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Experimental Investigation of Heat Transfer from a Flat and Surface Indented Plate Impinged with Cold Air Jet- Using Circular Nozzle

V.M.Jeevanlal [1], B.C. Anil Kumar [2]

[1]Department Of Mechanical Engineering, LBS College, Kasaragod, India (Post graduate researcher)
[2]Department Of Mechanical Engineering, LBS College, Kasaragod, India (Assistant professor)

Abstract: *Jet impingement is an efficient method for heating and cooling. Jet may be liquid or gas depending on the application. The present work experimentally investigates the heat transfer on a heated plate impinged with cold air jet. The plate material is stainless steel having dimension 150×150×2 mm and is electrically heated. Mild steel pipe is used as circular nozzle having diameter 10mm. A flat plate and a similar plate with surface indentation is employed for analysis. Varied the nozzle exit to target plate distance (Z/D) and varied jet velocity for obtaining Six Reynolds numbers. Study revealed that Nusselt number increased with increasing Z/D value up to a certain Z/D value then it starts decreasing. In two cases maximum Nusselt number obtained at a Z/D value of 6. It is found that Nusselt number increased with increasing Reynolds number for all distances. Results showed heat transfer augmentation with surface indented plate.*

Keywords: *Jet impingement, heat transfer, Nusselt number, Compressed air jet, circular nozzle*

1. Introduction

It's a well known fact that thermal management has a relatively large importance in almost all industries such as electronic cooling, textile and paper industries .We know that technology advances day by day which leads to high heat flux and we have to remove the heat generated in most efficient and easiest way to improve the performance of thermal system thus we can avoid the chance of failure. So a very effective thermal management system is required in industries for improving their performance. Lot of researches and experiments had performed to study the feasibility of new efficient technologies. The research works revealed the limitations of various conventional methods used in thermal management field.

There are number of traditional cooling techniques are in use, major traditional techniques are heat sink, heat sink with fan, heat exchanger, heat pipes etc. These conventional methods have lot of limitations such as low heat removal rate, space constraints in very small electronic equipments. Therefore we need an effective and efficient method for removing heat. Jet impingement cooling is an efficient method as it provides high heat removal rate.

Jet impingement cooling is considered as one of the extremely efficient method of cooling hot objects in industrial processes since it provides a high heat transfer rate through forced convection mode of heat transfer. It's a very efficient mechanism for rapid heating or cooling a surface. This method is capable to produce high localized transport rates. Single or multiple rows of jets are used to achieve high heat transfer rates. Various geometries used to impinge jet on target surface are axisymmetric (circular pipe or orifice), slot (2D) nozzles, rectangular (3D) nozzles and square (3D) nozzles. In this method we can control heat transfer from the surface by varying flow parameters such as jet exit velocity and geometrical parameters such as jet exit opening, jet-to- plate spacing, nozzle-to-nozzle spacing in case of array of jets. Jet impingement provides a very dynamic research area.

