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Enhancing Thermal Performance of a Solar Air Heater through Artificial Roughness on Absorber Plate

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ABSTRACT: Artificial roughness applied on the absorber plate is the most efficient method to improve thermal performance of solar air heaters. Experimental investigations appropriate to distinct roughness geometries shows that the enhancement in heat transfer is accompanied by considerable rise in pumping power. In view of the fact, a designer needs to carefully examine shape and orientation of roughness elements in order to choose the best fit roughness geometry for intended application. Thermal performance of conventional solar air heater can be improved by enhancing the heat transfer. Basically heat transfer enhancement techniques are active and passive techniques. Providing an artificial roughness on a heat transferring surface is an effective passive heat transfer technique to enhance the rate of heat transfer to fluid flow. Attempts have been made to increase heat transfer to air flowing through solar air heater duct using finned absorber, packed bed absorber, corrugated absorber, two-pass air flow, over-lapped glass plates, artificially rib roughened absorber, etc. The convective heat transfer coefficient of solar air heater is low due to the presence of viscous sub layer between the air and absorber plate which can be improved by providing artificial roughness on the heat transferring surface. Artificial roughness in the form of repeated ribs on the absorber plate is an effective technique to enhance the rate of heat transfer to flowing fluid in the roughened duct of solar air heater which also helps to break the laminar sub-layer and creates turbulence in the flow, which reduces the thermal resistance and greatly enhance the heat transfer. Enhancement in heat transfer results in higher thermal efficiency in case of rib roughened solar air heater as compared to conventional solar air heater having rib-roughness parameters of relative roughness pitch of 8, angle of attack of 60° relative roughness height of 0.047 and value of Reynolds number from 2564-6206. Finally comparison of thermal efficiency between smooth and roughened plate under the similar condition of air flow is carried out.

Keywords: Solar air heater; artificial roughness; Thermal efficiency; Effective efficiency

I. INTRODUCTION

The energy demand is growing continuously and rapidly, and it is impossible to meet the future demand with the presently available exhaustible energy sources. So, the technology is focusing on harnessing new and renewable sources of energy. Furthermore, the conventional energy sources are causing an alarming health hazard to the planet life. The use of solar energy is an intelligent option for the use of mankind which is available free of cost, in abundant and is a clean source for various applications [1]. The solar energy can be used directly or indirectly by converting it into thermal energy. Instead of direct use of solar energy, it is more useful when converted into thermal energy. Solar air heater is such a device, which converts solar energy into thermal energy.

It can be used for various applications like the heating of building, wood seasoning, drying of crops of fruits and vegetables, chicken brooding [2] as well as curing of industrial products [3]. It has many advantages like low fabrication, installation, and operational costs, and can be constructed by using cheaper and lesser amount of material. However, its efficiency is poor. The lower efficiency of solar air heater is attributed to poor heat transfer characteristics of air, and also the air cannot be used as storage fluid due to low thermal capacity [4]. The low efficiency of the solar air heater can be increased either by increasing the surface area of the absorber plate or by using certain artificial geometries on the absorber plate with some adverse effect of the increase in frictional loss in ducts which is needed to be taken care of by using proper, geometrical parameters and flow conditions.

The use of artificial roughness rib elements on the absorber plate is one of the effective ways which enhances the heat transfer coefficient of the air, thus increasing the heat transfer rate. These roughness rib elements breaks up the boundary layers and induces turbulence which results in heat transfer enhancement. These roughness elements being smaller in height as compared to duct size causes turbulence in the laminar sub layer adjacent to the wall without affecting the main turbulent zone in the flow. Several attempts have been made by various researchers in their experimental work to achieve the heat transfer enhancement through these solar air heaters by using different roughness elements on the surface of absorber plate. The researchers have used several geometries of artificial rib roughness elements with different parameters and materials till now. But still this area of research has large opportunity for doing novel work to achieve the heat transfer enhancement with new geometry with different parameters. This review is an attempt to summarize all these efforts and to arrive at a conclusion regarding the previous experimentation works and providing an opportunity in this area to the researchers to inquest the new materials, geometries and techniques to achieve the desired result of enhancement of heat transfer.

