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HEAT TRANSFER CHARACTERISTICS IN A DUCT WITH ROUGHENED PLATE IN AN SOLAR AIR HEATER

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Abstract- A computer simulation of transverse shape continuous type of artificial roughness geometry on the absorber plate of solar air heater duct has been carried out to investigate the heat transfer characteristics under simulated conditions using ANSYS. The Nusselt number, heat utilization, exit air temperature, and thermal efficiency has been computed as a function of Reynolds number and mass flow rates for different artificial roughness (relative pitch) on the absorber plate of air heater duct. The performance of roughened absorber plate has been compared with that of smooth plate and different results have been obtained, Reynolds number has been varied from 4000 to 16000 in the present study. On the basis of investigation, The Nusselt number obtained from ANSYS has been validated by comparing them with that obtained from Dittus-Boelter equation. It has been found that ANSYS results are in good agreement with that of Dittus-Boelter equation. ANSYS over predicts the Nusselt number by 5.8 %.Based on the analysis, it has been found that the performance of solar air heater can be enhanced by providing artificial roughness in the form of ribs on the underside of the absorber plate than the conventional flat plate solar air heater. Nusselt number has been found to be highest for an absorber plate having relative roughness pitch equal to 10. For, relative roughness pitch of 6, the value is lowest but higher than that for smooth plate. Thermal efficiency increases with increases in mass flow rate. The thermal efficiency is also highest for the plate with relative roughness pitch equal of 10 while it is lowest for relative roughness pitch of 6.The improvement in heat transfer coefficient is more at lower Reynolds numbers as compared to higher Reynolds numbers.

Keywords- Ansys, Reynolds Number, Flotran, Nusselt Number, Simulation

1. INTRODUCTION

Energy in various forms plays an important role in the development and economic progress of a country. The growth of population coupled with rising material standards of living has increased the rate of energy usage, which has created crisis of energy, especially in the developing countries. This has necessitated our dependence on non-conventional resources of energy, viz. solar energy, geothermal energy, wind energy etc. Of various alternatives, solar energy seems to be the brightest long term resource for meeting continuously increasing demand of energy.

For harnessing solar thermal energy, different types of collection devices are in use e.g., flat plate collectors for low temperature below 90 ^{0}C and focusing collectors for high temperature applications above 90 ^{0}C. Generally, water heating and air heating is done using solar flat plate collectors. Solar air heaters are very popular among solar thermal applications due to their simple design and low cost. Some engineering applications of solar thermal technology are domestic water heating, space heating, space cooling and refrigeration, distillation and drying of agriculture products etc.

The thermal efficiency of a solar air heater is generally less because of low heat transfer coefficient between absorber plate and air flowing in the duct. To make solar air heater more effective, thermal efficiency needs to be improved by using enhancement techniques. There are several methods which can be used to increase the efficiency of solar air heaters. Several studies have been published in the literature by Chaube *et al* [2006], Lanjwar *et al* [2011], Desrues *et al* [2012] etc. to increase the efficiency of solar air heaters. Various surfaces used to improve efficiency of air heater are finned surface, corrugated surface, and surface with artificial roughness etc. In the current scenario, the focus of researchers is on adding artificial roughness to absorber plate due to its several advantages over other methods. Artificial roughness can be increased by using various type of ribs, of which rectangular ribs are preferred due to ease of manufacturing and placement on absorber plate, better strength and due to convenience in optimization of roughness parameters. Due to better strength, the ribs are not disturbed in the high turbulent region.

On the basis of surface configuration roughness can be divided into two categories. First category corresponds to geometry where the gap between two ribs is small because of which re-circulating flow occurs. The other category where the gap between two ribs is large, eddies form only behind the roughness elements.

Several experimental investigations and numerical studies have been performed to study the effects of ribs of different geometry. But, experimental and numerical methods too are not adequate to visualize the effects of ribs on the performance of air heater. The computer simulation of heat transfers and air flow in a rectangular duct with constant heat flux has been carried out in the present work to visualize and study the effect of rectangular ribs on the performance of air heater by using ANSYS, an analysis and simulation software. Main parameters studied in this work is mass flow rate

1.1 Solar Air Heater

A solar air heater is a simple device to heat air by utilizing solar energy, which has many applications in drying agricultural products, such as seeds, fruits and vegetables, and as a low-temperature energy source. Also, solar air heaters are utilized for heating buildings with auxiliary heaters to save energy in winter-time. Solar air heaters can also be used for industrial purpose. Solar air heaters are simple in design and maintenance. Depending upon the air passage in the solar air heater the air heaters can be classified in the following ways:

1.1.1 Single glass cover air heater

In this type of air heater there is only one glass surface on the top and the absorber is below the glass plate as shown in Figure.1.1. The air flows below absorber plate.

