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Evaluation of Solar Air Heater with Different Roughness Design

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Abstract:** Since that the future of our planet is intricately entwined with the future choices of the energy, effective exploitation of non-conventional energy sources is becoming increasingly essential for modern world as fossil fuels are hazardous to environment and cannot sustain supply for long time as they are not renewable. Moreover, demand of energy is increasing rapidly. In this scenario, solar energy is being seen as potential viable resource for ever increasing hunger of the energy for the development of nation and by and large globe. In this seminar work, effort has been made to demonstrate this reality with proof of statistics from reliable sources. Furthermore, numerous new designs of Solar Air Heater are emerging in various aspects, in different number of roughness, in different cost. Extensive review of research done in this field in recent past is covered with their design characteristics and their suitability for specific conditions and applications with respect to their merits and demerits. We concluded from our study that the increase in parameters like flow rate and roughness height up to some desirable values lead to increase in the efficiency of SAH. In present case plate 3 with roughness height of 8mm and flow rate of 0.05kg/s showed the maximum efficiency of 51.6%.

I. INTRODUCTION

A. Energy

Energy is the prime requirement of any system. It serves as backbone to the modern world economic as well as domestic sector. Whether simple or complicated every system requires some form of energy input. With increased urbanization, modernization and particularly industrialization has led to the tremendous consumption of energy particularly exhaustible sources of energy. There are mainly two types of energy sources available that include;

1) Nonrenewable sources
2) Renewable sources

The non-renewable energy sources also called as conventional energy sources are exhaustible which include coal, petroleum, natural gas, etc. These sources once used can't be then reused or recycled, making these energy sources vulnerable to extinction. Hence one can't use such sources limitlessly without giving any due consideration to their availability. Further it has been predicted that these sources may last up to 75-100 years from now on, so alternative to such conventional sources of energy must be tracked. And one such alternative is the renewable sources of energy. The renewable energy sources also known as non-conventional sources are inexhaustible and are replenished naturally, these include solar energy, and hydroelectricity, wind energy, and biomass energy geo thermal energy etc. Around 30 nations have utilized these sources of energy to meet 20% of their energy requirements. To meet the growing energy demand high end researches are being carried out to utilize renewable energy sources more efficiently and to their fullest. Besides being readily available these resources are environment friendly i.e., these are least hazardous to both living and non-living creation. As an example, burning of coal produces lot of environmental and human issues in comparison to hydroelectricity or solar power which causes least damage. With all these advantages and benefits, renewable energy sources have turned out to be Centre of research attraction in recent times.

B. Solar Energy

The energy available due the presence of sun in the universe corresponds to the solar energy'. Solar energy accounts for the major share of world energy, approximately 1575-49837 EJ of solar energy are intercepted by earth annually which is far greater than the whole world annual consumption [559.8EJ]. Solar energy not only serves our energy demands but also proves to be very vital from environmental aspect, it provides pollution less energy at least cost. Further it keeps a check on fossil fuel price. It forms the promising alternative to the present energy demand and conventional sources of energy. The solar energy intercepted on earth is either in form of diffuse radiations or in the form of direct radiations. Diffuse radiations reach to the surface of earth after distraction or scattering caused due to presence of obstacles like dust particles, water vapors, and / or air molecules during their travel towards the earth.

While as direct radiations don't suffer from any such phenomenon and are received on the surface of earth without any distraction. Apart from this about 30% of radiant solar energy is reflected back, while rest of energy is absorbed by clouds, Oceans, Mountains, plants etc. The amount of solar energy that can be utilized by humans is limited by the factors like geography, time, cloud cover, and area of land available. The geography of a location decides its position or distances from the sun or equator, hence the amount of incoming solar radiations. Similarly, time of year/day or season also affects the availability of solar energy. Higher cloud cover reduces the number of incoming radiations. While availability of land constitutes the prime factor for collection of solar energy.
One of the major limitations of solar energy is its availability varies with time as such it is available during day but not during night. Further seasonal and weather conditions also effect the utilization of solar energy. Thus, giving rise to the concept of energy storage. Solar energy is utilized mostly by storing or collecting it in the form of thermal energy. Thus, making efficient storage and collection process of vital importance. Out of various collecting and storage systems available, Solar Air Heater or Collector is simplest and easy to use and construct.
The various applications where solar energy is used include heating of space, water heating, solar power plants, crop drying, furnaces, pumping, and cooking etc.

C. Solar Collectors

Solar collector is a device to capture and convert solar energy into thermal power by an absorbing medium, thereby utilizing it to heat the air. The ambient air is not able to absorb directly the sufficient amount of solar energy, so an intermediate technology is required. This intermediate technology is Solar Air Heater. The heated air can be put to multiple uses depending upon the utility, its applications may include building ventilation, drying crops, seasoning wood and for general heating purposes. Of all available solar technologies or solar systems Solar Air Heater is most economical and easy. The basic principle of solar air heater includes absorption of solar radiations by the application of absorbing medium and absorbing plate and convection of thermal energy to the working medium [air]. Then heated or warm air can be put to use according to the utility. Generally, two types of solar collectors are used to convert solar energy into thermal energy, these include

1) *Concentrating type Solar Collector*

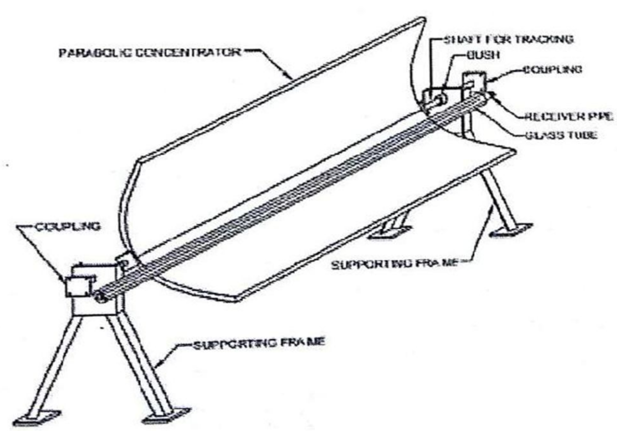

Figure 1.1 Concentrating solar collector.

As shown in fig.1.1 the concentrating solar collectors are designed to absorb maximum amount of solar radiations incident on it. These collectors make use of certain reflective as well as refractive surfaces to concentrate the large number of solar radiations on smaller area, thereby raising temperature. Such collectors find their use in industrial applications and power generation.

2) *Flat Plate Collector:* The flat plate solar collectors provide economical and easy way to utilize the solar energy with aid of absorber plate, glass cover and case to hold all the accessories as single unit. The solar energy is absorbed by dull black colored absorber plate after refraction through glass cover, i.e., energy from sun is transformed into thermal energy. This converted energy is then used to heat the working medium. Depending upon the working medium flat plate collectors are classified into two categories.

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a) Liquid Flat Plate Collector

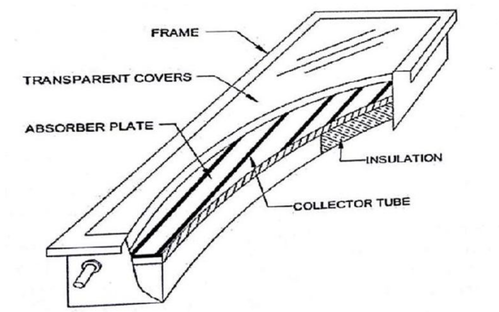

Figure 1. 2 Liquid heating solar heater.

It's a flat plate collector where medium to transfer heat is water. Here temperature of water is elevated by solar energy which can be further used for other energy-based requirements. The conventional liquid heating collector consists of a glass cover with an absorber plate placed in an iron frame with insulation on three sides and upper face facing sun is left insulation free.

b) Air Heating Flat Plate Collector: A traditional air heating collector is simple in design similar to the liquid flat plate collector; except that air is used as an energy transfer medium instead of liquid i.e., energy from sun is transferred to air via absorber plate. That's air heater converts solar energy into thermal energy by following simple thermodynamic principles that include absorption of solar energy by absorber plate, then convection of thermal energy from plate to air. Solar air heater is the most cost-effective device to hitch solar energy. A simple solar air heater entails of an iron frame, flat absorber plate, glass cover, inlet and outlet for air. An absorber plate usually colored black to absorb more solar radiations is placed in an iron frame covered with insulation on 3 sides while leaving the upper face covered with glass without any insulation cover, to let it absorb incident solar radiations. The heat from absorber plate is then convected to air flowing in the cavity between plate and glass cover where from heated air can be utilized according to the need or requirement. This forms the basic working of simple solar air heater.

D. Types Of Solar Air Heater

Solar air heaters are roughly classified into two categories:

1) Non porous solar air heater
2) Porous solar air heater

In a Non-porous solar air heater air streams over the absorber plate, i.e., most of heat is confined between the absorber plate and the glass cover, therefore the chances of heat loss are higher.in this type of solar air heater hot air flows over the absorber plate and much of heat is lost to the surroundings of the plate. This obviously leads to the decreased efficiency of the nonporous plate. While as in porous air heater solar radiations penetrate up to a greater depth into the system thereby decreasing the loss due to reflection and higher pressure drop. In many cases it may consist of slit and the expanded metal, overlapped glass plate absorber and transpired honey comb thus forming a matrix through which air passes. Of course, the choice of the matrix material selected will affect the efficiency of the system.

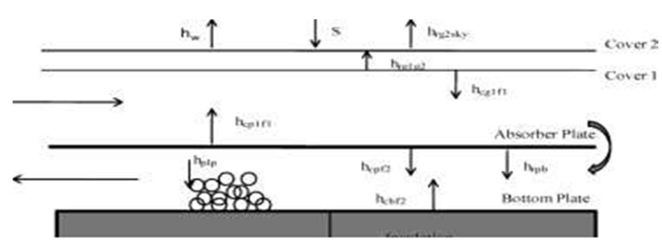

Figure 1.3 Non porous solar air heater.

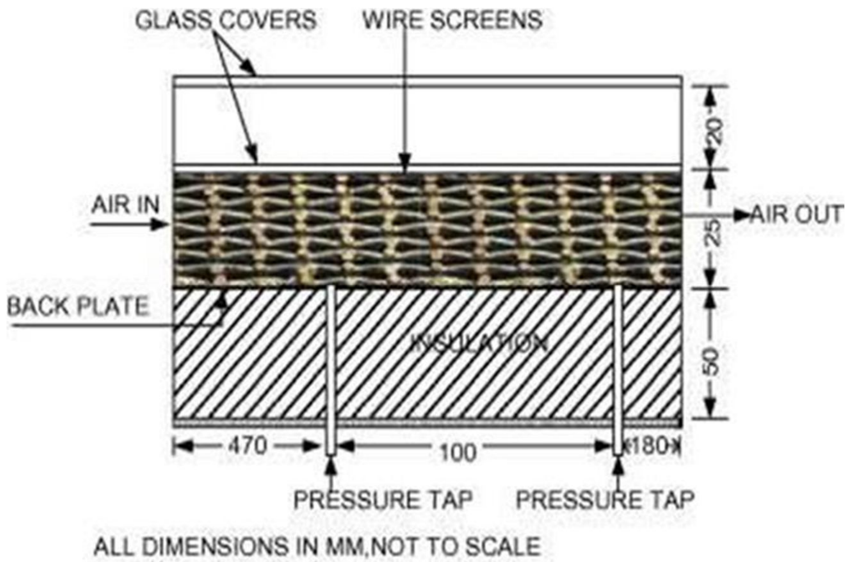

Figure 1.4 Porous solar air heater

Besides such simplicity in design and manufacture of solar air heater, yet there are factors that need some serious considerations. One such factor is, solar air heater is very less efficient on account of many reasons. One of the prime reasons for low efficiency of solar air heater is, lower convective heat transfer coefficient of air which results in poor convection of heat from plate to air. Further absorber plate gets heated to much higher temperature than what can be convected to the air, hence the most of the heat absorbed by plate is lost to environment. Thus, to upturn the efficiency, solar air heater has turned out to be center for recent research. Many ways are predicted to increase the efficiency these include;

a) Boost of heat transfer coefficient
b) Reduction on account of thermal losses
c) By increasing the amount of solar radiations incident on the solar air heater

Creation of boundary layer on heat transferring surface is main reason for lower heat transfer coefficient amid absorber plate and the flowing air. Thus, in order to increase the efficiency of SAH, its heat transfer coefficient has to be increased. There exist two ways to raise the heat transfer coefficient; firstly, effective heat transfer area has to be increased using extended fins etc., second method to improve heat transfer coefficient is to make available interruptions over heat transfer surface i.e., on absorber plate. The first method does not have any effect on convective heat transfer coefficient while as the second method increases the convective heat transfer coefficient. The interruptions provided on the heat transfer surface disturb the sub laminar boundary layer formed on to the surface, thus enhancing the convective heat transfer. The most effective method to increase the thermal efficiency of solar air heater with minimum or limited frictional losses is to provide the artificial roughness or interruptions on the heat transfer surface. While providing the turbulence promoters, it’s necessary to keep frictional resistance in consideration. Larger interruptions may imply higher pumping requirements. To keep frictional losses in check turbulence must be provided very close to the absorber plate i.e., in the sub laminar layer where the actual heat transfer takes place, also by keeping the height of roughness element small as compared to the duct dimensions help to serve the purpose. There exist various methods to provide the turbulence or roughness over heat transfer surface. These methods include providing two or three-dimensional ribs, grooves, dimples, scales, protrusions, compounding ribs, combining ribs and grooves, fixing circular wires, using metal mesh-shaped tabulators etc. Further roughness is also provided by orienting the ribs in different directions i.e., transversely, obliquely or orienting Y-shaped ribs either upstream or downstream. The different parameters used to define the roughness element over absorber plate include height of roughness element, pitch of roughness element, angle of attack, shape of roughness element, aspect ratio, etc. A brief explanation regarding these parameters is given below.

- *Relative Roughness Pitch (p/e):* It is termed as the fraction of distance between the two successive ribs to the height of ribs.
- *Relative Roughness Height (e/Dh):* Ratio of height of roughness to the equivalent diameter of air passage.
- *Angle of Attack (α):* It is termed as the angle at which air strikes the rib in SAH.