Earlier experiments dealt with roughness elements in pipe flow with water as flowing liquid. Use of ribs in pipe flow was extensively studied by Nikuradse [5]. He developed the velocity and temperature profile for sand grain roughened pipe flow and contributed to the study of the laws governing turbulent flow of fluids in roughened tubes, channels, and along rough plane surfaces with the law of similarity given by his previous authors. Nikuradse defined three regions or range of the fluid flow based on roughness Reynolds number (e+) through the roughened pipe which is described below.

(i) In the first range, the roughness height has no effect on the resistance for low Reynolds numbers. This range includes complete laminar flow and partly turbulent flow. The portion of turbulent flow included increases as the relative roughness height decrease.

(ii) In the second region, called as transition range, the effect of the roughness height is higher. The resistance increases with the increase in Reynolds number. The resistance depends on the Reynolds number and relative roughness of the surface.

(iii) The third region is the turbulent region where the resistance due to roughness is independent of the Reynolds number. It follows the quadratic law of resistance. Efficiency of flat plate solar air heater is low because of low convective heat transfer coefficient between absorber plate and flowing air. Higher thermal resistance increases absorber plate temperature leading to greater heat losses to environment.

Low value of heat transfer coefficient is due to the presence of laminar sub-layer that is broken by providing artificial roughness on heat transferring surface [1]. Efforts for enhancing heat transfer have been directed towards artificially destroying laminar sub-layer. Artificial roughness creates turbulence near wall and breaks laminar sub-layer. However artificial roughness results in high frictional losses leading to more power requirement for fluid flow. Hence turbulence has to be created in a region very close to heat transferring surface. Core fluid flow should not be unduly disturbed to limit pumping power requirement. This is achieved by keeping height of roughness element small in comparison to duct dimensions [2]. Important parameters that characterize roughness element are roughness element height (e) and pitch (p). These are expressed in terms of dimensionless parameters such as relative roughness height (e/D_h) and relative roughness pitch (p/e).

II. MATERIALS AND METHODS

Solar air heaters have been observed to have generally poor convective heat transfer coefficient from absorber plate to the air. This low heat transfer coefficient results in relatively higher absorber plate temperature leading to higher thermal loses to the environment and hence lower thermal efficiency. It has been found that the main thermal resistance to the convective heat transfer is due to the formation of laminar sub-layer on the heat-transferring surface. Efforts for enhancing heat transfer have been directed towards artificially disturbing this laminar sub- layer. Artificial roughness on the absorber plate has been used to create artificial turbulence near the wall or to break the laminar sub-layer.

The artificial rib roughness on the heat transferring surface of duct can significantly enhance the heat transfer from a surface but with simultaneous increase in friction losses. The artificial rib roughness in the form of transverse ribs, angled ribs, V-up ribs, V-down ribs, continuous ribs, discrete ribs, etc. have been investigated for the enhancement of the heat transfer from a surface. We use inclined circular rib as an artificial roughness underside the smooth absorber plate to break the viscous sub layer and to produce local wall turbulence (Han and Zhang, 1992; Gupta *et al.*, 1993; Taslim *et al.,* 1996). In solar air heater, the three walls of rectangular duct are smooth and insulated while only one wall i.e. absorber exposed to solar radiation. It is reported that, by using the roughness underside the absorber plate results in higher heat transfer enhancement than smooth plate. The air heater placed in actual atmosphere conditions towards south facing inclined at angle of 45° to the horizontal.

III. EXPERIMENTAL SET-UP

The experimental setup consist of a test duct with entrance and exit sections, G.I. pipe, orifice plate, flow valve, flexible pipe, blower and various devices for measurement of temperature , pressure drop and solar intensity (such as thermometers , manometer and solar radiation meter respectively). The rectangular duct contains test section besides entry and exit section. The top side of test section is artificially roughened with circular inclined ribs while the other surface is smooth. Air blower sucks the atmospheric air through heated rectangular duct. The air picks up heat from the heated absorber plate and the heated air flows through the orifice plate before the blower exhausts it to atmosphere. The air flow rate through the duct is regulated by means of control valve and it is measured using orifice. Temperature measurements of air are carried out by thermometers. Manometer is used to measure the pressure drop across the test section

IV. RESULTS AND DISCUSSION

Thermal and effective efficiency of solar air heater as a function of system and operating parameters have been computed with the help of a mathematical model. Results obtained under the present investigation have been reported and discussed in the following sub-sections.