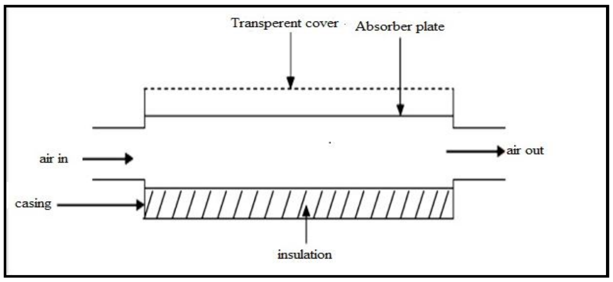

Figure. 1.1 Solar Air Heater

1.2 Performance Enhancement Techniques for Solar Air Heater

The performance of a flat plate solar air heater has been found to depend strongly on the rate of incident solar radiations, the losses from the absorber surface and the rate of heat transfer from absorber plate to the air. The following are some performance enhancement techniques for solar air heaters:

- Enhancement of intensity of solar radiation incident upon the solar collector
- By lowering convective as well as Radiative heat loss
- By using alternate medium or vacuum in the gap space
- By selective absorber surfaces
- Improvement of heat transfer from absorber plate
- By Increasing the Area of Heat Transfer without Effecting the Convective Heat Transfer Coefficient Such surfaces are termed as 'extended
- By Increasing Convective Heat Transfer Coefficient Using Artificial Roughness

1.3 Concept of Artificial Roughness

In order to attain higher heat transfer coefficient, it is desirable that the flow at the heat-transferring surface is to be made turbulent. Surface roughness is one of the first active techniques to be considered as means of augmented forced convection heat transfer. However, energy for creating such turbulence has to come from the fan or blower and this excessive turbulence leads to excessive power requirement to make the air flow through the duct. It is therefore desirable that the turbulence must be created only in the region very close to the heat transferring surface i.e. in the laminar sub-layer region only where the heat exchange takes place and the flow should not be unduly disturbed so as to avoid excessive friction losses. This can be done by keeping the height of the roughness element to be small in comparison with the duct dimensions. Although there are several parameters that characterize the arrangement and shape of the roughness, the roughness element height (e) and pitch (p) are the most important parameters. These parameters are usually specified in terms of dimensionless parameters, namely, relative roughness height, e/d (the ratio of height of roughness element to the equivalent diameter of the duct) and the relative roughness pitch, p/e (the ratio of pitch to height of roughness elements). The roughness elements can be two dimensional ribs or three dimensional discrete elements, transverse or angled ribs or continuous or broken ribs. Although square ribs are the most commonly used geometry but chamfered, circular, semi-circular and grooved sections have been investigated in order to get most beneficial arrangement **Han and Zhang [1992**]

Some important geometry and the parameters that characterize the geometry and substantially influence the performance are given in table below.

Table 1.1 Various Types of Roughness Geometries and Parameters Hans *et al [*2009]

S. No	Rib Geometry	Parameters
1.	Transverse ribs	e/d , p/e
2.	Continuous Angled ribs	e/d, p/e, α
3.	V-shaped ribs	e/d, p/e, α
4.	Angled ribs with gaps	e/d, P/e, α, g/p, d/W
5.	Transverse-chamfered ribs	e/d, p/e, ϕ
6.	V-shaped staggered discrete ribs	e/d, p/e, α, B/S, p′/p, S′/S
7.	Grooved- ribs arrangement	e/d, p/e, g/p
8.	Arc shaped ribs	e/d, p/e, α
9	W-Shaped discrete ribs	e/d, p/e, α
10	Wire mesh	e/d, p/e, L/e, S/e

1.4 Some Important Roughness Geometries

The use of artificial roughness in solar air heaters owes its origin from the several investigations carried out in connection with the enhancement of heat transfer in nuclear reactor, cooling of gas turbines blades and electronics equipment. These are few important geometries used in above mention application are given in figures below.