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II. LITERATURE REVIEW

The provision of using artificial roughness to enhance the convective heat transfer in solar air heater till date has proved to be most promising method. The main motive to use artificial roughness is to make flow close to absorber plate turbulent while giving due consideration to height of roughness. Usually, the height of roughness is kept small as compared to the duct dimensions.

A. Effect of rib Height and Pitch

Prasad and Saini [31] studied the outcome of various parameters like height of rib, roughness pitch and roughness height on laminar sub layer and flow pattern as clear in the figure below. They concluded that the maximum heat transfer was detected in close proximity of attachment point. They noticed that reattachment of sub laminar layer at rib could not occur for the relative roughness pitch ratio up to 8 and they also observed the decrease in heat transfer started beyond relative roughness value of 10.

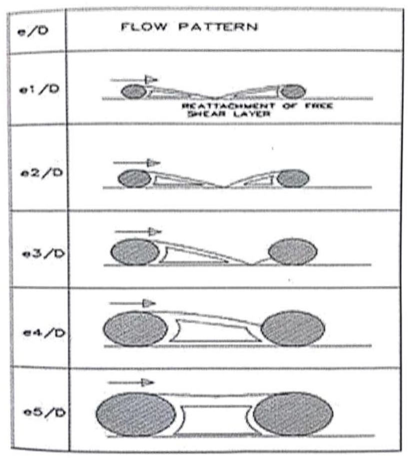

Figure 2.1 Effect of rib roughness height on flow pattern.

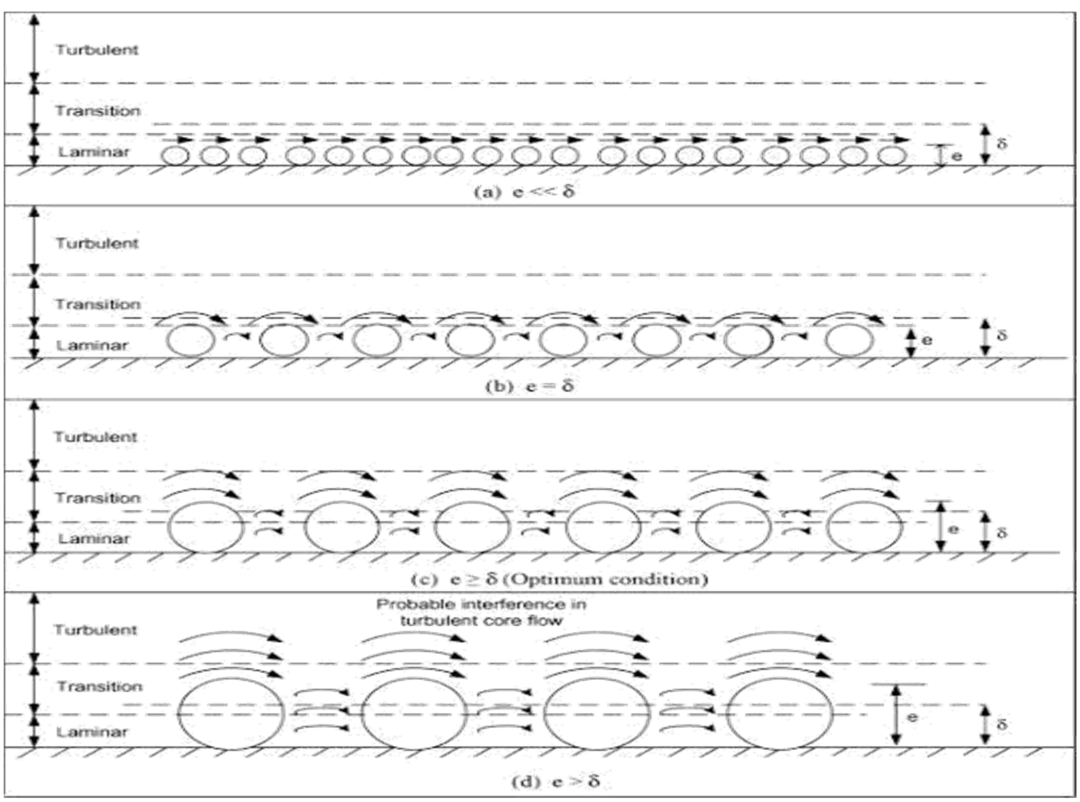

Figure 2.2 Effect of rib height on laminar sub layer.

B. Literature Review

Various research studies were conducted to note the aftereffects of roughness on the thermal efficiency of solar air heaters.

Early in 1950 Nikuradase [1] examined the effect on friction factor and velocity distribution using pipes that were roughened by sand attacking. H.M. Yeh, and T.T. Lin studied the effect on thermal efficiency of the solar air heater (SAH) by increasing the heat transfer area by addition of fins to the absorber plate [1,2] and concluded that efficiency amplified up to 15%. Sheeriff and Gurley [3] determined by using channels and pipes with roughness value of appropriate Reynolds number was 35.

Webb *et al.* [4] created turbulent flow in pipes, using repetitive ribs and calculated its effect on friction factor and heat transfer characteristics. Done and Meyer [5] investigated characteristics of the heat transfer while using some cavities and ribs as roughness. Tanasawa *et al.* [6] used three types of roughness components i.e. perforated plate type, fence type and silted type, and resolved that the perforated roughness element was competent in enhancing the thermal efficiency.

Han and Park [7] used rib turbulators as roughness element and concluded inclined ribs are more proficient in heat transfer than transverse ribs as these inclined ribs serve the purpose of breaking the sub layer viscous flow as well as creating the tributary flow. These studies also confirmed that the narrow aspect ratio had prominent and desirable effect on heat transfer. Convective heat transfer coefficient between absorber plate and air in a flat plate solar air heater can be enhanced by providing the absorber plate with artificial roughness. Artificial roughness is basically a passive heat transfer enhancement technique by which thermo hydraulic performance of solar air heater can be improved. The artificial surface roughness has been used extensively for the enhancement of forced convective heat transfer coefficient which further requires flow at the heat transferring surface to be turbulent. However, energy for creating such turbulence has to come from fan or blower and the excessive power is desirable. Therefore, it is required that the turbulence is created very close to the heat transferring surface so that the power required may be lessened. This can be done by keeping the height of the surface roughness elements to be small in comparison with the duct dimensions. Other factors responsible for these enhancements are shape of surface roughness elements, relative roughness height, angle of attack and many other also. Some of the factors are already discussed above.

Lau *et al [*8] used discrete ribs with angle of attack 90° as roughness and confirmed 10 to 15% growth in heat transfer. Further inclined separate ribs resulted in 10% to 20% surge in heat transfer.

Ichimiya *et al*. [10] used spongy type roughness on absorber plate and concluded that this type of roughness delivered greater thermal enactment as compared to the solid rib type roughness.

Han and Zhang [11] used parallel and V-shaped staggered discrete ribs on absorber plate and concluded these discrete ribs at an angle of 60° resulted in surge in heat transfer.

Gupta *et al.* [12] conceded out the new investigations by using inclined circular wire ribs as artificial roughness agent on absorber plate and concluded supreme heat transfer coefficient and friction factor were found when angle between air flow and rib was 60˚-70˚, with roughness height of 0.023 and at Reynolds number around 14000.

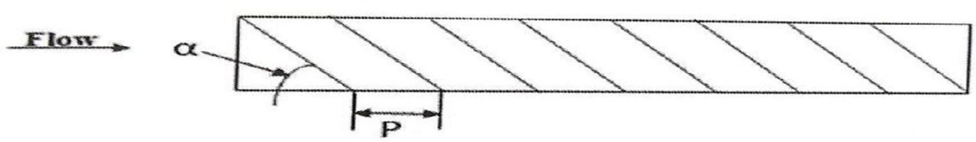

Figure 2.3 Angled circular rib used by Gupta *et al.*

Jaurkere *et al.* [15] used grooved rib roughness with Reynolds number 3000-21000, roughness height [relative] 0.0181-0.0363, relative roughness pitch 4.5-10 and groove position to pitch ratio 0.3-0.7. It was concluded that Nusselt number improved up to 2.75 times and friction factor also improved up to 3.61 times as compared to the to the smooth duct.

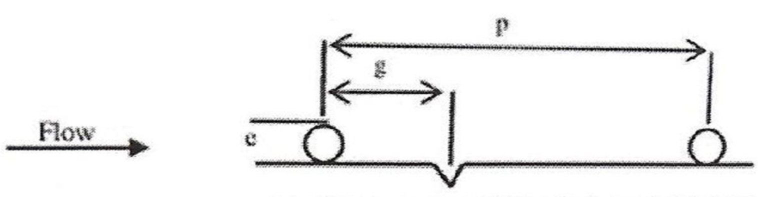

Figure 2.4 Roughness used by Jaurkere *et al*

Saini and Verma [16] utilized pit shaped roughness and probed its consequence on SAH, by taking the Reynolds number in between 2000 -12000, relative roughness pitch 8-12 and relative roughness height 0.18-0. 037. They concluded upturn in both Nusselt number and friction factor.

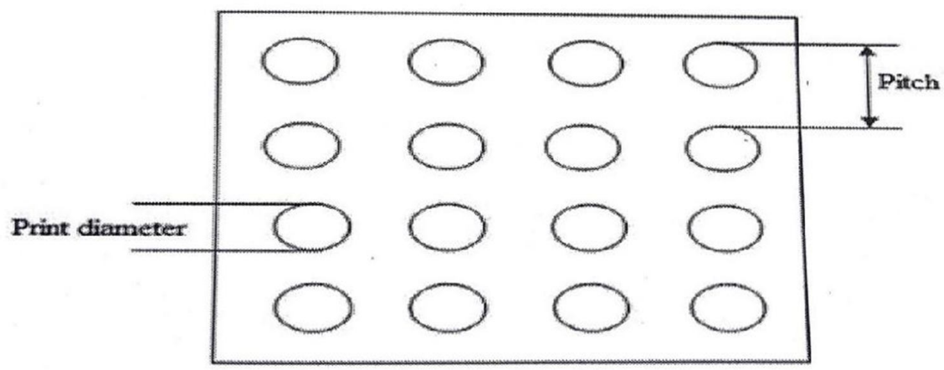

Figure 2.5 Roughness element used by Saini and Verma.

Layak *et al.* [17] used recurring transverse compound rib-groove arrangement as roughness on absorber plate and calculated the friction and heat transfer characteristics of solar air heater. They kept the parameters like relative roughness height and relative roughness pitch fixed 0.030 and 10 respectively, with four different groove positions 0.3, 0.4, 0.5 and 0.6 and reported groove position of 0.4 was best in terms of Nusselt number and friction factor enhancement.

Karmare and Tikekar [18] investigated the effect of using metal grit rib as artificial roughness on absorber plate on heat transfer and friction characteristics of solar air heater. The various parameters used include Reynolds number ranging from 4000-17000, relative roughness height 0.035-0.044, relative roughness pitch in between 12.5-36, and relative grit size 1-1.72 and it was concluded optimum values of parameters were found as relative grit size 1.72, relative roughness height 0.044, and relative roughness pitch as 17.5. The maximum value of Nusselt number and friction factor obtained was 187% and 213% respectively of initial value.

Saini and Saini [19] carried out experimental investigations with arc shaped ribs on absorber surface. The parameters covered included Reynolds number ranging from 2000-17000, relative roughness height in between 0.0213-0.0422, relative arc angle ranging from 0.333-0.6666 radians. It was concluded that relative roughness height of 0.0422 with relative angle of 0,333 resulted in maximum improvement of Nu number and friction factor.

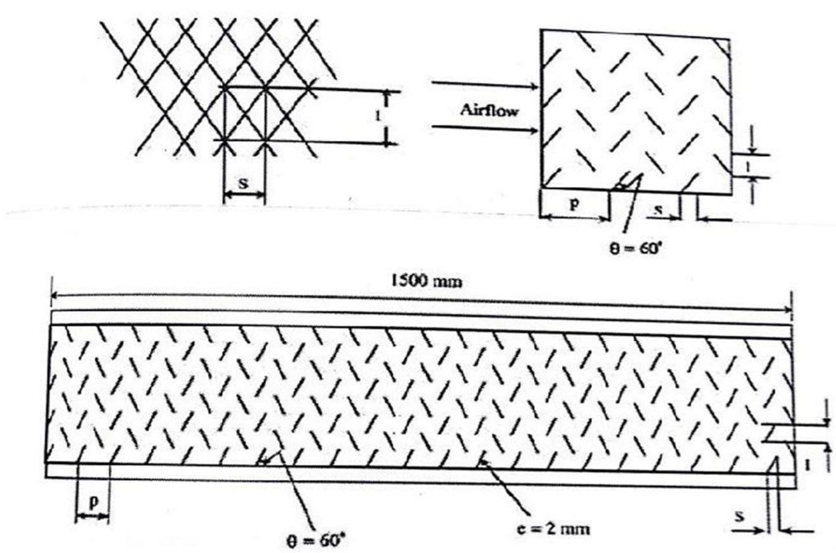

Figure 2. 6 Metal grit ribs used by Karmare and Tikekar

Karwa [20] besides taking regular parameters of solar air heater into consideration he also took aspect ratio in consideration (W/H). The various parameters involved were Reynolds number 2800-15000, aspect ratio 7.19-7.75, roughness height 0.0467-0.050 and roughness pitch fixed at 10. The results thus obtained showed a lot of improvement, increase in heat transfer coefficient was 1.999 times with respect to simple plate while increase in friction factor was 2.68-2.94 times.

Singh *et al.* [21] used uniform separated V-inverted ribs as artificial roughness. They kept Reynolds number 3000-15000, relative gap width 0.21-0.5, relative gap position 0.21-0.810, relative roughness height pitch and angle of attack as 0.01-0.04, 3-11, 30˚-75˚ correspondingly. The results obtained were, Nusselt number increased by 3.11 times as related to flat plate while as friction factor improved up to 3.04 times.

