Experimental Investigation of Solar Air Heater with Different Surface Roughness Geometries

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Abstract - *Generally it is found that the heat transfer coefficient between the absorber plate and working fluid of solar air heater is low which affects the thermal performance of a solar air heater leads to poor heat transfer between the absorber plate and air. It can definitely be improved by enhancement of heat transfer from the absorber plate by the use of artificial roughness which proved as effective technique to enhance the thermal efficiency of solar air heater. An experimental investigation was carried out for the thermal performance of artificially roughened absorbers under the actual outdoor conditions. Solar air heater operated in a closed loop mode with inlet air temperature of 28 ^{0}C. Ambient temperature varied from 27 ^{0}C to 31 ^{0}C in between rainy & winter meshing season of Vidarbha Region of Maharashtra. The performance results were analyzed according to different time slots.*

Key Words: Artificial roughness, Solar air heater, Roughness geometry, Nusselt number, Reynolds number. Friction Factor, Absorber plate, Heat transfer efficiency, Overall efficiency, Temperature, Pressure

1.INTRODUCTION

The Sun is a very large source of energy and earth intercepts about 1.8xl0^{11} MW of power, which is several thousands of times larger than the total energy rate on earth. Hence this quantity of energy consumption certainly can meet the present and future needs of this planet on a continuing basis. Thus, it is one of the most promising sources of energy. Unlike fossil fuels and nuclear energy, it is an environmentally clean source of energy. Secondly, it is free and available in adequate quantities in almost all pans of the world where people live. Solar energy is always in an advantageous position compared with depleting fossil fuels.

Fig -1: Solar Energy Utilization

In a tropical country like India most of the energy demands can be met by simple systems that can convert solar energy into appropriate forms. By proper application of technologies, excellent thermodynamic match between the solar energy resources and many end-uses can be achieved.

Despite the absorption and scattering of the solar radiation in the earth's atmosphere, amount of energy received on earth's surface in one hour would still be enough to cover the energy requirements of the whole world for one year. Hence the issue is not one of availability of solar energy, but of the feasibility of converting it into forms suitable for human use. As indicated earlier, 30% of solar radiation is reflected immediately back to the space. The remaining 70% is mainly used to warm the earth's surface, atmosphere and oceans (47%) or is absorbed for the evaporation of water (23%). Relatively very small proportions are used to drive the winds, waves and for plants (in photosynthesis). Ultimately, all the energy used on earth is radiated back to space, in the form of infrared radiation.

Solar energy usage has two fundamental facets. The first one comprises a variety of local applications characterized by collection, conversion and consumption of the solar energy on site. To this group, belong passive solar energy usage in buildings, heat production by solar radiation collectors, photovoltaic arrays for electricity generation, ambient heat use in heat pumps, and the conversion of wind, hydropower, or biomass into electrical energy, heat and gaseous or liquid fuels.

1.1 Various Applications of Solar Energy

Major application of solar energy include solar water and air heating, solar drying of agricultural products, salt production by evaporation of sea water, solar distillation on a community scale, solar cookers, solar engines for water pumping, food refrigeration, photovoltaic conversion, solar furnace, heating and cooling of buildings, solar thermal power generation, high temperature application for industrial process heat, etc. It can be generally classified as thermal and electrical applications different apps in one word in classification way

- Flat-plate collector
- Focusing or concentrating collector

- Solar Air Heating
- Solar pond
- Space heating
- Power generation
- Space cooling and refrigeration
- Distillation
- Drying
- Cooking

1.2 Solar Air Heaters

Compared to other solar collectors, solar air heaters (SAH) have some distinct advantages. The mode of heat transfer from the absorber plate and the working fluid is the main difference between liquid flat plate collectors and air heaters. The air heaters eliminate the need to transfer heat from the working fluid to another working fluid. Air is being directly used as the working substance, the system is less complicated and is compact. The corrosion problem, which can become serious in solar water heater, is completely eliminated in solar air heaters. Hence light gauge steel or Aluminium plates can easily be used. Hence, a solar air heater appears to be inherently cheaper and can last longer. Unlike liquid flat plate collectors, system is not pressurized and therefore, light gauge metal sheets can be used. In solar air heaters leakage is also not a big problem, unlike in liquid Collectors.