2. LITERATURE REVIEW

Shung et al. [1] studied the thermal performances of different shape porous blocks under an impinging jet. A numerical method (SIMPLEC) was used to solve the governing equations. Three different shape porous blocks were studied (rectangle, convex and concave).The results indicated that the heat transfer is mainly affected by the fluid flow near the heated region. For a lower porous block, the heat transfer is enhanced by three types of porous block. However for a higher porous block, heat transfer is only enhanced by the concave porous block.. D.H.Lee et al. [2], conducted a study in which the local heat transfer coefficients are measured for an air jet issuing from a long straight pipe and impinging perpendicular on a hemispherically convex surface. Experiments are made for Re=11,000 50,000, L/d=2-10 and d/D=0.034-0.089. The result shows that the stagnation point Nusselt No (Nu_{st}) increases with increasing value of d/D . Maximum Nusselt No at the stagnation point occurs at $L/d =$ 6 to 8 for all Re's and d/D's tested. BEHNIA et al. [3] numerically studied the problem of cooling of a heated flat plate by an axisymmetric isothermal fully developed turbulent jet. Computations performed with Normal-velocity relaxation turbulence model (V2F model). Local heat transfer coefficient predictions are compared to the available experimental data. Results showed excellent agreement with experimental data. The axisymmetric, incompressible, Reynolds averaged N-S equations were solved in conjunction with the k-ε and v^2 transport equations, and the f elliptic relaxation equation on a finite- difference grid. Several turbulent Prandtl Number formulas were examined. Simulations have been carried out for a constant Re (Re=23,000) and a wide range of aspect ratios (0.5≤ H/D≤ 14) to determine the dependence of the stagnation Nusselt no on H/D . This dependence is crucial in many applications of impingement cooling. While comparing it is observed that V2F model predictions are good in agreement with experimental data than k-ε model. W.M.Chakroun et al [4], conducted an experimental investigation of heat transfer from a round air jet impinging normally from below on to a heated square plate .Objective was to study the effect of roughness on both heat transfer and fluid flow characteristics. Smooth and rough plates were used in experiments. The roughness was composed of cubes of 1mm dimension distributed uniformly along the plate. According to author most of the works are carried out on smooth surface. But in most of the applications the surface is rough. The result was, the local and average Nusselt values for the rough plate should an increase ranging from 8.9% to 28% over those for the smooth plate. Victor A.Chiriac and Alfonso [5] had found from their literature review that the behavior of the two dimensional impinging jet in the laminar and transitional regime is not at all well known. The objective of this study was to characterize the behavior of the confined laminar impinging jet and the attendant heat transfer removal to the target wall. Results showed that in the steady regime, the stagnation Nusselt No increased monotonically with Re, and the distribution of heat transfer in the wall jet region was influenced by flow separation caused by re entrainment of the spent flow back in to the jet. L.L.Dong et al [6] conducted experiments to investigate the heat transfer characteristics of a row of three premixed, laminar butane/air flame jets impinging on water cooled flat plate. They inferred that the maximum local heat flux and the maximum area averaged heat flux occurred at a moderate nozzle to plate distance of 5d. Amy S and SRN [7], investigated the influence of a protruding pedestal on impinging jet heat transfer. V.Narayanan et al [8], presented an experimental study of flow field, surface pressure, and heat transfer rates of a submerged, turbulent, slot jet impinging normally on a flat plate. Study reveals that high heat transfer rates in the impingement region for transitional jet impingement, and a non monotonic decay in heat transfer coefficient for potential- core jet impingement..

3. SCOPE OF RESEARCH

Due to recent technological developments, the need for an effective and relatively simple thermal management system has reached an all time high. From almost all electronic equipments heat is generated from hotter chips. The conventional methods listed above can't be applied in small electronic equipments. Besides electronic equipments lot of other industries such as paper, textile, food etc requires an effective cooling system. Jet impingement cooling/heating method provides a better solution to present thermal management problems. The major advantage of this method is high heat removal rate. Therefore it is worthy to study about the jet impingement methods. It provides a very large area for research.

3.1 Problem Description and Objective

The heat removal rate by jet impingement method depends on surface area of plate, surface roughness, type of jet fluid, velocity of jet, type of nozzle and distance between nozzle exit and target plate. Here the problem is to find out the relation between heat removal rate and above listed parameters. It is known that heat transfer rate increases with increase in surface area. In this work it is required to calculate the heat transfer augmentation after replacing the flat plate with surface indented plate. . Circular indentations are provided on the target plate surface. The major objectives of the present work are to study the conventional and jet impingement heating and cooling methods, analyze heat transfer from vertical hot flat plate and a surface indented plate with circular nozzle.

4. EXPERIMENTAL STUDY

Experimental set up mainly consists of a compressor, air supply pipeline, mercury manometer, nozzle, plate fixed with heater, sliding mechanism for plate, digital temperature indicator etc. Fig 4.1 shows the layout of fabricated experimental set up. A two stage compressor is used for generating compressed air and which is supplied through a pipeline connected with an orifice and a pressure regulating valve. Provision for fitting nozzle is provided at the end of the supply line thereby we can use both square and circular nozzle.