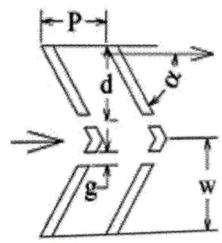

Figure 2. 7 Profile utilized by Singh *et al.*

Bopche and Tandale [23] used U-shaped roughness element on absorber plate of solar air heater and investigated its effect on thermal efficiency of solar air heater under range of parameters. Reynolds number 1800-3800, relative roughness height 0.0186-0.03986, relative roughness pitch of 6.67-57.14, arc angle 90 was the parameters used. The results followed were 2.388 and 2.5times increase in Nusselt number and friction factor respectively.

Bushan and Singh [24] used artificial roughness as shown in figure 2.8 below, and studied its effect on heat transfer and friction factor. The results obtained showed 3.8 times increase in Nusselt number and 2.2 times increase in friction factor respectively as compared to smooth duct.

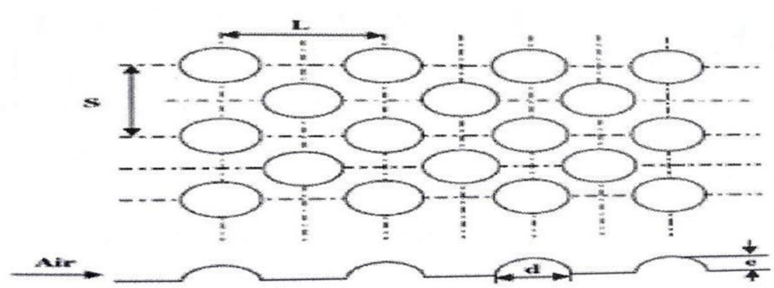

Figure 2. 8 Profile used by Bashan and Singh.

Varun *et al.* [25] they investigated the effect of using combination of traverse and inclined ribs as source of artificial roughness and concluded relative roughness pitch of 8 was the most favorable case for optimum performance of solar air heater.

The range of parameters included were Reynolds number 2000-14000, relative roughness pitch 3-8, relative roughness height 0.30 and aspect ratio was 10.

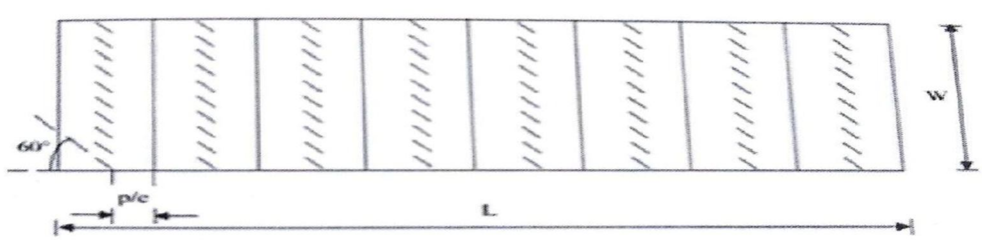

Figure 2. 9 Roughness used by Varun et al

Saho and Bhagoria [26] utilized broken ribs on rectangular duct as a source of turbulence in solar air heater. They studied effect of 90 broken ribs on the heat transfer and friction coefficient with Reynolds number ranging from 3000-12000, aspect ratio of 8 and pitch value 10=30. The roughness used resulted increase in heat transfer coefficient by 1.25-1.4 times compared to smooth plate.

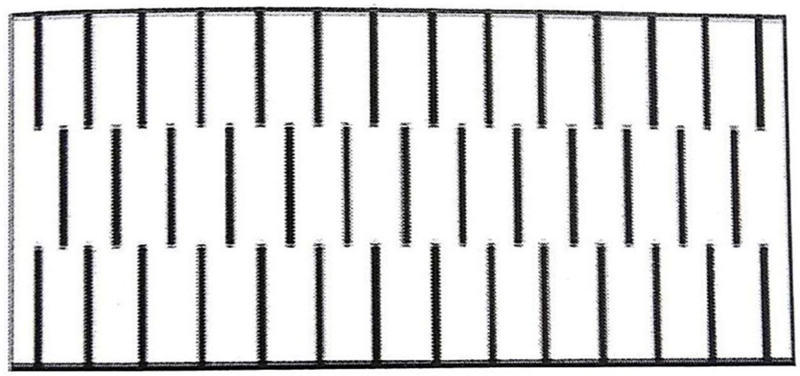

Figure 2.10 Roughness used by Saho and Bhagoria

Indrajit *et al.* [32] studied solar air heater with and without inserting longitudinal fins and indicated that the performance of the SAH with fins is significantly improved when the mass flow rates is 0.038 kg/s. Omojaro and Aldabbagh [33] (2010) studied single and double pass finned plate SAH with a steel wire mesh and concluded that, the thermal efficiency increases as the air mass flow rate increase. Alta *et al*. [34] (2010) they designed and tested three different SAHs without fins; with fins and double glass cover and with fins and single glass cover. They indicated that the double glass finned plate collector is the most efficient.

Mettawee and Assassa [35] (2006) studied the effect of using paraffin wax on the performance of the SAH. They concluded that the use of paraffin wax improves the performance of the SAH. H.E. Faith [36] (2011) analytically analyzed the performance of SAH using a set of staggered copper tubes as absorber filled with the PCM. He concluded that average daily efficiency is 63.4% compared with 38.7% for the conventional flat plate collector. M.M. Alkilani *et al* [37] they developed indoor SAH using a set of copper tubes as an absorber filled with the PCM with 0.5% mass fraction of aluminum powder to enhance the thermal conductivity of the PCM. They found that the utilization of the enhanced PCM keeps the system in operation for 8 h after sunset when m = 0.05 kg/s.

Mohit kumar.G *et al.* [38] studied through an experiment the development in thermal and hydraulic achievement of a dual pass solar air heater coarsened with myriads of C shape ribs. They obtained a Nusselt number of 415 for a corresponding P/e value of 24, α as 90^0 and Re value of 15000, which yielded a friction factor of 0.031 and a thermo hydraulic performance parameter of 3.48. They concluded that double flow solar air heater is extra competent than that of single flow arrangement, and multiple C shape geometry on two sides of absorber resulted in higher heat transfer to that of dispersed C shape roughness.

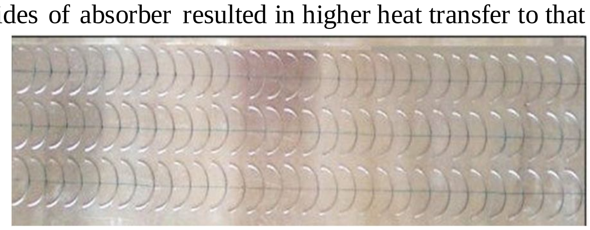

Fig.2.11. Multiple C shaped roughened absorber

The consequences of artificial roughened absorber plate with discontinuous V down ribs on the exergetic effectiveness of a solar air heater were examined by Sukhmeet Singh *et al.* [39]. They observed that for a Reynolds number of less than 18000, discrete V down ribs are suitable and for a Reynolds number of greater than 18000 plain prevalent solar air heater is convenient. They observed a maximum exertic efficiency for $\Delta T / I$ greater than 0.0175Km^2/W at a P/e value of 8, relative gap position of 0.65, α as 60◦, relative gap width of 1.0.

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A model was designed by Bashariaa *et al.* [40] to scrutinize the potency improvement of a solar air heater and cost benefit ratio using dual stream vogue as flat plate collector with permeable media and V furrow armament. They observed that the ability of solar air heater proving double pass double duct V gouge absorber increased by 4% to 15% as that of double pass flat plate collector. The outlet temperature was observed to increase from 2℃ to 8℃. They concluded that solar air heater thermal efficiency is mainly affected as follows: Increase in discharge of air results in an increase in effectiveness of collector, decrease in outlet temperature, and a rise in pressure drop and increment is cost of solar energy. Decrease in flow depth results in an rise in collector thermal efficiency, increase in outlet temperature, and a rise in pressure drop which drives to an increment in cost of solar energy due to increase in pumping expand. A growth in collector length gives an outcome of a decrease in thermal competence and a growth in outlet temperature and pressure drop. A visible rise in collector thermal efficiency, outlet temperature and pressure drop was perceived by using a porous media.

The way heat transfer and fluid flow attributes of a rectangular duct of an absorber plate with V molded ribs are affected were empirically researched by Ebrahim Momin *et al.* [41]. The research was done in the Reynolds number compass of 2500 to 18000, (e/D_h) as 0.02 – 0.034, α as 30° – 90° and a constant relative roughness pitch of 10. Owing to the flow segregations, reattachments and subordinate flows resulting because of roughness a substantial improvement in Convective heat transfer and a decrease in friction factor was observed. At higher values of e/D Nusselt number improves relatively low as that of friction factor since reattachments hardly occur. Nusselt number and friction factor were found to increase by a multiple of 2.30 and 2.83 reciprocally to that of a plain duct at α as 60^0. At a e/D value of 0.034 and α as 60^0, V cast ribs improve the value Nu by 1.14 and 2.30 times to that of oblique ribs and flat plate at a Reynolds number value of 17034.

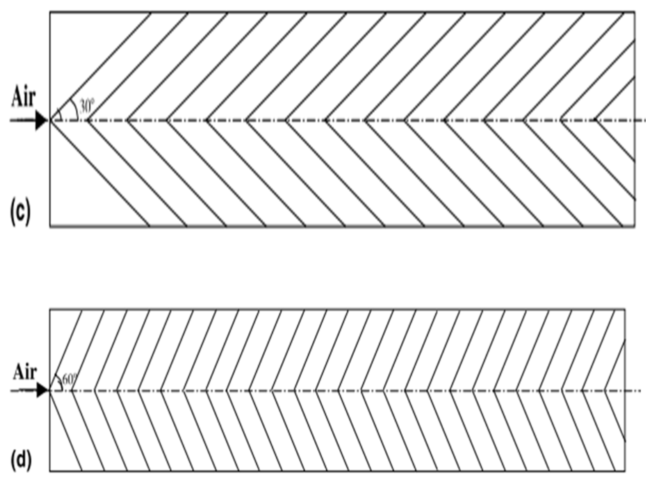

Fig.2.12 V shaped ribs

Vikram Bharath *et al.* [42] premeditated the influence of arc formed round shaped wires as turbulators in a SAH. Within the Reynolds number range of 3000 to 8000, e/D_h value of 0.034,duct aspect ratio (W/B) is kept 5 and relative roughness pitch (P/e) of 10, 20, 30 and 40 is considered. The study revealed that Nusselt number, friction factor and efficiency index is maximum for double arc shaped roughness, followed by single arc roughness and minimal for plain absorber plate.

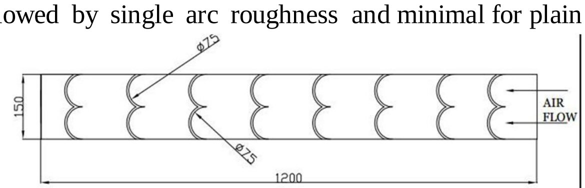

Fig.2.13. Double arc wire roughness geometry

Avdhesh Sharma *et al.* [43] experimentally explored the influence of raggedness between collector plate and air of a double pass SAH. Ribs are attached to solar collector at four different angles of range 30^0 to 75^0. With Reynolds number of range 4900 to 12000, e/D of range 0.022 to 0.044. The study revealed that heat transfer and friction factor attains a peak value at the e/D_h value of 0.044.

Sumit Joshi *et al.* [44] experimentally investigated the result of synthetic ruggedness provided by a combination of broken arc and staggered ribs on the performance of the collector. They observed that highest thermo hydraulic performance occurs in combination of broken arc and staggered ribs. Thermo hydraulic performance in highest and found to be 2.09 to 2.46 at a gap position (relative) of 0.6, P/e value of 10, and Reynolds number of range 3000 to 12000. A 33% increase in efficiency was observed for a union of broken arc and disconnected ribs in contrast to that of regular arc shaped ribs.

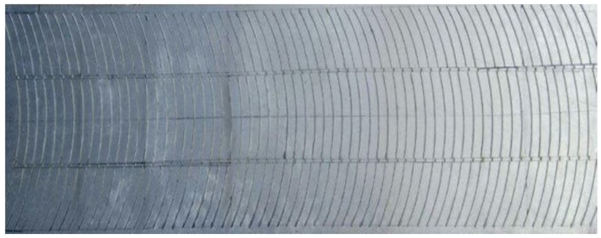

Fig.2.14. Broken arc and staggered ribs

Rajesh Kumar *et al.* [45] premeditated the outcome of using herringbone corrugated fins engaged to below of a collector plate on the production of a SAH. They considered the effect of discharge of air, fin pitch, fin spacing ratio, flow cross section aspect ratio and solar intensity and observed that efficacy of SAH increased from 36.2% to 56.6%. Corresponding to the values of fin pitch of 2.5 cm and fixed mass flow rate of 0.026 Kg/Sec. Herringbone corrugated fins result in better mixing of fluids and amplify the heat exchange rate due to arise in heat exchange area provided by fins. They found that collector efficiency increased by 18% when mass flow rate of air is increased from 0.016 Kg/Sec to 0.033 Kg/Sec at air temperature of 15 ^{0}C corresponding to fin pitch of 2.5 cm, mass flow rate of 0.01 Kg/Sec to 0.08 Kg/Sec. The thermo hydraulic efficiency attains a maximum value of 68.965% at 0.05 Kg/Sec discharge of air and due to pressure drop beyond mass flow rate of 0.05 Kg/Sec thermo hydraulic efficiency decreases to 64.4% at air flow rate of 0.08 Kg/Sec due to increase in heat transfer.. On reducing fin pitch from 2.5cm to 1cm, thermal efficiency increases from 66.85 % to 71.40 %.

Mukesh Kumar, Sahu *et al.* [46] investigated the improvement in thermohydraulic execution of a SAH with arc shaped string coarseness on the collector plate. They observed maximum thermal and effective efficiency values of 79.84% and 75.24% individually complementary to a rib height to duct hydraulic diameter ratio of 0.0422 a flow attack angle of 0.3333. They compared the results obtained to that of a customary solar air heater running under related status and observed an appreciable increase in efficiency by using an absorber plate possessing round wire rib irregularities in the cast of arc mold. They concluded that the model designed was optimal and more practical for coarsened solar air heater since, it contemplates the confines of pumping power consumption and thermal energy earn. It was observed that effectiveness raises in the Reynolds number range of 15000, after which it starts decreasing. Therefore, it is convenient to operate solar air heaters having arc mold wire coarsened absorber plate at lower Reynolds number (Re less than 15000).

