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Investigation of Heat Transfer and Flow Analysis of an Artificially Roughened Solar Air Heater Having Arc Roughness with Gap

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Abstract*—Artificial Roughness in form of ribs is convenient method for enhancement of heat transfer coefficient in solar air heater. This paper presents experimental investigation has been carried out to study the heat transfer and friction characteristics in solar air heater by using gap in arc shape roughness on one broad wall of solar air heater with an aspect ratio of 8:1,the roughened wall being heater while the remaining three wall are insulated . Range of parameters for this study has been decided on basis of practical considerations of system and operating conditions. The experiment encompassed Reynolds number(Re) range from 3000 to 15000, relative roughness pitch(p/e) of 8 ,relative roughness height(e/Dh) of 0.045 and angle of attack (α) of 60°.The gap width(g/e) is 1 and gap position(d/W) were varied in range of 0.25-0.50. The heat transfer and friction characteristics of this roughened duct have been comparing with smooth duct under similar flow condition. The maximum enhancement in Nusselt number and friction factor is observed to be 2.45 and 2.83 times of that of the smooth duct respectively. The thermo-hydraulic performance parameter is found to be maximum for the relative gap width and the relative gap position of

Keywords*— *Gap width ,Gap position, Nusselts number, Reynolds number, Friction factor, Thermo-hydraulic performance.

I. INTRODUCTION

Solar air heater is one of the basic equipment through which solar energy is converted into thermal energy .The main application of solar air heater are space heating ,seasoning of timber ,curing of industrial products and these can also be effectively used for curing/drying of concrete/clay building components .A solar air heater is simple in design and required little maintenance . However the value of the heat transfer coefficient between the absorber plate and air is low and this results in a lower efficiency .Low value of heat transfer coefficient is due to presence of laminar sub layer that can be broken by providing artificial roughness on heat transferring surface[1].Several methods including the use of fins , artificial roughness and packed beds in the ducts ,have been proposed for the enhancement of thermal performance .Artificial roughness in form of ribs and in various configuration has been used to create turbulence near wall or to break laminar sub-layer . Artificial roughness results in high friction losses leading to more power requirement for fluid flow. Hence turbulence has to be created in region very close to heat – transferring surface for breaking viscous sub-layer .The use of artificial roughness in solar air heaters owes its origin to several investigations carried out in connection with the enhancement of heat transfer in nuclear reactors and turbine blades .Several investigations have been carried out to study effect of artificial roughness on heat transfer and friction factor for two opposite roughened surface by Han[2,3].Han et al.[4-5],Wrieght et al.[7],Lue et al,[8-10],Taslim et al. and Hwang[12],Han and Park[14],Park et al.[15] developed by different investigators .The orthogonal ribs i.e. ribs arranged normal to the flow were first used in solar air heater and resulted in better heat transfer in comparison to that in conventional solar air heater by Prasad k, Mullick S.C. et al [16].Many investigators Gao x sunden B[17],Han J.C,Glicksman LR,Rohsenow WM[18],Prasad BN,Saini JS{19],Taslim ME,Li T,Kercher Dm[20],Webb RL,Eckert Erg,Goldstein RJ[21] have reported in detail the Nu and f for orthogonal and inclined rib-roughened ducts. The concept of V-shaped ribs evolved from the fact that the inclined ribs produce longitudinal vortex and hence higher heat transfer .In principal ,high heat transfer coefficient region can be increased two folds with V-shape ribs and hence result in even higher heat transfer et al. [20].The beneficial effect on Nu and f caused by V-shaping of ribs in comparison to angled ribs has been experimentally endorsed by several investigators Geo X,Sunden B{22],Karwa R.[23],Kukreja RT,Lue SC,McMillin RD[24],Lau SC,McMillin RD,Han JC[25], for different roughness parameters and duct aspect ratios .For V-shape ribs,the inter-rib local heat transfer coefficient reduces from leading edge(s) to trailing edge(s) in transvers direction[19,21,22],However in the flow direction ,the inter-rib local heat transfer coefficience varies like saw tooth [20,22,23].In addition ,multiple V-ribs have also been investigated with the anticipation that the more number of secondary flow cells may result in still higher heat transfer et at Lanjewar A,Bhagoria JL,Sarviya RM[26],Hans VS,Saini RP,Saini JS[27]. Based on the experimental studies carried out by various investigators, correlations for heat transfer and friction were developed (Table 1).