The major objective of the present study is to analyze the thermal performance of artificially roughened solar duct by varying the value of Reynolds number with inclined circular rib at 45°. In this chapter, the results of experimental investigation on thermal efficiencies are presented and discussed as a function of air flow rate. Results have also been compared with those of smooth duct under similar flow and thermal boundary conditions to determine the enhancement in thermal efficiency. The variation in thermal efficiency and temperature change corresponding to time discussed also.

In this section, the thermal performances of rectangular duct with one broad wall rib-roughened have been discussed. The range of rib roughness parameters viz., relative roughness pitch (P/e), angle of attack (α) were 8 and 60°, respectively. The Reynolds number was varied from 2564 to 6206. 5. Conclusions

An experimental study on thermal efficiency of solar air heater having artificial inclined rib roughened absorber plate has been carried out. The artificial roughness helps to break the laminar sub-layer inside the duct to create a turbulence of air so that more and more heat is transferred from the absorber plate as compared to smooth plate duct. An experimental setup has been designed and fabricated for data generation regarding thermal efficiency of solar air heater roughened with circular inclined rib on one broad wall. The thermal performance between smooth and roughened surfaces at different Reynolds number was compared.

A. Variation in ambient temperature and solar radiation for smooth duct.

Time effects the ambient temperature and solar radiation during the experiment at Re=2564. In this experiment, it was investigated that the ambient temperature and solar radiation varies with respect to time. According to time the value of ambient temperature gradually increases but due to some atmospheric condition, there is an instant decrease in value of ambient temperature. The value of solar radiation also goes to increase with respect to time but after the mid of the day its value goes to decreases. The range of ambient temperature lies between 27°C to 43°C and solar radiation varies from 160 W/m^2 to 850 W/m^2.

B. Variation of average outlet temperature and solar radiation for smooth duct.

The variation in average outlet temperature of rectangular smooth duct and thermal efficiency as the function of time at Re = 2564. In which the average outlet temperature of duct gradually increases and goes to its peak value at the mid of the day and after that the values of temperature goes to decrease. But the value of thermal efficiency goes to increase from morning to evening time or sometime the value remains constant due to atmospheric conditions. The average outlet temperature varies from 38°C to 60°C and thermal efficiency varies from 31% to 67%.

According to these experiments it has been investigated that the Reynolds number and average outlet air temperature are inversely proportional to each other. While increasing the Reynolds number the outlet air temperature decreases.

C. Variation in temperature and solar radiation for roughened duct

Time affects the ambient temperature and solar radiation. In this experiment, it was investigated that the ambient temperature and solar radiation varies with respect to time at Re = 2564. According to time, the ambient temperatures gradually increases but due to some atmospheric condition the value of ambient temperature remain constant or decreased. On the other side the value of solar radiation also increases with respect to time up to the mid of the day and after that its value goes to decrease. The range of ambient temperature lies between 34°C to 46°C and solar radiation varies from 160 W/m^2 to 850 W/m^2.

D. Variation of average outlet temperature and solar radiation for roughened rectangular duct

The variation in average outlet temperature of rectangular roughened duct and thermal efficiency with respect to time. In which the average outlet temperature of duct gradually increases and goes to its peak value at the mid of the day and after that the values of temperature goes to decrease. Similarly, solar radiation also increases slightly to 12:00 noon and after that it goes to decrease due to the rotation of earth. The value of average outlet temperatures is more as compared to smooth duct. The average outlet temperature varies from 49°C to 72°C and thermal efficiency varies from 38% to 77%. According to these experiments it has been investigated that the Reynolds number and outlet air temperature are inversely proportional to each other. While increasing the Reynolds number the outlet air temperature decreases.

E. Comparison

It has been concluded that the average thermal efficiency in roughened duct is more as compare to smooth duct. The variation in thermal efficiency varies from 36% to 60% in case of smooth duct whereas the value of thermal efficiency increases from 40% to 72% in roughened duct.

The thermal efficiency of roughened solar air heater is higher than the smooth solar air heater due to the breakage of laminar sub-layer by the artificial rib roughened that makes the flow to turbulent. By breaking the sub layer, higher value of heat transfer from absorber plate to the flow of air. Further it has been observed that there was increase in average thermal efficiency with increase in Reynolds number.