Conventional solar air heater consists of a flat plate collector with an absorber plate, transparent cover system at the top and insulation at the bottom and on the sides. Whole assembly is enclosed in a sheet metal container. Working fluid is air and the passage for its flow varies according to the type of air heater.

Materials for the construction of air heater are similar to the liquid flat plate collectors. Transmission of solar radiation through the cover system and its subsequent absorption in the absorber plate can be taken into account by expressions identical to those of liquid flat-plate collectors. In order to improve collection efficiency, selective coating on the absorber plate can be used.

Classification of Solar air heater

- Nonporous Type Solar Air Heaters
- Porous Type Solar Air Heaters

1.3 Components of Solar Air Heaters

1.3.1 Absorber Plate

The absorber plate should have high thermal conductivity, adequate tensile and compressive strength, and good corrosion resistance. Copper is generally preferred because of its extremely high conductivity and resistance to corrosion. Collectors are also constructed with aluminum, steel, Galvanized Iron (GI) sheets and various thermoplastics and metal ions.

1.3.2 Cover Plate

Cover plate or plates through which the solar energy must be transmitted is also extremely important part of solar air heater. Purposes of cover plates are

- To transmit as much as solar energy as possible to the absorber plate
- To minimize the loss from the absorber plate to the environment
- To shield the absorber plate from direct exposure to weathering

1.3.3 Insulation

Insulation is used to prevent loss of heat from the absorber plate due to conduction or convection. Usual insulating materials are rock wool or glass wool. Absorber plate should be insulated beneath and or in the side, depending on the type of design used. Important requirement of an insulator is that it should be heat resistant

1.4 Parameters Associated with the Construction of an Air Heater

1.4.1 Heater Configuration

Heater configuration is the aspect ratio of duct and length through which air passes.

1.4.2 Airflow

Air must be pumped through the heater. Increasing the air velocity will result in higher collection efficiencies.

1.4.3 Transmittance Properties of the Cover

The type and number of layers of cover material must be considered and spectral transmittance properties must be examined. In general, as temperature requirement is high, more number of covers is required. Principle underlying the use of multi covers is that each air layer between two successive covers provides a barrier against heat loss from the absorbing surface to the surroundings. However, with a large number of covers, reflective losses increase. Covers of high transmissivity and low reflectivity are desired to keep the amount of reflected and absorbed radiation low.

1.4.4 Absorber Plate Material Selective surfaces

It can improve performance of solar air heaters by increasing collector efficiency. Absorber is coated black to absorb maximum amount of incident radiation.

1.4.5 Natural Convection Barriers

Stagnant air interposes high impedance to convective heat flow between the absorber plate and the ambient air. Losses are reduced by the use of multiple covers or honeycombs.

1.4.6 Plate-to-air Heat Transfer Coefficient

Absorber can be roughened and coated to increase coefficient of heat transfer between the air and the plate. Roughness ensures high level of turbulence in the boundary layer of the flowing stream. For this reason, crumpled or corrugated sheets and wire screens are attractive as absorbing materials.

1.4.7 Insulation

Insulation is required at the absorber base to minimize heat losses through the underside of the heater.

Solar Radiation Data - Solar radiation data corresponding to the site are needed to evaluate heater performance.

2. Methodology

Solar air heaters have been used with success for many industrial and domestic applications such as drying farm produce, dehydrating industrial products, and space heating. Solar energy is important in low-temperature thermal applications because it replaces considerable amounts of conventional fuels.

2.1 Flat Plate Solar Air Heater

Several types of solar air heaters have been developed over the years, the flat plate type being the most common because it is simple to construct, easy to operate, and inexpensive to maintain. Since air is the working fluid, the problems of freezing or boiling of the fluid are obviated. However, the low density, low thermal capacity, and low heat conductivity of air requires larger ducts to transport the required energy. These are probably the important drawbacks of air panels. However, low cost and reliability makes them an attractive alternative. A conventional solar air heater generally consists of an absorber plate with a parallel plate below, forming a passage of high aspect ratio through which the air to be heated flows. A transparent sheet covers the absorber plate, while a sheet—metal container filled with insulating material is attached underneath and to the sides. There are two possible altematives to maximize the collection of useful energy from air heaters, namely (a) to maximize the collector area by lengthening the absorber plate while keeping channel depth and mass flow rate constants and (b) to make the channel deeper while keeping the surface area constant. However, for a system with design constraints on fan power and collector length, the only practical alternative is to increase the volume of air by making the channel deeper.

