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AN EXPERIMENTAL INVESTIGATION OF VARIATIONS OF PRESSURE DISTRIBUTION WITH REYNOLDS NUMBER AND SURFACE ROUGHNESS IN CIRCULAR WALL JET

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Abstract

An experimental study is carried out to investigate the coefficient of pressure distribution after emerging a circular wall jet over smooth and rough flat surfaces. The effects of the systematic variations of the range of jet exit Reynolds numbers and of relative roughnesses of the surface are carefully observed. The Jet exit Reynolds numbers ranges of 8799 - 18804 and the relative surface roughnesses of smooth ranging from 0.01371 to 0.01613 were considered for this investigation. A converging nozzle of diameter 6.2 mm was taken for the jet issuing while the length of the flow straightener tube was 320 mm, sufficiently larger than hydraulic diameter (120mm ID) to ensure fully developed flow. Dial gauge indicator and Pitot tube were used to measure the surface roughness and the velocity of flow respectively. It was observed that the overall co-efficient of pressure, Cp decreases with the increase of both jet exit Reynolds number and surface roughness. Since the fluid moving with higher kinetic energy initially and decays along the length of the surface due to viscous effect, the coefficient of pressure with higher value at starting point decreases with the increase of jet exit Reynolds number. The same trend also holds well with the increase of relative surface roughness because of the enhancement of frictional effect. The co-efficient of pressure remains more or less steady after a particular distance along the axial length of the surface.

Key Words: Circular wall jet, Surface roughness, Free jet, Pressure distributions.

1. Introduction

A wall jet is a stream of fluid blown tangentially along a wall and it has a wide range of applications, such as boundary-layer separation control over a wing, film cooling on turbine blades, circulation control airfoils, flow separation control from the surface, to construct a new type of air classifier which separates fine particles etc [8,11,12]. Fluid flow in the form of wall jets increases the momentum. Among the other types, circular wall jet is a common method of heating or cooling the solid surfaces. However, circular wall jet with turbulent characteristics is also of particular interest in engineering and industrial applications due to high heat transfer rates caused by eddy mixing. Earlier wall jet investigations were emphasized mostly on smooth surfaces. A variety of turbulence promoting schemes has been used in association with surface roughness. A little consideration will show that surfaces produced by different machining operations are of different characteristics. They show a remarkable variation when compared with each other. The variations are judged by the degree of smoothness. The surface roughness encountered, in practice, varies in their shape, size, distribution and arrangement, micro-scopical surface property, characteristics behavior with flow etc. In this experiment, surface roughness has been used to create the turbulence effect in the flow.

The present experimental study has been focused on the pressure distribution emanating a circular wall jet over flat surfaces (both smooth and rough). The fluid is allowed to flow with a stagnant surrounding fluid of atmospheric pressure which causes the energy transfers to the surrounding fluid leading to the gradual energy decay. The maximum velocity of the jet decreases in proportionality to $x^{-0.5}$, where x is the distance from the nozzle exit [12]. The inner region develops a wall boundary layer as in the flat surface while the outer region behaves like a free jet problem.

2. Literature Review

Tachie, M. et al. [9] reported the effects of surface roughness on the mean flow characteristics for a turbulent plane wall jet created in open channel. They showed that surface roughness increases the skin friction coefficient and the inner layer thickness, but the jet half-width is nearly independent of surface roughness. G. E. Myers, J. J. Schaur, R. H. Eustis [1], observed both the heat transfer characteristics and the relationship between the thermodynamic and the hydrodynamics properties of wall jets differ from the ordinary flat plate problem. The pressure distribution and the local and average Nusselt number due to impinging of a circular air jet over uniformly heated rough flat surfaces were investigated by Md. Nurul Islam [6]. M. D. Zhou et al. [7], measured components of velocity fluctuation in a plane turbulent wall jet and established the kinetic energy transfers that takes place in the wall jet under controlled perturbations. Experimental investigation with uniform flow was carried out by M. Sohel Rana et al. [10] for the pressure distribution on the smooth wedge surface for different included angles and different Reynolds numbers and around the sphere of different size. They found that the variation of static pressures is larger near the wedge vertex and gradually decreases along the length of the wedge surface. A. J. Hogg et al. [2] investigated and presented a new scaling law for the spatial variation of the mean velocity and lateral extent of a two-dimensional turbulent wall jet, flowing over a fixed rough boundary. They revealed that the characteristics of the jet depend weakly upon the roughness length associated with the boundary. Sato, Y, et al. [3] investigated experimentally and numerically the interaction between dispersed particles and fluid turbulence for a vertical down-flow turbulent wall jet embedded in a uniform stream. Modifications of the mean fluid velocity by the particles induced reduction in the Reynolds stress, which alters the turbulence production. F. J. Higuera [4] conducted a numerical and analytical study on the coupling of temperature and velocity fields in a laminar two-dimensional plane or circular wall jet over a horizontal plate of finite length with infinite Reynolds number. G. P. Hammond [5] investigated and established an analytical expression for the complete velocity profile of a plane turbulent wall jet in stagnant surroundings which is obtained by coupling Spalding's single formula for the inner layer with a sine function for the wake component.