N.K. Pandey *et al.* [47] practically studied the effect of using the numerous arcs with gaps as on collector plate of a SAH. An apex increment in Nu and friction factor was ascertained to be 5.85 to 4.96 separately. They observed that peak enrichment for Nusselt number comes out at Re value of 2100, gap width of 1, relative gap distance of 0.65 and relative roughness width of 5.

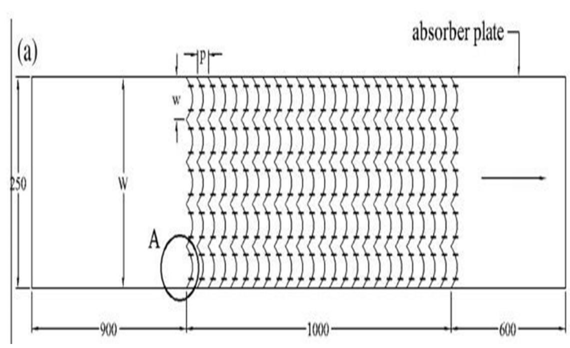

Fig.2.15. Multiple arcs with gaps on absorber plate

Different researchers used different roughness elements as presented below in table 2.1.

Table 2.1: Researcher and the roughness used.

S. No	Researcher name	Roughness used
01	Webb et al.	Rectangular repeated ribs
02	Done and Meyer.	Cavities and ribs
03	Tana sawa et al.	Perforated type
04	Han and Park.	Rib turbulators
05	Ichimiya et al.	Porous type
06	Han and Zhang.	V shaped staggered discrete rib
07	Gupta et al.	Inclined Circular wire rib

C. *Gap Finding*

From literature review we conclude that a lot of experimental and theoretical work has been done with artificial roughness plate to improve efficiency of SAH. But very few studies are available that are focused on the testing of SAH with different roughness designs under actual environmental conditions. Our study is thus focused on the effect of different roughness design on the performance of actual SAH.

D. *Objectives*

1) Fabrication of solar air heater
2) Thermal analysis of fabricated solar air heater using V-shaped wire roughness while keeping the roughness pitch fixed and varying the roughness height and air flow rate.
3) To predict the most useful roughness design to improve efficiency of solar air heater.

III. EXPERIMENTAL INVESTIGATIONS

A. *Experimental Set Up*

The experimental set up consists of a wooden frame of 880mm × 880mm × 25mm dimensions with an absorber plate 822mm × 822mm × 1mm attached on it. The whole assembly is placed inside an iron frame surrounded by rock wool insulation on all sides except the top face. The upper face of absorber plate is covered with a 6mm glass cover leaving 24mm gap between glass cover and the absorber plate. The absorber plate is 1mm thick aluminum sheet colored black on front face. An inlet 30mm diameter is provided on the bottom of set up to let the ambient air or air at lower temperature to enter solar air heater. Similarly, an outlet of 30mm diameter is provided at the right-hand side of solar air heater near the top end to let the hot air to come out.

Figure 3.1 Pictorial view of iron sheet, insulation and wooden block without absorber plate.

In order to reduce the heat loss from the solar air heater, it's well-insulated on all sides with insulating material (rock wool) between wooden block and the outer iron frame, except on top side which is left open to let the solar radiations fall on absorber plate.

Figure 3. 2 Solar air heaters with glass cover and absorber plate.

The wooden block or frame used to hold the absorber plate and provide the necessary passage for air to flow was selected because of easy availability, cost factor and insulating property. Further to reduce the leakage of air from the duct glass cover was sealed to the frame using glass clay.

B. Instrumentation Used

Various types of instruments were used during the course of work that includes air blower, thermocouple, anemometer, digital vernier caliper, data logger, electric socket and solarimeter.

1) *Air Blower:* An air blower of 800 watt is used to supply the ambient air to the solar air heater. The flow of air blower is regulated with the help of flow knob that allows maintaining different flow rates as desired during the experiment.

Figure 3. 3 Air Blower.

2) *Thermocouple:* For measuring the temperature at various locations including inlet air temperature, outlet air temperature and temperature of plate different thermocouples are used, that are in turn connected to a data logger that digitally indicates the required temperature.

Figure 3. 4 Thermocouple.

Figure 3. 5 Data loggers.

3) *Solarimeter:* This is an instrument required to measure solar radiations or intensity. It is used to measure the solar radiations during the experiment days.

Figure 3. 6 Modern solarimeter.

4) *Anemometer and Vernier Caliper:* To measure the velocity of air anemometer is used while as vernier caliper is used to measure the various diameters involved.

Figure 3. 7 Anemometer

Vernier caliper shown in figure 3.8 is used to measure the required dimensions involved during the experiment. The necessary diameters used are also measured by using the vernier caliper.

Figure 3. 8 Vernier calipers

5) *Absorber Plate:* The absorber plate used is an aluminum sheet of 1mm thickness and 87mm ×87 mm dimensions. The thermal conductivity of aluminum being 237 W/ (mk). The artificial roughness is also made from 4mm aluminum wire with same properties.

Figure 3. 9 Absorber plate.

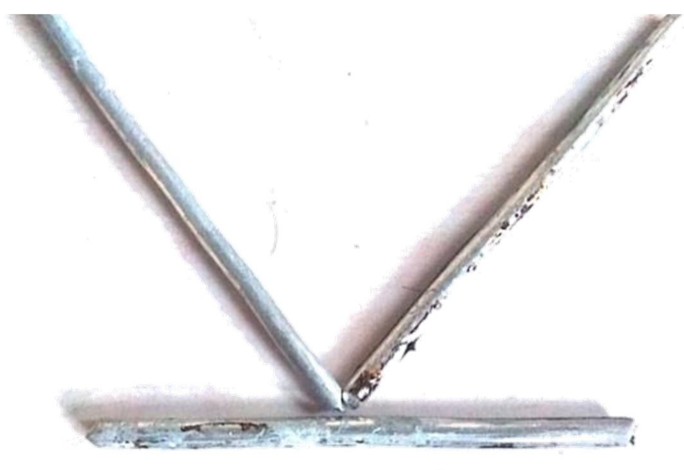

Figure 3. 10 Roughness rib.

C. Experimental Procedure

All the data collected during the investigations was according to the ASHRAE standards of testing the solar air heaters. Being an actual solar air heater data was recorded under natural solar environment i.e., sun was used as source of energy. Investigations were carried out in April and May 2020. Prior to start of investigations set up was kept under solar radiations for 6 hours to remove any sort of moisture and to reach a steady state. Different parameters recorded during investigation were as under;

1) Inlet and outlet temperature
2) Intensity of solar radiations
3) Temperature of absorber plate
4) Flow rate

In the very beginning of the experiment the whole set up was placed outside under clear sky so that sunlight is directly incident on the absorber plate for maximum time. After giving due consideration to the position of solar air heater, the solar air heater was set at 45˚ with the horizontal. The exact position was latitude N 32˚ 56'20, longitude 74˚ 57'17or 31˚2' NW. An air blower was connected to inlet in order to supply the air at faster rate. While three thermocouples where set at their required positions [inlet, outlet, plate] to measure the temperature. Four absorber plates with four types of roughness designs were investigated at three different flow rates each for three days. While the relative roughness pitch was kept fixed, the relative roughness was varied uniformly from 4 mm to 16 mm.

The readings so obtained were utilized to draw some valuable conclusions and results. On the basis of which efficient solar air heater design was predicted. The type of roughness used was 4mm aluminum wire bent at an angle of 85.108˚ into a V-shape with 90mm length. The angle of attack was almost 45˚, i.e., air flow was directed at an angle of 45˚.

Figure 3. 11 Roughness used.

IV. RESULTS AND DISCUSSION

The main aim behind the investigations was to determine the effect of artificial roughness used on the various parameters of solar air heater and to decide which configuration was most beneficial and feasible to utilize the solar energy most efficiently. The investigations are carried out for four absorber plates with different roughness height. Further each plate has been subjected to three different flow rates one day for each flow rate.

A. Absorber Plate 1

The absorber plate 1 is a simple aluminum sheet painted black to enhance the absorption of solar radiations. The absorber plate 1 is tested without any artificial roughness. On day first, low air flow rate is used to supply or pass air over the absorber plate, where process of absorption and convection takes place and incoming air is heated and passed over to outlet, and the temperature is recorded on the data logger after regular intervals of time for eight hours. The results obtained after three-day long analysis are represented in graphical representation below:

Figure 4. 1 Absorber Plate 1.

1) *Low flow rate [0.033kg/s]:* As obvious from the above graph the temperature varies continuously with the time, clear increase in outlet temperature is observed till 13:00 hours there after decreasing trend in temperature is seen. Rise in outlet temperature up to 52˚C at flow rate of 0.033kg/s is observed reason being action of solar air heater as plate is smooth without any artificial roughness. Average inlet temperature being 21.5˚C while outlet average temperature is observed to be 37 ˚C.

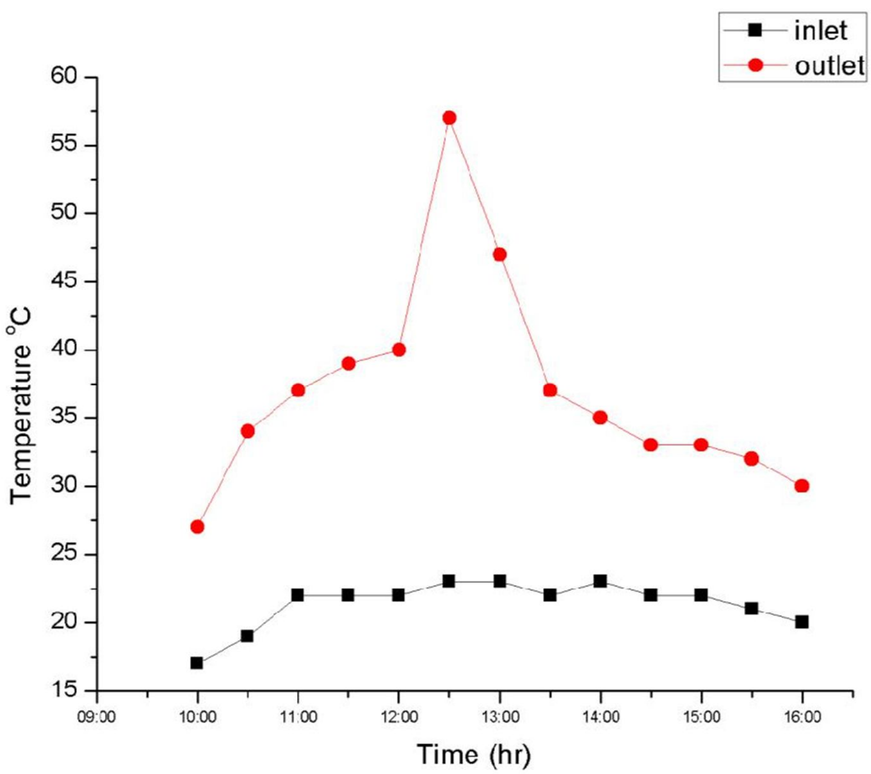

Figure 4. 2 Variation of inlet and outlet temperature wit time plate 1 at LFR.

2) *Medium flow [0.0414kg/s]:* Similarly, on day 2 same absorber plates are investigated at medium flow rate for about 12 hours and results are recorded and interpreted in the form of graph fig.4.3. Again, outlet temperature increases with time with average outlet temperature being 44.5 ˚C and average inlet temperature being 21.5 ˚C. The slight increases in average outlet temperature are on the account of increase in flow rate.

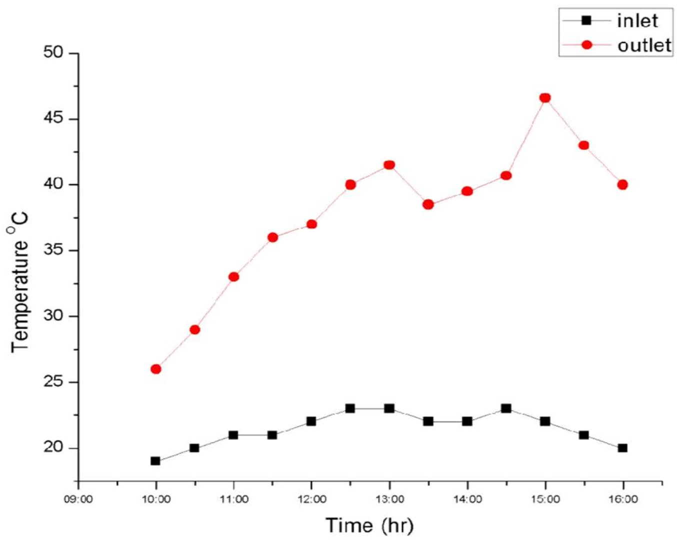

Figure 4. 3 Variation of inlet and outlet temperature with time plate 1 at MFR.

3) *High flow rate [0.05kg/s]:* After completion of two-day long investigations, plate 1 is subjected to high flow rate, and changes in outlet temperature are recorded. On day 3, partly due to increase in air flow rate and increase in solar radiations, average outlet temperature showed an increase up to 65˚C. Higher solar radiations imply higher solar energy available. Clearly from the above discussion, an increase in average temperature of solar air heater is obtained on increase in air flow rate. Now further, plates with artificial roughness are being investigated to give a comparative study of smooth and roughened absorber plate. Lastly the variation of efficiency with time is represented in the figure 4.5 for three different flow rates that have been used in the analysis of plate. It is found that with the increase in the flow rate, the efficiency is highly affected. The large increase in the efficiency is observed with increase in flow rate. Efficiency reached maximum mean value of 29% at flow rate of 0.05kg/s.

