PERFORMANCE EVALUATION OF SOLAR AIR HEATER WITH INTEGRATION OF AUGMENTED ABSORBER PLATE

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Abstract: A solar air heater is a device mainly used for space heating and crop drying. The reason for limited applications of solar air heater is its low thermal efficiency. This is due to inadequate heat transfer from absorber plate to the air (working fluid). As a result, the absorber plate temperature remains high and thus higher heat losses to the surroundings. The dominant contribution to thermal resistance between absorber plate and air is provided by development of viscous sub-layer on the plate body. The use of artificial roughness on the heat transfer area is one of the simplest and economical heat transfer enhancement methods. The artificial roughness enhances the heat transfer by avoiding the development of viscous sub-layer on the plate body or near the wall and creating turbulence Furthermore; roughness also acts as elements to increase effective heat transfer area. However, the penalty of this method is associated with the enhancement in pumping power due to increased pressure drop in the air flow path. There are various techniques adopted to enhance the heat transfer rate such as: use of secondary surfaces, increasing the effective thermal conductivity of the fluid, introducing secondary flows, increasing the difference between surface and fluid temperature, promoting flow attachment/reattachment, Enhancing effective thermal conductivity of the air flow, delaying the boundary layer development, etc.

Keywords: *Conventional Solar Air Heater, Heat Absorber Plate, Solar Incident Radiation Thermal Losses Artificial rib roughness, etc. ,*

I. Introduction

Since growing industrialization and population increase the power demand which adversely effects the environment. Globally this will result in climate change across the globe. Average temperature of earth to be maintain below 20°C according to Paris agreement. Since economic growth and environment both are vital for our existence, a quest for an alternative and safer source started after 1970s oil crisis and thus use renewable sources of energy has been found to be a testimony to this.

Renewable energy further has many sources like; solar energy, wind energy, biomass energy, tidal energy, hydroelectric energy, etc. However, the sun is directly or indirectly the ultimate source of all the energy on earth. It gives life to all living being on earth. The solar radiation emitted by sun is a type of electromagnetic wave which has wavelength range in 0.30 and 3 μm. This energy can be utilize in many ways; by photo voltaic channels to convert into electricity, refrigeration, natural ventilation and drying, photosynthesis, etc. The major 2 contribution of renewable energy is in electricity generation, and electricity is the most liquid form of energy, which can be used to produce almost any kind of work. Most of the research in solar energy is also solar PV channel-based. The solar utilizing appliance after PV channel is Concentrated Solar Power, amounts only 10% of the total solar installed capacity 586 GW worldwide. There are certain small-scale devices to utilize solar energy like; solar air heaters (SAH), solar chimneys, solar lanterns, solar pumps, water heaters, solar cookers, thermal l energy storage, water treatment, etc., that can save the need for electricity for a particular application. It is generally said; saving electricity is the generation of electricity. Another important aspect of such devices is the high solar conversion, low capital-cost, non-corrosive and non-reactive air as a working fluid, and eco-friendly, cheap construction material than PV channels.

The present study is focused on such non-electric or solar thermal technology-based device solar air heater. It is a device that absorbs insulation to heat air, and heated air has various industrial, agricultural, commercial, and household applications. However, a large volume of air is required to handle due to its low density, and its thermal properties are also poor as compared to a solar water heater. The solar air heater has an important place among solar heat collectors. Its role has been mostly misunderstood or ignored. With the recent trend of providing both heating and cooling with solar energy, liquid heaters for high temperature operation have gained more popularity. As far as the ultimate application of heating air to maintain a comfortable environment is concerned, the solar air heater is the most logical choice. Heating a fluid by the sun, then transferring heat to the air results in loss of temperature potential available. If the limitations of solar energy applications in terms of attainable temperatures and related efficiencies as well as the low cost requirements are considered, it would be wiser to eliminate any heat transfer operation. Direct use of the air circulated through the solar air heater as the working substance also reduces the number of components required in the system. Solar-heated air could be used more effectively for drying under controlled conditions. Solar heaters supplying hot air to a conventional drier or special designs combining the air heater and the drying cabinet in one package have cost and efficiency advantages for drying applications. Solar air heaters also eliminate corrosion and leakage problems which may be difficult and costly to overcome. The cost of the air heater could be substantially lower than the liquid systems. Higher pressures experienced in liquid heaters necessitate the use of heavy-gauge sheet metal or tubes. The air heater could be designed using less material, even some scrap of no commercial value. The limitation of the heat transfer from the absorber plate to the working fluid for air heaters could be a major problem for improperly designed collectors.

