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Computer aided thermo-hydraulic performance analysis of solar air heater with ribbed roughness on the absorber plate

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Abstract

Heat transfer and friction correlations are developed for turbulent flow in solar air heater ducts having a repeated ribbed roughness on the absorber plate. Software program is developed using 'C++' programming language to determine the effect of various parameters on heat transfer and friction in solar air heater duct with ribbed absorber plate. This software can be used for iterative work to identify the optimum design parameters. Use of artificial roughness in the form of repeated ribs on the absorber plate has found to be a convenient method for the enhancement of heat absorption capacity of the solar collector. The different parameters of ribbed roughness are relative roughness pitch (p/e), relative roughness height (e/D_h), and angle of attack of flow (α) and the range of these parameters are decided on the basis of practical considerations of the system and operating conditions. Based on similarity considerations correlations for the Nusselt number and friction factor in terms of these parameters have been developed.

***Keywords**:* Heat Transfer; Friction factor; Stanton number; Nusselt number; Efficiency index

1. INTRODUCTION

Solar air heaters form the major component of solar energy utilization system, which absorbs the incoming solar radiation, converting it into thermal energy at the absorbing surface, and transferring the energy to a fluid flowing through the collector. The efficiency of solar air heaters has been found to be low because of low convective heat transfer coefficient between absorber plate and the flowing air, which increases the absorber plate temperature, leading to higher heat losses to the environment. Several methods including the use of fins, ribbed roughness and packed beds in the ducts, have been proposed for the enhancement of thermal performance of these collectors. Use of roughness in the form of repeated ribs has been found to be a convenient method for enhancing the heat transfer to fluid flowing in the duct.

It is an investigation made to improve the thermo-hydraulic performance of solar air heaters by using ribbed roughness on the absorber plate. Rib roughened solar air heaters perform better than the plane ones under the same operating conditions.

The parameters influencing the heat transfer characteristics include Reynolds number (Re), angle of attack of flow (α), relative roughness pitch (p/e), relative roughness height (e/D_h) and the aspect ratio (W/B) of the air heater duct. The range of parameters for this study has been decided on the basis of practical considerations of the system and operating conditions. Thus, even a marginal increase in the efficiency of air heaters can substantially reduce the cost of pumping power and effective area required to collect the fixed quantum of heat energy. In this study, ribs of various parameters are used in the computer program and performance of such systems has been investigated. This software program developed using C++ language can be used for iterative work to find the best optimum design.

The purpose of using artificial roughness on the absorber surface is to make the flow turbulent adjacent to the wall that is laminar sub layer region. Many investigations have been made to select a range of roughness elements, which reduces friction losses and at the same time enhances the heat transfer. Abdul-Malik et al. [1] developed expressions for heat transfer and friction factor for fully developed turbulent flow in a solar air heater duct. They found increase in both Nusselt number and friction factor with increase in roughness height. J.C. Han [2] carried out an experimental study of fully developed turbulent air flow in square ducts with two opposite rib roughened walls and observed that the average friction factor was 2.1 to 6 times that for four sided smooth duct. The Stanton number of the ribbed side is about 1.5 to 2.2 times that of the four-sided smooth duct when relative roughness pitch varies from 40 to 10. R.L. Webb et al. [3] conducted a comparative study between the roughened tubes and smooth tubes in design of heat exchangers. This study is conducted mainly to achieve enhancement of heat transfers capacity and to reduce the friction factor. R.L.Webb et al. [4] developed heat transfer and friction correlations for turbulent flow in tubes having repeated rib roughness. The correlations are verified with experimental data taken with relative roughness height 0.01 to 0.04 and relative roughness pitch 10 to 40 and Prandtl number 0.71 to 37.6.N. Sheriff et al. [5] investigated experimentally the heat transfer and friction characteristics of a surface with discrete roughness. It is shown that pumping power required to force the fluid for same heat transfer surface and fluid temperature difference, will be minimum when $(f_r/f_s) < (St_r/St_s)^3$. This shows any increase in the friction factor increases the heat transfer characteristics of roughened surface resulting in a more efficient heat transfer surface. E.M. Sparrow et al. [6] conducted experiments to determine the heat transfer, pressure drop and flow field responses to the rounding of the peaks of a corrugated wall duct. J.C. Han et al. [7] investigated effects of heat transfer and friction for rib roughened surfaces. Correlation for friction factor and heat transfer was developed to account for rib shape, spacing and angle of attack. Ribs at 45° angle of attack are found to have superior heat transfer performance at a given friction power when compared to ribs at a 90° angle of attack of flow. D.L. Gee et al. [8] contributed experimental information for single phase forced convection in circular tube containing a two dimensional rib roughness. In their investigation they have used a thermo-hydraulic performance parameter 'efficiency index' η, which can be defined as the ratio of enhancement factor of heat transfer coefficient to that of friction coefficient. $\eta=(St_r/St_s)/(f_r/f_s)$. M.J. Lewis [9] carried out an elementary analysis for predicting the momentum and heat transfer characteristics of a hydraulically rough surface. In this work analytical model for flow over rough surface is developed.