3. Methodology

According to the American Society of Mechanical Engineer (ASME) standard, techniques used for the measurement of surface roughness are profiling methods, area profiling methods and area averaging methods.

Profiling methods probe the peaks and valleys of the surface under test with a high-resolution probe that senses the height of the surface and produces a quantitative surface profile while Area profiling methods extend the technique into three dimensions, either by rastering a series of profiles or by some type of quantitative imagine process. And finally, Area averaging method is the most common method known as Root Mean Square Method which can be defined as,

$$\text{R.M.S.} = \sqrt{\frac{h_1^2 + h_2^2 + h_3^2 + - - - - - + h_n^2.}{n}} \quad \text{in microns}$$

Where, h_1, h_2, h_3----------h_n are the ordinates measured on both sides of the mean line and n is the number of ordinates. This RMS method has been used to measure the average height of the surface roughness in the present investigation.

4. Experimental Set-Up

The experimental set-up is shown in Figure-1. The two main components of the experimental setup are as i) Air jet and pressure measuring system and ii) Jet support frame.

The air jet was issued from a circular copper tube of inside diameter 6.2 mm. The length of the tube was 320 mm, which was sufficiently larger than hydraulic diameter (120mm ID) to ensure fully developed flow. The jet system and different views are shown in Figure-1.

The jet arrangement consisted of an air blower (1.5 hp), a variac, a filter cum settling chamber, a flow straightener, a Pitot tube, an inclined manometer for air, a converging nozzle of diameter 6.2 mm. Investigations were performed on five test surfaces, one was smooth and the rests were of different roughnesses. The surfaces artificially roughened by scribers of various sizes in random manner. Dial gauge indicator was used to measure the surface roughness which was calculated by RMS method. 140 mm square mild steel sheet (K=54 W/m.k) having thickness 0.195mm was used as the flat surface. Throughout the experiments the jet was centered along the surface, airflow was adjusted by a variac. Then velocity of flow of air was measured by Pitot tube and jet Reynolds number was calculated for stable and fully developed flow. At this position, pressure distribution over flat surface due to jet of air was recorded. The procedure was followed for every surface, smooth as well as rough and for different Reynolds number.