Chao et al.[28]examined the effect of an of angle of attack and number of discrete ribs, and reported that the gap region between the discrete ribs accelerates the flow, which increases the local heat-transfer coefficient. In a recent study ,Chao et al.[29] investigated the effect of a gap in the inclined ribs on heat transfer in a square duct and reported that a gap in the inclined rib accelerates the flow and enhances the local turbulence, which will result in an increase in the heat transfer. They reported that the inclined rib

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NOMENCLATURE

A_p	Absorber plate area, m^2	T_i	Inlet air temperature, °C
A_{duct}	Flow Cross-section area=WH, m^2	T_o	Outlet air temperature, °C
A_o	Throat area of orifice plate, m^2	P	Rib pitch, m
A_s	Area of smooth plate, m^2	P/e	Relative roughness pitch
e	Rib height ,mm	T_{pav}	Mean plate temperature, °C
e/Dh	Relative roughness height	T_{fav}	Average temperature of air, °C
f	Friction factor	Re	Reynolds number
W	Duct width, m	W/H	Channel aspect ratio
H	Duct depth, m	V	Velocity of air
K	Thermal conductivity of air, W/mK	d/W	relative gap position
m	Mass flow rate, kg/s	ΔPo	Pressure drop in duct, Pa
C_d	Coefficient of discharge (0.62)	Nu	Nusselt number of roughened duct
C_p	Specific heat of air, KJ/kg K	Nus	Nusselt number of smooth duct
D_o	Diameter of the orifice of the orifice plate		
D_p	Inside diameter of the pipe	Greek symbols	
h	Convective heat transfer coefficient, W/m^2K	α	rib angle of attack,degree
g	Gap width, m	ß	ratio of orifice diameter to pipe diameter
g/e	Relative gap width	η	thermo-hydraulic performance parameter
Δh	Difference of height on manometer fluid	ρ	density of air, kg/m^3
I	Heat flux .W/m^2	ρ	density of manometric fluid,kg/m^3

arrangement with a downstream gap position shows higher enhancement in

Table 1 Correlations developed for heat transfer and friction for different roughness geometries used in solar air heater duct

Authors	Roughness Geometry	Range of Parameters	Principal Findings
Prasad and Mullick [51]	Transverse wire rib	e/D: 0.019 P/e: 12.7 Re: 10000-40000	14% improvement in thermal performance was reported at a Reynolds number 40000 over smooth duct.
Bhagoria et al. [39]	Transverse wedge shaped rib	p/e: 60.17xϕ- .0264<p/e<12.12 W/H: 5, e/D: 0.015-0.033,ϕ: -8°- 15°,Re: 3000-18000	2.4 and 5.3 times enhancement in Nu and f were reported over smooth duct for p/e of about 7.57 and wedge angle of about 10°.
Karwa et al. [40]	Chamfered rib	p/e: 4.58, 7.09,e/D: 0.0197, 0.0256, 0.0441,ϕ: - 5°,W/H: 6.88, 6.98,9.38,Re: 3750-16350	50-120% and 80- 290% enhancement in Nu and f were reported over smooth duct.
Saini and Saini [48]	Expanded metal mesh	e/D: 0.012-0.0390,L/e: 25-71.87,S/e: 15.62-46.87 Re: 1900-13000	4 and 5 times enhancement in Nu and f were reported over duct with transverse ribs.
Sahu and Bhagoria [31]	90° broken transverse rib	W/H: 8,e/D: 0.0338 p: 10, 20, 30 e: 1.5,Re: 3000-12000	1.25–1.4 times enhancement in heat transfer coefficient was reported over smooth duct for roughness pitch of 20.
Jaurker et al. [32]	Rib-grooved roughness	P/e: 4.5-10, e/D: 0.0181-0.0363,g/p: 0.3-0.7,Re: 3000-21000	2.7 and 3.6 times enhancement in Nu and f were reported over smooth duct for p/e of 6.
Saini and Saini [42]	Arc shaped rib	W/H: 12,P/e: 10,e/d: 0.0213– 0.0422,α/90: 0.3333–0.6666 Re: 2000–17 000	3.8 and 1.75 times enhancement in Nu and f were reported over smooth duct.

