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Cooling Heat Transfer Analysis using Multiple Inline Inclined Air Jet Impingement

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Abstract - Air cooling has its own advantages in packaging technology and such many applications. The analysis of multi-jet impingement cooling process is performed. Air is used as fluid in present system. A simulated component with heater plate is cooled with four jets. All jets are placed inline or considered in a row. The jets are inclined to base and reference target to be cooled. The inclination of each jet is changed according to various configurations from 60 and 120 Degree to make packaging as compact as possible. Different configurations are examined and best combination is selected for study of variation of target to jet distance. Interface of flow from one jet with other is creating turbulence and effect of this on cooling target plate is studied experimentally. The graphs are plotted giving variations of Nusselt number as per Reynolds number in laminar range up to 2000. Jet inclination combination with first jet -inside, second jet - outside, third jet - outside, and fourth jet – inside is considered as giving best results with inclinations as 60-120-60-120 degree respectively. The laminar flow, with jet position inline, in which jet fluid flow lines gets mixed and creating turbulence gives higher average Nusselt number indicating better cooling performance. Further experiments using various fluids and various jet combinations / inclinations may be performed. The correlation is presented showing variation between Nusselt number and Reynolds number for typical case.

***Keywords** – Packaging, Cooling, Jet impingement, Inclined Jet, Average Nusselt number.*

I. INTRODUCTION

Industries like plastic, paper pulp, power generation, and electronic equipment's or packing, majority of electronics component fail due to vibrations, dust, and/or high temperature. Cooling them is of major concern and impingement heat removal is assumed to be an encouraging heat transfer augmentation technique. [1]

It is well know that jet impingement in packaging industry results in high convective heat transfer coefficients when it is compared to additional conventional styles of single phase heat transfer systems. Impinging jets are used in many diverse applications that require high heat removal capacity such as cooling of hot jet engine turbine blades, turbine seals, f[1]ood processing, drying of paper, textile industries, high density electronics, etc. To avoid quenching flaws, such as alteration, cracking, and decarburization, plastic molds with multifaceted cavity and great accuracy need pre-hardening treatment. In which, spray cooling can be useful for growth of the controllability in the cooling process and grasp the finest cooling results.

The liquid impingement is an effective method for cooling used in many applications because of its capacity to transfer very high heat fluxes. But in case of cooling of steel plate as there of chances of corrosion and water or liquid is available in bulk of quantity. If it is available in bulk quantity then there is problem of drainage of liquid after usage or there must be arrangement provided for cooling of liquid in the sense of repeated usage.

Hence air cooling is preferred over water or liquid cooling due to several advantages. In this way there is need for more research in air cooling methods. This very useful method for cooling of combustion engine analyzing furnaces.in this experiment we are going to focus on the air jet impingement by using multi jet arrangement.

II. LITERATURE REVIEW

Jets of Confined type and non-confined types using air impingement [2], jets by impinging normally upward onto a flat target plate [3], staggered arrays of five air jets confined in a channel using experiment technique [4], are reported. The cross flow cooling system [5] is also reported. Classifications and review of jets are also presented [6]. Twisted tapes for developing swirling jet [7], Coaxial Jet Mixing with Swirled Inner Jet [8] rotating jet [9] are used for investigation. Cooling of two cylinders (with fine surface) in row line by using a slot jet of air [10] spent air exits [11] are showing variations in physical structure / method of jet. Different fluids are used to carry heat from hot surface. De-ionized water [12] confined air and water jets [13] mist jet impingement cooling using air-liquid mist [14] [15] fluids with nanoparticles (mixture of water and Al_2O_3 nanoparticles) [16] electrically charged micro droplets can fully exploit the droplet cooling capacity [17]. Fluid used by jet is also one important choice constraint for jet, for financial considerations, the method of jet production can also consider as the considerable factors. Single jet using oil as fluid, and it is impinged on the lowermost exterior face of the plate is used [18]. Synthetic jet [19], synthetic pulsating jet [20] high formation frequency synthetic jets [21] tested and found as better efficient including micro-jet cooling [22].

