

Abstract

An experimental investigation was carried out to measure the fluid flow and heat transfer characteristics over a rectangular surface in uniform flow. The angles of the rectangular surface were considered at $\alpha = 0^\circ, 10^\circ, 20^\circ, & 30^\circ$ and Reynolds numbers were varied for coefficient of pressure and temperature distributions. In the present investigation, the pressure distribution and heat transfer characteristics over rectangular surface due to uniform flow was investigated. Experiment was performed for Reynolds numbers 5572, 6006, 6631 and 7003 and included angle of $\alpha = 0^\circ, 10^\circ, 20^\circ, & 30^\circ$.

Effect of Reynolds Numbers on Fluid Flow and Heat Transfer Characteristic over a Rectangular Prism in Uniform Flow

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It was observed that the coefficient of pressure increases with the increases of the Reynolds numbers and decreases along the length of the surface. The coefficient of pressure became more or less steady at a distance $X = 0.025$, but shown maximum value at the stagnation point. If the Reynolds number increases the flow is separated from the surface. It was also observed that the local Nusselt number increases with the increases of Reynolds number and decreases along the length of the surface. The local Nusselt number becomes more or less steady at a distance $X = 0.015$, but shown maximum value at the stagnation point.

1. Introduction

The fluid flow characteristic on various shapes is encountered in many engineering situations. The shape of the rectangular prism and flow characteristics around it is of primary importance for the determination of pressure and temperature over the rectangular prism and perfect position is an another important factor to determine the flow characteristics. At fixed angular position of prism the effect of various Reynolds numbers of the fluid flow has been investigated. In industrial application, it necessary to find out fluid flow characteristics, pressure and temperature distribution over a rectangular prism, the result of this investigation can be applied in the field of heat transfer, combustion engineering or in the cooling systems of rectangular type electronic boards. In the present experiment, subsonic wind tunnel is used. In the wind tunnel an induced type fans and honey combs helps to get straight flow of air. When a fluid is flowing over a solid boundary, a layer of fluid that comes in contact with the boundary surface adheres to it on account of viscosity. Since this layer of fluid cannot slip away from the boundary surface, it attains the same velocity as that of the boundary.

The pressure difference decreases slowly as the flow of fluid advances over the rectangular surface. At the boundary surface the frictional forces retarded the motion of the fluid in a thin layer. This retarded layer of fluid further causes retardation for the adjacent layers of the fluid, there by develops a small region in the immediate vicinity of the boundary surface in which the velocity of flowing fluid increases gradually from zero at the boundary surface to the velocity of the main stream. The region is known as boundary layer region, since there is a large variation of velocity in a relatively small distance, there exists a fairly velocity gradient ($\delta v/\delta y$) normal to the boundary surface. As such in this region of boundary layer even if the fluid has small viscosity, the corresponding shear stress $\tau = \mu(\delta v/\delta y)$ is of appreciable magnitude.

For an ideal fluid flowing past a rectangular prism, it is possible to obtain analytically the pressure and temperature distribution over it. The highest intensity of pressure occurs at the frontal edge. This is due to the stagnation point. At the stagnation point velocity is zero, where pressure is high. Temperature distribution has various applications in the industrial purposes for finding out the flow of fluid flow and heat transfer

characteristics over a rectangular surface. The temperature distribution also used in cooling system and combustion engineering. In practical application, however, the flow field around rectangular surface is important. Experimental investigation was concerned with finding the temperature and pressure distribution on the rectangle of different Reynolds number.

2. Literature review

Sohankar, A. *et. al.* [1] have investigated experimentally and numerically the two dimensional unsteady flow over a square cylinder. The range of incidence angle and Reynolds number considered from 0° to 45° and 45 to 200 respectively. On the laminar range of flow the Karman Vortex sheet obtained behind the square cylinder during the investigation, well agreed with the published results. The decrease of blockage for zero incidences result in a slight decrease in Strouhal number, mean drag and RMS lift. The vortex shedding occurred within the range of Reynolds number from $40 < Re_{cr} < 55$ and Re_{cr} decreases with the increase of incidence angle.

Vlachos, P.P. and Hajj, M.R. [2] have used a Digital Particle Image Velocimetry (DPIV) to obtain the instantaneous variations of the separated flow over a prism. Significant variation between a wake expansion, vortex formation, vortex shedding and reattachment is observed.