There are several ways to improve the heat transfer coefficients and/or increase surfaces such that efficiencies would be comparable with liquid heaters. One disadvantage of solar air heaters is the need for handling larger volumes of air than liquids due to the low density of air as a working substance. Another disadvantage is the low thermal capacity of air. In cases where thermal storage is needed, water is superior to air. Water may be used both as a heat transfer and a heat storage substance. In many localities, however, an antifreeze solution has to be used to overcome the frost problem. If an antifreeze solution is used, the cost of the thermal storage fluid may become prohibitively high due to the high cost of antifreeze solutions. The suggested use of an antifreeze to water heat exchangers (water being the storage substance) reduces the storage system cost, but the slight loss in temperature available and the expense of an extra heat exchanger must be justified. The final choice of the working fluid for solar energy is a complicated matter that necessitates a careful comparative analysis of thermal performance, operation, maintenance, and economic parameters. In fact, the ultimate goal in solar energy or any form of energy utilization is to decrease the cost of energy collected in cents per kilowatt hour. The cost effective design may not necessarily be the one using the most efficient solar collector, it is rather a combination of high efficiency, low fabrication, installation, and operation costs, and other practical aspects that are related to the specific application in mind. Solar air heating is a solar thermal technology in which the energy from the sun, insulation, is captured by an absorbing medium and used to heat air.

II. OBJECTIVES

A vast number of investigations on cross-section, orientation, shape, and size of ribs are available. But to the best knowledge of the present authors, not a single study has been carried out that compares V-shaped and arc shaped ribs in the same boundary conditions. Addressing this issue, present study analyses the performance of SAH using both kinds of ribs. Determination of Nu and Friction factor have been done by applying suitable mathematical correlations for the range of Re 3000-15000. Similar geometrical features like relative roughness pitch, relative roughness height, relative gap width and angle of attack have been considered while comparing the ribs. The magnitude of Thermal-hydraulic performance parameter (THPP) of V-shaped and arc shaped ribs at different values of Re ranging from 3000-15000 has been evaluated and findings have been presented and discussed. Also, a comparison has been drawn between numerical and experimental results and discussed in the sections below. The findings of this investigation will help engineers of solar air heater in deciding an appropriate kind of ribs geometries for enhancing the heat transfer. Based on the gaps identified from the literature, specific objectives have been decided to achieve the road map are as follows:

- To find the optimum geometrical configuration of the asymmetrically heated smooth SAH duct for its length, width, and aspect ratio.
- To find the optimum configuration of augmented surfaces for absorber plate in terms of blockage ratio (d/H), clearance ratio (c/d), relative longitudinal pitch ratio (P/d), in the optimized smooth SAH-duct.

III. PROBLEM IDENTIFICATION

The world is facing the challenges of the adverse effects of fossil fuels and the increasing global energy demand. A significant amount of global energy is consumed in certain applications like heating, cooling, ventilation in buildings, and drying in the agriculture and food processing industries, which can be saved by the solar air heater. The thermal efficiency of a solar air heater is very low. Geometrical optimization of a SAH-duct is not reported in terms of its length, width, and aspect ratio. Many heat transfer enhancement techniques have been borrowed from the past development in fundamentals of heat transfer and gas turbine blade research. An attempt has been made to geometrically optimize the smooth SAH-duct followed by augmented surface.

Problem statement

Application of artificial roughness has been one of the most widely accepted methods of augmenting the performance of SAH. However, attempt has been made to compare the performance of different types of ribs under similar boundary conditions and flow properties. An attempt has been made to find out the value of THPP (which obviously indicates the performance of a SAH) experimentally and validate with correlations. Studies aimed towards finding optimum roughness configuration for maximum thermal efficiency of SAH are scantly available. This study reviews various roughness element geometries employed in SAH, with specific aim to arrive at optimized geometrical parameters for the different configurations of these roughness elements.