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Karmare and Tikekar[33]	Metal grit rib	e/D: 0.035 to 0.044,p/e: 12.5–36,l/s: 1.72–1,Re: 4000–17,000	Upto 2 and 3 times enhancement in Nu and f were reported over smooth duct.
Saini and Verma[44]	dimple-shaped rib	P/e: 8-12me/D: 0.0189-0.038,Re: 2000–12000	The maximum value of Nu was found corresponds to (e/D) of 0.0379 and (p/e) of 10
Varun et al. [45]	Combination of transverse and inclined rib	P/e: 3-8,e/D: 0.030,Re: 2000–14000 e: 1.6mm,p: 5-13,W/H: 10	Best thermal performance was Reported over smooth duct for (p/e) value of 8.
Arvind kumar et al. [46]	Discrete W-shaped rib	e: 0.75–1.5mm,p/e: 10,e/D: 0.0168–0.0338,W/H: 8:1,α: 30–75^o,Re: 3000–15000	2.16 and 2.75 times enhancement in Nu and f were reported over smooth duct corresponds to e/D of 0.0338 and α of 60^o.
Hans et al. [47]	Multi V-shaped rib	e/D: 0.019–0.043,W/w: 1–10 α :30^o–75^o P/e: 6–12,Re: 2000–20000	6 and 5times enhancement in Nu and f were reported over smooth duct corresponds to p/e of 8 and α of 60^o.
Sukhmeet [43]	Discrete V-down rib	p/e: 4-12,e/D: 0.015-0.0.043,d/w: 0.2-0.8,g/e: 0.5-2.0,Re: 3000–15,000,α: 30^o-75^o	3.04 and 3.11 times enhancement in Nu and f were reported over smooth duct corresponds to p/e of 8, α of 60^o and e/D of 0.043.
Anil Kumaret al. [41]	Multi v-shaped ribs with gap	W/w: 6,P/e: 10,e/D: 0.043 α: 60^o W/H: 12,Re: 2000–20,000,Gd /Lv :0.24–0.80 g/e: 0.5–1.5	6.32 and 6.12 times enhancement in Nu and f were reported over smooth duct.

heat transfer compared to that of the continuous inclined rib arrangement.