Esfahani, A.S. [3] has investigated the three dimensional unsteady flow around a square cylinder with zero angle of incidence at Reynolds number ranging from 150 to 500 and large eddy simulation at Reynolds number 22×10^3 . The two-dimensional and three-dimensional numerical investigations have been carried out. The influences of Reynolds number, body ratio and angle of incidence have been investigated. Wake frequency, mean drag and lift and various surface pressures are calculated.

Katinas, V. *et. al.* [4] have investigated numerically the turbulent flow of air over a prism. The standard κ - ϵ and LKE models have been used to simulate the three dimensional flow over a rectangular prism. The 48 mm high flat prismatic wall normal to the free flow with higher hydraulic drag and 16 mm high flat prismatic wall normal to the free flow with lower hydraulic drag have been considered for the investigation. It is observed that the 16 mm high flat prismatic wall prism has good agreement with the experimental result.

Noda, H. and Nakayama, A. [5] have investigated the effect of turbulence on pressures and forces over cylinders of rectangular cross section. The rectangular objects of different length to height, that is, aspect ratios (B/D) have been investigated. For the cylinder with smaller B/D the flow does not reattach with or without turbulence in the free stream but cylinder with higher B/D of 2.5 or larger the main effects of the turbulence in the inflow free stream are to laterally move the separated shear flow off the upstream corners and cause intermittent reattachment on the side surface of the cylinders.

Sohankar, A. *et. al.* [6] have investigated numerically the two dimensional unsteady flow over a rectangular prism different side ratios, various angle of incidence and for Reynolds number ranging from 100 to 200. It is observed that the behavior of all quantities at low angle of incidence ($\alpha \leq 20^\circ$) and at high angles of incidence ($\alpha \geq 70^\circ$) is sufficiently different from the values at $21 < \alpha < 70$. The increase of side ratio decreases the Strouhal number significantly. It is observed that the two separation points are fixed at the two corners, which are located on projected side.

3. Fluid flow phenomena

When a fluid flows over a solid boundary, a layer of fluid, which comes in contact with the solid surface, adheres to it on account of viscosity. Since this layer of fluid cannot slip over the boundary surface, it attains the same velocity as that of the boundary. The pressure difference decreases slowly as the flow of fluid advances over the rectangular surface. At the boundary surface the frictional force retarded the motion of the fluid in a thin layer. This retarded layer of fluid further causes retardation for the adjacent layers of the fluid, there by developing a small region in the immediate vicinity of the boundary surface in which the velocity of flowing fluid increases gradually from zero at the boundary surface to the velocity of the main stream. The region is known as boundary layer in the boundary layer region since there is a large variation of velocity in a relatively small distance, there exists a fairly velocity gradient ($\delta v / \delta y$) normal to the boundary surface. As such in this region of boundary layer even if the fluid has small viscosity, the corresponding shear stress $\tau = \mu(\delta v / \delta y)$ is of appreciable magnitude. Several problems involving the flow of fluid around submerged objects are encountered in various engineering fields. Such problem may have either a fluid flowing around a stationary object or an object moving through a large mass of stationary fluid or both the object and the fluid being in motion. In this experiment the rectangular prism is being stationary in the wind tunnel.

Flow around surface-mounted, three-dimensional bluff-bodies are characterized by region of flow separation, vortex formation and flow reattachment. One generic flow that encompasses all flow around bilge corners, chines and keels. In other applications, flow characteristics in the separation and reattachment are directly related to the local as well as overall friction drag and heat transfer coefficients.

In the flow around a rectangular cylinder, the sharp corner is natural point of separation. It was found that the separation point for the square cylinder at zero angle of incidence is located at the rear corner for Reynolds number less than 125. By increasing the Reynolds number the separation points move along the side surfaces from rear corner towards the frontal corner. At a Reynolds number of about 125, a small back-flow region is observed at the top and bottom of the body and this region is larger at higher Reynolds number.