IV. MOTIVATION

Solar air heater is one device which functions like a heat exchanger and has simple design. Its absorber plate absorbs incident solar radiation and heats the air flowing over it. The rise in temperature and vapor content of air at the exit depend on the required application. In India, several small scale industries of food packaging, fruit, spices, and crop drying have shown an inclination towards the use of SAH in place of the conventional electrical air heater. Particularly in southern India where moisture content is always high, cloth drying remains a big issue. As an initiative, hospitals and hotels have shown interest in application of solar air heater for cloth drying. However, the limited application of SAH is due to its very low thermal efficiency ($\eta_{th} <$ 50%). Even if we neglect heat losses by conduction, convection, radiation and air leaks, only half of the incident solar energy can contribute to the temperature rise of incoming air.

There are many methods and techniques to improve its thermal efficiency like: multipassing, multi-glazing, fins, baffles, blockages, obstructions but the most widely appreciated and recognized means is the implication of artificial repeated-rib roughness. Smooth absorber plate has lower value of coefficient of heat transfer. Augmentation of rate at which heat is transferred can be achieved by various means and induction of roughness over the absorber plate is one of such methods. It has been an established fact that these roughness elements aid in enhancing the performance of the solar air heater. From construction point of view it is a flat shape plate collector of solar radiation which has blackened or painted absorber plate to absorbs maximum possible solar radiation, a transparent cover at the top to trap maximum possible solar radiation, and insulation is provided at the bottom wall and on the side walls. All these major parts are enclosed in a sheet-metal container. The working fluid air is made to flow either below or above the absorber plate. Solar air heater is advantageous in many ways:

A simple and compact design. Air is safe, it can directly come in contact with vegetables, crop, food, etc. unlike water heater.

There is no problem of corrosion and leakage as air is relatively non reacting substance.

Air does not freeze and pressure rises very low so can be constructed with cheaper material and maintenance cost is very low.

The space heating-cooling-ventilation of commercial and domestic buildings, food packing,• processing, and drying industries, crop drying in agriculture, cloth drying in hotels and hospitals consume a lot of electricity, which may have come from fossil fuels or renewable energy resources.

A solar heater and solar air dryer is a good alternative for this energy consumption, which• can lower a huge load on total electricity consumption for these applications, as it can be installed directly on the site of application and made to run with minimum energy requirement.

A SAH also has very high conversion efficiency due to low construction, operational,• storage, and transmission cost.

V. EXPERIMENTAL SETUP

The experimental schematic setup as shown in Fig.5.1 consist of a wooden duct of the rectangular cross-section having an entrance, test, and exit sections with one side heated, and the remaining three sides are insulated. The heated side is the absorber plate, which has augmented surfaces mounted over it for heat transfer enhancement (HTE) through vortex shedding. Ambient air is made to flow through this duct via a blower, the air gets heated, which can be used for various applications. In the instrumentations; the venture meter measures mass flow rate, the micro manometer measures pressure drop along the test sections, and the thermocouple layout with temperature indicators measure inlet, outlet, and heated side temperature. This is the brief construction and working of the experimental setup, the details are discussed in the following subsections; fabrication, instrumentation, and working of the setup.