Aharwal et al. [30] carried out experimental investigation of heat transfer and friction factor characteristics of a rectangular duct roughened with repeated square cross-section split-rib with a gap, on one broad wall arranged at an inclination with respect to the flow direction. A gap in the inclined rib arrangement enhances the heat transfer and friction factor of the roughened ducts. The increase in Nusselt number and friction factor is in the range of 1.48–2.59 times and 2.26–2.9 times of the smooth duct, respectively, for the range of Reynolds numbers from 3000 to 18,000. The maximum values of Nusselt number and friction factor are observed for a gap in the inclined repeated ribs with a relative gap position of 0.25 and a relative gap width of 1.0.Table 2 summarizes the various arrangements of discreatizing the ribs employed by these investigators. The studies of Han et al.[5],Lau et al.[8] and Taslim et al.[11] not covered the wide range of roughness and operating parameters as would be required for detailed analysis for detailed optimal design or selection of roughness parameter to be used in conventional solar air heaters .Most of the investigations carried out so far have applied artificial roughness on two opposite wall with all four walls being heated .However in case of solar air heater ,roughness elements are applied to heated wall while remaining three walls are insulated .Heated wall consists of absorber plate and is subjected to uniform heat flux(insulation).This makes fluid flow and heat-transfer characteristics distinctly different from those found in case of two roughened walls and four heated wall duct Producing a gap in the inclined rib is found to enhance the heat transfer by breaking the secondary flow and producing higher level of turbulence in the fluid downstream of the rib .A similar gap in both the limbs of v-rib further enhances the heat transfer by introducing similar effects in both the limbs. Further the use of multi v-rib across the width of the plate is found to enhance the heat transfer by increasing the number of secondary flow cells several times. It is thought that producing gaps in all the limbs of multi-v geometry will bring about considerably large enhancement in comparison to that of simple single v-rib arrangement. It will therefore be pertinent to investigate the effect of various geometrical and flow parameters on the heat transfer and friction characteristics of rectangular duct having its absorber plate roughened with multi v-rib with gap in the limbs of V..Hence the present investigation has been taken up to determine the optimum location and width of gap in an arc shape rib to form a discrete rib. In the present work, experimental investigation on the performance of solar air heater ducts, having the absorber plate with artificial roughness in the form of arc shape rib, provided with gap , has been carried out .The flow Reynolds number has been varied between 2500 and 17000. The aspect ratio is constant (8:1).The variations of nusselt number and friction factor as a function of roughness parameters arc shape gap position and gap width have been evaluated to examine the thermo-hydraulic performance of the system to ascertain the benefit of this selected roughness geometry.

II. ROUGHNESS PARAMETERS:

The roughness parameter are determined by rib height(e),rib pitch(p) and gap in arc shape ribs .These parameters have been expressed in the form of the following roughness parameters:

(i) Relative gap width(g/e)
(ii) Relative gap position(d/W)

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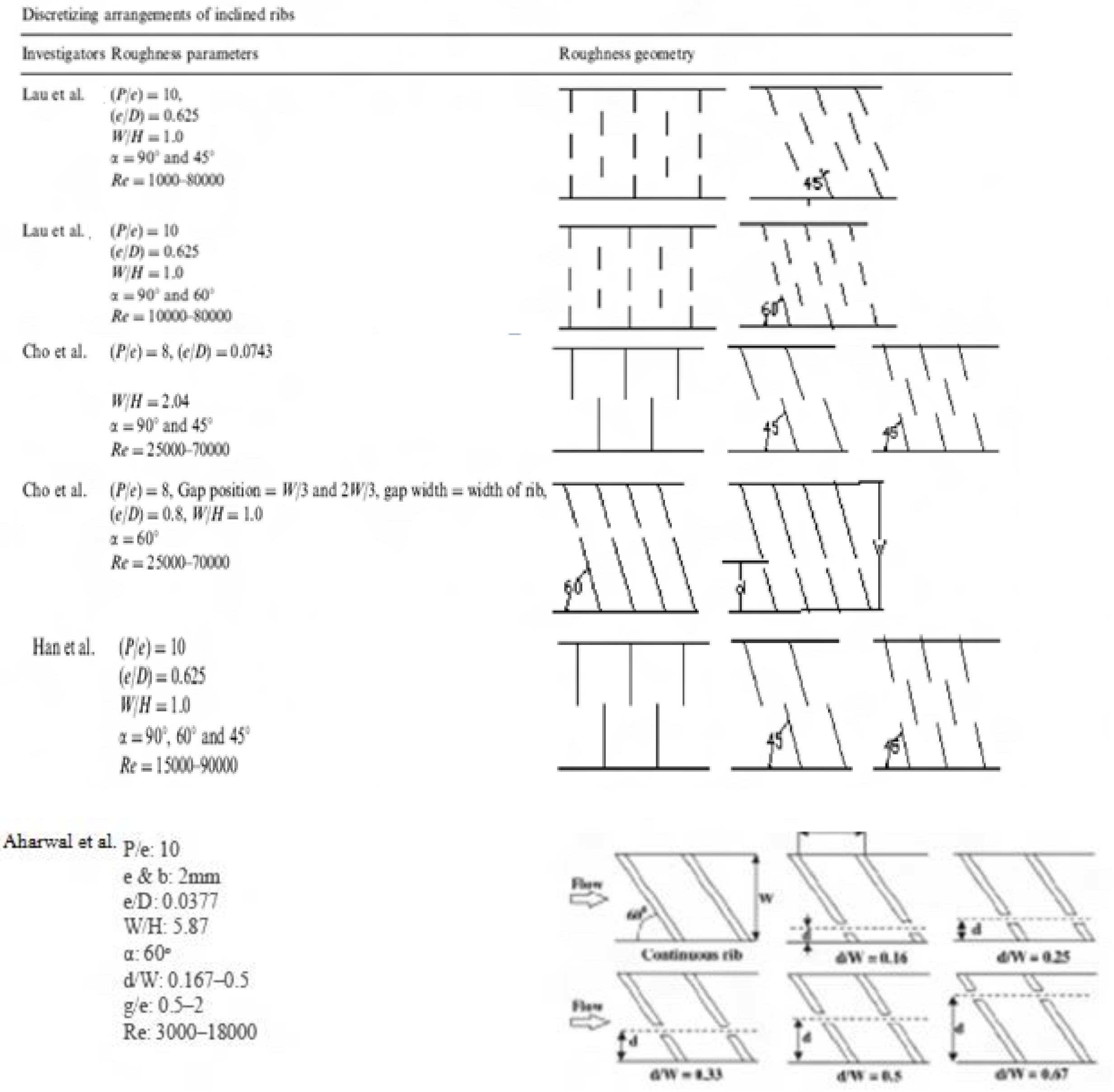
The range of these dimensionless roughness parameters and Reynolds numbers employed in this investigation are given Table 3.