2. Computer aided analysis

Solar air heaters generally have rectangular flow passage formed by two plates one of which is the absorber plate of the collector, which absorbs the incoming solar radiation and converts it into thermal energy at the absorbing surface and transfers the energy to the flowing fluid through the collector. Solar air heaters usually have duct with a high aspect ratio. In this study duct with aspect ratio ranging from 1 to 10 with width much greater than height is selected for purpose of analysis.

The following correlations are developed for heat transfer coefficient and friction factor for both smooth and roughened duct. Topside of the duct is roughened with artificial roughness and the remaining three sides are smooth and insulated. In this investigation small diameter wires are considered as the roughness elements.

a) $f_s = 0.079\,Re^{-0.25}$ (1)

b) $f_r = 2/[0.95(p/e)^{0.53}(\alpha/45)^{-0.16}+2.5\ln(D_h/2e)-3.75]^2$ (2)

c) $f_{av} = \{[(W/B)+2]\,f_s + (W/B)\,f_r\} / 2[(W/B)+1]$ (3)

d) $e^+ = (e/D_h)\,Re(f_r/2)^{½}$ (4)

e) $R_M(e^+) = [(2/f_r)^{½}+2.5\ln(2e/D_h)+3.75](\alpha/45)^{0.16}$ (5)

f) $St_s = 0.023/(Re^{0.2}\, Pr^{0.6})$ (6)

g) $St_{av} = (f_{av}/2)/\{1+(f_{av}/2)^{½}[4.5(e^{+})^{0.28}Pr^{0.57}(\alpha/45)^{-j} - R_M\,(e^{+})]\}$ (7)

h) $N_{us} = S_{ts}$ Re Pr (8)

i) $Nu_{av} = St_{av}$ Re Pr (9)

j) $\eta = (St_{av}/St_s) / (f_{av}/f_s)$ (10)

The investigations are carried out for Reynolds number (Re) range of 5000-30000, angle of attack of flow (α) of 20°-90°, relative roughness pitch (p/e) of 10-40, relative roughness height (e/D_h) of 0.01-0.04 and aspect ratio (W/B) of 1-10 for a fixed value of Prandtl number (Pr) of 0.71.

The effect of different parameters on the friction factor, Stanton number and efficiency index are analyzed. The output of the computer program written in C++ language is used for theoretical analysis. Flow chart is shown in Fig.1.