For an ideal fluid flowing past a rectangular prism, it is possible to obtain analytically the pressure and temperature distribution over it. The highest intensity of pressure occurs at the frontal edge. This is due to the stagnation point. At the stagnation point velocity is zero, where pressure is high. Temperature distribution has various applications in the industrial purposes for finding out the flow of fluid flow and heat transfer characteristics over a rectangular surface. The experimental result helps for determining the shape of various rectangular surfaces used in the Industries for different purposes. The temperature distribution also used in cooling system and combustion engineering. In practical application, however, the flow field around rectangular surface is important. Experimental investigation was concerned with finding the temperature and pressure distribution on the rectangle of different Reynolds number.

4. Methodology

Reynolds number of the flow is calculated by $Re = VW/\nu$, where $V = \sqrt{2 \times g \times H}$, W is characteristic length, ν is the kinematics viscosity of air and $H = \nabla P/\gamma$. The coefficient of pressure is denoted by C_p and it is equal to $C_p = (P - P_{wall}) / (1/2 \times \rho \times V^2)$ where P is the pressure of fluid in the prism surface and P_{wall} is the pressure at the wall of the wind tunnel and ρ is the density of air at ambient temperature. The Nusselt number is calculated by $Nu = q \cdot dx / k_a (T_{wall} - T_{\infty})$, where $q = -K_s (T_2 - T_1) / dx$, q is the heat flux, K_s and K_a is the thermal conductivity of steel and air respectively. T_a and T_{wall} is the ambient temperature and wall temperature of rectangular prism at steady state condition respectively.

5. Experimental set up

A Subsonic horizontal type wind tunnel has been used during the experiment. This tunnel has four main sections

- a) Honey comb.
- b) Contraction section.
- c) Test section.
- d) Diffuser section with fan assembly.

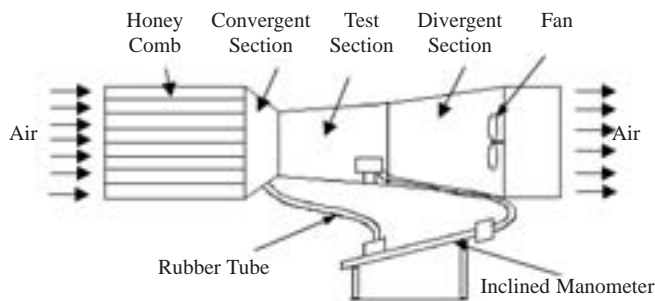


Figure 1. Pressure measurement apparatus

For this experiment a rectangular prism sections was made of GI sheet having length 23 cm, width 20 cm, thickness 9 cm. The prism is used to measure the pressure distribution and for the temperature distribution. Wooden frame is used to

support the rectangular section during the experiment in the test section of the wind tunnel. With the help of this frame the rectangular prism is rightly clamped in the test section. An inclined manometer of low range is used to determine the pressure distribution at various points of the rectangular surface. Forty five pieces of copper tubes is used in the rectangular surface for the measurement of pressure. Each of the tube was one inch in length and diameter was 2.5 mm. The center line velocity is calculated by Pitot tube for determination of the Reynolds number of the flow.

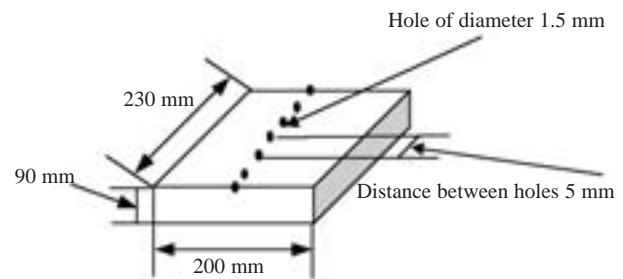


Figure 2. The rectangular prism with holes.

The difference of pressure is calculated considering the wind tunnel wall pressure as the reference pressure. Manometer reading shows the pressure difference between the wind tunnel wall pressure and the pressure at the holes on the surface of the rectangular prism, which is $\nabla p = (P - P_{wall})$. The angle of incidence is considered at 10°. Honeycomb is used to maintain the streamline flow into the wind tunnel. Air enters in to the tunnel through honeycomb and flow to contraction section at uniform rate. The flow of air directly flows through the test section where the rectangular prism is kept. At the end of the diffuser section there is an induced type fan which sucked air coming from test section and provide uniform streamlined flow of air. The prism was clamped with the frame at angular position by using nut & bolt. The readings were taken simultaneously from the stagnation point to the last point. The velocity of the flow in the wind tunnel was fixed at different Reynolds number and the same process is repeated to determine the coefficient of pressure.

