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Experimental average Nusselt number characteristics with inclined non-confined jet impingement of air for cooling application

S.B. Ingole [a,*], K.K. Sundaram [b]

[a] Indira College of Engineering and Management, Pune, India
[b] Vishwakarma Institute of Technology, Pune, India

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ABSTRACT

Jet impingement is exceedingly operational for numerous field applications including electronics cooling and process industry. Its implementation comfort makes it common for many applications. The paper deals with investigation of heat transfer characteristics of a cooling flat surface. It is cooled by air jet impinged at an inclination of 15–75° to target plate. For understanding variation in cooling performance, comprehensive experiments are performed with different configurations of inclined jets on hot surface. For simplicity in using air, it is recommended for verity of applications as cooling fluid. Air Inclined jet with Reynolds Number in the range of $2000 \leqslant Re \leqslant 20{,}000$ is examined for the circular Inclined jet. The target to inclined jet perpendicular height (H) is varied from $0.5 \leqslant H/D \leqslant 6.8$ for understanding effect of H on cooling performance of different locations on target plate. The investigation leads to equations for average Nusselt Number for inclined non-confined air jet for cooling applications.

1. Introduction

Cooling applications are having high importance in thermal engineering. The applications like electronics cooling, heat treatment, and process uses are rerecorded, which uses various techniques. Out of these, jet cooling has numerous advantages including its implementation in practice. A single and multiple jets are documented. Sometimes sprays are also used for cooling applications. The spray angles of 0–60 are tested, for which there is temperature drop is observed because of the reduction in spray volumetric flux supplied to the target at the larger spray angle beyond 500 [1]. Jet or sprays from bottom of the target plate are investigated in general [1,2]. Various fluids are used as impingement medium like air, water and oil [3] for cooling applications. Even various cross sections of jet like circular, slot and elliptical [4] are also investigated during heat transfer study. It is observed that instead of cooing applications, jets are also tested for heating application by supplying hot air as a fluid.

Some experimentations are performed by using different approaches like in channel flow to understand effect of exit air from channel. Investigations are also performed to test jets in wind tunnels related to various thermal and fluid characteristics [5]. Mixing of different jets will generate more turbulence, and the same principle is tested with two jets, both perpendicular to target as well as mixed with an angle are investigated [6]. Numerical study was also performed for jets. The jets used are of typical nature and configuration for numerical study [7].

There is no specific geometrical and fluidic parameters like Jet Diameter and Reynolds Number used for Jet cooling applications, but it differs from case to case – application to application. Also air is used as major fluid for jet cooling. For angular jets researchers worked with different angle of impingement or range of angles for impingement, from 0° to 90°. Majority of inclined jets are investigated as they impingement at the center of target plate. During electronics cooling applications, space constraints deliberations will force to think on oblique jet impingement. Slot jets, circular jets, elliptical jets are studied [8]. Basically, hydraulic diameter is the governing parameter for altogether analysis. To use a circular jet will help to develop system easily, with less space utilization or requirement [9,10]. The study considers a circular jet for scheduled experiments. The straight (90°) jet will need more space. The inclined jet came in to existence to overcome this issue [4,11]. The present study aims to investigate heat transfer characteristics related to Nusselt Number at jet inclination of 15–75° to target plate

2. Inclined jet flow

Inclined jets can be used for heating as well as cooling objects. Let us consider a two dimensional Inclined jet (X & Y directions) for

* Corresponding author.
E-mail addresses: sbingole1@rediffmail.com (S.B. Ingole), vit_sundaram@yahoo.com (K.K. Sundaram).

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Nomenclature

Greek symbols

α	thermal diffusivity (m^2/s)
β	coefficient of thermal expansion (1/K)
ν	kinematic viscosity (m^2/s)
θ	inclination angle

Subscripts

a	actual
avg	average
conv	convection heat transfer
in	inside
L	with reference to characteristic length
o	stagnation condition
out	outside
p	perpendicular
s	surface
Y	along Y axis