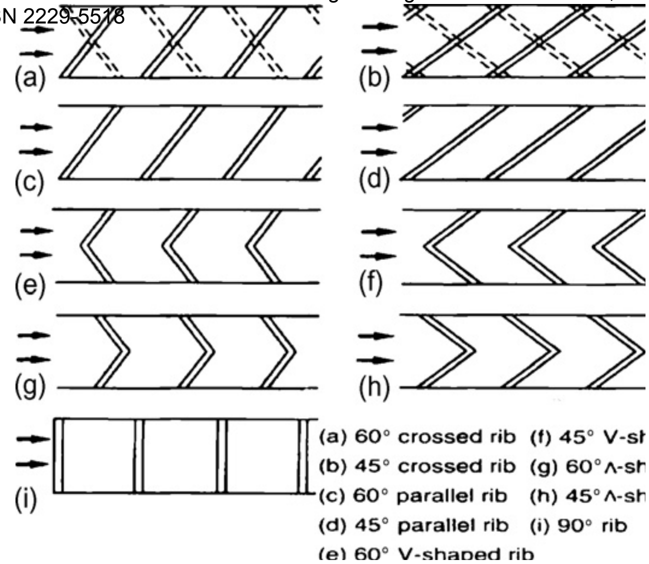

Figure. 1.2 Different configuration of Ribs used by Han and Zhang Hans *et al* [2010]

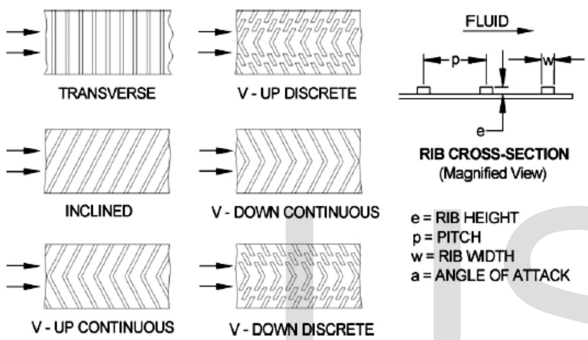

Figure. 1.3 Different configuration V-Shaped Ribs Muluwork. [2000]

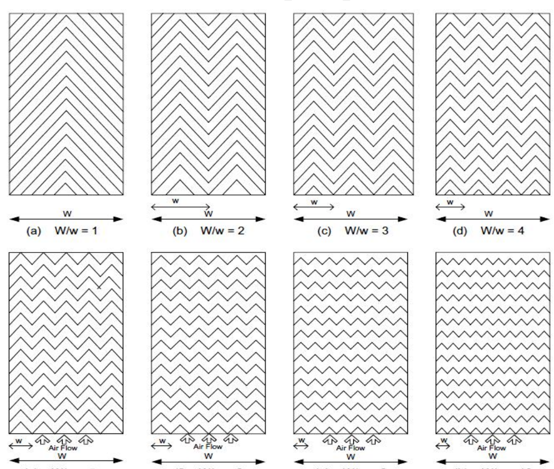

Figure. 1.4 Multiple V ribs geometry on absorber plate. Aharwal [2008}

On the surface configuration, one can divide the roughness into two different categories. The first category corresponds to a geometry where the gap between the two ribs is small and is occupied by a re-circulating flow. This type of roughness is known as "*d* type" roughness. The second type refers to a situation where the gap between the ribs is larger. This type of roughness is characterized by eddies that form behind a roughness element. This type of roughness is known as "*k*-type" roughness.

2. MATERIALS AND METHOLOGY

The performance of an air heater largely depends upon absorber plates which absorb heat from a source and transmit to air flowing over it. Therefore, an absorber plate must be designed and tested thoroughly before the fabrication of an air heater It is not always feasible to experimentally test the system, mainly due to cost consideration. System simulation is another way to study the performance of the system under various working conditions. Rough surfaces are widely used to enhance convective heat transfer by the promotion of higher turbulence levels. The drawbacks of roughening are increase in frictional and form drag. Consequently, efforts have been done to optimize the roughness designs. Several theoretical studies have been performed to analyze the heat transfer characteristics of various types of rough surfaces. This is largely due to difficulties in conducting experiments and high turbulence intensities that increase difficulties of measurement. Because of this reason numerical studies are becoming more common. In the turbulent region, simulation technique plays a critical role in determining the results with more accuracy.