Values of parameters

S.No.	Parameter	Value
1.	Relative roughness pitch (p/e)	8
2.	Rib height(e)	2mm
3	Relative roughness height (e/D)	0.0452.
4.	Angle of attack (α)	60°
5.	Relative gap position(d/W)	0.25-0.50
6.	Relative gap width(g/e)	1
7.	Duct aspect ratio (W/H)	8
8.	Reynolds number(Re)	3000-15000

Table:2.



Discretizing arrangements of inclined ribs

Investigators	Roughness parameters	Roughness geometry
Lau et al.	$(P/e) = 10,$ $(e/D) = 0.625$ $W/H = 1.0$ $\alpha = 90^\circ$ and 45° $Re = 1000\text{–}80000$	
Lau et al.	$(P/e) = 10$ $(e/D) = 0.625$ $W/H = 1.0$ $\alpha = 90^\circ$ and 60° $Re = 10000\text{–}80000$	
Cho et al.	$(P/e) = 8$, $(e/D) = 0.0743$ $W/H = 2.04$ $\alpha = 90^\circ$ and 45° $Re = 25000\text{–}70000$	
Cho et al.	$(P/e) = 8$, Gap position = $W/3$ and $2W/3$, gap width = width of rib, $(e/D) = 0.8$, $W/H = 1.0$ $\alpha = 60^\circ$ $Re = 25000\text{–}70000$	
Han et al.	$(P/e) = 10$ $(e/D) = 0.625$ $W/H = 1.0$ $\alpha = 90^\circ$, 60° and 45° $Re = 15000\text{–}90000$	
Aharwal et al.	P/e: 10 e & b: 2mm e/D: 0.0377 W/H: 5.87 α: 60° d/W: 0.167–0.5 g/e: 0.5–2 Re: 3000–18000	

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III. EXPERIMENTAL PROGRAM AND PROCEDURE