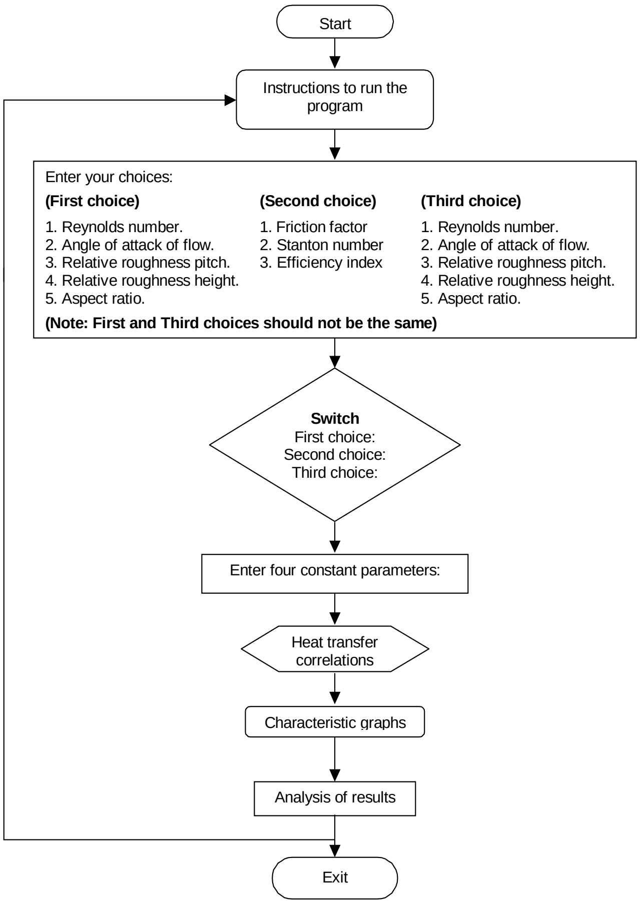


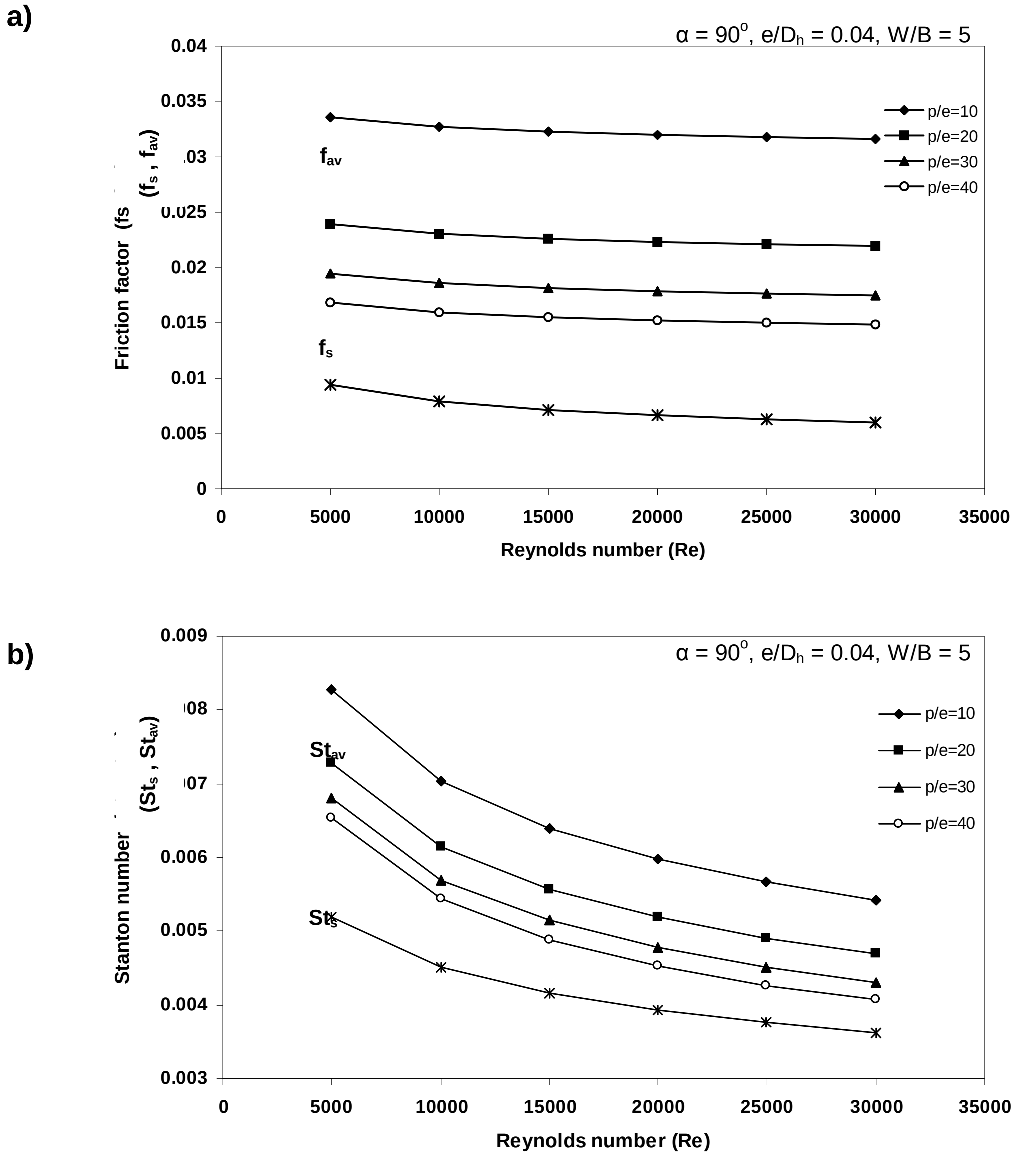
Figure 1: Flow chart of the computer program