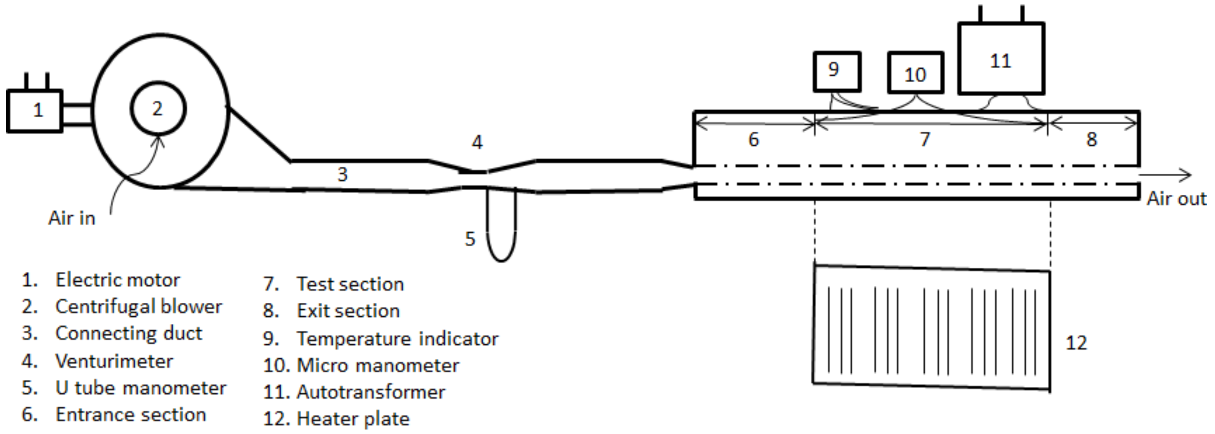

Fig.5.1 Schematic diagram of experimental setup.

Fabrication

In the fabrication of SAH-duct, we have smooth duct passage of variable aspect ratio, fitted with augmented surfaces, absorber or heater plate, insulation, and blower assembly connecting to SAH duct as per the geometrical configurations mentioned in the Tab.A.1 with range of parameter.

Table 5.1 Different geometrical variables

Parameter	
Heat flux	Q
Reynolds number	Re
Entrance length of SAH-duct	El
Test section length of SAH-duct	Tl
Exit length of SAH-duct	EL
Width of SAH-duct	b
Height of SAH-duct	H
Aspect ratio	AR
Blockage ratio	d/H
Clearance ratio	c/d

SAH-Duct of smooth passage

Wood, aluminium, steel, and galvanized iron are the most commonly used materials for the construction of the SAH-duct. Length, width, height, and aspect ratio of the duct are very important parameters and must be chosen wisely to satisfy the application of outlet heated air. The length of the test section, entry, and exit section are provided as per the ASHRAE standards [93-77], Entrance is provided so that fully developed flow can be obtained in the test section as the existing correlations are valid only for fully developed flow. Exit length is required to minimize the end effects in the test section.

Heater plate

Although in real-time studies, sunlight is the source of heat, but in the simulated environment, one may use, halogen bulbs or nichrome wires for the experimental studies. The controlled simulated environment is preferred when the matter of the experiment is not affected by the real-time study results. In the present study, the effect of AR, d/H, c/d, and P/d will be investigated, and the optimum value or range obtained will be applicable to the different magnitude of heat source energy.

Blower and its parts

As air is the working fluid, so a blower is used to provide airflow in the SAH-duct passage. It has a circular pipe for the supply of air which is connected to the rectangular shape cross-section of the SAH-duct via a fabricated funnel shape structure made of galvanised iron sheet. The blower is run by a motor to provide a different mass flow rate of air as per the Re range by changing the voltage supply via AC-DC converter.

Instrumentation

Mainly three variable properties are required to perform experimental studies; inlet, outlet, and absorber plate surface temperature, the mass flow rate of air, and pressure drop across the test section. In instrumentation, the measurement devices used to measure these variables are discussed briefly with their technical aspects.

Air flow measurement

The pressure measuring deivce is fitted in the length of the pipe connected to the blower for air supply to the SAH-duct. The pressure is measured at the inlet and throat positions along the length, whose pressure difference is shown with the help of manometer in terms of water level difference in its two limbs.

Pressure measurement

A micro manometer of the least count 0.01 mm of water is used for a small pressure drop across the test-section part of the SAH-duct. The probe of the micro manometer is placed at the inlet and outlet of the test section of the SAH-duct and the resultant pressure difference is shown via its display screen.

Data reduction for experimental study

In the data reduction part, mass flow rate, pressure drop, and temperature values will be obtained are used to reduce this data into dimensionless parameters like Nusselt number and friction factor for qualitative and quantitative analysis of the performance of the SAH-duct in different case studies.