Forty five pieces of thermocouple wires were soldered in every 0.5 cm distance along the length of the rectangular surface. Also a flat type heater (350 W) was attached by steel clamp at the lower portion of the rectangular surface. When there is no flow of air, the switch of the heater was on and continued till the steady state temperature of the rectangular surface rise up to 90°C, which was shown in a temperature recorder. The flow of air is started at $Re = 5572$ and the temperature is taken from the temperature recorder. Thus a complete set of reading was taken for the rectangular prism at an incidence angle 0°. Similar process is repeated for other Reynolds number and Nusselt number is calculated from the distribution of temperature.

5. Result and discussion

In the present investigation, the pressure distribution and heat transfer characteristics over rectangular surface due to uniform flow was investigated. Experiment was performed for Reynolds numbers 5572, 6006, 6631 and 7003 and included angle 0° , 10° , 20° and 30° .

The distribution of coefficient of pressure over the rectangular surface for Reynolds number 6006 and incidence angle 10° is shown in the **Figure 3**. It is observed that the coefficient of pressure C_p decreases with the increase of surface axial length. The rate of decrease is slow. The maximum value of coefficient of pressure is shown at the stagnation point. The distribution of coefficient of pressure for different Reynolds numbers and incidence angles 10° is shown in the **Figure 4**. It is observed that the coefficient of pressure decreases with axial length of the prism surface, but increases with the increase of Reynolds number. The variation of coefficient of pressure at different incidence angle and at Reynolds number 6006 is shown in the **Figure 5**. It is observed that the coefficient of pressure increases with the increase of incidence angle. The co-efficient of pressure became steady at $X = 0.025$ but

shown maximum value at the starting point. If the Reynolds number increases the flow is separated from the surface.

The distribution of local Nusselt number over the rectangular surface for Reynolds number 6006 and incidence angle 10° is shown in the **Figure 6**. It is observed that the local Nusselt number Nu_x decreases with the increase of surface axial length. The rate of decrease is high close to the stagnation point. The maximum value of local Nusselt number is shown at the stagnation point. The distribution of local Nusselt number for different Reynolds numbers and incidence angles 20° is shown in the **Figure 7**. It is observed that local Nusselt number decreases with axial length of the prism surface, but increases with the increase of Reynolds number. The variation of local Nusselt number at different incidence angle and at Reynolds number 6006 is shown in the **Figure 8**. It is observed that the local Nusselt number increases with the increase of incidence angle. The Nusselt number becomes steady at $X=0.015$ but shown maximum value at the starting point. Because of higher Reynolds number turbulence is generated in the laminar sub-layer. Which then mixed in the buffer layer of the boundary. For higher Reynolds number the flow have contain higher kinetic Energy.

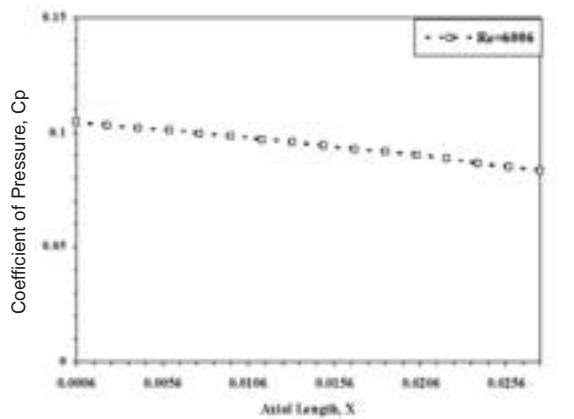


Figure 3. Distribution of coefficient of pressure along the rectangular prism surface at Reynolds number 6006 and at incidence angle 10° .