Symbols

A	area (m^2)
AR	angle ratio (θ_a/θ_p)
D	diameter of inclined jet (m)
E	energy (Watts)
g	acceleration due to gravity (m/s^2)
H	distance between inclined jet and target plate (m)
h	convective heat transfer coefficient (W/m^2 K)
I	current (A)
k	thermal conductivity of fluid used in Inclined jet (W/m K)
Nu	Nusselt number (dimensionless)
P	perimeter (m)
Ra	Rayleigh number (dimensionless)
Re	Reynolds number (dimensionless)
T	temperature (°C)
V	voltage (V)
v	velocity (m/s)
X	distance along X direction, from inclined jet up to peak point position (m)

understanding the physics. The Inclined jets are impinged on target plate using ambient air with nozzle diameter D. For slot jet hydraulic diameter of jet is to be considered, which 2 W for slot nozzle is. Whenever fluid exit from Inclined jet it is having uniform velocity at the exit. (Zone 'a') Whenever fluid traffics from the inclined jet exit section, there is momentum exchange between inclined jet & surrounding or it takes place because of viscous diffusion of momentum. It will cause pulling addition fluid along with inclined jet. This will cause increase in free boundary as well as potential core. The potential core is that part in which initial velocity is preserved in free inclined jet. In the zone 'b' the shearing layers are having larger velocity gradient as shown in Fig. 1.

For jet, inclined at 90° to target plate, generally called as perpendicular jet, the point of impingent of inclined jet on the target surface is called stagnation point [12]. But during inclined impingement of Inclined jet, the point where Inclined jet axis intersect to target surface is called as geometrical stagnation point and the distance from leading edge is called as geometrical stagnation point distance.

In the geometry of Fig. 1, H is on the vertical perpendicular line, which is height from lowest opening edge of inclined jet to target plate. It is specifically defined as it is easy to measure it physically. It is to be resolved that maximum velocity of inclined jet decreases as inclined jet fluid drives away from the exit plane.

The impingement zone is shown by two dotted vertical lines. In case of angular inclined jet, impingement region is asymmetric because of higher velocity component in X direction compared to Y direction. In the impingement zone because of direct inclined jet impact on target surface, inclined jet is decelerated. After impact, it will be bowed in positive & negative direction where the flow is accelerated again. The Inclined jet thickness has minimum up to certain distance from stagnation point & then it increases.

In the region 'c' (other than impingement zone), the fluid enters in the unconfined fluid (which is at zero velocity). This leads to deceleration of inclined jet again drastically which is termed as downhill wall inclined jet. Similarly, in the negative direction the wall Inclined jet of lower mass flow rate arises called as the uphill wall Inclined jet, in region 'd'. In case of uphill wall Inclined jet the velocity of fluid flow is smaller than downhill wall Inclined jet. This indicates as we move from geometrical stagnation point in negative X direction, velocity parallel to target surface increases from zero to certain value & then decrease again. This is dissemination of inclined jet in surrounding unconfined fluid. During the flow in the wall Inclined jet section, the thickness increases. The average velocity decreases and the position of maximum velocity shifts progressively away from target surface wall.

The boundary layer is developed in the stagnation region as well as wall Inclined jet region. The no slip condition occurs with the impingement region and wall Inclined jet region which favorably help in heat transfer from target to fluid.

The jet inclinations are defined in various ways, specially depends on orientation of target surface. In present case, the target plate is horizontal and θ_a is actual inclination with target surface, whereas θ_p is constant 90° i.e. vertical jet making 90° angle with target as shown in Fig. 1. This parameter is considered with the intention of comparing θ_a with 90° jet (perpendicular jets) which are widely investigated.

The properties of fluid, surface texture also plays vital role in inclined jet application.

3. Experimental apparatus

The experimental set up used for investigation is shown in Fig. 2. A target plate is made up of Stainless steel of thin foil. Electric supply was given to target plate with bus bars of copper. The electrical supply which is connected to main line of 230 V and 5 A is given to transformer. This is then converted to 3 V and 50 A electric supply for heating. Out of this total energy 30 W is loss due to radiation calculated by measuring Emissivity of target surface. To avoid buckling of target plate, the provision to make it tighten using springs is present in housing of target plate. For avoiding heat loss through conduction from heater to housing, the arrangement is made. Forty location points (A1, A2, ...) are located on target plate as shown in Fig. 3. The noncontact type infrared thermometer is used to measure the temperatures at each of these point. The heated horizontal, smooth, target plate is cooled by impinging air jet which is placed on leading edge of target plate. The jet is of circular cross-section, non-confined and inclined (inclination angle as shown in Fig. 1) in nature and impinged on top side only. The bottom side of jet