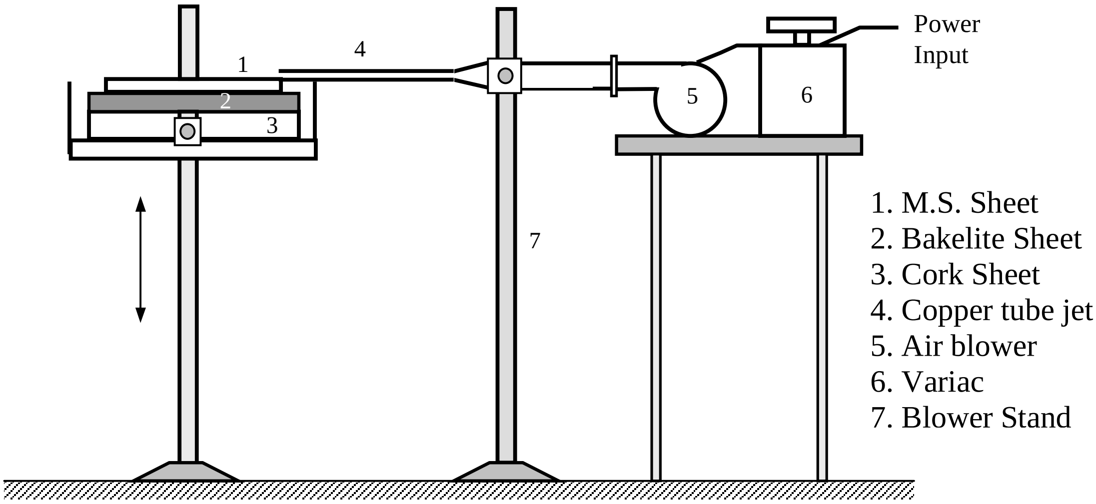

Fig. 1. Schematic diagram of Experimental Setup

5. Results and Discussion

In the present investigation the pressure distribution and heat transfer characteristics over smooth and rough surfaces due to circular wall jet was investigated. Experiments were performed for jet Reynolds number of 8799, 10777, 16849 and 18804 for jet diameter of 6.2 mm. The surfaces were considered of smooth ($\in =0$) and relative roughnesses of 0.01371, 0.01435, 0.01581 and 0.01613.

The distributions of co-efficient of pressure over the surface of different roughnesses were plotted for different Reynolds number in Fig. 2 to Fig. 6. Also the distributions of co-efficient of pressure were plotted for different relative roughnesses in Fig. 7 to Fig. 10.

Figure 2, shows the distribution of co-efficient of pressure, C_p along the length of the smooth surface at various Reynolds number, Re. It was observed that the co-efficient of pressure decreases with the increase of Reynolds number and with the length of the surface as well while it becomes steady at X = 12.0. C_p always was found the maximum value at the starting point of the length, because agitation plays vital role in the laminar sub-layer. The turbulence that creates in the laminar sub-layer due to the protrusions of the rough surface, is absent in smooth surface. If the Reynolds number increases the flow is separated from the surface. The decreasing rate of co-efficient of pressure is higher at lower Reynolds number. Figure 3 to 6 show the variation of co-efficient of pressure at different Reynolds number for various surface roughnesses. The similar trend was observed as for the smooth surface, but the relatively lower values of the starting point as well as of the lengths along the surface. With the increase of the surface roughness, there was a spectacular dropping off C_p while the length, where C_p gets almost steady, was shifted to a higher value. This can be attributed due to the increased turbulence created by the surface.

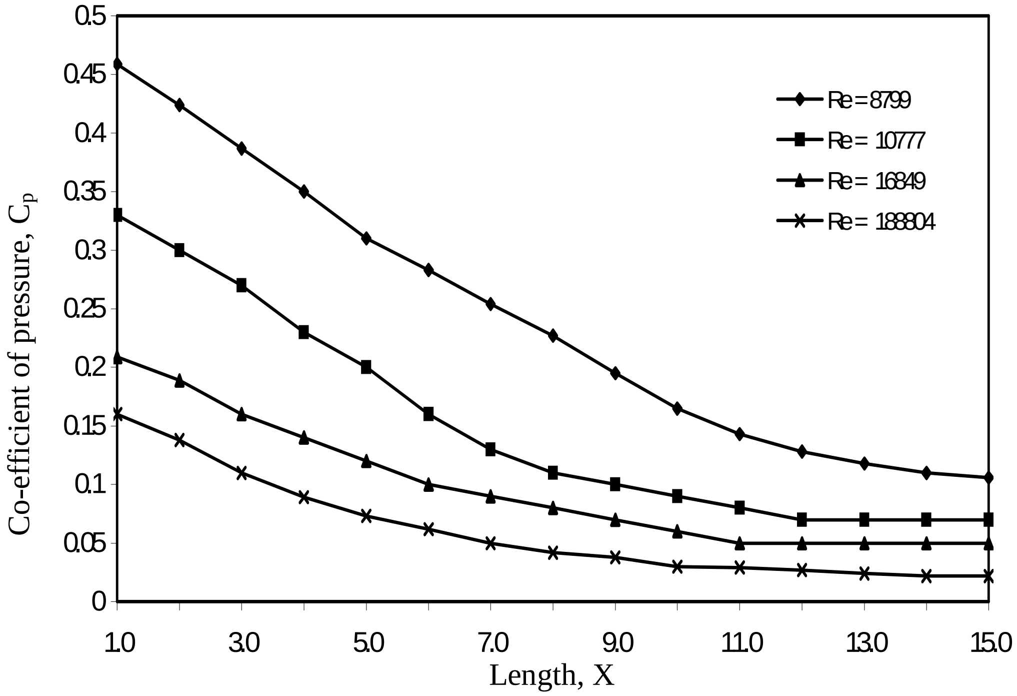

Fig. 2. Distribution of co-efficient of pressure, C_P along the length of the smooth surface ($\in$ =0) at various Reynolds numbers