3. Computer Results and Discussions

Effect of Reynolds number on friction factor, Stanton number and efficiency index for different values of relative roughness pitch is shown in Fig. 2.

It is observed that friction factor and Stanton number for both smooth and roughened ducts decreases as Reynolds number increases. Also, efficiency index decreases as Reynolds number increases. Decrease in friction factor is due to a distinct change in the fluid flow characteristics as a result of roughness that causes flow separation, reattachments and the generation of secondary flows. Stanton number depicts the heat transfer rate. Decrease in Stanton numbers are mainly due to increased heat losses due to turbulence. Similarly comparative values for a smooth and roughened duct clearly show that heat transfer characteristics are better for roughened duct. Also, when compared to smooth duct the roughened one has two to three times increase in value of friction factor mainly due to artificial roughness elements. In general any increase in Reynolds number increases turbulence and hence not desirable for a better performance of air heater duct.

It is also observed that friction factor and Stanton number decreases with increase in the value of relative roughness pitch. The decrease in friction is more prominent when compared to Stanton number. Therefore, with increase in the value of relative roughness pitch though both friction factors and Stanton numbers decreases and efficiency index increases. The value of relative roughness pitch 40 produces the highest value of efficiency index as it corresponds to a lower value of friction factor.



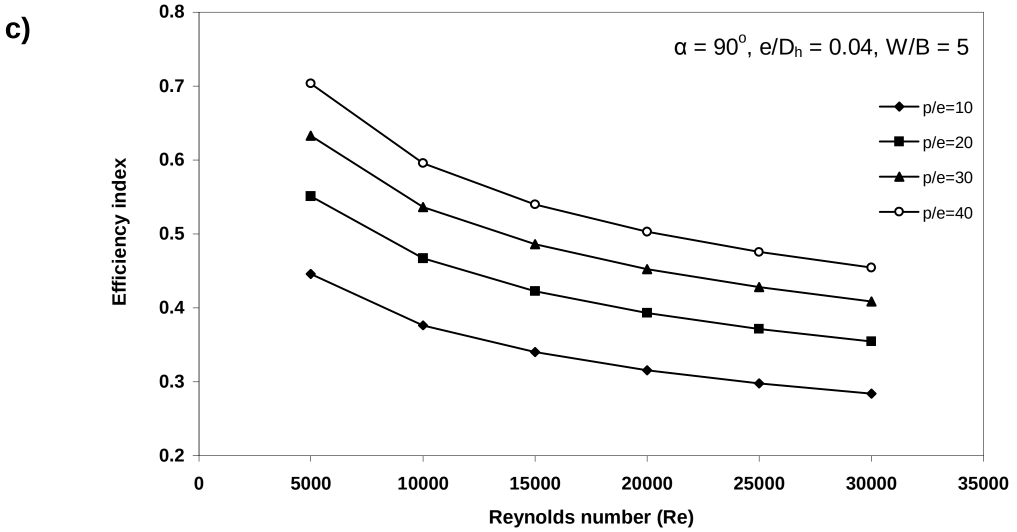


Figure 2: Effect of Reynolds number on a) friction Factor
b) Stanton number c) efficiency index for different relative roughness pitch