In order to increase the thermal efficiency of solar air heaters, the absorbed heat must be transferred to the air flowing above, underneath, both above and underneath or through the absorber plate.

2.2 Design & Sketching of Proposed Model

Creo Elements (formerly Pro/Engineer), PTC's parametric, integrated 3D CAD/CAM/CAE solution, is used by manufacturers for mechanical engineering, design and manufacturing. Pro/Engineer was the industry's first rule-based constraint 3D CAD modeling system. The parametric modeling approach uses parameters, dimensions, features, and relationships to capture intended model behavior. Creo Elements provides a complete set of design, analysis and manufacturing capabilities on one, integral, scalable platform. These required capabilities include Solid Modeling, Surfacing, Rendering, Data Interoperability, Routed Systems Design, Simulation, Tolerance Analysis, and NC and Tooling Design.

Fig -2: 3D Sketch of Proposed Model

2.3 Development of SAH Model

In the present work, a detailed technical study was performed in all types of solar air heaters. Flat plate type of solar air heater was developed and performance evaluation was carried out in every variation and compared with each other. The various types of surface geometries were designed and tested are listed below:

- Aluminium Collector with plane Surface
- Aluminium Collector with Dimpled Shape Surface Geometry
- Aluminium Collector with Cuboid Shape Surface Geometry

2.3.1 Components used in Model

- Metal pipes
- MDF sheet
- Polycarbonate sheet
- Polycarbonate sheet
- Insulation (Hitlon sheet)
- PVC sheet
- Metal strips (Aluminium)
- Electric motor
- Temperature sensors
- Transformer 12-0-12V, 1amp
- Speed regulator
- Miscellaneous (Nut-bolts, screws, wires, tapes, sticking, bonding solutions etc.)

2.3.2 Surface Geometry making Components

- MDF Sheet
- Aluminum sheet
- Geometry / Array pieces
- Selective Black coat
- Insulation Material

2.3.3 Construction of Model

In order to compare the efficiency of the Aluminium collector, two more types of collectors were also fabricated with same materials and design features. The performances of the collectors were investigated and compared with each other. Brief fabrication procedure is step by step explained below:

- According to requirement, first of all a 3D sketch of proposed model is developed in 3D modeling software. The design parameters are assumed as per existing conventional model.

- The metal pipes are used to make complete basic structure and whole frame of model is fabricated according to design parameters using nuts & bolts. The surfacing of the table shaped structure is enveloped by medium density fiber sheet (MDF Sheet).

- The basic structure is so constructed that it will create one inlet section for ambient air inlet and one outlet section for air to be inducted on either side as shown in **fig-3**

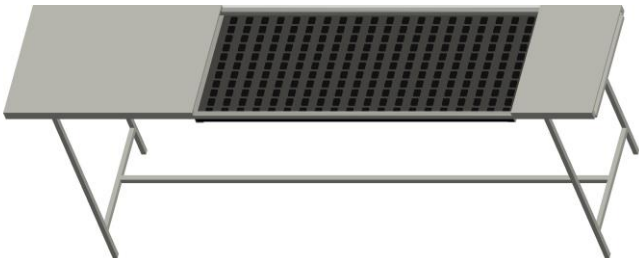

Fig -3: Schematic view of absorber

- In between the inlet & outlet section, there is a space is accumulated for radiation absorption where selective coated corrugated Aluminium sheet is placed and the section is covered by transparent polycarbonate sheet.

- The radiation heat absorbing section is insulated by heat insulation material i.e. Hitlon Sheet for the prevention of heat loss.