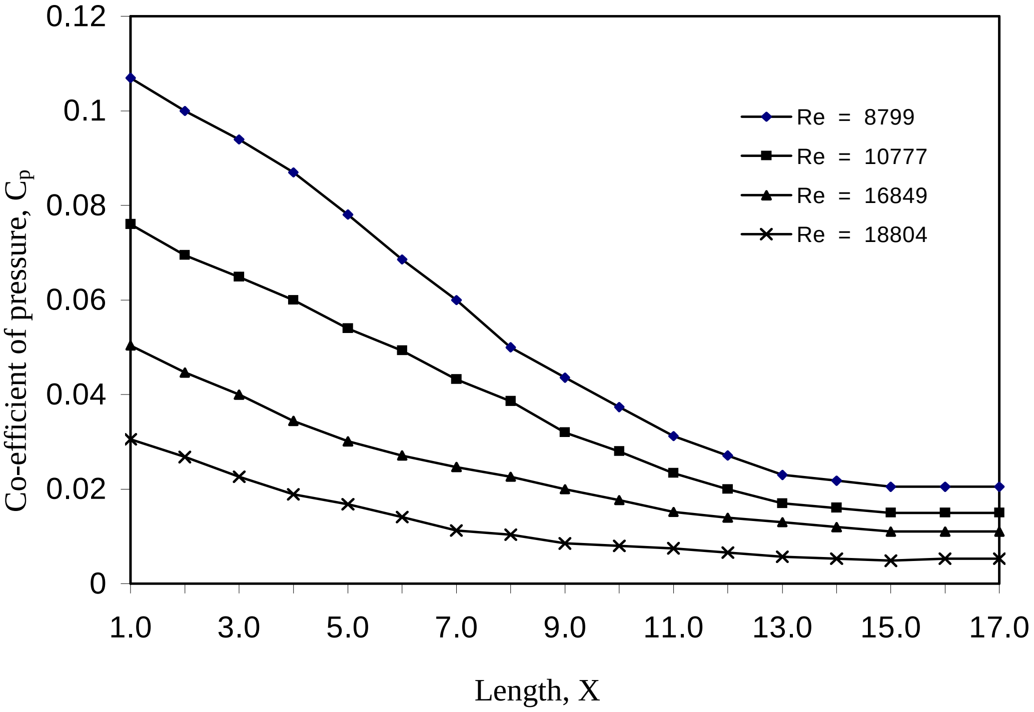

Fig. 3. Distribution of co-efficient of pressure, Cp along the length of the surface roughness ε = 0.01371 at various Reynolds number.