The physical exit profile of jet gives diverse flow patterns of jet. Elliptical shape [23] semi restrained impinging group of jets with reference to influence of jet geometry (circular and cusped ellipse) [24], variety of inlet and outlet geometries of jet using liquid [25] like straight, chamfer inlet, chamfer outlet, chamfer in and outlet, countered inlet, and countered in and outlet, are studied.

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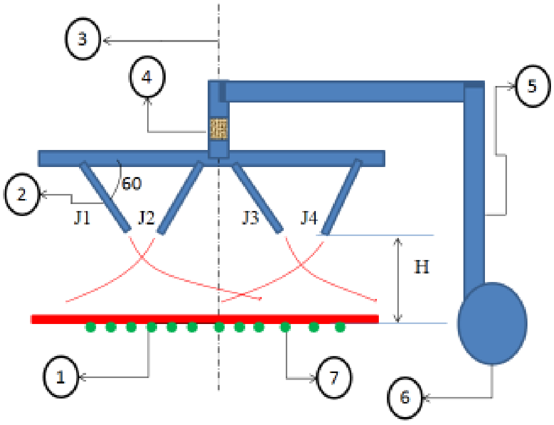
Triangular, square, pentagonal, and hexagonal shapes [26], with this slot jet and circular jets [27] are used regularly. Frequency of jet indicates magnitude of pulsation of jet and such pulsating jets are analyzed [21] [28]. Flow streams, vortices and eventually heat transfer also be contingent on the surface on which jet is to be imposed. Jet on a pin fin heat sink [29], jet on and around a central pedestal [30], jet on micro channel heat sink [31] are studied. Inclined jet is one of the major interesting subarea and inclinations can be given in various references becoming interesting due to mixing of fluid currents. [32] [33] Heat transfer features in a conduit are observed to recognize consequence of exit air from conduit, using the Target plate inclined at an angle to base position. [34] The laminar stream of a liquid jet constrained by inclined plane [35], impinging circular jet at 90° to 150° from bottom. [36], inclined vertical surface characteristics by using horizontal air jet [37] also investigated. Wind tunnel can be used for experimental work. [38]. Jets can be also used for heating an object. [39] Compared with perpendicular jet, in inclined jet also the cross section area of jet affects and dissimilarities are witnessed in literature. [40] Local convective heat transfer from a upright heated surface with angle to base (as 90 to 45 degree) of circular jet with free surface is examined [41] [42]. Two inclined jets for different geometry [43] and Reynolds number to increase effective cooling area. Various correlations are presented for inclined jets. [44] [45] Cross flow of fluid [46] is studied using 2D jets. A spray cooling effect on cooling performance for electronics applications with different spray angles (0, 20, 40, 50, and 60 Degree) are investigated. [47] Natural convection between a downward facing inclined wall, [48], the hot body to be cooled is positioned in moving situation [49] are also indicated.

III. PROBLEM STATEMENT

The objective is to identify effect of multiple jets cooling in which jets are inclined to reference surface. Every jet has different inclination, because of which turbulence is created, and affecting heat transfer. The objectives are: to develop test rig of multiple jet system, to prepare target plate as an object simulate to surface to be cooled, understand flow pattern and turbulence, and its effect on target cooling.

IV. EXPRIMRNTAL STUDY



1- Target surface with heater, 2 – Inclined jet, 3- Center line reference, 4- Plenum Chamber, 5- Hose pipe, 6- Blower, 7 - Thermocouples

Fig. 1 : Experimental Setup of inclined jet

The schematic illustration of experimental arrangement is given in Fig. 1, with snapshot in Fig. 2 in which rectangular heating plate of 400×150mm with its thickness of 1mm is used as target hot surface. Heating capacity of heater maximum 800 watt, a dimmer stat is used to vary the heat supplied to the heating plate, out of which 150W are used during presented experiment.