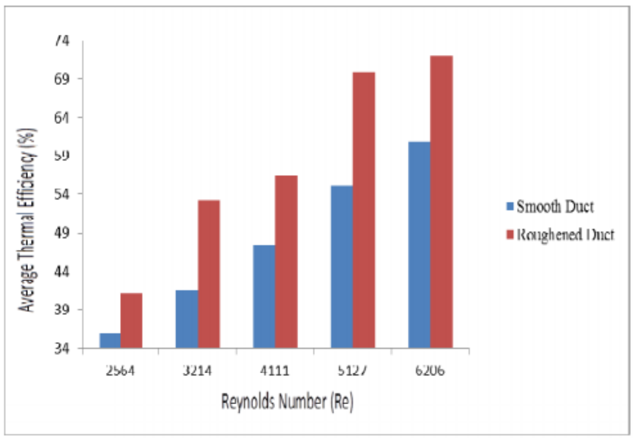

Fig. 1. Average thermal efficiency v/s Reynolds number between smooth and roughened duct.

In the present paper, thermal and thermohydraulic performance of smooth as well as roughened solar air heater has been investigated with the help of a mathematical model. Absorber plate of solar air heater is assumed to be roughened with formation of protrusions. Thermal efficiency and effective efficiency have been used as criteria for evaluating thermal and thermohydraulic performance of solar air heater. Based upon maximum thermal and effective efficiency of roughened solar air heater, optimum value of each roughness geometry parameter has been obtained. Thermal efficiency criteria has resulted optimum value of each roughness geometry parameter independent of temperature rise parameter. However, effective efficiency criteria has resulted optimum value of each roughness geometry parameter as a function of temperature rise parameter. For the range of system and operating parameters, maximum enhancement in thermal efficiency and effective efficiency for roughened solar air heater has been found of the order of 2.3 and 2.2 times respectively as compared to solar air heater having smooth absorber plate. In order to facilitate the designer, design plots have been prepared for finding optimum value of each roughness geometry parameter as a function of temperature rise parameter.

Methodology of artificial roughness is considered to be a good technique for enhancing rate of heat transfer between absorber plate and air flowing through duct of solar air heater.

F. Highlights

The paper presents results of an outdoor experimental study on performance of smooth and roughened duct solar air heaters. Study shows thermal performance enhancement due to the use of v-down discrete rib roughness on the absorber plate. Experimental data has been utilized to validate mathematical models for both smooth and roughened duct solar air heaters. The presented model can be utilized for performance prediction of smooth or roughened duct solar air heaters.

G. Comparison between thermal efficiency of smooth and roughened duct

(i) From the table 1, it is clear that there is increase in average thermal efficiency from 5 to 11% by using roughened duct. Further, it has also seen there is increase in thermal efficiency with increase in Reynolds number for both the ducts i.e. smooth and roughened duct. Results of the experimental study of thermal efficiency for both smooth duct solar air heater and air heater with v-down discrete rib roughness have been compared with the predicted values from a mathematical model to validate the presented model.

Table 1.

Reynolds Number (Re)	Thermal Efficiency Smooth Duct in (%)	Thermal Efficiency Roughened Duct in (%)
2550	36.09	41.09
3214	41.50	53.20
4111	47.51	56.51
5127	55.27	69.74
6206	60.83	72.11

The standard and average deviations of the predicted and experimental data of thermal efficiency are about ±11% and 8%, respectively. The reasons for the deviations have been identified as the uncertainties in the estimates of the wind heat transfer coefficient, heat transfer coefficients and sky temperature from the available correlations.

(ii) The enhancement in the thermal efficiency due to artificial roughness on the airflow side of the absorber plate has been found to be 12.5–20% depending on the flow rate; higher enhancement is at the lower flow rate, which is attributed to the enhancement in the heat transfer coefficient due to the employment of the roughness.

(iii) The plate temperature excess (mean temperature of the plate over the ambient temperature) for the roughened absorber plate is significantly lower (18.5–40.8 K) than the smooth duct (33–53.2 K), which clearly indicates a lower operating temperature and hence increased thermal efficiency due to the reduced heat loss from the roughened duct solar air heater compared to the smooth duct air heater.

