of electronics. IEEE Trans Compon Packaging Manuf Technol 2003;26:539–546. [CrossRef]
[21] Arjocu SC, Liburdy JA. Identification of dominant heat transfer modes associated with the impingement of an elliptical jet array. J Heat Transf 2000;122:240–247.
[22] Dano BPE, Liburdy JA, Kanokjaruvijit K. Flow characteristics and heat transfer performances of a semi confined impinging array of jets: effect of nozzle geometry. Int J Heat Mass Transf 2005;48:691–701. [CrossRef]
[23] Whelan BP, Robinson AJ. Nozzle geometry effects in liquid jet array impingement. Appl Therm Eng 2009;29:2211–2221. [CrossRef]
[24] Kanamori A, Hiwada M, Oyakawa K, Senaha I. Effect of orifice shape on flow behavior and impingement heat transfer. Open Transp Phenom J 2011;3:9–16. [CrossRef]
[25] Sheriff HS, Zumbrunnen DA. Effect of flow pulsations on the cooling effectiveness of an impinging jet. J Heat Transf 1994;116:886–895. [CrossRef]
[26] Brignoni LA, Garimella SV. Experimental optimization of confined air jet impingement on a pin fin heat sink. IEEE Trans Compon Packaging Technol 1999;22:399–404. [CrossRef]
[27] Lee DH, Chung YS. Jet impingement cooling of chips equipped with multiple cylindrical pedestal fins. J Electron Packag 2007;129:221–228. [CrossRef]
[28] Jang SP, Kim SJ. Fluid flow and thermal characteristics of a microchannel heat sink subject to an impinging air jet. J Heat Transf 2005;127:770–779. [CrossRef]
[29] Terekhov VI, Kalinina SV, Mshvidobadze YM, Sharov KA. Impingement of an impact jet onto a spherical cavity. Int J Heat Mass Transf 2009;52:2498–2506. [CrossRef]
[30] Al Mubarak AA, Shaahid SM, Al-Hadhrami LM. Heat transfer in a channel with inclined target surface cooled by single array of centered impinging jet. Therm Sci 2013;17:1195–1206. [CrossRef]
[31] Naresh R, Ravinarayana BN. Experimental investigation of heat transfer on an inclined plate impinged with cold air jet. Int J Sci Eng Technol Res 2014;3:1843–1849.
[32] Song J, Lee JW, Yu MS, Shin S, Kim BS, Cho HH. Thermal characteristics of inclined plate impinged byunderexpanded sonic jet. Int J Heat Mass Transf 2013;62:223–229. [CrossRef]
[33] Choo K, Kang TY, Kim SJ. The effect of inclination on impinging jets at small nozzle-to-plate spacing. Int J Heat Mass Transf 2012;55:3327–3334. [CrossRef]
[34] Ma CF, Zheng Q, Wu K, Gomi T, Webb BW. Local characteristics of impingement heat transfer with oblique round free surface jets of large Prandtl number liquid. Int J Heat Mass Transf 1997;40:2249–2259. [CrossRef]
[35] Nakabe K, Fornalik E, Eschenbacher JF, Yamamoto Y, Ohta T, Suzuki K. Interactions of longitudinal vortices generated by twin inclined jets and enhancement of impingement heat transfer. Int J Heat Fluid Flow 2001;22:287–292. [CrossRef]
[36] Singh A, Prasad BVSS. Heat transfer and flow visulisation of equilateraly staggered jet arrangement on aflat surface. ASME 2020 Turbomachinery Technical Conference and Exposition; 2020 June 22–26; London, UK: American Society of Mechanical Engineers; 2020. pp. 1–10.
[37] Chirade S, Ingole SB, Sundaram KK. Review of correlations on jet impingement cooling. Int J Sci Res 2015;4:3107–3111.
[38] Yang YT, Wang YX. Three-dimensional numerical simulation of an inclined jet with cross-flow. Int J Heat Mass Transf 2005;48:4019–4027. [CrossRef]
[39] Ramezanpour A, Shirvani H, Mirzaee I. A numerical study on the heat transfer characteristics of two-dimensional inclined impinging jet. In: Iyer MK, Toh KC, Mui YC, editors. Proceedings of the 5th Electronics Packaging Technology Conference; 2003 Dec 12; Singapore: IEEE; 2003.