- At the outlet section, there is a heat induction system is installed in the form of air blower as shown in **fig-4**

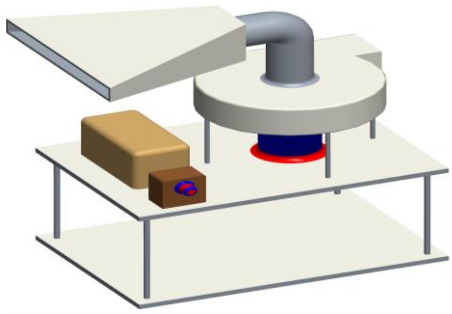

Fig -4: Schematic view of Centrifugal Blower

- The casing of centrifugal blower id constructed by using both MDF sheet & fiber sheet and fiber impeller is fixed with AC electric motor in the blower.

- As it is a centrifugal blower, there is a conical inlet section fabricated according to the outlet section of main assembly and is connected to the center axis of blower casing so that it will induct the heated air from outlet section of main assembly.

- The outlet of the blower is free to environment for air temperature reading and testing purpose.

- The Electrical & Electronic components in the model are electric motor for blower which is directly operated by AC 230V current. The speed of blower is regulated by using AC Speed regulator.

- The Electronic components are temperature sensors for temperature measurements at various sections like Inlet section, Outlet section, Mid-section, outlet section of blower & ambient temperature. The all sensors are powered by 12-0-12V, 1Amp transformer as each of them consumes at least 100ma current.

The complete assembly of model is shown in **fig-5**

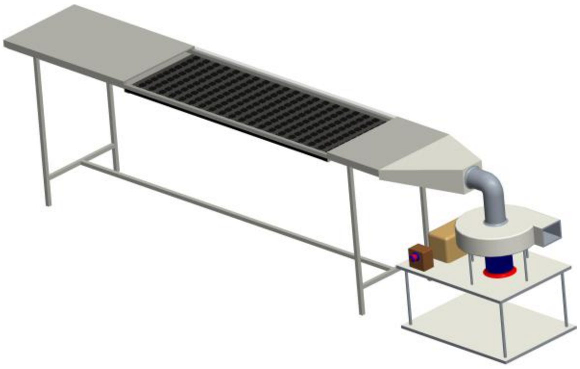

Fig -5: 3D Sketch of Proposed SAH Model

2.3.4 Working of SAH

Fig-5 shows the isometric view of the solar air heater. The air is passed through the solar air heater having a rectangular channel size of 600 x 370 x 39 mm} Selective coated 24 SWG plane Aluminium sheet acted as absorber plate and Hitlon insulation was packed bottom and sides of the absorber plate to suppress the heat losses. 6mm polycarbonate sheet was used as glazing material. The air channel was formed in between the absorber plate and transparent cover. The roughness geometries were positioned in the air passage and it was attached to absorber plate. The length of the rough surface is around 100 cm and it occupied 57% of collector's width. The height of the setup is 60 cm and it was positioned vertically upward pointing to the glass plate. A plenum chamber was provided at the outlet of the collector to stabilize the air flow out and it was connected to a centrifugal blower. The two temperature sensors are situated in each section for average temperature reading. The setup is exposed to sun radiation at different time of the day like 9am, 12pm, 3pm, 6pm so that different readings will be collected for all three surface roughness geometries.

4. Experimentation

4.1 Experimental Procedure

The experiments were conducted on the terrace of workshop. The materials and the methods for performance evaluation are as follows. The tests were conducted between 9.00 am to 6.00 pm solar time. During the experimental period, the following quantities were measured: ambient air temperature, Ta; hot air outlet from the collector, To temperature of the top glass, T_g solar radiation, 1; inlet air temperature, T,; and air velocity through the panel and mass flow rate, m.