To study the effect of arc shape with gap rib geometry on the heat transfer and friction characteristics of airflow in the rectangular duct an experimental set up has been designed and fabricated .The schematic diagram of the experimental set-up in shown in Fig.1.The flow system consists of an entry section, a test section and an exit section, mixing section, transition section, a flow meter and a centrifugal blower. The entry and exit length were 177mm (2.5√WH) and 353mm (5√WH) respectively. The test section is of length 1500mm(33.75Dh).In the exit section of after 200mm three equally spaced baffles are provided in 100mm length for the purpose of mixing the hot air coming out of solar air collector to obtain uniform temperature of air at the outlet. An electric heater having a size of 1500mm x 216mm was fabricated by combining series and parallel loops of heating wire Mica sheet of 1mm is placed between the electric heater and absorber plate. The heat flux may be varied from 0 to 1000 W/m2 by a varriac across it. The absorber plate is 1 mm(20SWG) thick GI sheet with rib-roughness formed on its bottom side. The topside of the entry and exit section of the duct is covered with smooth face 8mm thick plywood. The mass flow rate of air is measured by means of an calibrated orifice meter connected with an inclined manometer and the control valves provided in the lines control the flow. Calibrated copper-constantan 0.3mm thermocouples were used to measured the air and absorber plate temperature at different locations. A micro manometer measured the pressure drop across the test section of the duct. Before starting the experiment, all instruments and components of experimental set-up have been checked for proper operation .After switching on blower, joints of set-up have been checked for air leakage. After assembling the roughened plate, energy for heating is supplied to roughened entrance section and to test section. Data have been noted under steady state condition which has been assumed to have reached when plate and air temperature showed negligible variation for around 10 min duration . Steady state for each test run has been obtained in about 1.5-2h. After the steady state has reached, the heater assembly voltage and current, the plate temperatures, the inlet and exit air temperatures and the pressure drop across the duct and across the orifice plate have been recorded.

The following parameters were measured during the experiments:

1. Inlet air temperature of collectors
2. Outlet air temperature of collectors
3. Temperature of plate
4. Pressure drop across the orifice plate
5. Pressure drop across the test section of the duct.

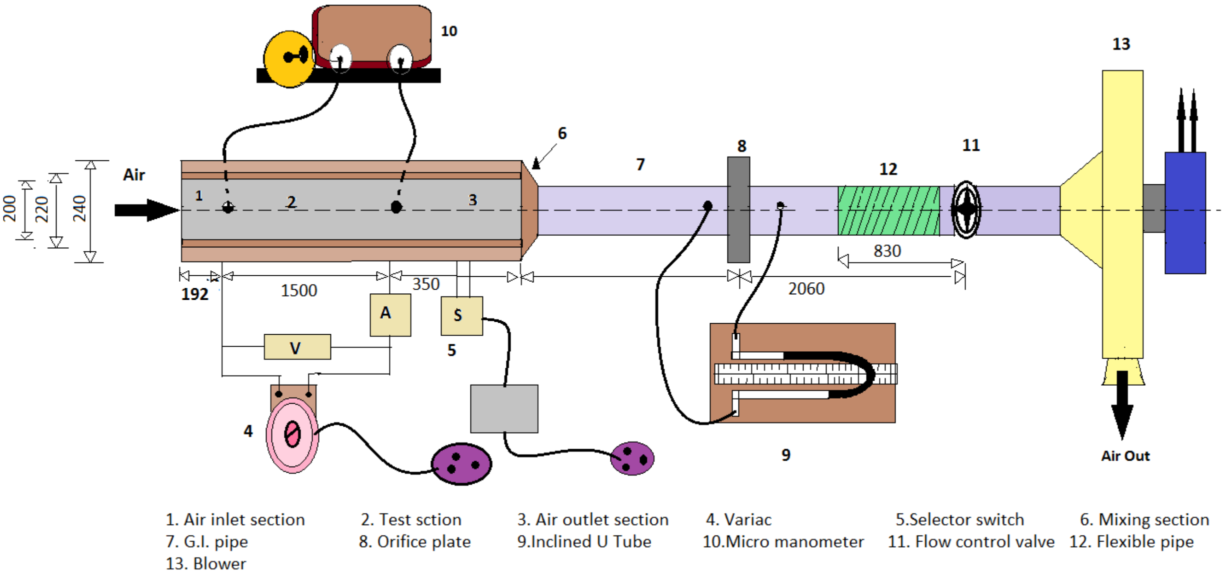

Fig.1: Schematic Diagram of Set-up

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Fig.2 :Roughened absorber plates

IV. DATA REDUCTION

Steady state value of the plate and air temperatures in the duct at various locations were obtained for a given heat flux and mass flow rate of air. Heat transfer rate to the air .Nusselt number and friction factor have been computed from the data. These values have been used to investigate the effect of various influencing parameters viz. the flow rate, the relative roughness height and the angle of attack of flow on the Nusselt number and friction factor.