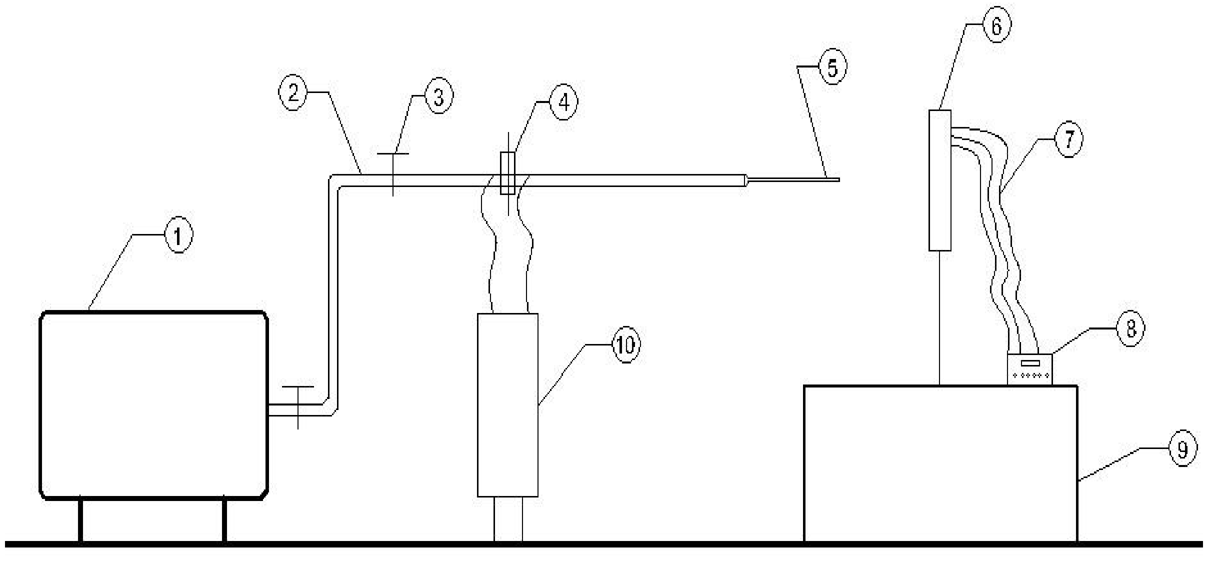

Fig1. *Schematic of Experimental setup*

A heater is fixed with target stainless steel plate and for axial movement of plate a sliding mechanism is employed. Thermocouples are used for temperature measurement at various locations of plate. Digital temperature indicator shows the temperature.

1. Compressor
2. Main air supply pipe
3. Pressure regulating valve
4. Orifice meter
5. Nozzle
6. Square steel plate
7. Thermocouple
8. Digital temperature indicator
9. Stand
10. Mercury manometer

Figure 2. *Air supply line with valve, orifice and nozzle*

Figure 3. *Flat plate*

Figure 4. *Five thermocouples radially connected*

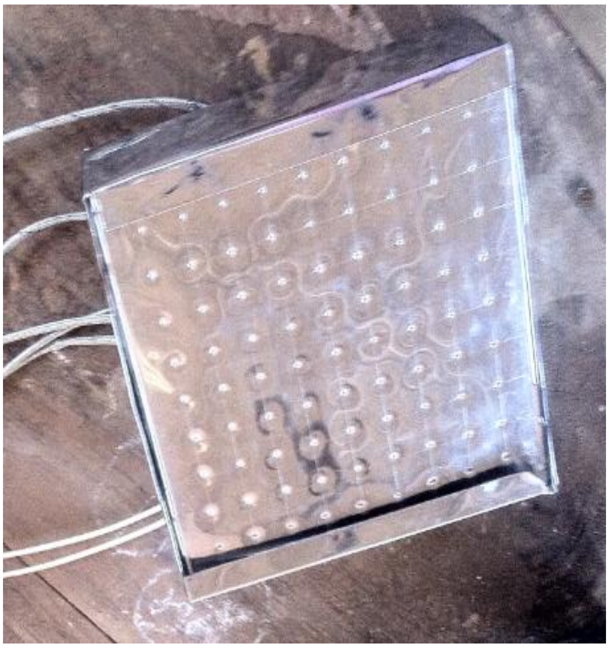

Figure 5. *Surface indented plate*

Two stage reciprocating air compressors are used for generating compressed air. Impinging plate is made up of stainless steel having dimensions 150mm×150mm×2 mm. Compressed air jets is issued to the plate surface through circular nozzle of diameter 10mm.Plate is heated with an electrical coil. J-type thermocouples are employed to measure temperature. Orifice meter of 10mm diameter and a mercury manometer is used for volume flow rate measurement of air. Pressure regulating valve helps to vary the jet speed. A sliding mechanism used for varying the Z/D distance. Digital temperature indicator is employed for measuring temperature over time.