For every variation of solar air heaters, individual Surface roughness geometry is used for testing. A 0.18-HP centrifugal fan was used to make the air flow through the collector. The blower was connected to the outlet of the solar air heater through a triangular section and duct. The velocity of the centrifugal blower was adjusted using a manually controlled regulator. The air mass flow rate was calculated from the measured velocity at the output of the collector and the experiment was repeated with different mass flow rates each day. The maximum and average temperatures were recorded for each mass flow rate. The instantaneous and average efficiency over the day for a particular mass flow rate was calculated. All the parameters were recorded in every 3 hour. The experiments were conducted for different mass flow rates for the two types of experimental set up. The pressure drop across the collector was examined for all the mass flow rates studied. Pumping power was calculated from the measured value of pressure drop. Tests were conducted outdoors for all the collectors under identical conditions on clear days. The flow rate was kept constant for all the collectors during the experiment. The collector was subjected to different mass flow rates like 20, 45, 70, 80, 100 and 130 kg/m^{2}h which cover the normal range of air flow rates. An experimental set up is shown in **Fig-6**

Fig -6: Actual Fabricated SAH Model

4.2 Instrumentation and Measurement of Various Thermo physical Parameters

The measured variables in all the experimental set-ups include digital temperature sensor normal to the absorber surface, ambient air temperature, inlet and outlet temperature, top glass temperature as well as the temperature of the absorber plate at various points. The air mass flow rate was calculated from the output air velocity. The pressure drop across the collector was monitored for different air mass flow rate. The air was inducted by centrifugal blower. Solar radiation intensity was measured with a calibrated Solarimeter having a least count of 2 mW/cm² with ± 2% accuracy on the full scale range of 0-120 mW/cm² The velocity of the centrifugal blower was adjusted using an externally controlled regulator. The temperatures of air at the inlet, outlet and at the top glass and absorber plate were monitored using an W1209 Digital Temperature Control Module which records the temperatures at the required points for every minute. The pressure drop across the collector was measured by using a U—tube manometer filled with water.

4.3 Performance Equations

The performance of a flat-plate collector operating under assumed steady-state conditions can be described by the following relationship

$$\frac{Q_u}{A_c} = I(\tau\alpha) - U_L\left(T_p - T_a\right) \qquad \text{(A)}$$

If one introduces the parameter called collector heat removal factor, F_R,

Eq. (A) can be rewritten as

$$\frac{Q_u}{A_c} = F_R I[(\tau\alpha)_e - F_R U_L\left(T_p - T_a\right)] \text{ (B)}$$

Then the collector efficiency, η], can be written from Eq. (A) and Eq. (B),

$$\eta = [(\tau\alpha)_e - U_L\left(\frac{T_p - T_a}{I}\right)] \qquad \text{(C)}$$

OR

$$\eta = F_R[(\tau\alpha)_e - U_L\left(\frac{T_p - T_a}{I}\right)] \qquad \text{(D)}$$

However, for solar air heaters taking in air at ambient temperature (T_i = T_a), it is advantageous to utilize the following equation for thermal efficiency

$$\eta = F_o[(\tau\alpha)_e - U_L\left(\frac{T_o - T_i}{I}\right)] \qquad \text{(E)}$$

where A is the area of the collector (m²), Q" is the useful heat gain rate of the collector (W), F_o is the heat removal factor referred to the outlet temperature, η is the overall efficiency of the collector, FR is the heat removal factor related to the inlet temperature, τ is the transmittance of the glass cover for direct radiation at nonnal incidence, α is the solar absorbance of the absorber plate for direct radiation at normal incidence, $(\tau\alpha)_e$, is the effective transmissivity-absorptivity product, UL is the collector heat loss coefficient between the absorber plate and the atmosphere (W/m²k), including allowances for side and rear losses, I is the intensity of solar radiation (W/m²) T_a is the ambient temperature (°C), T, is the inlet temperature of air (°C), To is the outlet temperature of air (°C) and T_p is the average temperature of the absorber surface of the solar collector (°C).

Eq. (E) indicates that a plot of efficiency against $\left(\frac{T_o - T_i}{I}\right)$ will result in a straight line whose slope is F_o U_L and ordinate axis-intercept is F_o $(\tau\alpha)_e$; if F_o U_L and $(\tau\alpha)_e$ are not very strong functions of operating parameters like mass flow rate, intensity of solar radiation, ambient temperature, and wind velocity variations. This approach, similar to the one conventionally used for solar flat-plate collectors, undoubtedly, assumes that the dependence of F_o on mass flow rate which positively exists, is weak. Furthermore, considering that the performance can be expressed by another equation, containing the temperature gain produced by the collector and expressed as

$$\eta = \frac{mC_p(T_o - T_i)}{I} \qquad \text{(F)}$$

Where m is the mass flow rate per unit collector area (kg/m²h) and C_p, is the specific heat of air (kJ/kg°C). Thus, by measuring the air flow rate, solar intensity at the inclined plane, outlet and inlet air temperatures of the heater, one can find the efficiency.