(iv) The experimental friction factor results have been found to be in reasonable agreement with the predicted data for both the roughened (5.7% average deviation) and smooth duct (6.1% average deviation) from the predicted values from the equations given in the mathematical model. Thus the presented mathematical model can be used for the thermo-hydraulic performance prediction.

(v) The results of a detailed thermo-hydraulic performance study of solar air heater with v-down discrete rib roughness using the mathematical model validated here are available in the form of plots of thermal and effective efficiencies from an earlier study, which has been reproduced here. The results of the study regarding the effect of variation of various parameters on the predicted collector performance have also been reproduced.

V. CONCLUSIONS

(i) It has been observed that as the value of Reynolds number increases the value of thermal efficiency also increases.

(ii) Circular inclined rib on the absorber plate enhances the rate of heat transfer as compared to smooth duct.

(iii) Comparison between smooth and roughened duct at different Reynolds number shows that average thermal efficiency increases from 5 to 11%.

VI. SCOPE FOR FUTURE WORK

(i) In present work, circular inclined roughness geometry is under investigation. So more work is required for artificial rib roughness such as V-shaped, W-shaped, transverse with gap.

(ii) In present work, thermal efficiency is calculated by varying the Reynolds number. So many other parameters remained to be calculated, such as heat transfer and friction characteristics by using artificial roughness in conventional solar air heater.

(iii) There is need to study the CFD work such as fluent in this area to take in sight of fluid dynamics.

REFERENCES

[1] A. Kumar, R.P. Saini, J.S. Saini, "Development of correlation of Nusselt number and friction factor for solar air heater with roughened duct having multiple v – shaped with gap rib as artificial roughness", *Renewable Energy*, Vol. **58**, pp.151-163, 2013.

[2] Sukhmeet Singh, S. Chander, J.S. Saini, "Investigations on thermo-hydraulic performance due to flow-attack-angle in V-down rib with gap in the rectangular duct of solar air heater", *Applied Energy*, Vol. **97**, pp.907-912, 2012.

[3].A. Lanjewar, J.L. Bhagoria, R.M. Sarviya, "Heat transfer and friction in solar air heater duct with w-shaped rib roughness on absorber plate", *Energy* doi: 0.1016/j. energy, 2011.

[4].V.S. Hans, "Heat Transfer and Friction Characteristics of Multiple V-Rib Roughened Solar Air Heater", Ph.D. thesis, Indian Institute of Technology Roorkee, India, 2010.

[5].V.S. Hans, R.P. Saini, J.S. Saini, "Heat transfer and friction factor correlations for a solar air heater duct roughened artificially with multiple V-ribs", *Solar Energy,* Vol. **84**, pp.898-911, 2010.

[6].K.R. Aharwal, B.K. Gandhi, J.S. Saini, "Heat transfer and friction characteristics of solar air heater ducts having integral inclined discrete ribs on absorber plate", *International Journal of Heat and Mass Transfer,* Vol. **52**, pp.5970-5977, 2009.

[7].S. Kumar, R.P. Saini, "CFD based performance analysis of a solar air heater duct provided with artificial roughness", *Renewable Energy*, Vol. **34**, pp.1285-1291, 2009.

[8].T.S. Kumar, V. Mittal, N.S. Thakur, A. Kumar, "Second law analysis of a solar air heater having 60° inclined discrete rib roughness on absorber plate", *African Journal of Environmental Science and Technology,* Vol. **4**, 913-929, 2009.

[9]. A. Kumar, J.L. Bhagoria, R.M. Sarviya, "Heat transfer and friction correlations for artificially roughened solar air heater duct with discrete w-shaped ribs", *Energy Conversion and Management,* Vol. **50**, pp. 2106-2117, 2009.

[10].Varun, R.P. Saini, S.K. Singal, "Investigation of thermal performance of solar air heater having roughness elements as a combination of inclined and transverse ribs on the absorber plate", Renewable Energy, Vol. 33, pp.1398-1405, 2008.

[11].S.K. Saini, R.P. Saini, "Development of correlations for Nusselt number and friction factor for solar air heater with roughened duct having arc-shaped wire as artificial roughness", *Solar Energy*, Vol. **82**, pp.1118-1130, 2008.

[12].R.P. Saini, J. Verma, "Heat transfer and friction factor correlations for a duct having dimple-shaped artificial roughness for solar air heaters". *Energy,* Vol. **33**, pp.1277-1287, 2008.