In the next step, Nu is calculated in the following step; First, the average surface temperature of the absorber plate is calculated by the values obtained from the thermocouples installed over its surface as discussed previously:

$$T_p = \frac{T_1 + T_2 + \cdots + T_n}{N}$$

Similarly inlet and outlet temperature at the test-section part of the SAH-duct are calculated as:

$$T_i = \frac{T_a + T_b + T_c}{3}$$

The values obtained for Ti and To are used to calculate the magnitude of air mean fluid temperature also known as film temperature as:

$$T_f = \frac{T_i + T_o}{2}$$

The net heat gain by the air flow across test-section can be given by;

$$Q = mC_p(T_o - T_i)$$

where,

Cp = specific heat capacity of air

This heat gain Q, by the air flow is provided from convection loss by absorber plate as:

$Q = hA_p(T_p - T_f)$

Where, Ap = absorber plate area = W×H h

= heat transfer coefficient is given by:

$$h = \frac{Q}{A_p(T_p - T_f)}$$

Finally Nu = Nusselt number is given by:

$$Nu = \frac{hD_h}{k} \qquad Nu = \frac{hD_h}{k}$$

Working of experimental setup

First of all parts of the experimental setup are checked for loose parts, leakage of air, and proper connections of wires and joints. After the initial inspection, the variac is set at constant heat flux, and the blower is set to run at constant mass flow. The setup is made to run for at least an hour to bring it under a stable state. It means, the heat supplied by the heater plate provides constant heat flux, which is absorbed by the absorber plate which in turn supplies it to the airflow via convection. Generally, a steady-state is said to have been achieved, if reading in all measuring devices stops changing within acceptable, especially temperature which takes the largest time to get stable or in equilibrium. First, the smooth SAH-duct is studied and readings of the U-tube manometers, micro manometer, and all thermocouples are recorded for further data reduction. Next, all cases of different parameters will be investigated with required modifications in the setup. All results are used for the comparative and technical analysis to get the optimum configuration. An experimental results validation test was run for the smooth SAH-duct at the constant value of the AR and heat flux at Re. The recorded values of heat transfer and flow properties are used to calculate the values of f and Nu. These values are compared with the results from Blasius correlation for f and Dittus- Boeltier for Nu, where the difference between the experimental and correlation values will be lie within the acceptable limits..

VI. CONCLUSION

In the present study, an effort has been made to improve the thermal-hydraulic performance of a solar air heater via a geometrical optimised smooth SAH-duct with different types of ribs. In variable geometrical parameters, the effect of length L, width W, aspect ratio AR, blockage ratio d/H, clearance ratio c/d, and longitudinal pitch ratio P/d is investigated at different Re. Following observations are briefly summarised based on the energy status, literature survey,

- Initially, SAH was investigated only for crop and fruit drying. Now, it has applications in building ventilation, cloth drying, food packaging, hybrid PVT, and coupled solar air dryer.
- It is desired to investigate the selected optimum rib configurations under identical boundary conditions and SAH-duct to develop a general idea about their relative thermal-hydraulic performance.
- Combinations of different rib-geometries can also be used for the enhancement of heat transfer.
- Transverse vortex generators for heat transfer enhancement in duct flows are never studied in SAH-duct domain.
- Aspect ratio effect of the rectangular SAH-duct can be studied to see its role in performance of the SAH-duct.
- More sophisticated instruments for temperature visualization over the absorber plate and to capture turbulence in the air flow can be used to learn further complexity or details of the heat transfer and fluid flow.
- Higher range of Re can be investigated in SAH-duct domain to see its effect on the thermal-hydraulic performance.
- In further comparative studies, V-shape and arc-shape ribs with staggered ribs in front of the gap provided can be investigated.