5. OBSERVATIONS

Table -1: Environmental and performance parameters of Plane Surface Geometry

Flow Rate (Kg/m²h)	Ambient Temp (⁰C)	Inlet Air Temp (⁰C)	Max Rise in Temp (⁰C)	Overall Efficiency (%)	Pressure Drop (Pa)
20	29	30	37	17	15
40	28	28	27	22	56
55	30	30	37	44	69
80	28	31	27	47	89

Table -2: Environmental and performance parameters of Dimpled Shaped Surface Geometry

Flow Rate (Kg/m²h)	Ambient Temp (⁰C)	Inlet Air Temp (⁰C)	Max Rise in Temp (⁰C)	Overall Efficiency (%)	Pressure Drop (Pa)
20	28	30	37	18	10
40	29	33	30	23	32
55	29	31	28	33	48
90	28	34	27	45	93

Table -3: Environmental and performance parameters of Cuboid Shaped Surface Geometry

Flow Rate (Kg/m^2h)	Ambient Temp (^0C)	Inlet Air Temp (^0C)	Max Rise in Temp (^0C)	Overall Efficiency (%)	Pressure Drop (Pa)
45	29	33	54	55	28
70	28	32	34	57	34
80	29	30	22	59	65
100	28	31	21	60	95
130	30	31	18	63	100

6. RESULT ANALYSIS

Comparison of the results of Plane, Dimpled Shape & Cuboid Shape showed a substantial enhancement in thermal efficiency as a result of using selective coated Aluminium Surface Plate as absorber.