2.1 Methodology

The following methodology is adapted for modelling and analysing heat transfer in the duct in simulated condition:

- **Selection of flow domain**
- **Flow regime**
- **Creating the finite element mesh**
- **Applying boundary conditions**
- **Setting FLOTRAN analysis parameters**
- **Solving the problem**
- **Examining the results**

In last step the post process output quantities are calculated and the results in the output are examined. The following results are evaluated:

- Convective heat transfer coefficient
- Temperature distribution in duct
- Pressure distribution in duct

2.2Terms Used in Analysis

- Hydraulic equivalent diameter
- Reynolds number (Re)
- Nusselt number (Nu)

2.2.1 Parameter Analysis

Artificially roughened solar air heater has been considered for the analysis of different performance parameters having different types of roughness and geometries on the underside of the absorber plate. The details of roughness, operating parameters and range of flow has been given in Table 2 and a schematic diagram of experimental setup of solar air heater has been presented in Figure 2.1.

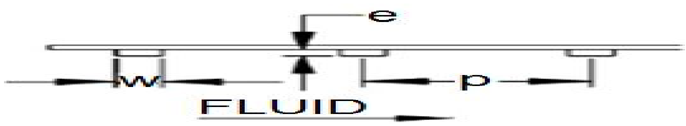

Figure 2.1: Absorber Plate Showing the Roughness Element

Table 2 Value of Different Parameters

S.NO	PARAMETERS	VALUES
1	Relative roughness pitch(P/e)	6-25
2	Rib height (e)	3.4 mm
3	width (b)	5.8 mm
4	Relative Roughness height (e/D_h)	0.0442
5	Duct aspect ratio (W/H)	25
6	Duct height(H)	.04 m
7	Reynolds number (Re)	4000-16000

4. RESULTS

When fluid enters a closed channel at a uniform velocity, the fluid particles in the layer in contact with wall of the channel come to complete rest. This layer also causes the fluid particles in the adjacent layers to slow down gradually, as a result of friction. To make up this velocity reduction, the velocity of the fluid at the mid-section of the rectangular duct has to increase to keep the mass flow rate through the rectangular duct constant. As a result, velocity gradient develops along the channel. As the roughness element lies under the absorber plate, the flow becomes turbulent because of reattachment points or brakeage of hydrodynamic boundary layer at regular intervals. In this process heat transfer coefficient, friction factor and pumping power of fluid increase due to the presence of this artificial roughened rectangular duct. The results show the behavior of Nusselt number with different operating parameters of solar air heater having rectangular ribs on the backside of the absorber plate. The effect of roughness and operating parameters on the heat transfer coefficient has been examined and a comparison of performance of roughened solar air heater with that of conventional solar air heater having smooth duct has been made.

Validation of ANSYS results for the Smooth Duct

4.1 For Nusselt number (Nu)

The values of Nusselt number (Nu) obtained from the ANSYS results have been compared with the values obtained from Dittus-Boelter equation in Fig. 4.1. It has been observed from the ANSYS results that the variation in results predicted by ANSYS and from equation lie within 6.5%, which indicates that predicted results are in good agreement with those estimated from Dittus-Boelter equation. Dittus-Boelter equation has been given in Eq. 4.1.

$$Nu_s = 0.023\, Re^{0.8} Pr^{0.4} \quad \{\text{for } 3000 < Re < 20000\} \qquad (4.1)$$

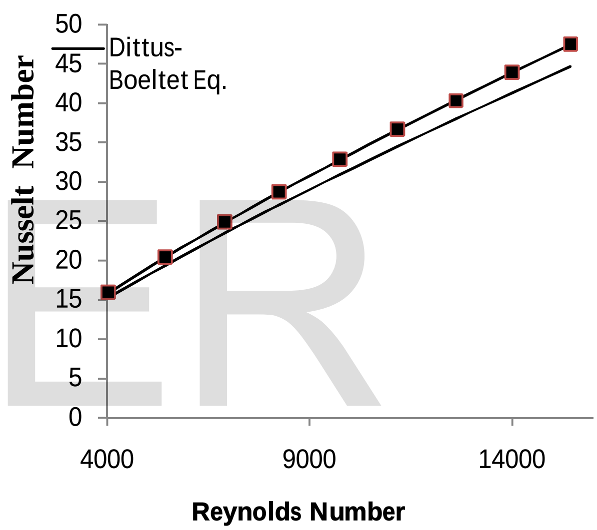

Figure- 4.1 Comparison of Nusselt number predicted by ANSYS and estimated by Dittus- Boelter equation for smooth duct