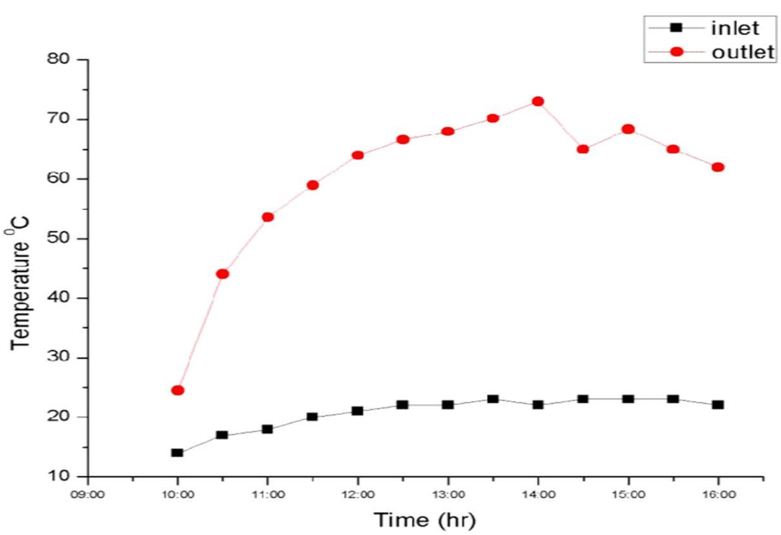

Figure 4. 4 Variation of inlet and outlet temperature with time plate 1 at HFR.

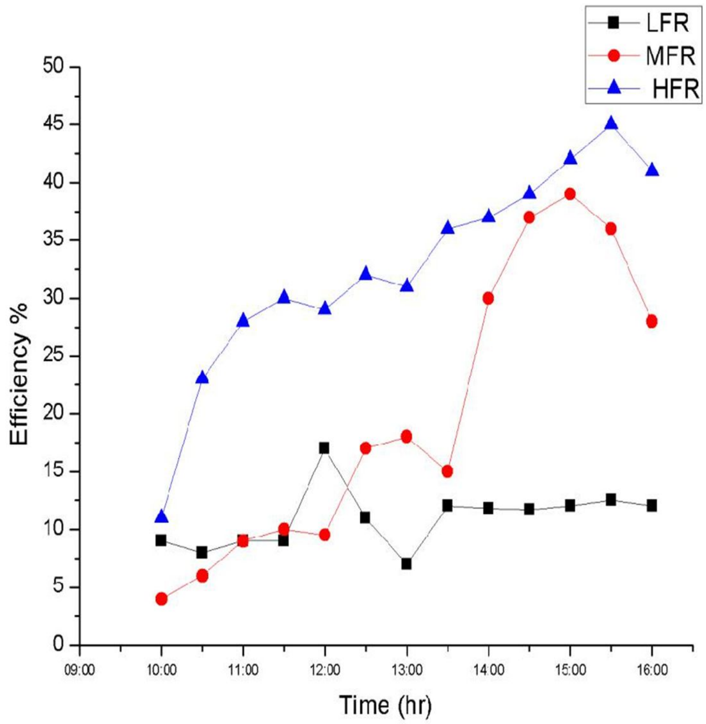

Figure 4. 5 Variation of efficiency with time

B. Absorber Plate 2

The second absorber plate figure 4.6 investigated had V-shaped roughness element attached to it. The roughness element used had angle of 85.108˚ and height of each rib was about 4mm. In order to see the effect of roughness used the plate was again tested at three different flow rates for three days and results were presented in the form of following graphs.

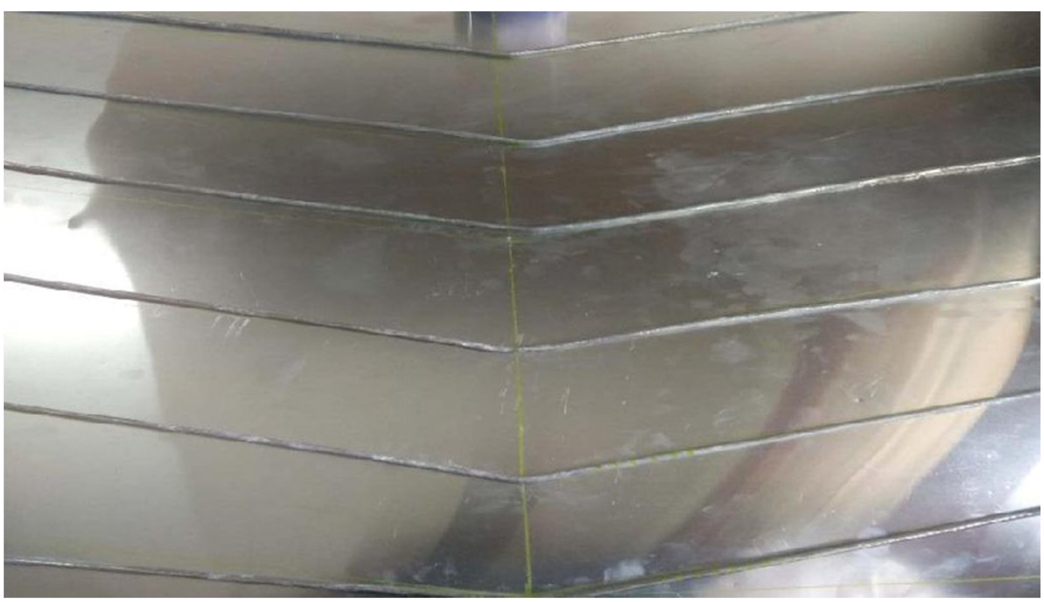

Figure 4. 6 Plate 2 with artificial roughness.

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1) Low flow rate [0.033kg/s]: It's quite visible from the graph figure 4.7 that average outlet temperature has increased from 44˚C to 64 ˚C an increase of about 20 ˚C in the mean temperature. Such a large increase in the average temperature shows the pronounced effect of roughness used. The roughness used serves the purpose of providing the turbulence to the air flow, thereby increasing the heat transfer. The laminar sub layer that is the layer close to the plate or heat transfer layer is disturbed resulting in the enhancement in heat transfer from air to the absorber plate. The large temperature difference between inlet and outlet temperature proves to be very essential for increasing the efficiency of solar air heater.

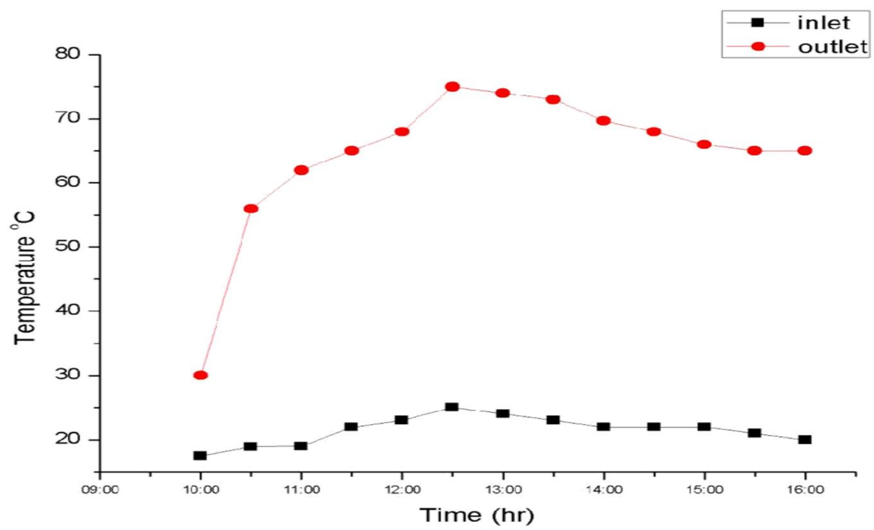

Figure 4. 7 Variation of inlet and outlet temperature of plate 2 at LFR.

2) *Medium flow rate [0.0414kg/s]:* At the medium flow rate small increase in average temperature was observed over the period of time partly due to increase in flow rate. While as roughness element being same, no pronounced increase in mean outlet temperature was observed as compared to the previous case. An average temperature of 65 ˚C at outlet was recorded. From the figure 4.8 its clear artificial roughness used had pronounced effect as in case 1, while changing the flow rate in case 2 from minimum to medium, average temperature though increased but slightly rather than the abrupt increase as in case 1.
3) *High flow rate [0.05kg/s]:* Similarly figure 4.9 shows the results obtained at high flow rate [.05kg/s]. Same results were obtained with little increase in average temperature on the account of increasing flow rate.

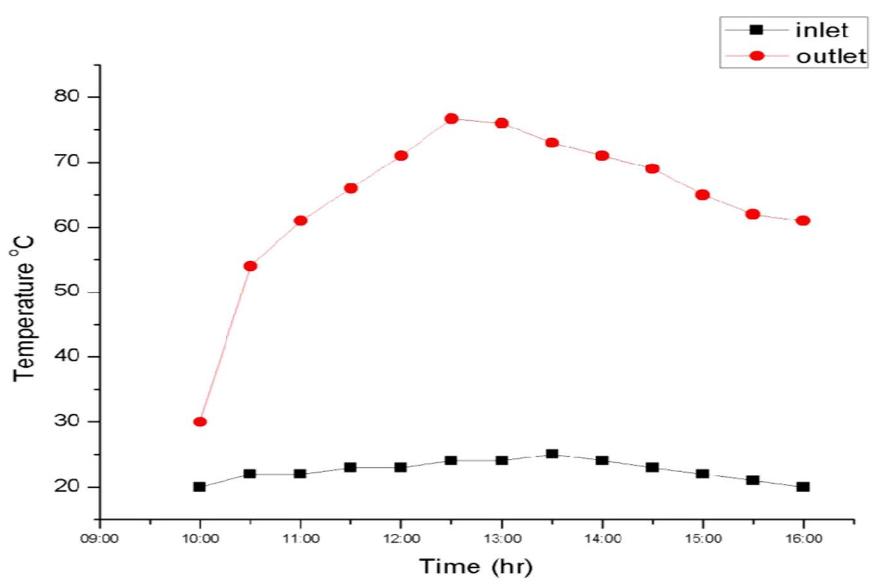

Figure 4. 8 Variation of inlet and outlet temperature with time for plate 2 at MFR.

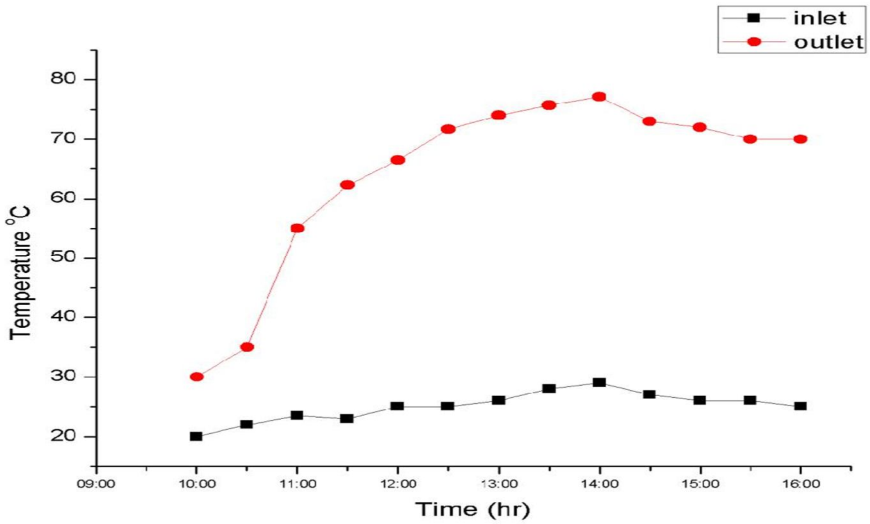

Figure 4. 9 Variation of inlet and outlet temperature at HFR.

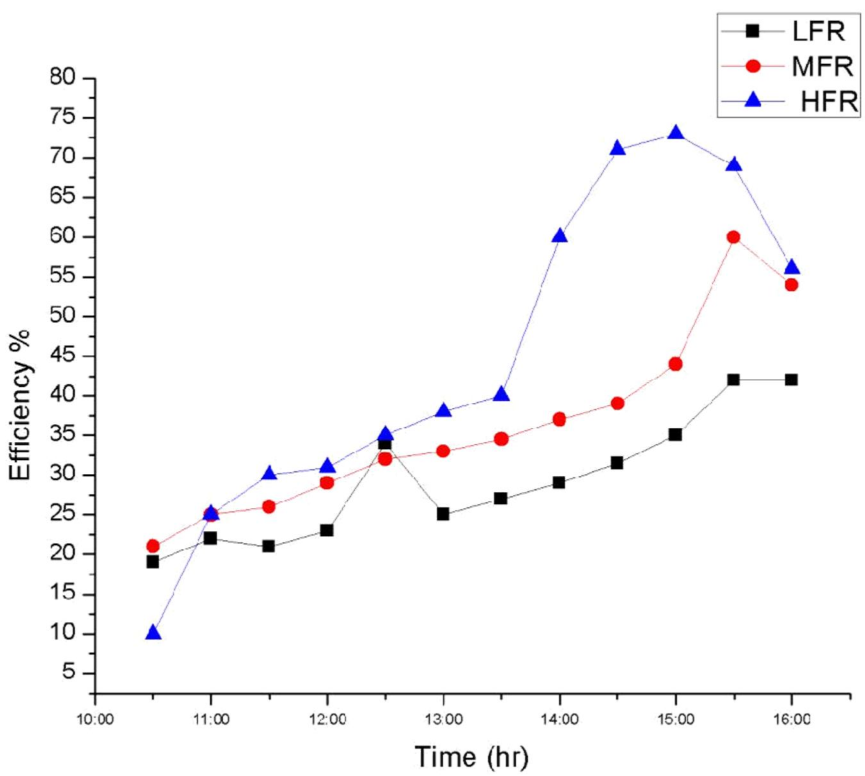

Figure 4. 10 Variation of efficiency with time.

Now from figure 4.10 it is clearly visible that efficiency increases with increase in the air flow rate. During studies maximum efficiency corresponding to plate second was found to be 74% at flow rate of 0.05kg/s. Increase in efficiency corresponds to the increase in the temperature difference between inlet and outlet during the testing period. The maximum mean efficiency of plate 3 was found to be 49% at flow rate 0.05kg/s.