4.1 Mean air and plate temperatures

The mean air temperature or average flow temperature T_{fav} is the simple arithmetic mean of the measure values at the inlet and exit of the test section. Thus,

$$T_{f\,av} = (T_i + T_{oav})/2$$

4.2 Pressure drop calculation

Pressure drop measurement across the orifice plate was made by using the following

$$\Delta P_o = \Delta h \times 9.81 \times \rho_m \times 1/5$$

4.3 Mass flow measurement

$$m = C_d \times A_o \times [2 \rho \ \Delta P/ (1 - ß^4)]^{0.5}$$

4.4 Heat transfer measurement

$$Q_a = m\, C_p\, (t_o - t_i)$$
$$h = Q_a / A_p\, (t_{pav} - t_{fav})$$
$$Nu = hD/k$$

4.5 Friction Factor:

Friction factor is given by:

$$F = (2 * \Delta P_{micro} * D_h * \rho)/(4 * 1.3 * G^2)$$

Where G=m/wh is the mass velocity of air.

4.6 Thermal efficiency

The efficiency is calculated By:

$$\eta = Q_a / A_P I$$

where: I= Heat flux

V. RESULTS AND DISCUSSION

Figs. 3 show effect of Reynolds number on Nusselt number and Figs. 4 show effect of Reynolds number on friction factor for arc shape with gap rib. Nusslet number increases whereas friction factor decreases with an increase of Reynolds number as expected. But values of Nusselt number and friction factor are different as compared to those for smooth plate due to change in the fluid flow characteristics as a result of roughness that causes flow separations, reattachments and generation of secondary flows. It is seen that value of Nusselt number increases with increase in Reynolds number. As Reynolds number increases thickness of boundary layer decreases and so convective resistance decreases. A decrease in convective resistance increases Nusselt number as Nusselt number being ratio of conductive resistance to convective resistance of heat flow. It can be seen that for lower values of Reynolds number, the improvement in the Nusselt number over the smooth duct is small as the projections of the roughness elements lie entirely within the laminar sub-layer. As seen from Fig.3 enhancements are noticeable and justify use of artificial roughness. Maximum enhancement of Nusselt number is found to be 2.45,2.36, 2.35 and 2.41 times that for smooth duct for relative gap position (d/W) of 0.50,0.40,0.30 and 0.25.. Similarly for the maximum enhancement in friction factor is found to be 2.83, 2.76, 2.72 and 2.78 times that for smooth duct.

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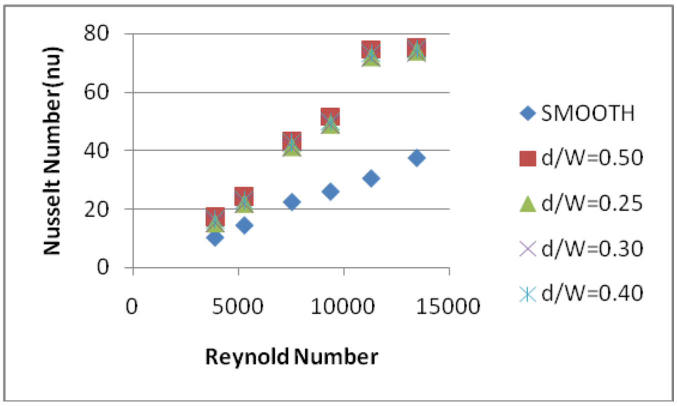

Fig.3 Effect of Reynold No. on Nusselt No. for different relative gap position(d/W)