[13]. S.P. Sukhatme, J.K. Nayak, "Solar Energy, Principles of Thermal Collection and Storage", Tata McGraw-Hill Publishing Limited, New Delhi, India, 2008.

[14].A. Layek, J.S. Saini, S.C. Solanki, "Second law optimization of a solar air heater having chamfered rib-groove roughness on absorber plate", *Renewable Energy*, Vol. **32**, pp.1967-1980, 2007.

[15].S.V. Karmare, A.N. Tikekar, "Heat transfer and friction factor correlation for artificially roughened duct with metal grit ribs", *International Journal of Heat and Mass Transfer*, Vol. **50**, pp.4342-4351, 2007.

[16].A.R. Jaurker, J.S. Saini, B.K. Gandhi, "Heat transfer and friction characteristics of rectangular solar air heater duct using rib-grooved artificial roughness", *Solar Energy*, Vol. **80**, pp.895-907, 2006.

[17]. A. Chaube, P.K. Sahoo, S.C. Solanki, "Analysis of heat transfer augmentation and flow characteristics of a solar air heater", *Renewable Energy* ,Vol. **31**, pp.317-331, 2006.

[18]. M.M. Sahu, J.L. Bhagoria, "Augmentation of heat transfer coefficient by using 90° broken transverse ribs on absorber plate of solar air heater", *Renewable Energy*, Vol. **30**, pp. 2057-2063, 2005.

[19]. R. Karwa, R.D. Bairwa, B.P. Jain, N. Karwa, "Experimental study of the effects of rib angle and discretization on heat transfer and friction in an asymmetrically heated rectangular duct", *Journal of Enhanced Heat Transfer*, Vol. **12**, pp.343-355, 2005.

[20]. N.S. Thakur, J.S. Saini, S.C. Solanki, "Heat transfer and friction factor correlations for packed bed solar air heater for a low porosity system", *Solar Energy,* Vol. **74**, pp.319-329, 2003.

[21]. R. Karwa, "Experimental studies of augmented heat transfer and friction in asymmetrically heated rectangular ducts with ribs on the heated wall in transverse, inclined, v-continuous and v-discrete pattern", *International Communications in Heat and Mass Transfer,* Vol. **30,** pp.241-250, 2003.

[22]. J.L. Bhagoria, J.S. Saini, S.C. Solanki, "Heat transfer coefficient and friction factor correlations for rectangular solar air heater duct having transverse wedge shaped rib roughness on the absorber plate", *Renewable Energy*, Vol. **25**, pp.341-369, 2002.

[23]. R. Kumar, R.S. Adhikari, H.P. Garg, A. Kumar, "Thermal performance of a solar pressure cooker based on evacuated tube solar collector", *Applied Thermal Engineering*, Vol. **21**, pp.1699-1706, 2001.

[24]. H.P. Garg and R.S. Adhikari, "A novel design of a natural convention type multi effect humidification (MEH) – dehumidification solar distillation plant (100 liters capacity per day)", *Desalination (An International Journal*) , Vol. **152**, pp.55 – 65, 2001

[25]. K.B. Muluwork, S.C. Solanki, J.S. Saini, "Study of heat transfer and friction factor in solar air heaters roughened with staggered discrete ribs", *Proceeding of 4th ISHMT-ASME and 15th National Conference on Heat and Mass Transfer, Pune, Jan.12-14, 2000.*

[26]. D.R. Mills, G.L. Morrison, "Compact Linear Fresnel Reflector solar thermal power plants", *Solar Energy*, Vol. **68**, pp.263-283, 2000.

[27]. S.D. Sharma, D. Buddhi, R.L. Sawhne, A. Sharma, "Design, development and performance evaluation of a latent heat storage unit for evening cooking in a solar cooker", *Energy Conversion and Management* Vol. **41**, pp.1497-1508, 2000.

[28]. H.P. Garg, J. Prakash, "Solar energy: fundamentals and applications", Tata McGraw-Hill Education, Delhi, India, 2000.

[29]. D.Y. Goswami, F. Kreith, J.F. Kreider, "Principles of Solar Engineering", Taylor and Francis, Philadelphia, USA, 2000.