This surface temperature of heating steel plate is measured with the help of non –contact type infrared thermometer which is exposed to the jet. The heating plate is sandwiched between two plates which are tightened by the nut and bolt arrangement. For varying the distance between the steel plate and out let of jets the platform of the plate is moved up and down along with vertical axis. This is done by rack and pinion mechanism and moved manually. A centrifugal blower with plenum chamber is used to supply air under pressure to the jet. Plenum chamber is used to make air flow stable and also for reduction in fluctuations. Hot wire anemometer is used to measure velocity of the air jet. A tap is provided for variation in and control of flow of air to the jet duct to change Reynolds number. A sliding mechanism is provided for the angular movement of all the four jet for varying current of flow of air. Air jets J1, J2, J3, J4 size 5mm are used for varying flow of fluid on target plate for cooling purpose at different angles.

When the plate is heated, for measuring the temperature of the plate of particular points a non-contact type infrared thermometer is used. After measuring the temperature of plate, jets are allowed to cool the steel plate at constant velocity and pressure at which they all have same angle. In this way heated steel plate is cooled by multi air-jet impingement cooling.

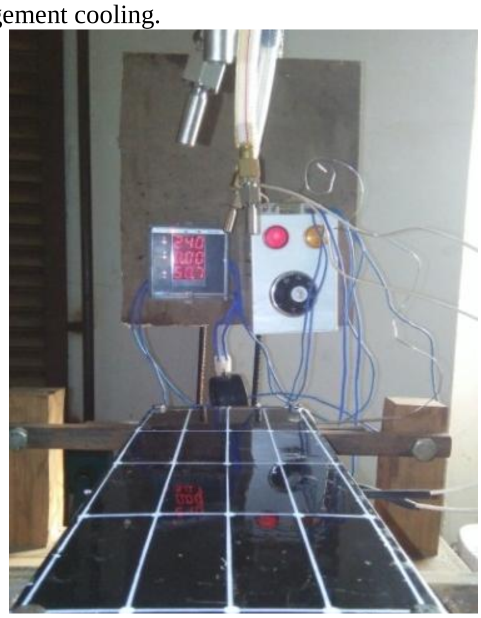


Fig. 2 : Photo of setup

The inclination angle arrangements are used as shown in Fig. 1. The Fig. 3 shows the terminology used in this research. The center line crossing at midpoint of reference plate is the 'Center line reference'. The 'In' term indicates inside flow towards center line of the reference plate, and 'out' flow indicates away from center of the reference plate. Inclinations initially are examined as per different configurations as Case A, B, and C. Out of which Case B is giving highest average Nusselt number.

Hence additional analysis is performed further for same jet inclinations combinations and with varying height for fixed diameter of jet.

Following assumptions are considered during study.

1) The discharge and velocity is same through all the jet.
2) Heat loss from all the faces except top surface is negligible
3) The thickness of the plate is same throughout the area.

The parameters and their ranges used during experimentation are as shown in

TABLE ITABLE IParameters and ranges

S. No.	Parameter	Range / Value
1.	Heat Input	150W
2.	Diameter of jet	5mm
3.	Jet inclination with reference plane	$60\text{-}120^0$
4.	Height between target and jet	50, 150mm
5.	Velocity	1 to 5 m/s
6.	Reynolds number	500-2000

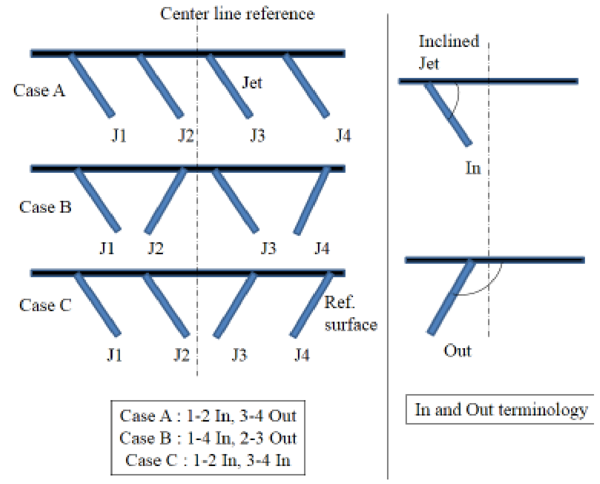


Fig. 3 : Terminology and Cases

V. DATA REDUCTION

The convective heat transfer coefficient is to be calculated as h= convective heat transfer coefficient (W/m^2 ^{0}C)

$$h = \frac{Q}{A(Tavg - Tatm)} \qquad (1)$$

Where, A = area of plate (m^2), Q = heat flux (W/m^2), T = Temperatures.