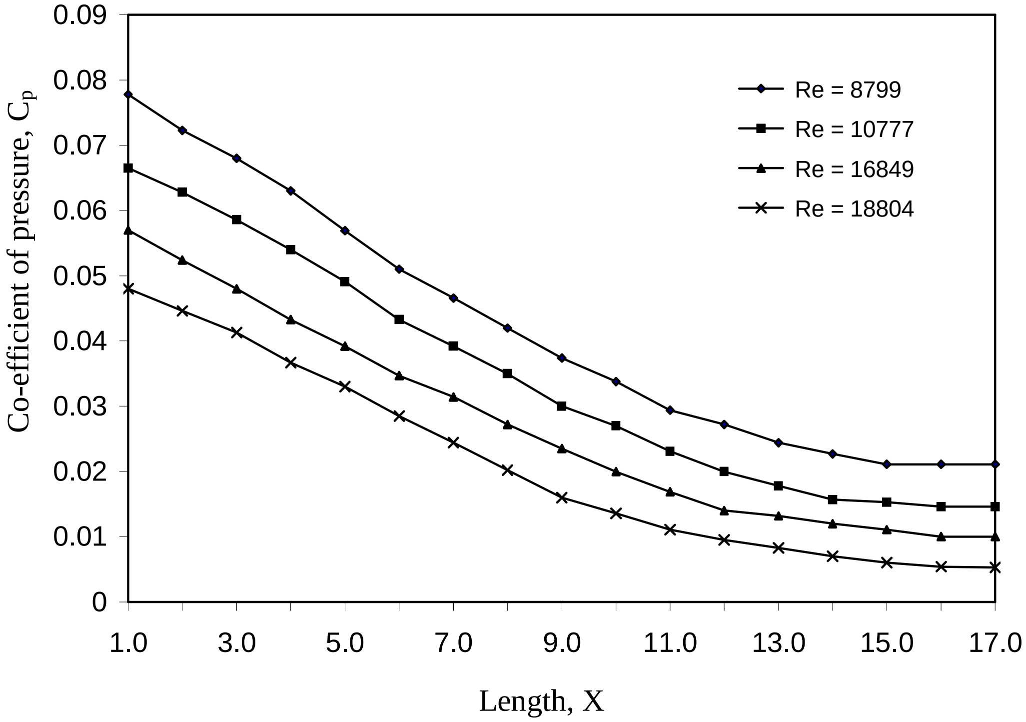

Fig. 4. Distribution of co-efficient of pressure, Cp along the length of the surface roughness ε = 0.01435 at various Reynolds number.

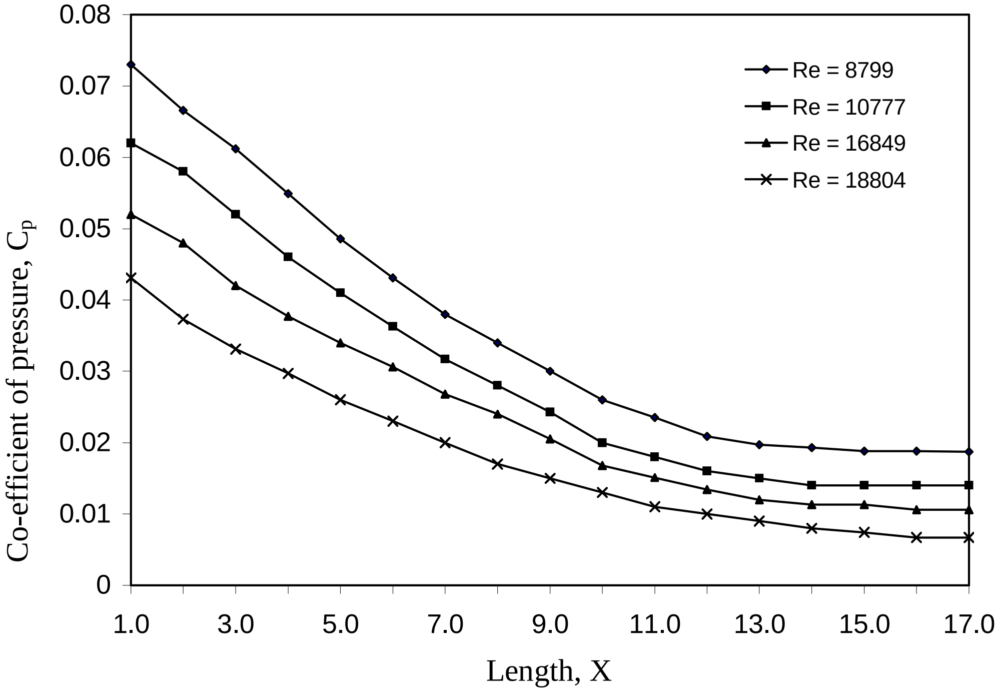

Fig. 5. Distribution of co-efficient of pressure, Cp along the length of the surface roughness ε = 0.01581 at various Reynolds number.