Experiment carried out with six Reynolds numbers ranging from 10000 to 60000. Various Z/D distances fixed are 1,2,4,6,8,10 and 12.

4.1 Experiment Methodology

1) Measure atmospheric temperature with the help of thermometer. It is essential to calculate heat transfer coefficient since heat transfer coefficient is the ratio between amount of heat convected out and difference of plate surface and atmospheric temperature.
2) Provide AC supply to heating coil and measure current and voltage for finding the heat flux generated in the target surface. Coil is arranged on the plate in such a way that plate becomes heated uniformly
3) Start compressor by closing outlet valve; allow the tank to fill with air. This compressed air is allowed to pass through the air supply line and finally impinged to target surface through a nozzle
4) Wait until the plate become uniformly heated(attained steady state temperature) and note all temperature reading from data logger. Five thermocouples are connected radially on the plate
5) After heating plate uniformly open the compressor outlet valve of compressor and set a particular velocity by adjusting pressure regulating valve
6) For a particular velocity note down the manometer reading and measure the air jet temperature Wait sometime for temperature become steady over the plate surface and note down the plate temperature after impinging the air jet
7) Change the nozzle exit to plate (Z/D) distance and repeat the same procedure
8) Repeat same procedure for various Jet velocity (By adjusting pressure regulation valve)

4.2 Mathematical Relations

For calculating heat transfer coefficient (h) convective heat transfer relation for flat plate is used

$$T_s = \frac{q_{conv}}{h} + T_a \quad (1)$$

$$h = \frac{q_{conv}}{T_s - T_a} \quad (2)$$

h = Heat transfer coefficient (W/m^2K)

q_{conv} = Net convective heat flux (W/m^2)

T_s = Temperature of target plate at a given point (˚C)

T_a= Air jet temperature (˚C)

Net convective heat flux (q_{conv}) is calculated by using following relation. This is a basic convective heat generation calculation relation by considering heat flux and heat losses from the impinging plate

$$q_{conv} = q_{joule} - q_{loss} \quad (3)$$

q_{joule} = Heat flux (W/m^2)

q_{loss} = Total heat loss from impinging plate (W/m^2)

The heat flux generation in target plate can be calculated by using the voltage and current across the wire. For this heat flux calculation area of plate is also considered. Following relation is used

$$q_{joule} = \frac{V\,I}{A_s} \tag{4}$$

V = Voltage across the heating coil (V)

I = Current (A)

A_s= Surface area of plate (m^2)

Total heat loss from impinging plate consists of both radiation loss and natural convection loss. Therefore following relation is used for the calculation of total heat loss from the plate.

$$q_{loss} = q_{rad} + q_{nat} \tag{5}$$

q_{rad} = Radiation loss from plate surface (W/m^2)

q_{nat} = Heat loss by natural convection from plate (W/m^2)

Now it is possible to calculate Nusselt number by using the heat transfer coefficient h, diameter of nozzle d, and thermal conductivity of air k.

$$Nu = \frac{hD}{k} \tag{6}$$

Nu = Nusselt number

h = Heat transfer coefficient ($W/m^2 K$)

D = Diameter of nozzle exit (m)

k = Thermal conductivity of air (W/mK)

Volume flow rate through the pipe is calculated by using the well known equation

$$Q = c_d\sqrt{2gH}\ \frac{A_1 A_2}{\sqrt{{A_1}^2 - {A_2}^2}} \tag{7}$$

Q = Volume flow rate (m^3/sec)

c_d = Coefficient of discharge of orifice meter

A_1 = Area of pipe (m^2)

A_2 = Throat area of orifice meter (m^2)

g = Acceleration due to gravity (m/sec^2)

Discharge or volume flow rate is also given by

$$Q = A_1 v \quad (8)$$

A_1 = Cross sectional area of pipe (m^2)

v = Velocity of flow (m/sec)

Reynolds number is calculated by using the relation

$$Re = \frac{\rho v D}{\mu} \quad (9)$$

5. Experimental Results and Discussions

Nusselt number provides a direct measure of convective heat transfer coefficient ‘h’.In this work stagnation point and radial Nusselt number are plotted. Above listed relations are employed for calculating Nusselt number. Experiments conducted with varying Reynolds numbers 10155.44, 20129.54, 30103.65, 40077.75, 50051.85 and 60025.95 and selected nozzle exit to plate (Z/D) distances as 1,2,4,6,8,10 and 12.