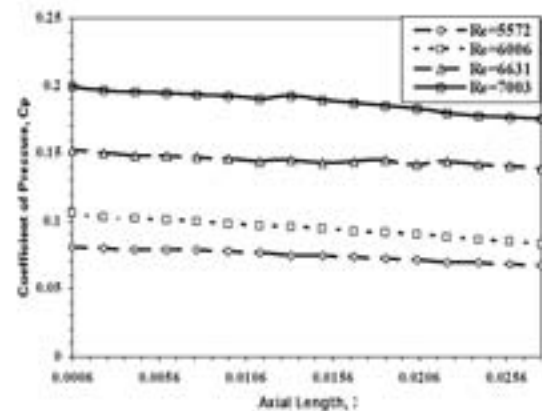


Figure 4. Variation of coefficient pressure along the axial length of the rectangular prism surface at incidence angle 10° for different Reynolds number.

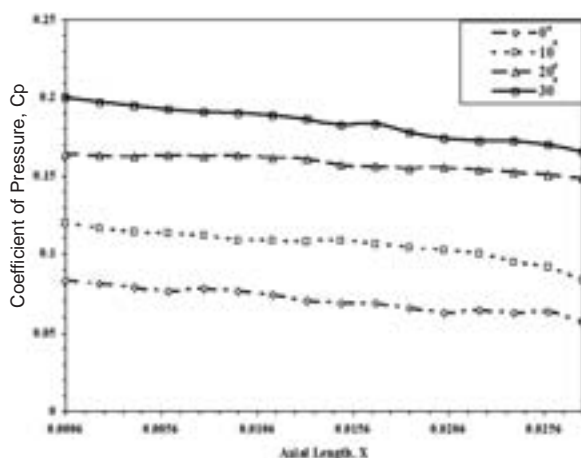


Figure 5. Variation of coefficient pressure along the axial length of the rectangular prism surface at Reynolds number 6006 for different incidence angle.

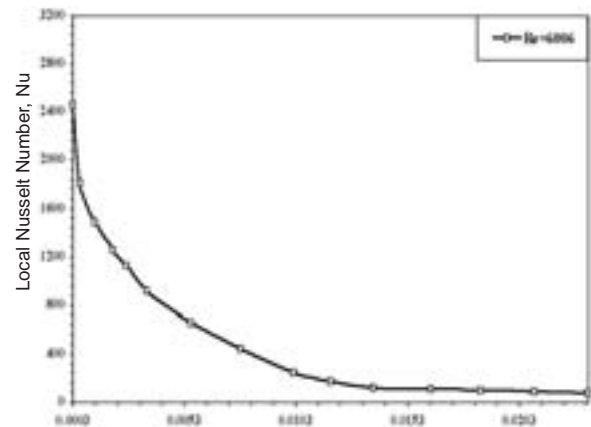


Figure 6. Distribution of Local Nusselt number along the rectangular prism surface at Reynolds number 6006 and at incidence angle 10° .

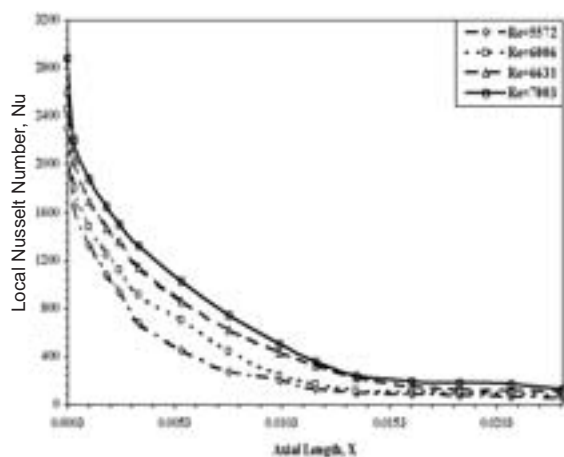


Figure 7. Distribution of Local Nusselt number along the rectangular prism surface at incidence angle 20° for different Reynolds number.

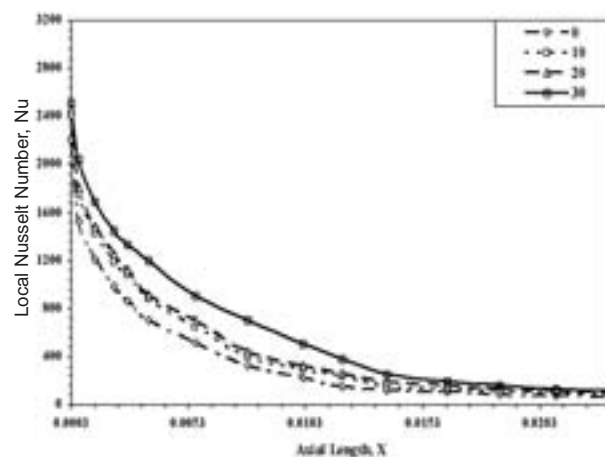


Figure 8. Distribution of Local Nusselt number along the rectangular prism surface at Reynolds number 6006 for different incidence angle.