REFERENCES

[1] L. Abhay, V. P. Chandramohan, and V. R. K. Raju. Numerical analysis on solar air collector provided with artificial square shaped roughness for indirect type solar dryer. J. Clean. Prod., 190:353–367, 2018.
[2] A. Z. Aghaie, A. B. Rahimi, and A. Akbarzadeh. A general optimized geometry of angled ribs for enhancing the thermo-hydraulic behavior of a solar air heater channel - A Taguchi approach. Renew. Energy, 83:47–54, 2015.
[3] K. R. Aharwal, B. K. Gandhi, and J. S. Saini. Experimental investigation on heat-transfer enhancement due to a gap in an inclined continuous rib arrangement in a rectangular duct of solar air heater. 33:585–596, 2008.
[4] K. R. Aharwal, B. K. Gandhi, and J. S. Saini. International Journal of Heat and Mass Transfer

Heat transfer and friction characteristics of solar air heater ducts having integral inclined discrete ribs on absorber plate. Int. J. Heat Mass Transf., 52(25 -26):5970–5977, 2009.
[5] S. Alfarawi, S. A. Abdel-Moneim, and A. Bodalal. Experimental investigations of heat transfer enhancement from rectangular duct roughened by hybrid ribs. Int. J. Therm. Sci., 118:123–138, 2017.
[6] J. Alvarez, M. Pap, and A. Valencia. Turbulent heat transfer in a channel with bars in tan- dem and in side by side arrangements. Int. J. Numer. Methods Heat Fluid Flow, 10(8):877– 895, 2000.
[7] G. S. Beavers, E. M. Sparrow, and J. R. Lloyd. Low Reynolds number turbulent flow in large aspect ratio rectangular ducts. Trans. ASME, pages 296–299, 1971.
[8] D. Bernoulli. Hydrodynamica, sive De viribusetmotibusfluidorumcommentarii. Opus Academicum, Argentorati, 1738.
[9] J. L. Bhagoria, J. S. Saini, and S. C. Solanki. Heat transfer coefficient and friction factor cor- relations for rectangular solar air heater duct having transverse wedge shaped rib roughness on the absorber plate. Renew. Energy, 25(3):341–369, 2002.
[10] A. K. Bhargava, H. P. Garg, and V. K. Sharma. Theoretical analysis of some configurations of double exposure solar air heaters. Energy, 7(4):377 –388, 1982.
[11] R. W. Bliss Jr. The derivations of several âPlate-efficiency factorsâ useful in the design of flat-plate solar heat collectors. Sol. Energy, 3(4):55–64, 1959.
[12] S. B. Bopche and M. S. Tandale. Effect of artificial roughness on heat transfer and friction factor in a solar air heater. Sol. Energy, 41(1):555–560, 2016.
[13] J. Brouillettet, R.M.E.C., Meyers. Heat transfer and pressure-drop characteristics of inter- nally finned tubes. ASME, Paper No.:1–9, 1947.

[14] B. Y. Cao, M. Chen, and Z. Y. Guo. Effect of surface roughness on gas flow in microchannels by molecular dynamics simulation. Int. J. Eng. Sci., 44(13-14):927–937, 2006.
[15] M. Y. Chang and T. F. Lin. Experimental study of aspect ratio effects on longitudinal vortex flow in mixed convection of air in a horizontal rectangular duct. Int. J. Heat Mass Transf., 41(4-5):719–733, 1998.
[16] S. W. Chang, K. F. Chiang, and C. Y. Lin. Channel aspect ratio effect on thermal per- formance of air-water slug flow through U-bend channels. Int. J. Therm. Sci., 76:11–29, 2014.
[17] H. M. T. Charters and W. W. S. Effect of Thermal Entrance Region on Turbulent Forced- Convective Heat Transfer for an Asymmetrically Heated Rectangular Duct with Uniform Heat Flux. Technical report, University of Melbourne, Victoria 3052, Australia, 1969.
[18] W. W. Charters. Some aspects of flow duct design for solar-air heater applications. Sol. Energy, 13(2):283–288, 1971.
[19] A. Chaube, P. K. Sahoo, and S. C. Solanki. Analysis of heat transfer augmentation and flow characteristics due to rib roughness over absorber plate of a solar air heater. Renew. Energy, 31(3):317–331, 2006.
[20] J. P. Chiou, M. M. El-Wakil, and J. A. Duffie. A slit and expanded aluminum foil matrix solar collector. Sol. Energy, 9(2):73–80, 1965.