The average Nusselt number can be found out for entire surface as:

$$Nu_a = \frac{h \times Lc}{k} \qquad (2)$$

Where, h = convective heat transfer coefficient (W/m^2 ^{0}C), Lc = Characteristics Diameter of single jet (m), k = conductivity of air (w/m^{0}c).

Also the Nusselt number can be correlated with Reynolds number, which is measured using jet air outlet velocity, using hot wire anemometer. The experiment deals with the multi-jet system, in which all jets of same diameter are used. The Reynolds number based on single jet diameter is considered as characteristics size and to be calculated as (for laminar air jet flow)

$$Re = \frac{V \times d}{\nu} \qquad (3)$$

Where, V = velocity of the jet (m/s), d = diameter of the jet (m), ν = kinematic viscosity of air (m^2/s)

VI. RESULTS AND DISCUSSION

First the Case A, B, C as shown in Fig. 3 are tested for cooling effect for constant jet diameter as 5mm. It is observed that results of temperature variation are promising where jet impacts and mixes with each other. It might be due to more turbulence created in case B, and results of same are promising for cooling effectiveness i. e. case J1-in, J2-Out, J3-Out, J4-in. Temperature are noted after steady state is achieved. The local Nusselt number are calculated which then converted to average Nusselt number on the basis of entire target plate. The jet inclination is of 60, 120, 60, 120 Degree respectively for jet diameter of 5mm. Hence case B with jet diameter of 5 mm is taken further for analysis of effect of height variation. The vertical perpendicular distance between targets to jet is 50mm and 150mm. In presented case, air is used as a fluid medium and hence the value of Prandtl number is considered as constant.

Fig. 4 shows variation of Nu (Nusselt number) as per variation of Re.Pr (Reynolds number x Prandtl number) for target to jet height as 50mm. Similarly for 150 mm of target to jet distance, variations of Nusselt number with reference to Re.Pr are shown in Fig. 5. It is observed that, the maximum Nusselt number is almost up to 500.

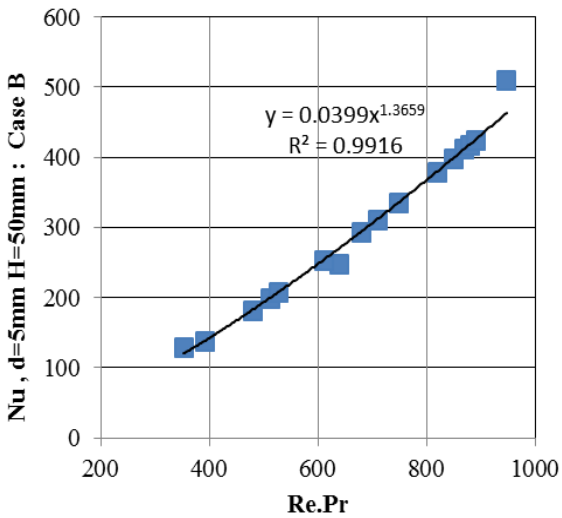


Fig. 4 : Nu variation for H as 50mm, Case B

The Eq. 4, is in associations of average Nusselt is proposed as follows, which is function of non-dimensional Reynolds number and Prandtl number.

$$Nu_a = C(Re.Pr)^K \qquad (4)$$

The value of constants C and K for two experimental conditions with target to jet perpendicular height H from 50 and 150 are calculated by regression analysis and curve fitting. These are listed in TABLE II