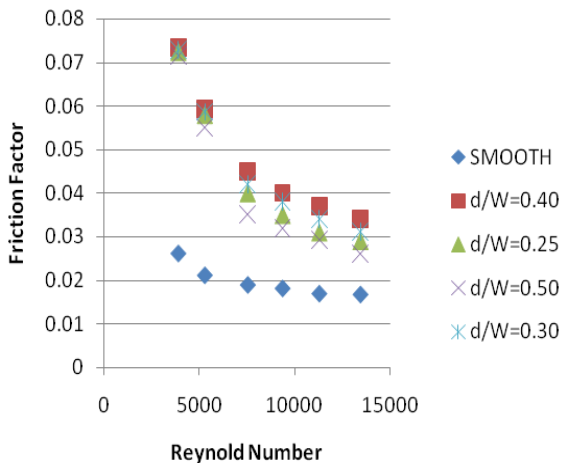

Fig..4 Effect of Reynold number on Friction factor for different relative gap position(d/W)

VI. THERMO-HYDRAULIC PERFORMANCE

Artificial roughness on absorber plate results in enhancement of heat transfer. Enhancement is accompanied by increase in friction factor. The roughness geometry be selected so that heat transfer is maximized while friction losses are at minimum value. This is fulfilled by considering heat transfer and friction characteristics simultaneously. A parameter that facilitates simultaneous consideration of thermal and hydraulic performance is given by Webb and Eckert [21] as $(Nur/Nus)/(fr/fs)^{1/3}$. This parameter is plotted in Fig. 5 against Reynolds number for different relative gap position . It is seen that in general thermo-hydraulic performance maximum in relative gap position (d/W) is 0.50 as compare to other three (d/W=0.25,0.30,0.40,) at constant angle of attack is 60˚.

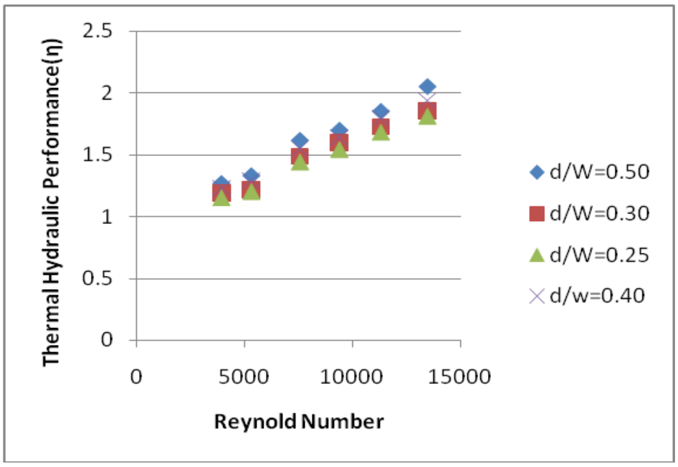

Fig.5. Effect of Reynold No. on Thermal hydraulic performance for differentrelative gap position(d/W)

VII. CONCLUSION

The present paper shows the feasibility of heat transfer enhancement using arc shape with gap roughened plate in solar air heater for turbulent flow with uniform heat flux. Heat transfer coefficient

and friction factor are determined experimentally using air as working fluid for Reynolds number range of 3000–15,000. Based on the results following conclusions are drawn from this work:

(I) Nusselt number increases and friction factor decreases with increasing Reynolds number.

(II) A gap in the arc rib arrangement enhances the heat transfer and friction factor of the roughened ducts. The increase in Nusselt number and friction factor is in the range of 1.46–2.45 times and 1.54–2.8 times of the smooth duct, respectively, for the range of Reynolds numbers from 3000 to 15,000.

(III) The maximum values of Nusselt number and friction factor are observed for a gap in the arc shape repeated ribs with a relative gap position of 0.50 and a relative gap width of 1.0.

(IV) The thermo-hydraulic performance analysis of roughened ducts shows that the relative gap width of 1.0 and a relative gap position of 0.50 results in a higher value of efficiency parameter.

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