[40] Li BQ, Cader T, Schwarzkopf J, Okamoto K, Ramaprian B. Spray angle effect during spray cooling of microelectronics : Experimental measurements and comparision with inverse calculations. Appl Therm Eng 2006;26:1788–1795. [CrossRef]
[41] Bartoli C. Free convection enhancement between inclined wall and air in presence of expired jets at temperature difference of 40 K. Exp Therm Fluid Sci 2011;35:283–290. [CrossRef]
[42] Benmouhoub D, Mataoui A. Inclined plane jet impinging a moving heated wall. Fluid Dyn Mater Process 2014;10:241–260.
[43] Tong AY. On the impingement heat transfer of an oblique free surface plane jet. Int J Heat Mass Transf 2003;46:2077–2085. [CrossRef]
[44] Ingole SB, Sundaram KK. Review of experimental investigation in heat transfer for jet impingement cooling. Int Rev Mech Eng 2012;6:346–356.
[45] Pawar S, Patel DK. The impingement heat transfer data of inclined jet in cooling applications: A review. J Therm Sci 2020;29:1–12. [CrossRef]
[46] Ingole SB, Sundaram KK. Cold zone exploration using position of maximum nusselt number for inclined air jet cooling. Arch Mech Eng 2017;64:533–549. [CrossRef]
[47] Ingole SB, Sundaram KK. Experimental average Nusselt number characteristics with inclined non–confined jet impingement of air for cooling application. Exp Therm Fluid Sci 2016;77:124–131. [CrossRef]
[48] Oztop HF, Varol Y, Koca A, Firat M, Turan B, Metin I. Experimental investigation of cooling of heated circular disc using inclined circular jet. Int Commun Heat Mass Transf 2011;38:990–1001. [CrossRef]
[49] Eren H, Celik N. Cooling of a heated flat plate by an obliquely impinging slot jet. Int Commun Heat Mass Transf 2006;33:372–380. [CrossRef]
[50] Ingole SB. Cooling heat transfer analysis using multipleinline inclined air jet impingement. Int J Eng Innov Technol Explorig Eng 2019;9:535–540. [CrossRef]
[51] Kito M. Effect of inclination of impinging jets on flow and heat transfer characteristics. Int J Sci Eng Investig 2012;1:42–47.
[52] Yoon SH, Kim MK, Lee DH. Turbulent flow and heat transfer characteristics of a two-dimensional oblique plate impinging jet. KSME Int J 1997;11:476–483. [CrossRef]
[53] Chiriac VA, Rosales JL. The cooling impact of a pair of confined angled air jets impinging on a printed circuit board. In: Ramakrishna K, editor. The Ninth Intersociety Conference on Thermal and Thermomechanical Phenomena In Electronic Systems; 2004 Jun 1-4; Las Vegas, USA: IEEE; 2004. pp. 641–648.
[54] Ingole SB. Heat transfer analysis for multiple jet cooling of high temperature electronics target. 2017 International Conference on Intelligent Computing and Control Systems; 2017 Jun 15-16; Madurai, India: IEEE; 2017. pp. 215–220. [CrossRef]
[55] Zunaid M, Husain A, Chauhan BS, Sahu R. Numerical analysis of inclined jet impingement heat transfer in microchannel. Mater Today Proc 2021;43:557–563. [CrossRef]
[56] Baghel K, Sridharan A, Murallidharan JS. Inclined free-surface liquid jet impingement on semi-cylindrical convexcurved and flat surfaces: Heat transfer characteristics. Int Commun Heat Mass Transf 2021;121:105116. [CrossRef]
[57] Ianiro A, Cardone G. Heat transfer rate and uniformity in multichannel swirling impinging jets. Appl Therm Eng 2012;49:89–98. [CrossRef]
[58] Zuckerman N, Lior N. Jet impingement heat transfer : Physics, coorlations, and numerical modelling. Adv Heat Transf 2006;39:565–631. [CrossRef]
[59] Ingole SB, Sundaram KK. Heat transfer enhancement factor characteristics for collective cooling using inclined air jet. In: editor. 17th IEEE Electronics Packaging Technology Conference; 2015 Dec 2-4; Singapore: IEEE; 2015. pp. 1–6. [CrossRef]
[60] O'Donovan TS,. Murray DB. Effect of vortices on jet impingement heat transfer. International Heat Transfer Conference, 2006. [CrossRef]
[61] Shin MS, Senguttuvan S, Kim SM. Investigations of flow and heat transfer characteristics in a channel impingement cooling configuration with a single row of water jets. Energies 2021;14:4327. [CrossRef]