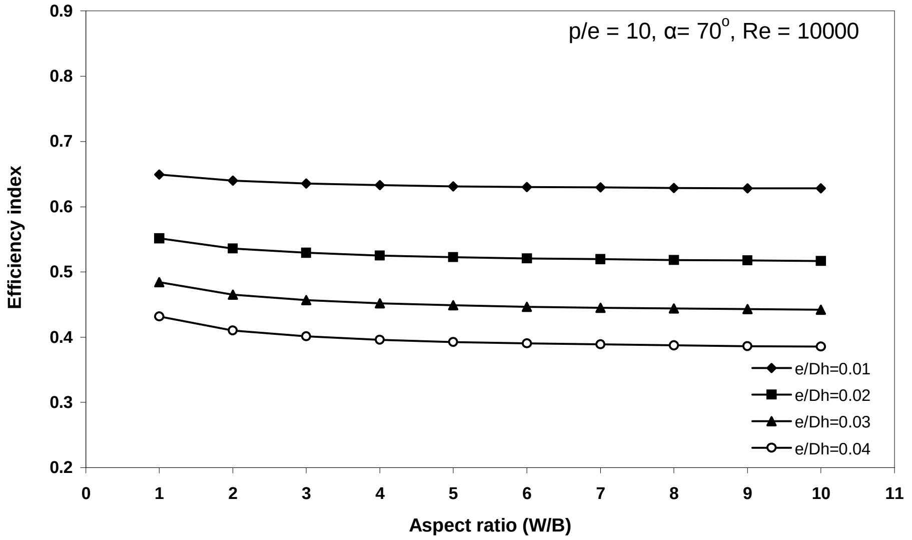


Figure 3: Effect of aspect ratio on efficiency index for different relative roughness height

Effect of aspect ratio on efficiency index for different values of relative roughness height is shown in Fig.3. Results shows that there is no significant effect of aspect ratio on efficiency index for different values of relative roughness height. Hence aspect ratio of 5 is considered as for this value the width is much greater than the height.

From the above discussions it is observed that average friction factor and Stanton number are affected in similar manner by the changes in parameters. When average friction factor increases then, Stanton number also increases but one may dominate over the other. If the Stanton number is dominant, then efficiency index of the duct increases where as if friction factor is dominant, the efficiency index of the duct decreases. Therefore, efficiency index can be defined as the ratio of enhancement factor of heat transfer coefficient to that of friction coefficient.