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C. Absorber Plate 3

For absorber plate 3 fig.4.11 roughness elements with double the relative roughness height as compared to roughness element 1 were used. The height of each roughness element was 8mm and 6mm roughness elements were used on absorber plate with 87mm×87mm dimensions and the effect of change in various parameters including outlet temperature, efficiency is presented in the graphical form in corresponding figures. For plate 3 with roughness element having double the relative roughness as compared to the plate 2, the average temperature at outlet increased up to 71 ˚C i.e., an increase of 27 ˚C. Such a large increase in outlet temperature results from the turbulence generated due to the roughness element used. Also increasing flow rate had an impact on the average outlet temperature that showed an increase.

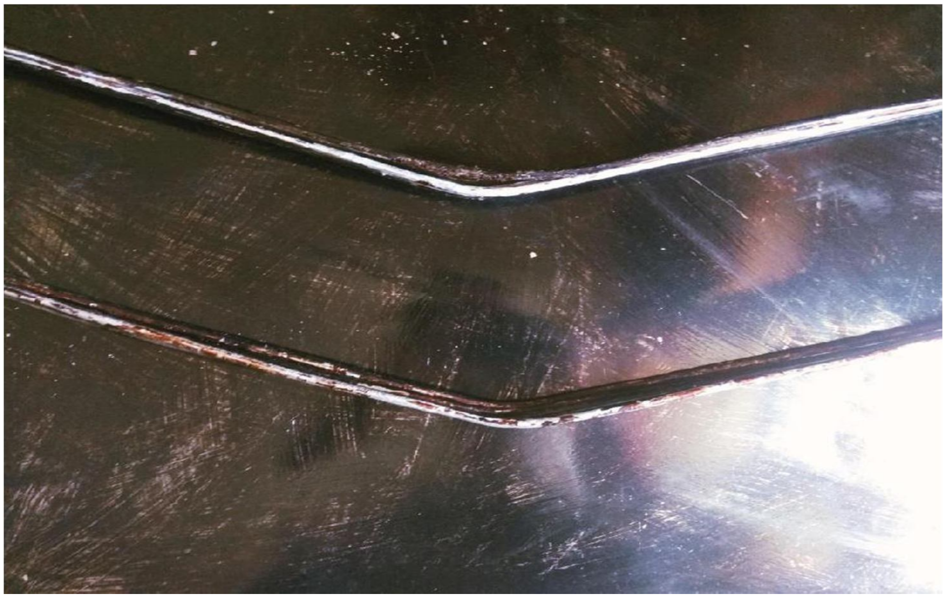

Figure 4. 11 Plate 3 with roughness.

The graphs showing the variation of different parameters as of inlet and outlet temperature of the air with respect to time has been show for different plates are given in the following pages. The graphs for three different flow rates viz. low flow rate, medium flow rate and high flow rate of air have been shown. A comparative study of different plates will be easier from the graphs.

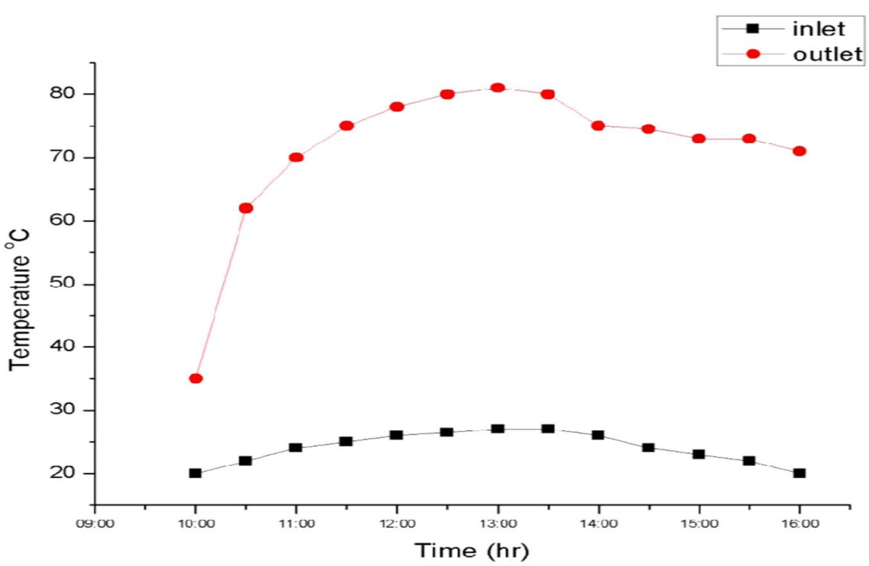

Figure 4. 12 Variation of inlet and outlet temperature of plate 3 at LFR.

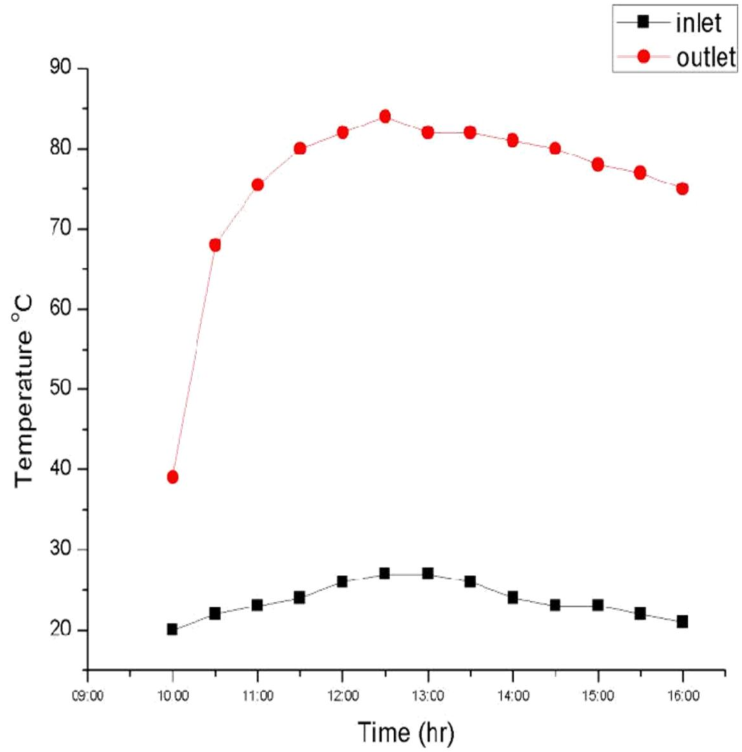

Figure 4. 13 Variation of inlet and outlet of temperature of plate 3 at MFR.

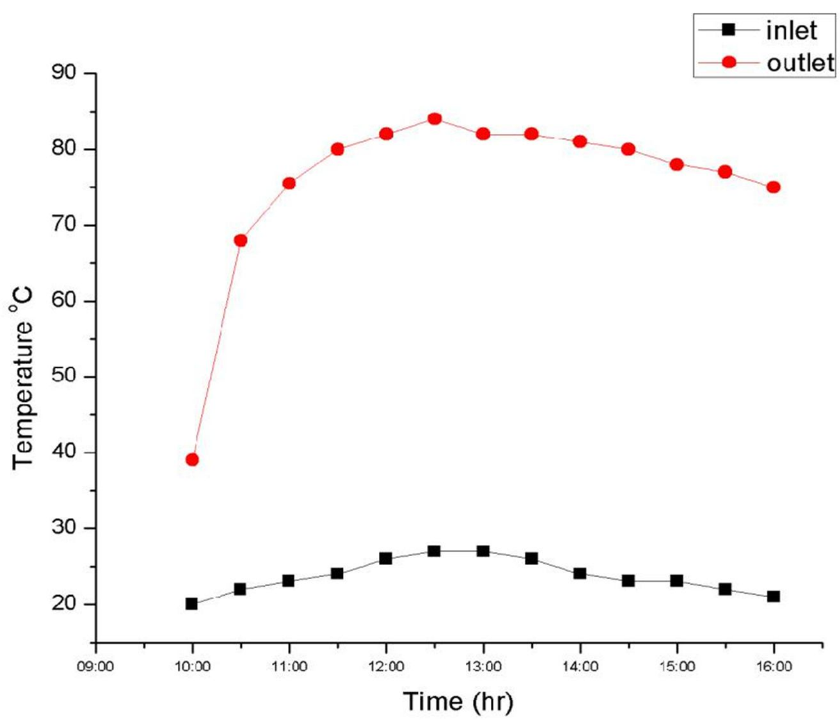

Figure 4. 14 Variation of inlet and outlet temperature for plate 3 at HFR.

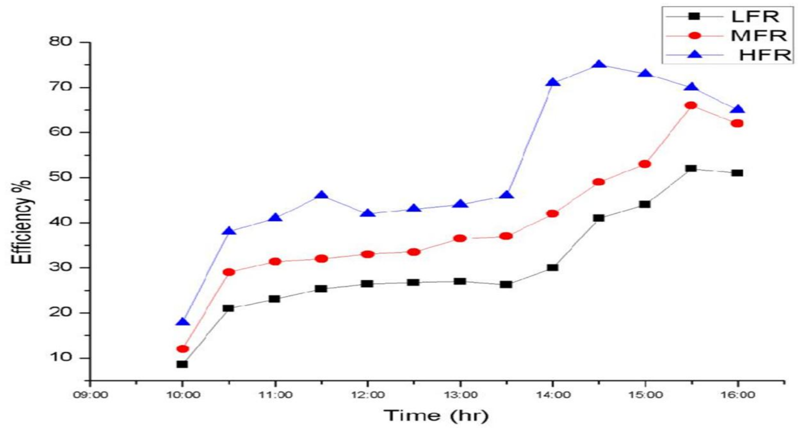

Figure 4. 15 Variation of Efficiency with Time.

A slight increase in mean temperature resulted with increase in the flow rate while keeping the roughness element same. The maximum outlet temperature recorded was about 83 ˚C while average temperature recorded was higher than plate 3 with low and medium flow rates by 4 ˚C. On whole the net heat transfer showed an increase. Similarly, efficiency showed considerable increase with increasing flow rate and the height of roughness. The maximum mean efficiency of solar air heater with plate 3 was found to be 50% at flow rate 0.05.

D. Absorber plate 4

At three different flow rates plate 4 fig.4.16,4.17,4.18 was investigated for three days and results recorded are presented in the form of graphs. The absorber plate 4 had same geometrical shape as the previous roughness elements used, the only difference was in the relative roughness height of the roughness element used, this time relative roughness height was increased 2times the previous value. After three days of investigations, the trend in outlet and inlet temperature observed is represented by figure 4.16, 4.17, 4.18. From the graphs below increase in outlet temperature is visible, with maximum outlet temperature ranging from 83 ˚C - 87 ˚C. The increase in temperature is mainly due to increase in the roughness height and flow rate, which in turn causes turbulence in solar air heater as a result of which heat transfer rate is expected to increase. The turbulence caused due to the roughness element breaks the sub laminar layer of air flowing close to surface of solar air heater, thereby increases the heat transfer between plate and the air. While as variation of efficiency with time is also shown in 4.19 where efficiency increases with time and reaches a maximum value of 85% but the maximum mean efficiency is found out to be 49% at flow rate of 0.05kg/s.

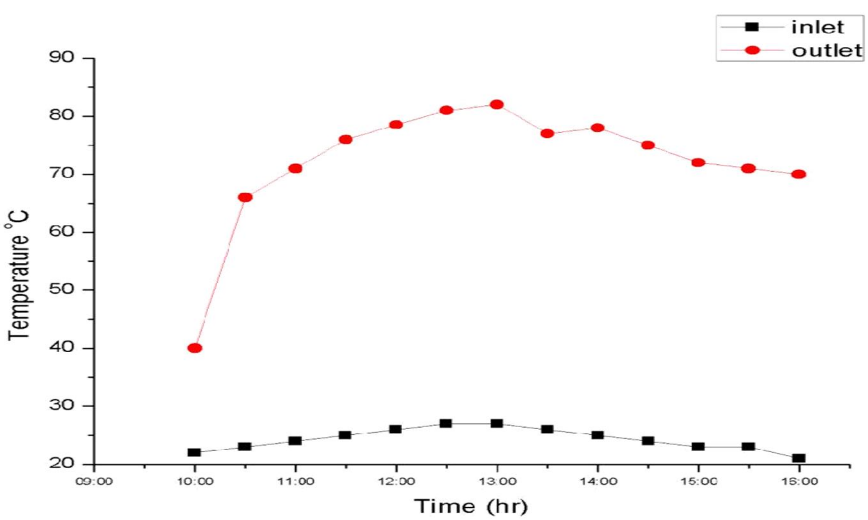

Figure 4. 16 Variation in inlet and outlet temperature for plate 4 at LFR.

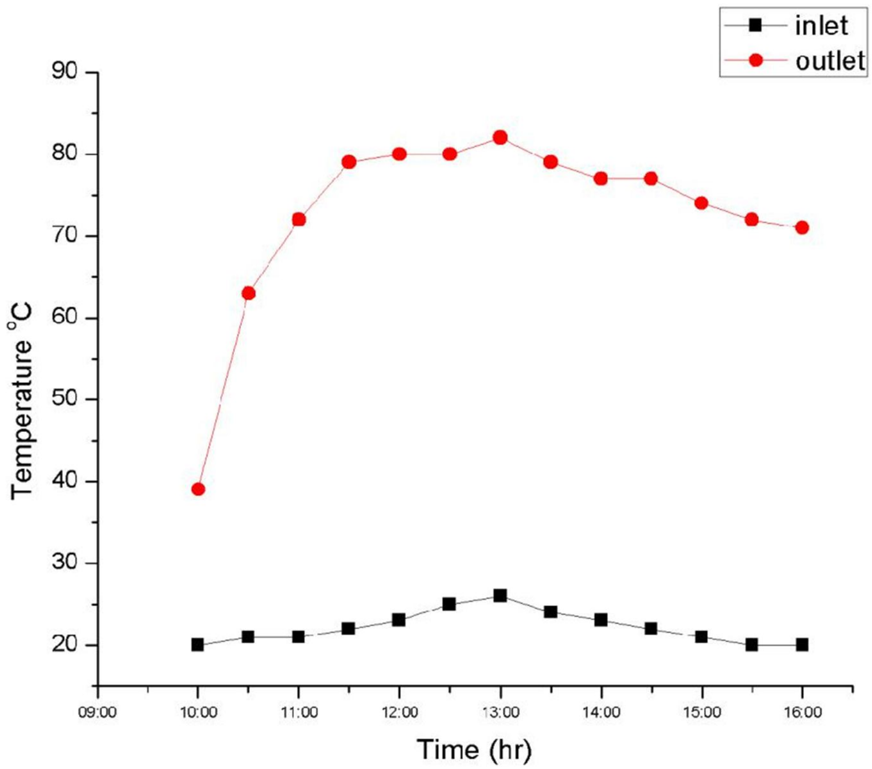

Figure 4.17 Variation in inlet and outlet temperature for plate 4 at MFR.