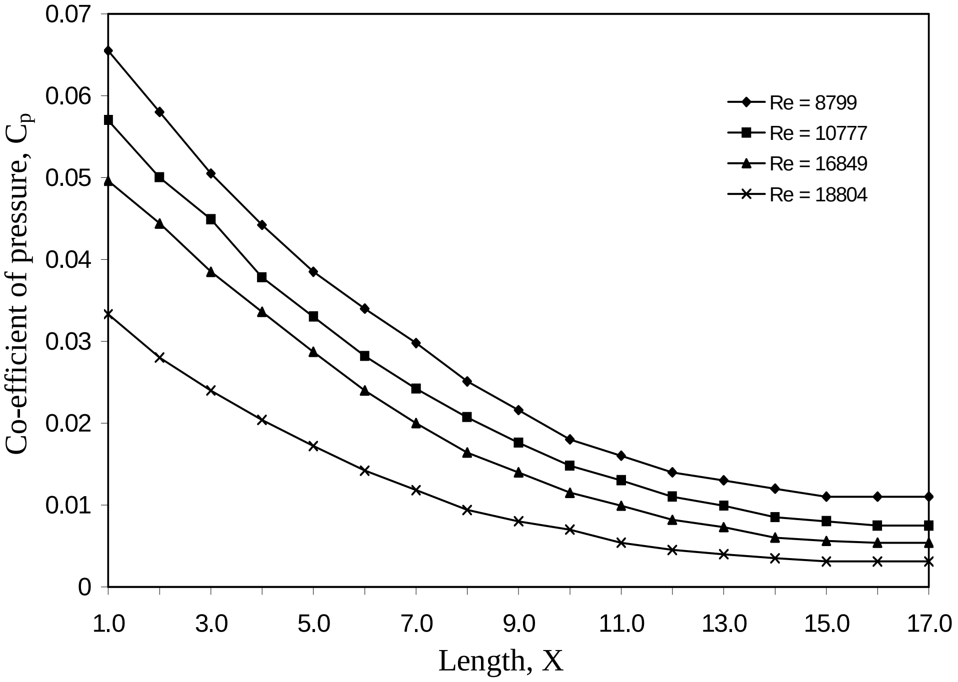

Fig. 6. Distribution of co-efficient of pressure, Cp along the length of the surface roughness ε = 0.01613 at various Reynolds number.

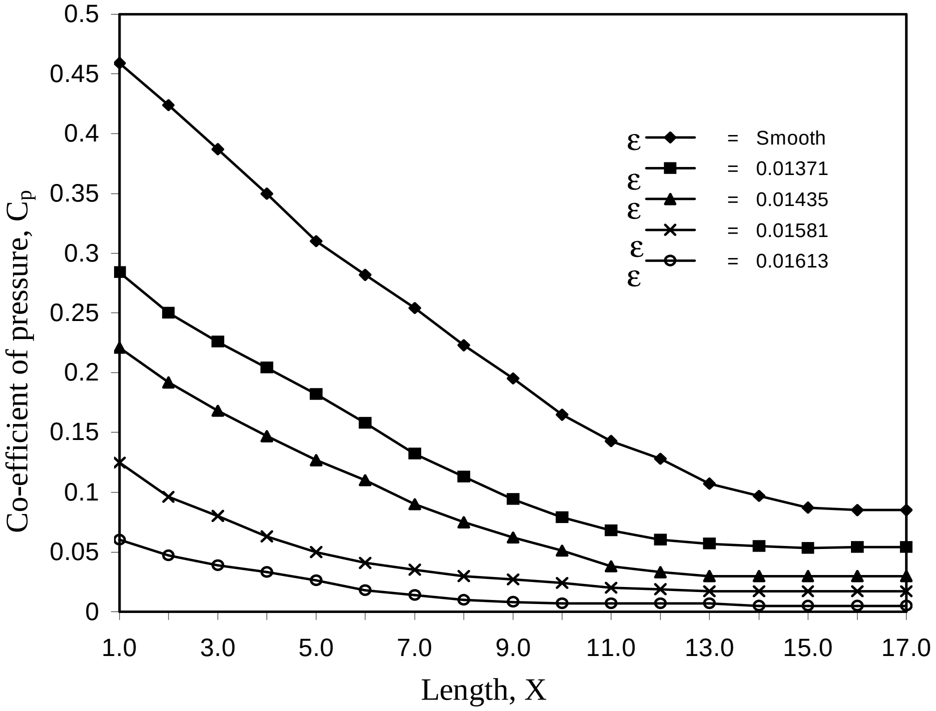

Fig. 7. Distribution of co-efficient pressure Cp along the length of the surfaces at jet exit Reynolds number Re = 8799