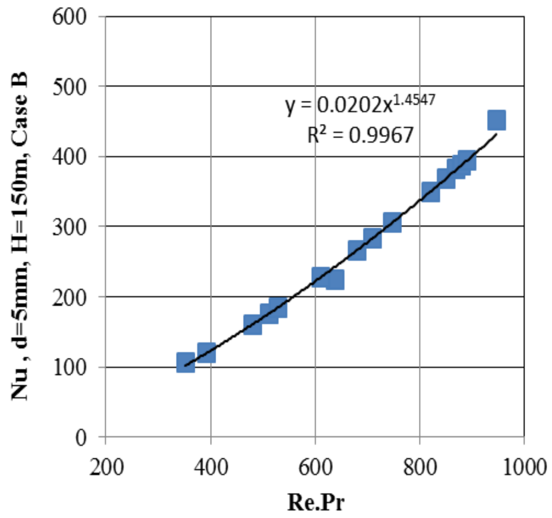


Fig. 5 : Nu variation for H as 150mm, Case B

TABLE IIConstants in correlations

	C	K
H=50mm	0.0386	1.3748
H=150mm	0.0202	1.4541

By considering average of above data constants, the final equation to calculate average Nusselt number (Nu_a) is presented as:

$$Nu_a = 0.029(Re.Pr)^{1.41} \qquad (5)$$

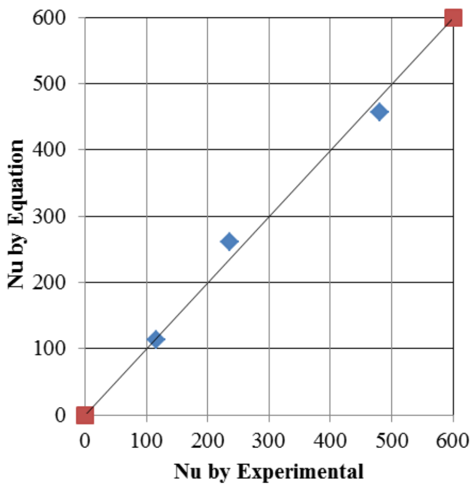


Fig. 6: Nu by experiment and equation

As the presented results are dealing with experiments related to cooling systems and uses instruments such as Temperature measurement sensors, velocity measurement not wire anemometer, etc, uncertainty analysis will be the important to present. The uncertainty analysis performed during experimentation and calculation of related parameters is as below in Table III.

This Eq. 5 is valid for stated conditions:

1. Case B as J1-in, J2-Out, J3-Out, J4-in
2. Inclined jets,
3. Inline condition,
4. Angle of 60-120-60-120 degree,
5. Laminar air flow (Re from 500 to 2000),
6. Target to jet height as 50 to 150mm.

The results obtained by experiment and equation (Eq. 5) are compared and found matching as in Fig. 6

TABLE IIIUncertainty analysis

S. No	Parameter	Symbol	Uncertainty
1	Diameter of jet	D	2.6%
2	Height of jet to target	H	1.7 to 11 %
3	Jet Air Velocity	V	0.48 to 2.4 %
4	Current supplied to heater	I	5 %
5	Voltage applied to heater	V	0.19 %
6	Temperature of heater plate	T	0.5 %
7	Angle of jet inclination	Ɵ	1.34 to 6.7 %
8	Length of target plate	X	0.38 %
9	Width of target plate	Y	0.95%
10	Reynolds Number	Re	6.6 to 4.5 %
11	Heat supplied	Q	5 %
12	Nusselt Number	Nu	5.66 to 8.06 %

VII. CONCLUSION

Air cooling of hot target is experimentally investigated, in view of packaging technology to make units compact as possible in terms of low width packaging solutions. As width is smaller, all jets to be placed in line for cooling system. Multi-jet impingement cooling system is referred in presented case. Air is used as medium to cool. All jets are placed inclined to base reference surface to mix their flow creating turbulence. The inclination of each jet is changed according to various configurations from 60 and 120 Degree for understanding their effect. Various configurations are evaluated and best combination is selected for study of variation of target to jet distance. The graphs are plotted giving variations of Nusselt number as per Reynolds number in laminar range up to 2000. The correlation is specified showing variation between Nusselt number and Reynolds number for distinctive case. During experimental analysis of inclined air jet flow, testing is performed for cooling cases assuming its wide applications including electronics cooling. Case B as J1-in, J2-Out, J3-Out, J4-in is considered as giving best results with inclinations as 60-120-60-120 degree. The laminar, inline, jet flow lines gets mixed and creating turbulence gives higher average Nusselt number indicating better cooling performance. The correlation is also presented by comparing experimental and equation results. Further experiments using various fluids and various jet combinations / inclinations may be performed.

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