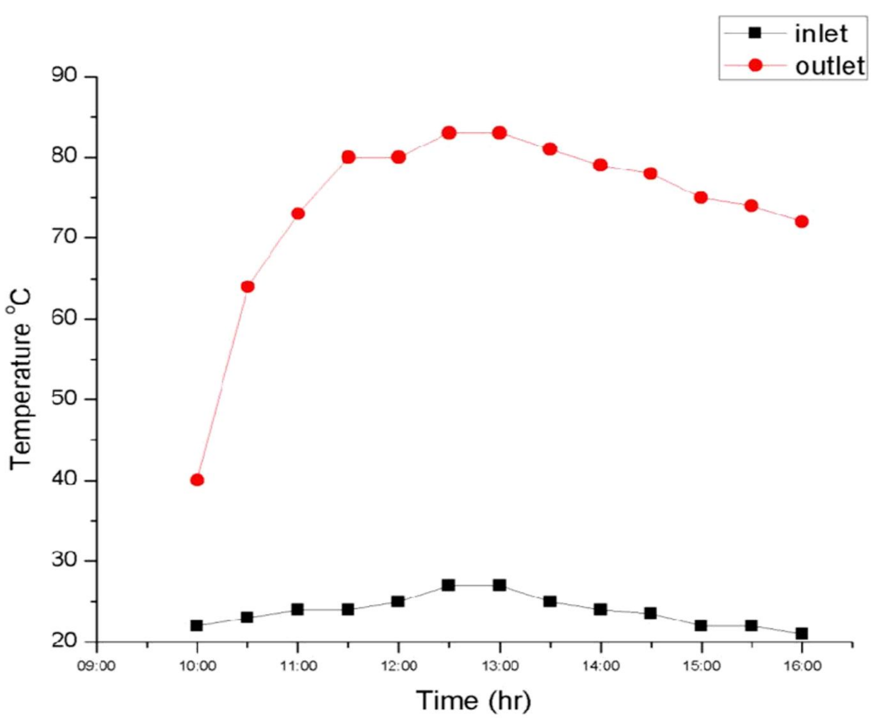

Figure 4. 18 Variation of inlet and outlet temperature with time at HFR.

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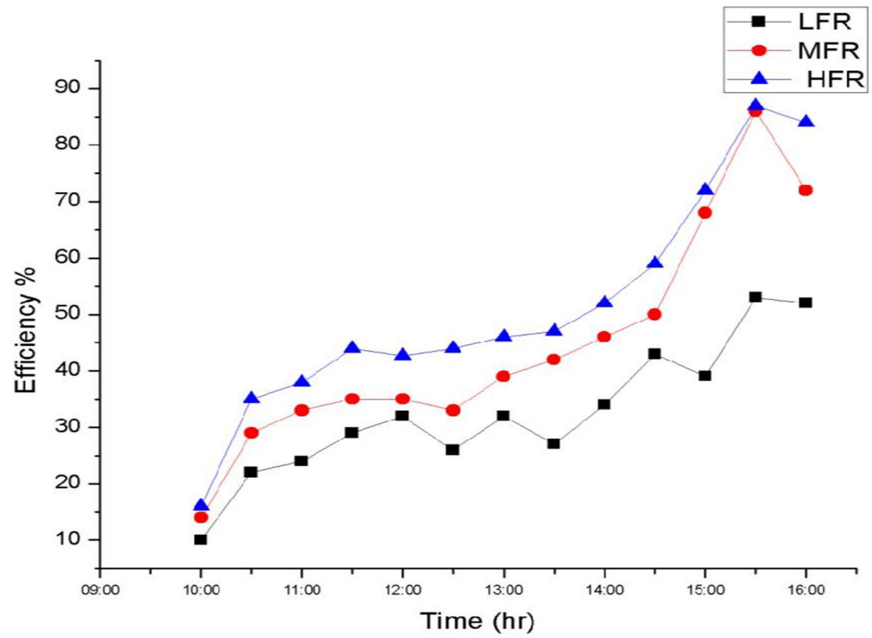

Figure 4. 19 Variation of Efficiency with Time.

From the investigations carried out it can be concluded absorber plate 3 at flow rate 0.05kg/s was most efficient, with mean efficiency of 50.03%.

E. Variation of intensity with Time

The variation of intensity of solar radiations with time during the experiment on required dates is shown in fig. 4.20, it is clear from the graph solar intensity has been continuously varying, and affecting the process of heat absorption or varying the amount of energy available at a given time, making location and position of solar air heater an important consideration.

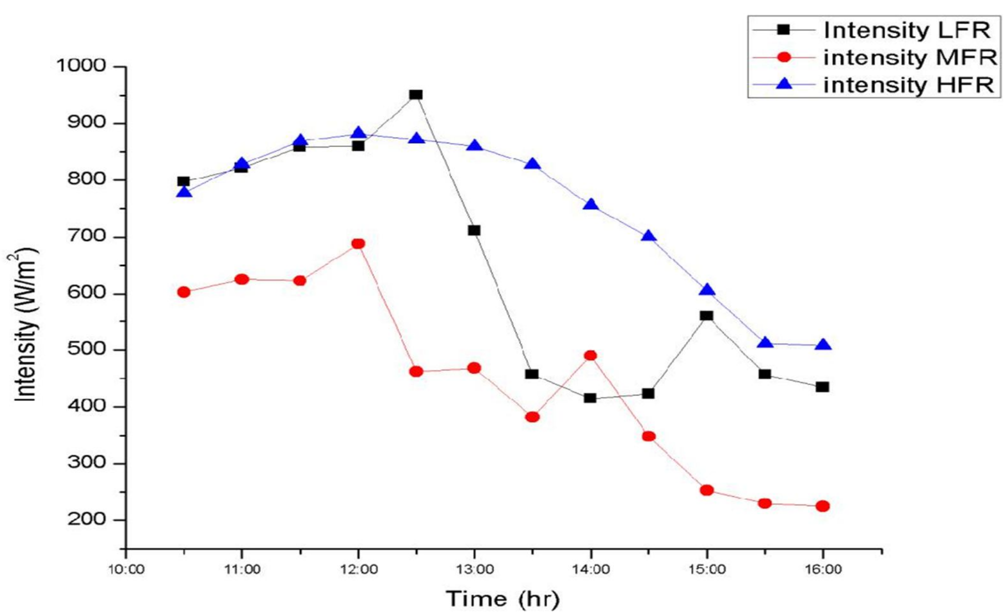

Figure 4. 20 Variation of intensity with time for plate 1.

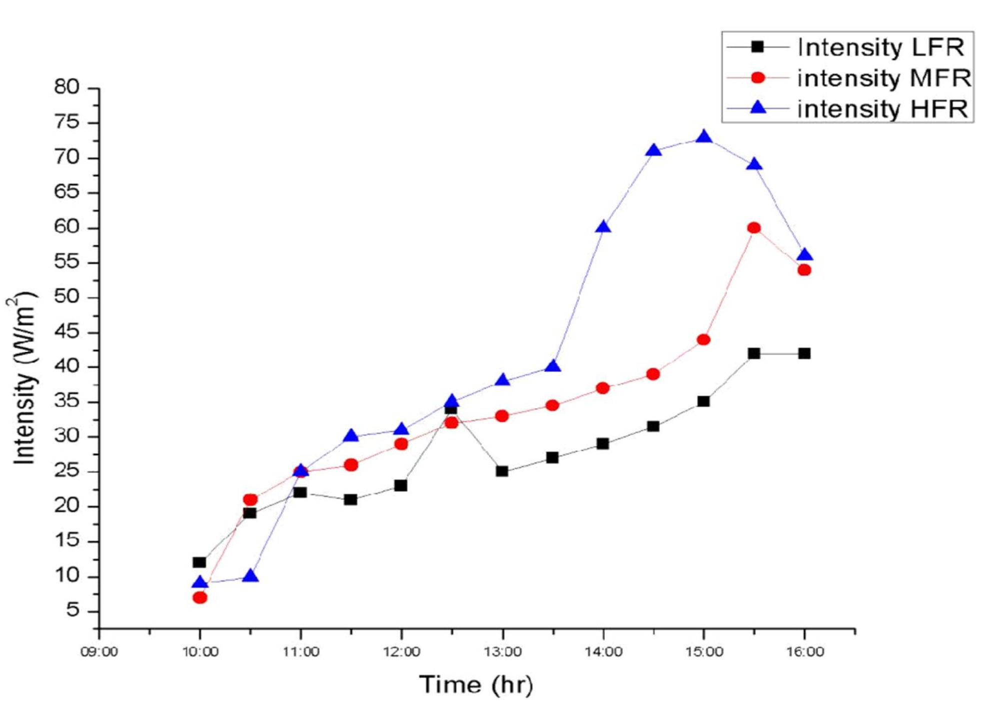

Figure 4. 21 Variation of intensity with time for plate 2

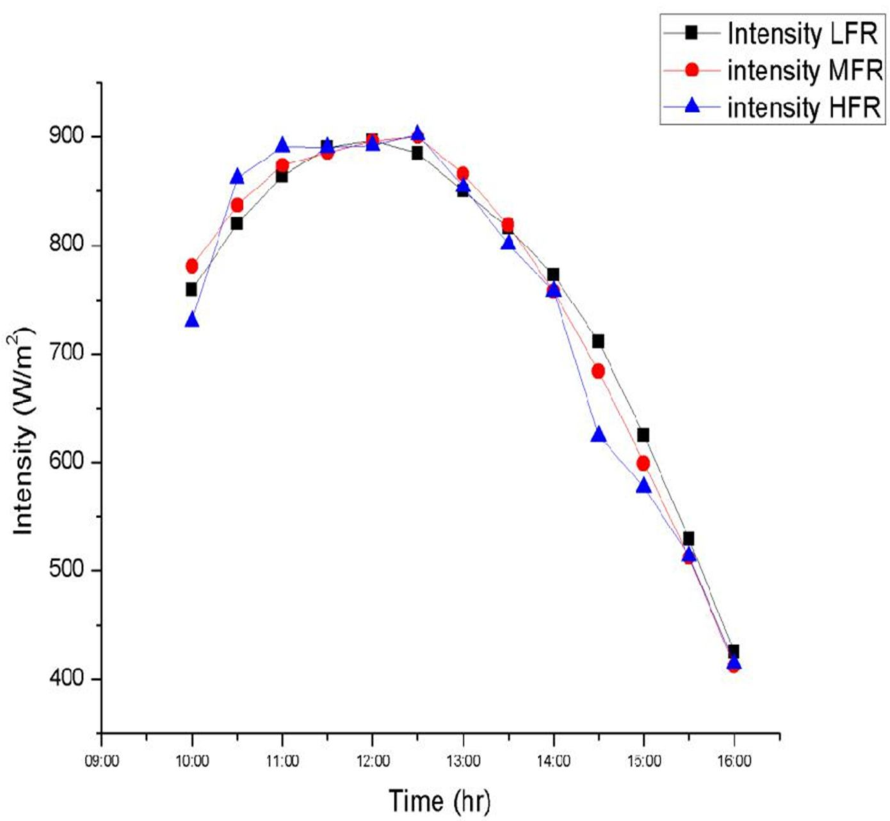

Figure 4. 22 Variation of intensity with time for plate 3.

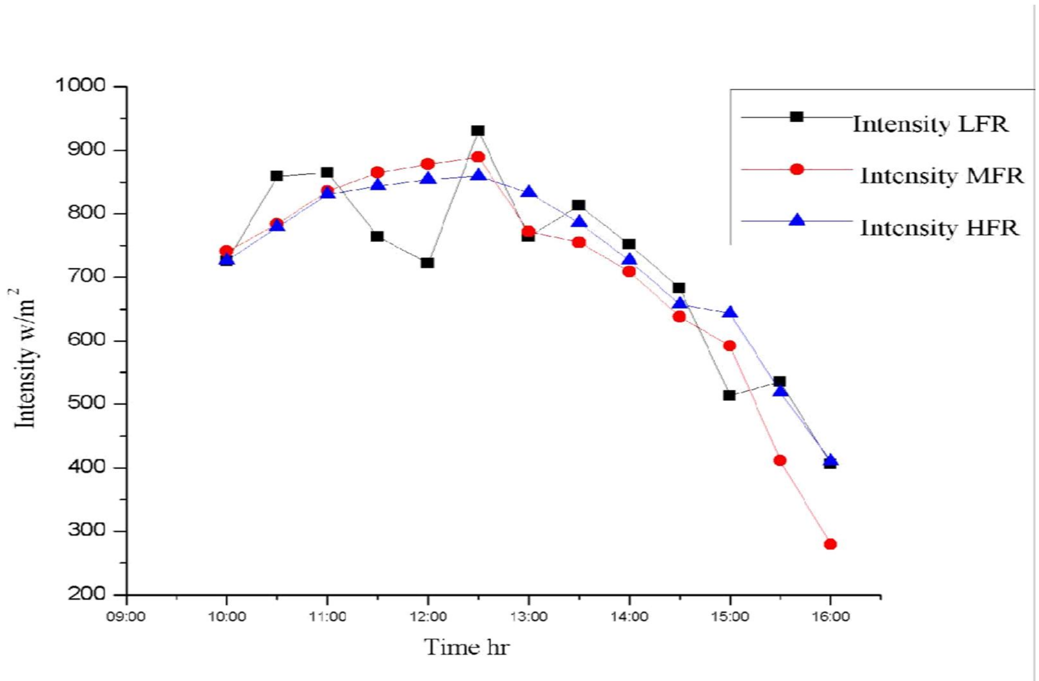

Figure 4. 23 Variation of intensity with time for plate 4.