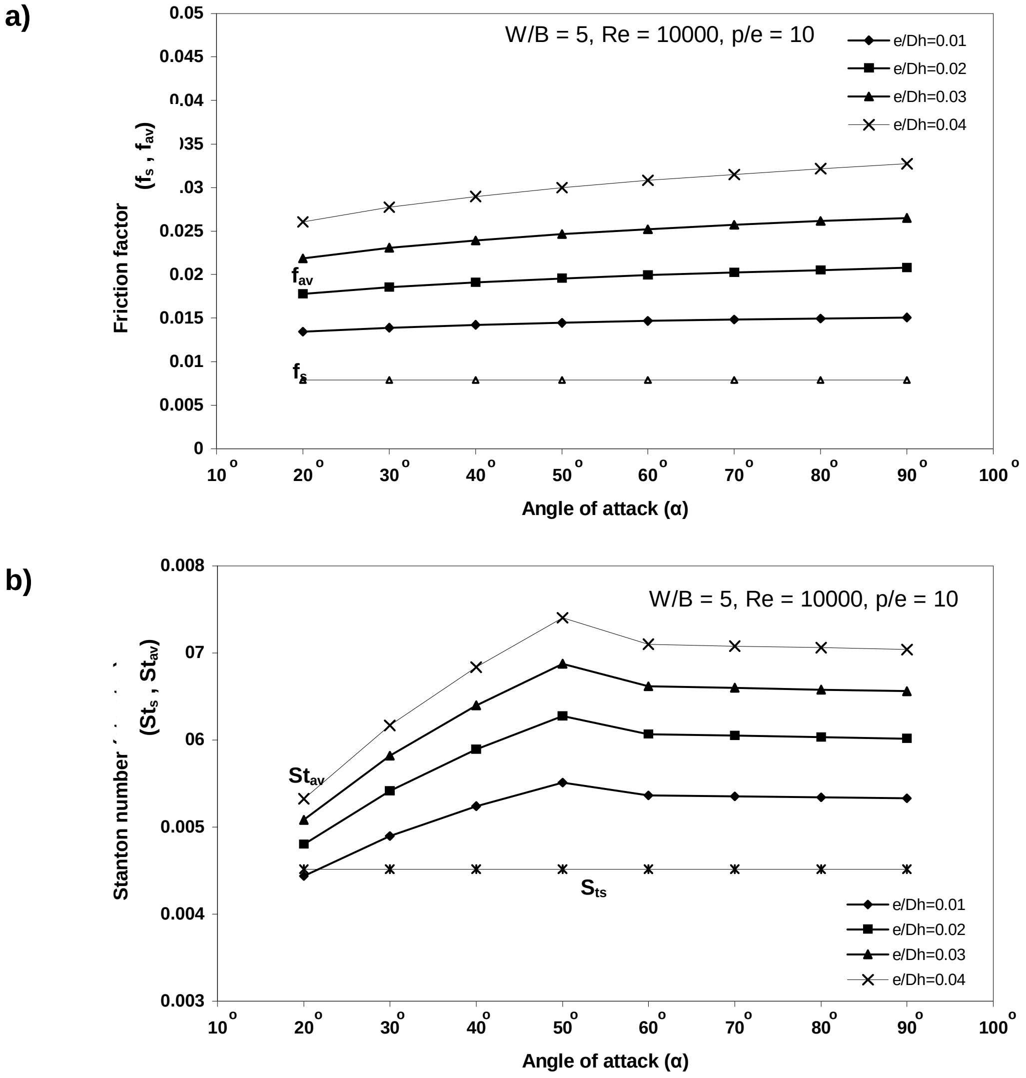
Effect of angle of attack of flow on friction factor, Stanton number and efficiency index for different values of relative roughness height is shown in Fig. 4.

In the above figures it is observed that any increase in the value of angle of attack of flow increases frictional resistance for airflow. The value of friction factor for smooth duct is much lower than friction factor for roughened duct, which means that introduction of roughness elements, produces the frictional drag for the flow of air through the duct. Also, it is observed that initially increase in the angle of attack of flow improves the heat transfer characteristics reaching the maximum at 50^o and then further increase in angle of attack of flow reduces the Stanton number. Reason for the occurrence of maximum value at 50^o is yet to be investigated. Also efficiency index is peak at an angle of attack of flow 50^o and for larger angle of attack of flow efficiency index shows a downward tendency. Stanton number for roughened duct at 50^o angle of attack of flow is 20% to 60% more compared to that of smooth duct.

Any increase in the value relative roughness height increases the friction factor and Stanton number. Also from figures it is clear that efficiency index is higher for lower values of relative roughness height. Results show that increase in value of relative roughness height gives greater increase in friction factor compared to the increase in the Stanton number. Hence it is observed that efficiency index decreases as the relative roughness height increases. The value of relative roughness height 0.01 produces the highest value of efficiency index as it corresponds to a lower value of friction factor.