Conclusion

It is concluded that co-efficient of pressure along the rectangular surface decreases when distance increases and co-efficient of pressure increases with increasing Reynolds numbers and incident angle. Similarly Nusselt number decreases with the increases of axial length and Nusselt number increases with the increase of Reynolds numbers and incident angle.

References

- [1] Sohankar, a. et. Al., 'Low Reynolds number flow around a square cylinder at incidence: study of blockage, onset of vortex shedding and outlet boundary condition', International Journal for Numerical Methods in Fluids, Vol. 26, 39-56 (1998).
- [2] Vlachos, P. P. and Hajj, M. R., 'Unsteady flow characteristics of flow over a surface-mounted prism', Department of Engineering Science and Mechanics, Virginia Tech., Blacksburg VA, 24060, USA.
- [3] Esfahani, A. S., 'Numerical Study of laminar, transitional and turbulent flow past rectangular cylinders', Department of Thermo and Fluid Dynamics, Chalmers University of Technology, 1998.
- [4] Katinas, V. et. al., 'Experimental and numerical study of three dimensional turbulent flow over a rectangular prism', PHOENICS Journal of CFD, Volume 11, No. 2, PP 187-197.
- [5] Noda, H. and Nakayama, A., 'Free-stream Turbulence effects on the instantaneous pressure and forces on cylinders of rectangular cross section', Technical Research Institute, Mitsui Construction Co. Ltd., Komaki, 270-0132, Nagareyama, Japan.
- [6] Sohankar, A., Norberg, C. and Davidson, L., 'A Numerical Study of Unsteady Two-Dimensional Flow Around Rectangular Cylinder at Incidence' Internal Report Nr. 96/25, Department of Thermo and Fluid Dynamics, Chalmers University of technology, Gothenburg, Sweden.
- [7] Djilali, N. and Grath store I.S., "Turbulent Flow Around A bluff rectangular plate", Part 1. Experimental investigation". ASME Journal of fluid Engineering, Vol. 113, pp.51-3, 1991.
- [8] Test, FT an Lessman, R.C., "An Experimental study of heat transfer during forced convection over Rectangular Body". ASMF Journal of HEAT TRANSFER, VOL. 106, PP. 276-283, 1980.
- [9] Ota. T. and Ita saka, M., "A separated and Reattached flow on A blunt flow plate", ASME Journal of fluid Engineering, Vol. 98, pp. 79-86, 1976.
- [10] Katinas, V., Vatekunas P. and Zukauskas, A. " Experimental and Numerical study of three-dimensional Turbulent Flow Over A Rectangular Prism". Phoenix Journal of CFD & applications, Volume 11, No2, pp 187-197.

Nomenclatures

C_p	Co-efficient of pressure.
D	Height of the rectangular prism in mm
L	Length of the rectangular prism in mm
P	Pressure of fluid in the prism surface in N/m^2
P_{wall}	Pressure at wall of the wind tunnel in N/m^2
Re	Reynolds number = VD/ν
V_α	Velocity of air in m/sec
w	Width of the rectangular prism in mm
x	Centre to centre distance between two adjacent holes on the rectangular prism surface in mm
X	Axial location, x/w
α	Angular rotation of the rectangular prism in degree
γ	Specific weight of air in N/m^3
ν	Kinematics viscosity of air in m^2/sec
ρ	Density of air in kg/m^3
T	Temperature at the different point of prism surface
T_α	Ambient Temperature
q	Heat flux in W/m^2 °C
K_s	Thermal Conductivity of steel in W/m^2 °C
K_a	Thermal Conductivity of air in W/m^2 °C
dx	Distance between two thermocouple wires
Nu_x	Local Nusselt number
T	Local temperature
T_{wall}	Wall temperature (G.I sheet) at steady state