4.2 Effect of Reynolds number on convective heat transfer coefficient

Figure 4.3 shows the variation of convective heat transfer coefficient with Reynolds number. As the Reynolds number increases, the heat transfer coefficient also increases for different values of relative roughness pitches. The variation in heat transfer coefficient is low at small Reynolds numbers while it is large at higher Reynolds numbers. This behavior seems due to increased turbulence at higher Reynolds numbers and also due to breakage of thermal boundary layer at higher Reynolds numbers**.**

4.3Effect of Reynolds number on Nusselt number

Figure 4.3 shows the variation of Nusselt number with Reynolds number. As the Reynolds number increases, the Nusselt number also increases for different values of relative roughness pitches. The variation in Nusselt number is low at small Reynolds numbers while it is large at higher Reynolds numbers due to breakage of thermal boundary layer at higher Reynolds numbers and large turbulence.

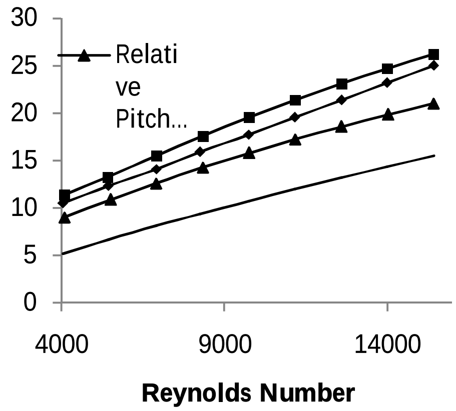

Fig. 4.2 Comparison of smooth and roughened plates for different values of Convective heat transfer coefficient

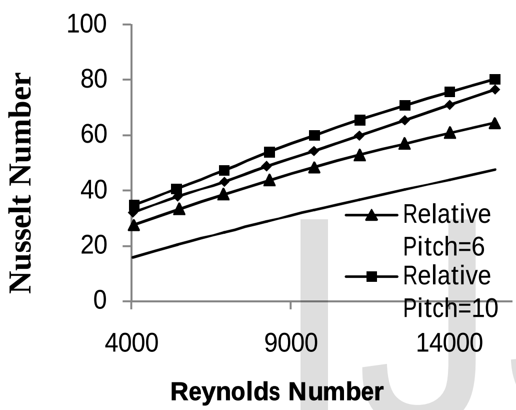

Fig. 4.3 Comparison of Nusselt Number Smooth and Roughened Plates

4.4Effect of Reynolds number on heat utilization

Utilization of heat given to system is an indication of performance of the collector. In order to estimate the value of heat utilization, losses have been determined for different value of Reynolds number. The total heat supplied minus losses gives the amount of heat utilization. Fig. 4.4 shows the variation of heat utilized in duct with Reynolds numbers for different values pitch. From the plot, it is observed that the heat utilization increase with increase in Reynolds number for all the values of pitch. This effect is due to amount of losses for different values of Reynolds number. The losses for low Reynolds number are higher as compared to losses at increased Reynolds number. Also it is observed that variation in heat utilization for different pitch for same Reynolds number is insignificant at higher values of Reynolds numbers. This phenomenon is probably due to the fact that collector is operating at lower temperatures where losses become insignificant collector is operating at lower temperatures where losses become insignificant.