It is observed from the previous discussions that for a solar air heater duct with artificial rib roughness on the absorber plate on one side and with smooth insulated other three sides of the duct the optimum set of parameters are given below.

a) Relative roughness pitch (p/e) = 40
b) Aspect ratio (W/B) = 5
c) Angle of attack of flow (α) = 50^o
d) Relative roughness height (e/D_h) = 0.01



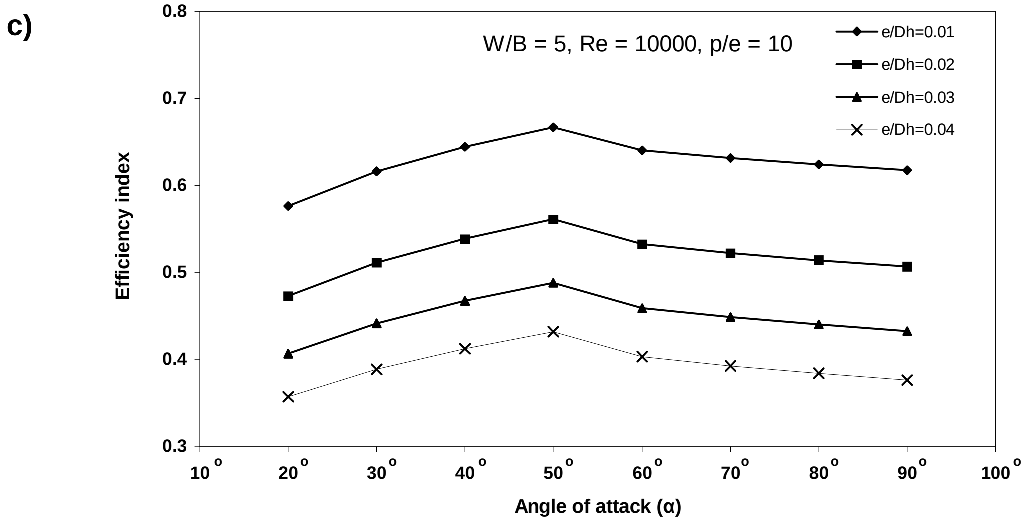


Figure 4: Effect of angle of attack of flow on a) friction Factor b) Stanton number c) efficiency index for different relative roughness height

4. Conclusion

Based on the above discussions following conclusions can be drawn:
a) The maximum enhancement in Stanton number and friction factor for roughened duct is observed to be 1.13 and 1.19 times that of the smooth duct, respectively.
b) Minimum friction factor and Stanton number occurs for relative roughness pitch of 40, relative roughness height of 0.01. Whereas, efficiency index is maximum for these values.
c) If Stanton number variations are dominant then efficiency of the duct increases whereas if friction factor variations are dominant then efficiency of the duct decreases.
d) Friction factor decreases with decrease in angle of attack of flow. Whereas, Stanton number and efficiency index are maximum at 50° for all the values of relative roughness height and relative roughness pitch. Reason for the maximum values at 50° is yet to be investigated.
e) The empirical expressions for the friction factor and heat transfer can be used for designing and predicting the performance of a solar air collector with the ribbed roughness on the absorber plate.

Nomenclature

A_c	Area of absorber plate (m^2)
B	Height of the duct (m)
C_p	Specific heat of air (J/kg K)
Dh	Hydraulic diameter of duct (m)
e	Height of roughness element (m)
e/D_h	Relative roughness height
e+	Roughness Reynolds number
f	Friction factor (dimensionless)
h	Heat transfer coefficient (W/m^2 K)
k	Thermal conductivity of air (W/m K)
L	Test length (m)
m	Mass flow rate of air (kg/s)
Nu	Nusselt number
p	Rib pitch (m)
p/e	Relative roughness pitch (dimensionless)
Pr	Prandtl number
q	Rate of heat transfer to air (W)
RM	Momentum transfers roughness function
Re	Reynolds number
St	Stanton number
V	velocity of air in the duct (m/s)
W	Width of the duct (m)
W/B	Aspect ratio

Greek symbols

Δp	Pressure drop in the test length (N/m^2)
α	Angle of attack of flow (degree)
η	Efficiency index or Thermo-hydraulic performance parameter
ρ	Density of air (kg/m^3)

Subscript

s	Smooth duct
r	Roughened duct
av	Average

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A Brief Author Biography

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