F. Comparative Study Of Outlet Temperatures For Each Plate

The result or the effect of low flow rate on each absorber plate in terms of outlet temperature is presented in the fig.4.24. Large increase in average outlet temperature is seen from plate 1 to plate 2 as roughness size increases from plate 1 to plate 2. Further average outlet temperature goes on increasing while moving from plate 1 to plate 4, but increase in average outlet temperature is more visible up to plate 3 thereafter average temperature difference at outlet shows very little or less increment corresponding to the prior plate. This implies roughness height can't be increased indiscriminately, after certain value of roughness height, heat transfer shows decline, for our case the height corresponding to maximum heat transfer or maximum increase in outlet temperature was 8mm, while the gap between cover plate and absorber plate was 18mm.

1) *Case 1:* At low flow rate

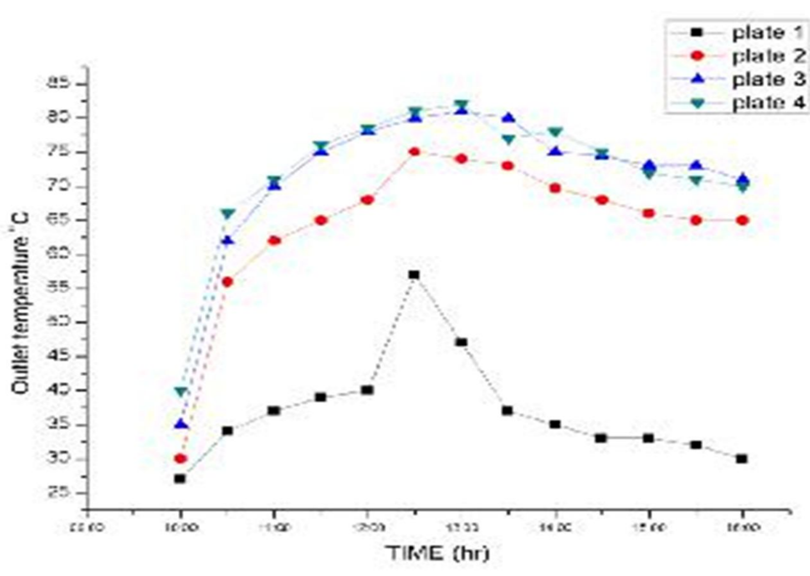

Figure 4. 24 Variation of outlet temperature with time at LFR.

2) Case 2: At medium flow rate

Fig.4.25 shows the effect of medium flow rate on the 4 plates used, it's clearly seen that plate 3 is most efficient and gives better results.

3) Case 3: At high flow rate

Fig.4.26 shows effect of high flow rate on the performance of 4 plates used. Again plate 3 with roughness height 8mm and roughness pitch of 12mm gives better results, compared to other plates. The absorber plate 3 shows an average temperature of 81.9˚C which is far greater than other three plates used. The average temperatures showed by plate 1, 2, 4 is 65 ˚C, 69 ˚C, 74 ˚C.

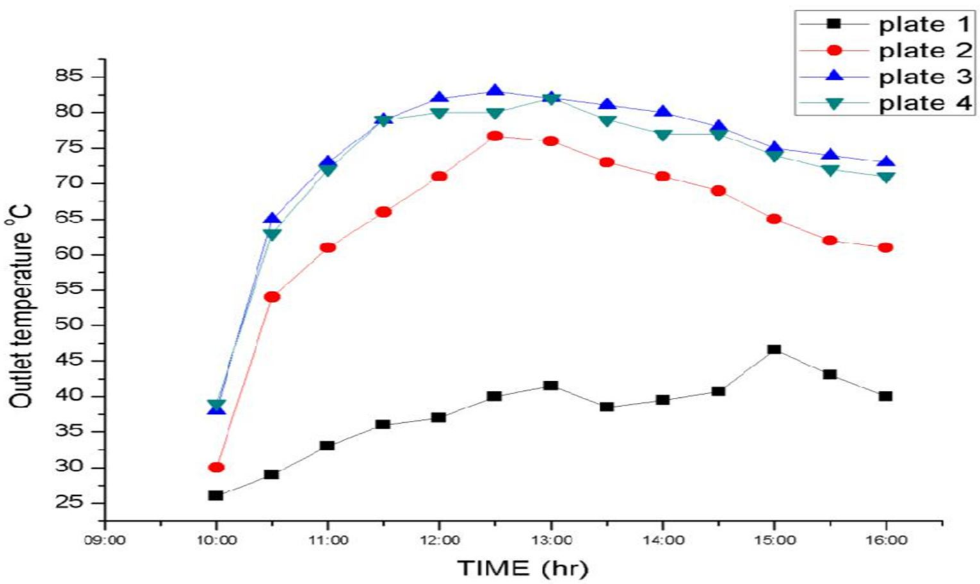

Figure 4. 25 Variation of outlet temperature with time at MFR.

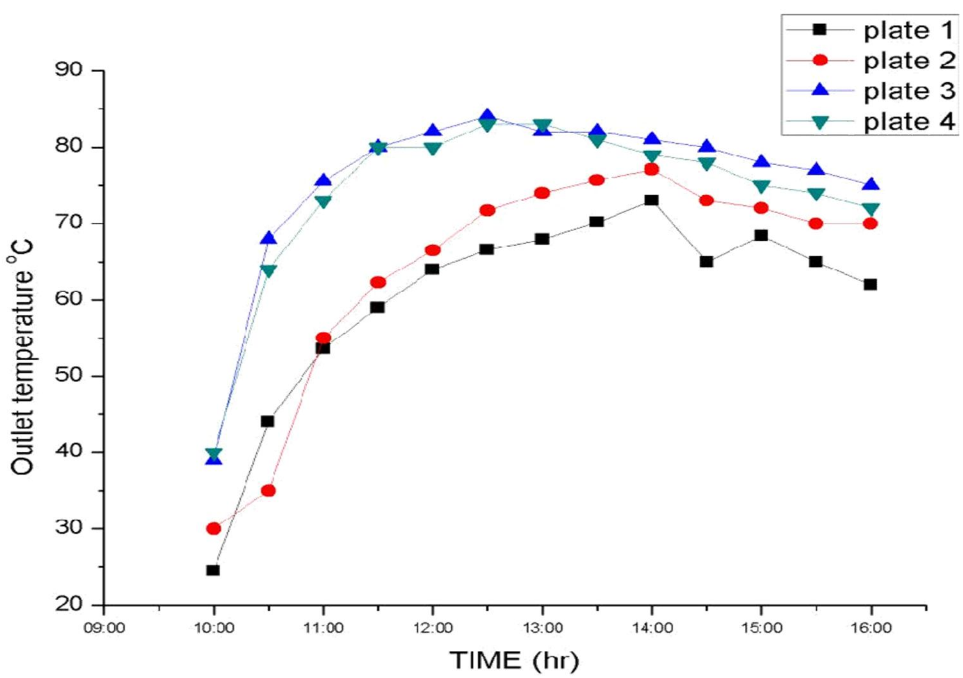

Figure 4. 26 Variation of outlet temperature with time at HFR.

G. Comparative Study of Efficiency of each plate at Different flow Rates

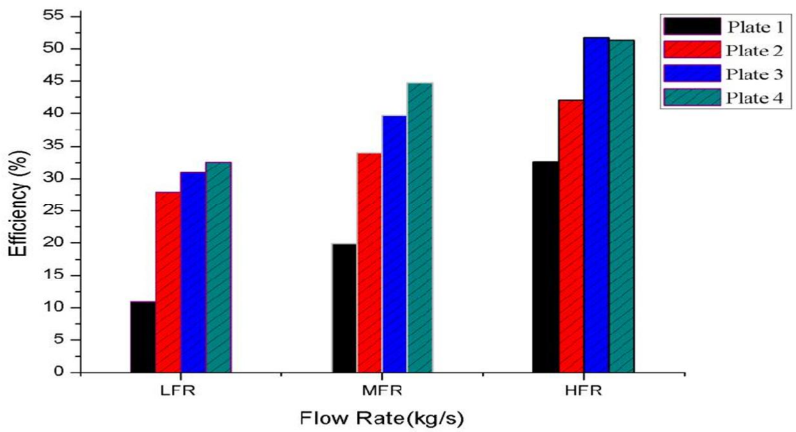

Figure 4. 27 Overall efficiency of each plate at different flow rates.

It is clear from the figure 4.27 that efficiency shows increase with increase in flow rate for each plate. At LFR efficiency increases from 10.5 % (plate 1) up to 33 % (plate 4). The increase in efficiency is due to increase in roughness height of plate. Now moving further from LFR to MFR, again efficiency shows rise from plate 1 to plate 4, the reason being increase in both flow rate and the roughness height, as both the parameters cause the turbulence along the surface of absorber plate. At HFR plate 3 shows maximum efficiency (51.6%), thereby limiting the further increase in roughness height. So, it is concluded that plate 3 at HFR with roughness height of 8mm is the most efficient plate.

V. CONCLUSION AND SCOPE FOR FUTURE

A. Conclusions

In the present work investigations of actual solar air heater were carried out using artificial roughness of different relative roughness and at different flow rates. The results on comparison with smooth absorber plate without any roughness showed a lot of improvement. The average mean temperature at outlet showed increase and efficiency of solar air heater increased without involving any extra cost. Following conclusions are drawn from the investigations carried out;

1) Roughened solar air heaters are more efficient than the simple smooth solar air heater. In present case mean temperature at outlet increased up to 33 ˚C as compared to simple solar air heater. Thereby increasing the heat transfer between air and the absorber plate.
2) Increase in roughness height from 4mm to 16mm resulted increase in heat transfer, mainly due to turbulence created on the absorber plate.
3) The gap between the glass cover and the roughness of absorber plate beyond which no visible increase was found in heat transfer was 10mm.
4) The absorber plate 3 with roughness height of 8mm and at flow rate 0.05kg/s was most optimal design, which showed efficiency of about 51.6%, an increase of 22% compared to smooth absorber plate 1.
5) Further keeping in view, the pumping cost, i.e., energy required to pump the air into the solar air heater, a limit is set beyond which increasing air flow rate is not feasible.
6) Further amount of solar radiation available also affects the performance of solar air heater so the position and location should be decided such that maximum solar radiations are incident on the absorber plate.

B. Future Scope

1) Hybrid roughness can be used to achieve the better results.
2) Phase change materials can be used to further brighten the scope of solar air heater on daily basis.
3) Angle of attack can be varied.
4) CFD can be applied to study the nature of air flow.

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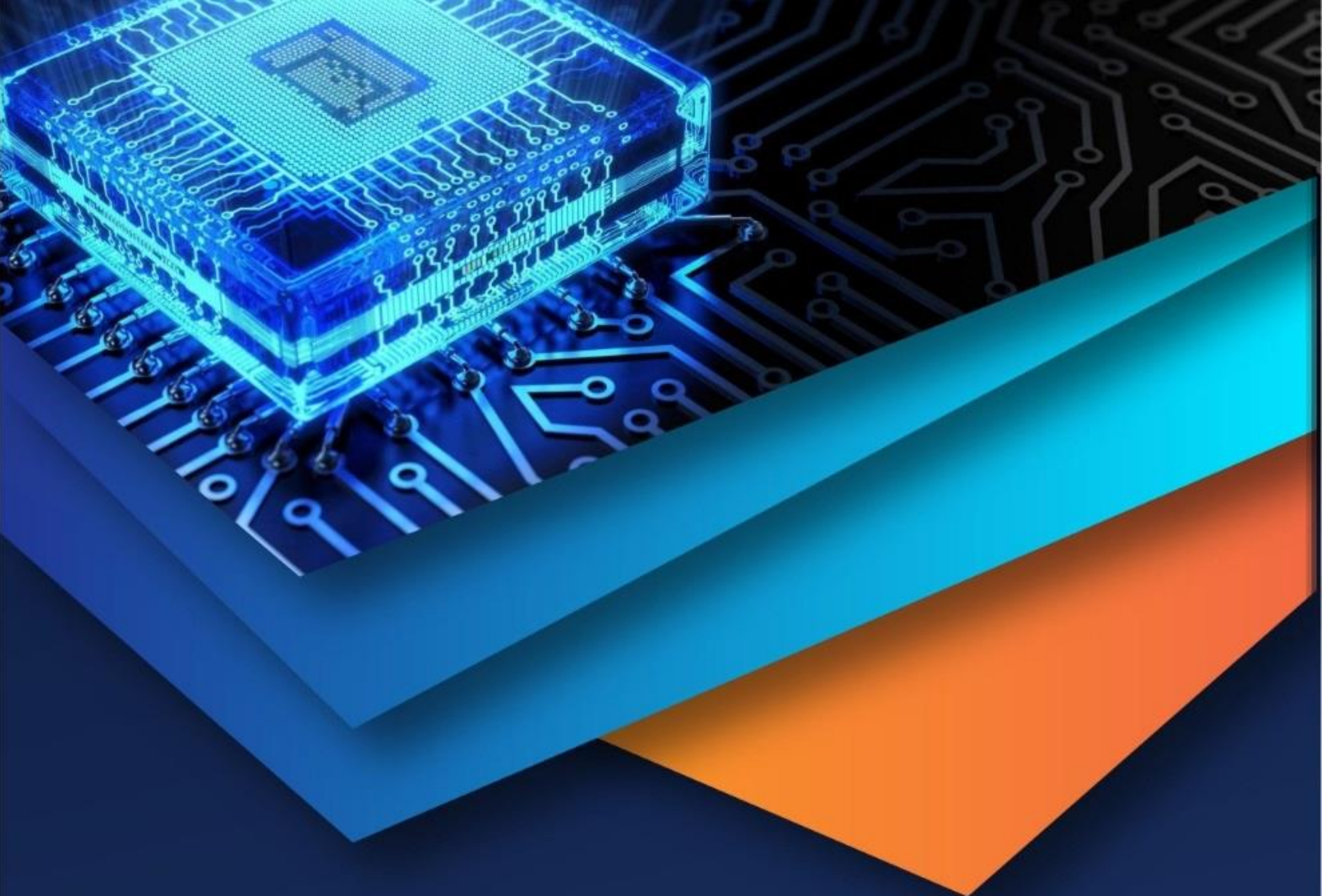

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