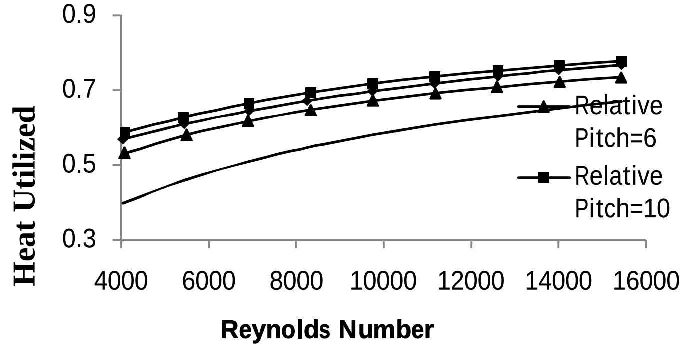

Fig. 4.4Comparison of smooth and roughened plates for different values of heat utilizes

4.5 Effect of mass flow rate ontemperature of air at exit of duct

Fig. 4.5 shows the variation of temperature of air at exit with mass flow rate. As the mass flow rate increases, the heat carrying capacity of air increases. Because of this heat utilization also increases, but the rate of increase of heat capacity is more significant than the rate of increase of heat utilization. Therefore, the temperature of air at exit decreases as a result increase in mass flow rate.

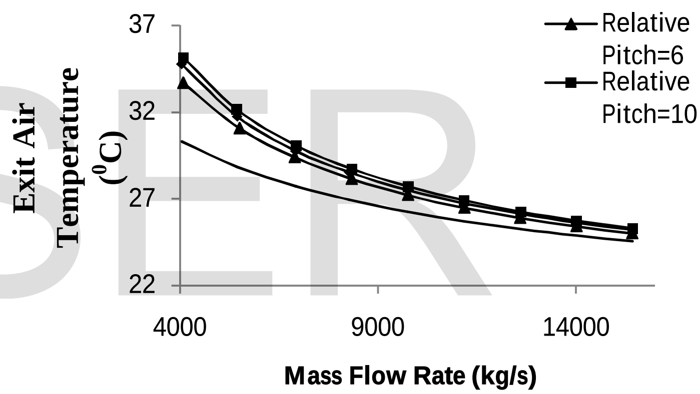

Fig. 4.5 Comparisons of smooth and roughened plates for different values of Temperature of air at exit of duct

4.6 Effect of Reynolds number on thermal efficiency

Fig. 4.6 shows the variation of thermal efficiency with Reynolds number. As the Reynolds number increases, the heat transfer coefficient increases and collector operates at lower temperature of absorber plate which reduces the heat loss and increases thermal efficiency. Maximum efficiency is obtained for plate having relative roughness pitch (p/e) =10 in the entire range of Reynolds number under study.

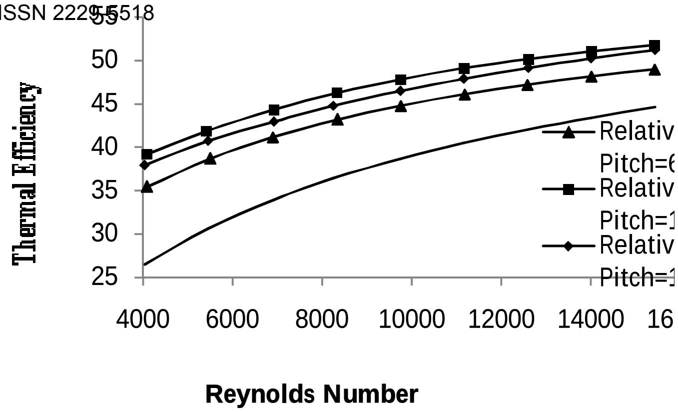

Fig. 4.6 Comparison of Smooth and Roughened Plates for Different Values of thermal

4.7 Correlation for Nusselt number

A statistical correlation has been developed on the basis of regression analysis of the ANSYS results. The power law relation between Nusselt number and Reynolds number is given below:
The following correlations for Nusselt numbers have been obtained

For p/e=10

$$Nu = 0.134264 \times Re^{0.66}$$

For p/e=15

$$Nu = 0.139245 \times Re^{0.65}$$

For p/e=6

$$Nu = 0.139045 \times Re^{0.63}$$

CONCLUSION

A computer simulation of transverse shape continuous type of artificial roughness geometry on the absorber plate of solar air heater duct has been carried out to investigate the heat transfer characteristics under simulated conditions using ANSYS. The Nusselt number, heat utilization, exit air temperature in the duct and thermal efficiency has been computed as a function of Reynolds number and mass flow rates for artificial roughness on the absorber plate of air heater duct. The performance of roughened absorber plate has been compared with that of smooth plate and different results have been obtained, Reynolds number has been varied from 4000 to 16000 in the present study.

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