5.1 Flat Plate with Circular Nozzle

Plotted stagnation Nusselt number and radial Nusselt number.

Experiment revealed that the stagnation point Nusselt number increases with increasing nozzle exit to plate distance (Z/D) up to Z/D = 6 then with further increment of Z/D resulted in decreasing of Stagnation Nusselt number. But stagnation Nusselt number increased with increasing Reynolds number. Radial Nusselt number is found decreasing with increasing radial distance.

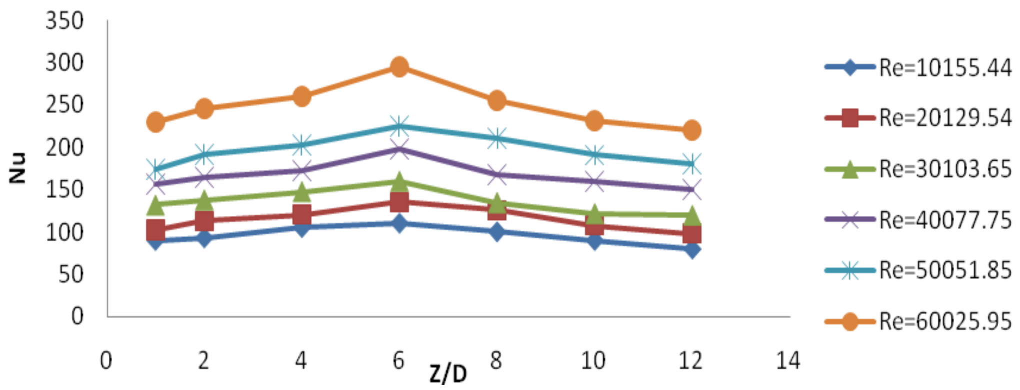

Fig6. *Stagnation point nusselt number- flat plate with circular nozzle*

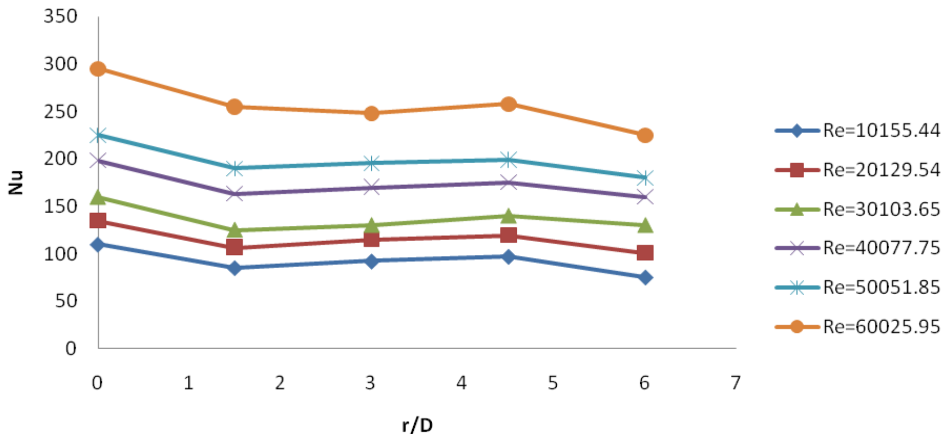

Fig7. *Radial nusselt number at Z/D= 6- flat plate with circular nozzle*

5.2 Surface Indented Plate with Circular Nozzle

Figure 8 and figure 9 shows the variation of stagnation and radial Nusselt number during analysis of surface indented plate with circular nozzle. In this case also maximum stagnation Nusselt number obtained at a Z/D value of 6. When comparing with first maximum Nusselt number increased from 295 to 315. It shows a heat transfer augmentation while flat plate is replaced with surface indented plate.