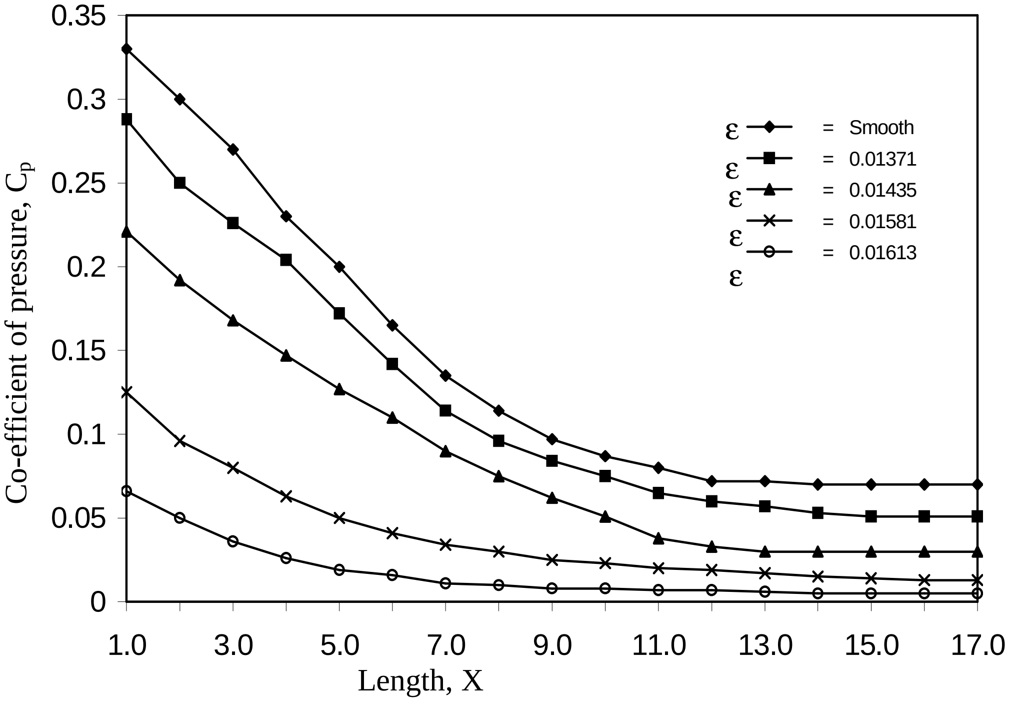

Fig.8. Distribution of co-efficient pressure Cp along the length of the surfaces at jet exit Reynolds number Re = 10777

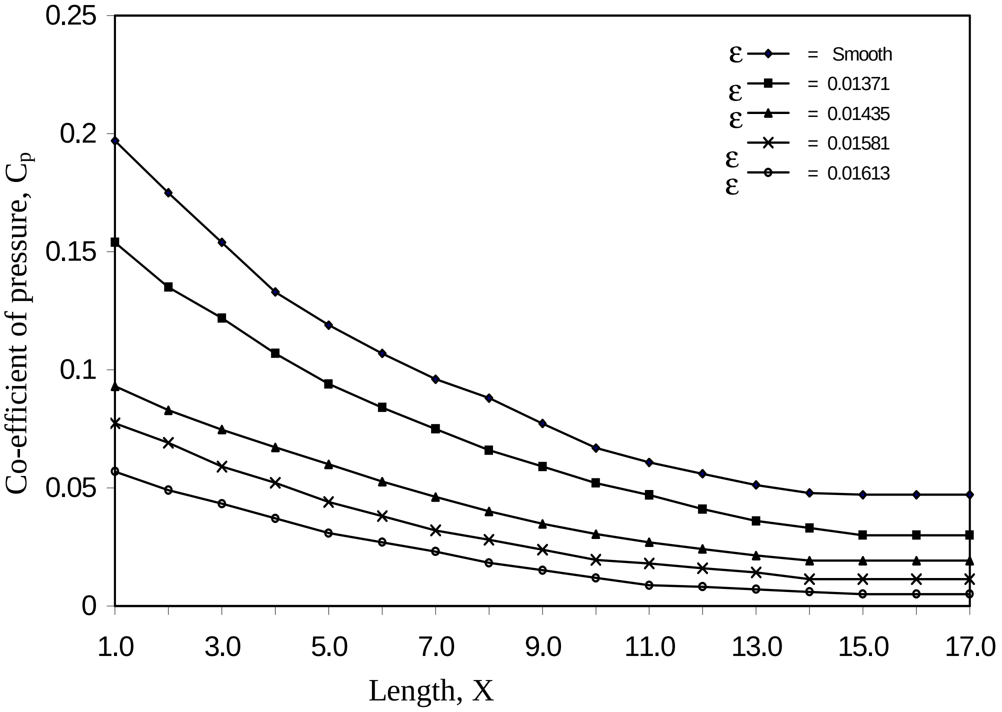

Fig. 9. Distribution of co-efficient pressure Cp along the length of the surfaces at jet exit Reynolds number Re = 16849.