[30]. R. Karwa, S.C. Solanki, J.S. Saini, "Heat transfer coefficient and friction factor correlations for the transitional flow regime in rib-roughened rectangular ducts", *International Journal of Heat and Mass Transfer*, Vol. **42**, pp. 1597-1615, 1999.

[31]. K. Pottler, C.M. Sippel, A. Beck, J. Fricke, "Optimized finned absorber geometries for solar air heating collectors", *Solar Energy*, Vol. **67**, pp.35-52,1999.

[32]. R.L. Sawhney, P.N. Sarsavadia, D.R. Pangavhane, "Development of a multipurpose solar crop dryer", Proc. of National Solar Energy Convention, University of Roorkee, pp.315 – 322, 1998.

[33]. M.E. Taslim, D.M. Kercher, Darryl e. Metzger memorial session paper: "Experimental heat transfer and friction in channels roughened with angled, v-shaped, and discrete ribs on two opposite walls", *Journal of Turbo-machinery*, Vol. **118**, pp.20-28, 1996.

[34]. S.K. Samdarshi, S.C. Mullick, "Generalized analytical equation for top heat loss factor of a flat-plate solar collector with N glass covers", Trans. *ASME Journal of Solar Energy Engineering*, Vol. **116**, pp.43-46, 1994.

[35]. J.C. Han, Y.M. Zhang, "High performance heat transfer ducts with parallel broken and V-shaped broken ribs", *International Journal of Heat and Mass Transfer*, Vol. **35**, pp.513-523, 1992.

[36]. J.A. Duffie, W.A. Beckman, "Solar Engineering of Thermal Processes", John Wiley and Sons Inc. Publication, New York, USA, 1991.

[37]. B.N. Prasad, J.S. Saini, "Optimal thermo-hydraulic performance of artificially roughened solar air heaters", *Solar Energy* Vol. **47**, pp.91-96, 1991.

[38]. B.N. Prasad, J.S Saini, "Effect of artificial roughness on heat transfer and friction factor in a solar air heater", Solar Energy, Vol. 41, pp.555-560, 1988.

[39]. M.S. Bhatti, R.K. Shah, "Turbulent and Transition flow convective heat transfer in ducts," chapter 4 in "Hand book of single-phase convective heat Transfer", Editors Kakac S, Shah R. K., Aung W., John Willey & sons, New York, 1987.

[40]. W. Helmbold, "Independent house heating in temperature climate". Proc. Int. Workshop on Energy Conservation in Buildings, CBRI, Roorkee, pp.33-40, 1984.

[41]. K. Prasad, S.C. Mullick, "Heat transfer characteristics of a solar air heater used for drying purposes", *Applied Energy*, Vol. **13**, pp.83-93, 1983.

[42]. P. Persad, S. Satcunanathan, "The thermal performance of the two-pass, two glass-cover solar air heater", ASME *Journal of Solar Energy Engineering*, Vol. **105**, pp.254-258, 1983.

[43]. A. Malhotra, H.P. Garg, A. Patil, "Heat loss calculation of flat plate solar collectors", *Journal of Thermal Engineering*, Vol. **2**, pp.59-62. 1981.

[44]. D.R. Mills, "Two-stage tilting solar concentrators". *Solar Energy*, Vol. **25**, pp.505-509, 1980.

[45]. T.A. Reddy, C.L. Gupta, "Generating application design data for solar air heating systems", *Solar Energy*, Vol. **25**, pp.527- 530, 1980.

[46]. T.A. Reddy, C.L. Gupta, "Design and performance of an air collector for industrial crop dehydration," *Solar Energy*, Vol. **20**, pp.19-23, 1978.

[47]. S.A. Klein, "Calculation of flat plate collector loss coefficients", S*olar Energy*, Vol. **17**, 79-80, 1975.

[48]. K. Selçuk, "Thermal and economic analysis of the overlapped-glass plate solar-air heater", *Solar Energy*, Vol. **13**, pp.165-191, 1971.

[49]. C.L. Gupta, H.P. Garg, "Performance studies on solar air heaters", *Solar Energy*, Vol. **11**, pp.25-31, 1966.

[50]. H.C. Hottel, B.B. Woertz, "The performance of flat plate solar heat collectors", *Trans. ASME*, Vol. **64**, pp.91-104, 1942.