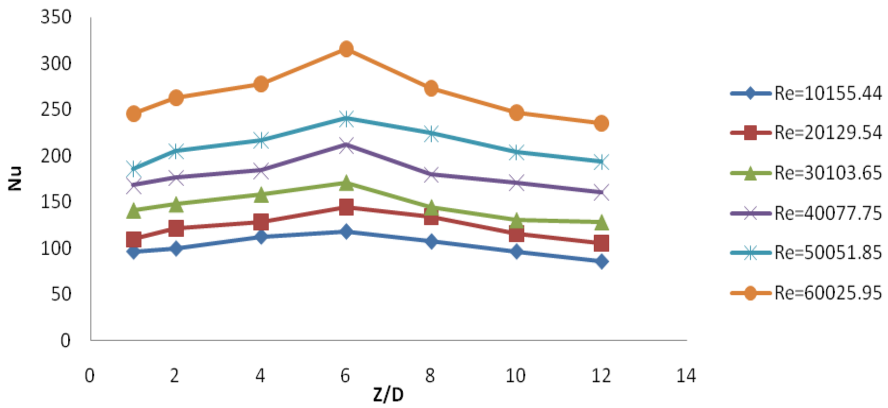

Fig8. *Stagnation point nusselt number – surface indented plate with circular nozzle*

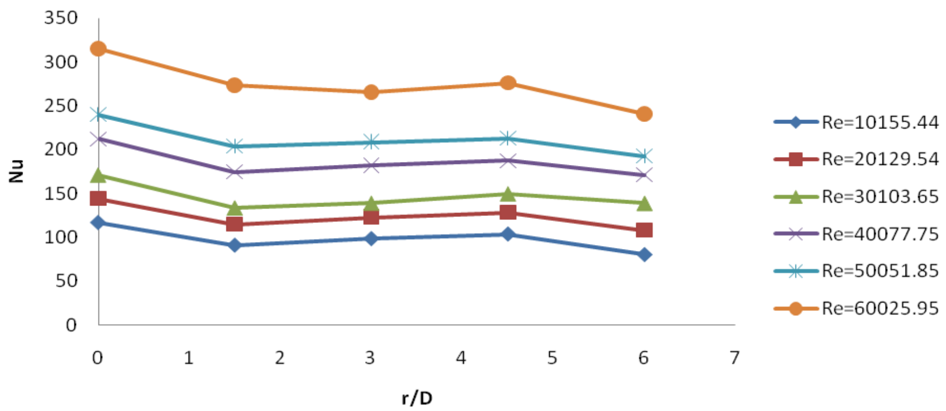

Fig9. *Radial nusselt number at Z/D= 6 – surface indented plate with circular nozzle*

Table1. *Maximum Nusselt number values*

Maximum Nusselt number	Combination of plate and Nozzle	
	Plate	Nozzle
295	Flat plate	Circular nozzle
315	Surface indented plate	Circular nozzle

6. CONCLUSION

Jet impingement method is a universally accepted efficient method. For reducing limitations of some conventional cooling or heating methods, the invention and use of some effective alternative methods is necessary. So lot of research works carried out and numerous works are going on. Some efficient cooling or heating methods are required by electronic industry, textile industry, paper industry, aircraft etc. It is found out that jet impingement method is an efficient mean for heating and cooling purposes. The problem in this field is never end because technology is advancing day by day. Jet impingement methods have several advantages when comparing with other conventional methods. Nowadays it is used in several applications. A jet may be a liquid jet, gas or air jet. The usage of jet medium is based on the type and complexity of the problem. Usage of air as jet medium is fair since it is free and easily Impinging jets have been studied over the years for their importance in industrial applications, mainly in cooling, heating or drying. Jet impingement technique provides high levels of convective heat and mass transfer. A lot of experiments can be performed on jet impingement cooling. During present work it is observed that stagnation Nusselt number increased with Z/D and at a Z/D value of 6 it provides maximum stagnation Nusselt number for all Reynolds numbers. Surface indented plate gave higher heat transfer coefficient because of the increment in surface area. Due to surface indentation the roughness may increased ,that may play a role in heat transfer augmentation[4]. From the experiment it is found that convective heat transfer coefficient is increased considerably when flat plate is replaced with surface indented plate.

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AUTHOR'S BIOGRAPHY

Jeevanlal VM is presently doing M Tech in Thermal and Fluids Engineering at L B S College of Engineerig, Kasaragod.

Anilkumar B C is currently working as Assistant professor in Mechanical Engineering Department, L B S College of engineering, Kasaragod.