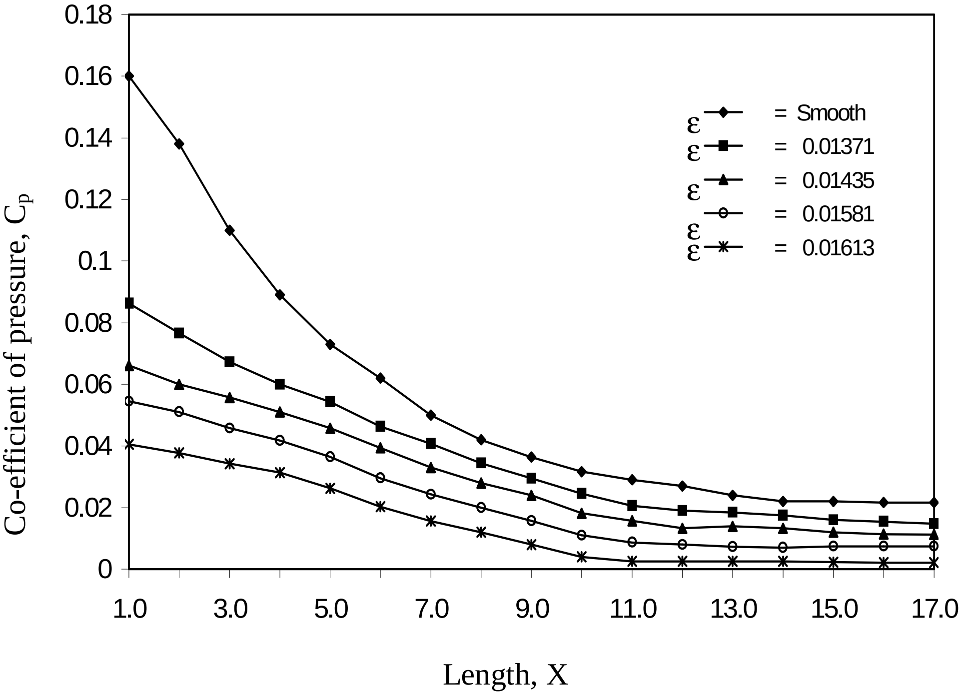

Fig. 10. Distribution of co-efficient pressure Cp along the length of the surfaces at jet exit Reynolds number Re = 18804

Figure 7, shows the distribution of co-efficient of pressure along the length of the surface at jet exit Reynolds number Re = 8799. It was observed that the co-efficient of pressure decreases with the increase of relative roughness of the surfaces. It was apparent that the diminishing rate of co-efficient of pressure is relatively higher at smooth surface and surface of lower relative roughness as well, but the curve becomes almost flat in nature at higher values of surface roughness. As the average height of the protrusions increases, the turbulence generated by this in the laminar sub-layer causes the flow separated from the surface and mixed with the buffer layer. It was also observed that the starting value of co-efficient of pressure is superior at smooth surface and it is in decreasing fashion with the increase of relative roughness of the surface.

Figure 8 to 10, show the variation of coefficient of pressure, C_p along the length of the surface X for different Reynolds number at smooth and rough surfaces. Again, the co-efficient of pressure drops down with the increase of surface roughness at every Reynolds number and the decreasing rate shows the similar trend as was at lowest value of Reynolds number i.e. at Re=8799. Moreover, the starting value of C_p on smooth surface is remarkably higher for the lowest Reynolds number (8799) having a value 0.46 and it goes down about three times for the highest Reynolds number (18804) under consideration in this study to a value of 0.16. The same fashion also holds well for the rough surfaces as well but the surface of highest roughness which drops down only very little amount.

6. Conclusions

In light of the discussion of results the following conclusions were drawn as a consequence of present work. Variation of pressure distribution due to circular wall jet over a surface depends on surface roughness, jet Reynolds number in the following manner: Co-efficient of pressure decreases with the increase of jet Reynolds number and jet Reynolds number has significant effect on pressure distribution. Co-efficient of pressure decreases with the increase of surface roughness. Maximum co-efficient of pressure is at the initial point for all relative surface roughnesses and all jet exits Reynolds number within the range of parameters considered in the Experiment. The decreasing rate of co-efficient of pressure is higher at smooth surface and surfaces of lower relative roughness.

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