6.1 Graphical Analysis of Plane Surface Geometry

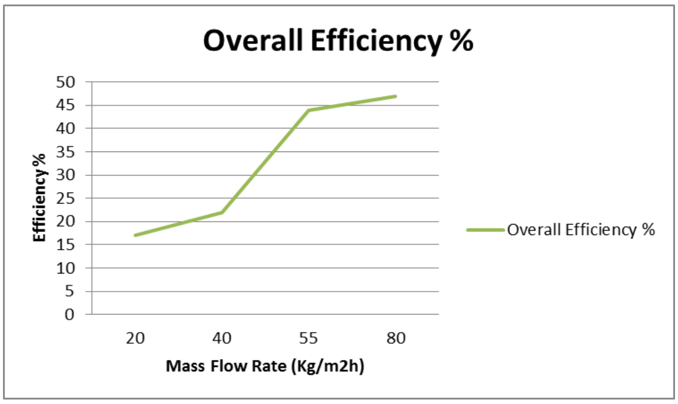

Chart -1: Overall Efficiency v/s Air Mass Flow Rate

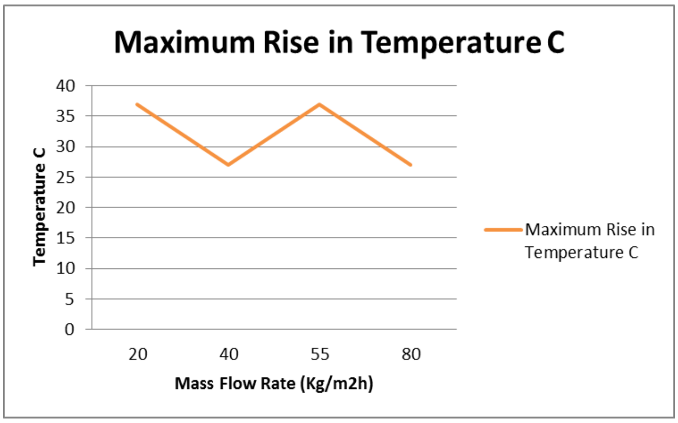

Chart -2: Temperature v/s Air Mass Flow Rate

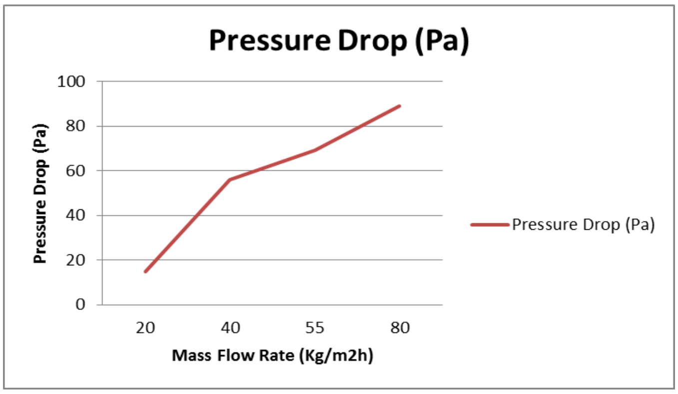

Chart -3: Pressure Drop v/s Air Mass Flow Rate

6.2 Graphical Analysis of Dimpled shape Surface Geometry

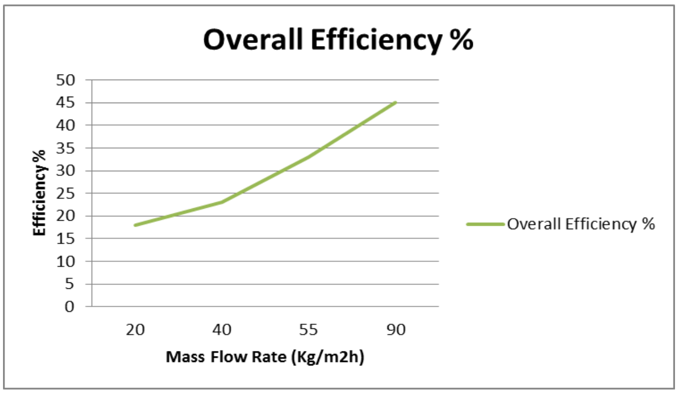

Chart -4: Overall Efficiency v/s Air Mass Flow Rate

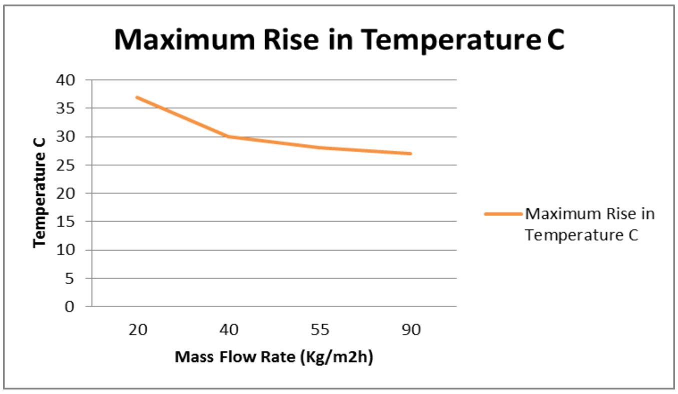

Chart -5: Temperature v/s Air Mass Flow Rate

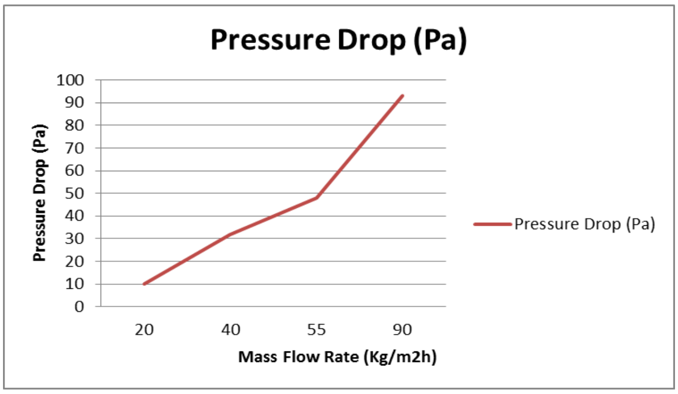

Chart -6: Pressure Drop v/s Air Mass Flow Rate

6.3 Graphical Analysis of Cuboid shape Surface Geometry

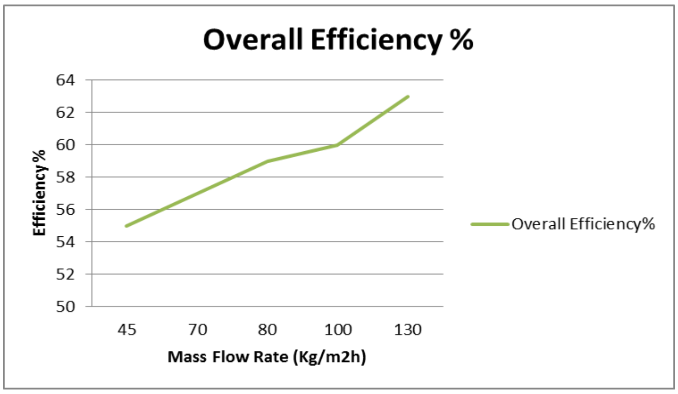

Chart -7: Overall Efficiency v/s Air Mass Flow Rate

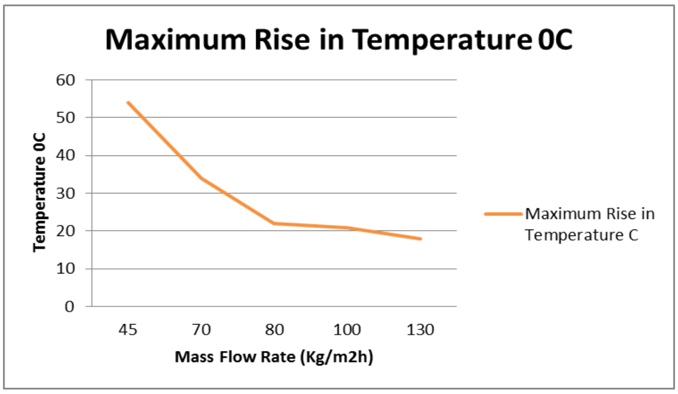

Chart -8: Temperature v/s Air Mass Flow Rate

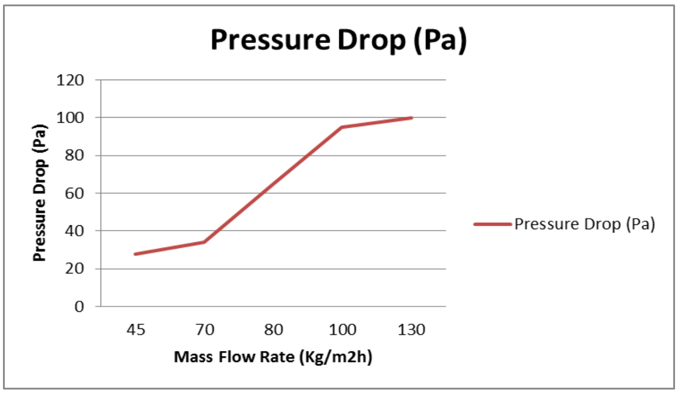

Chart -9: Pressure Drop v/s Air Mass Flow Rate

Among the different types of Surface Roughness Geometries tested, maximum outlet temperature was observed for Cuboid Shaped Surface Roughness Geometry. The temperature attained was 87.6°C at 12.50 p.m for a mass flow rate of 45 kg/m²h. The rise in temperature for Cuboid Shape of 54.1°C (above ambient) was remarkable in this study. The average efficiency for the same mass flow rate was 55%. The better thermal performance of Cuboid Shape is probably due to the better convective heat transfer between the Aluminium absorber plate and air. The absorber plate was 'selective coated black chrome Aluminium sheet' which has high absorptivity.

The second highest maximum temperature was recorded for Dimpled Shaped Surface Roughness Geometry, which was for the same mass flow rate in which the Dimpled Shape attained its maximum temperature i.e. 45 kg/m²h. The maximum temperature attained was 76.6°C, which was above 43.3°C above ambient. The overall efficiency calculated for this mass flow rate was 52.55%.

As seen from the above charts, the maximum temperature attained for overflow aluminium collector was 70.9°C, 69.8°C and 704°C, respectively. This temperature was for corresponding flow rates of 20, 55 and 72 kg/m²h. At low mass flow rate studied, say 45 kg/m²h, the highest value of efficiency was calculated for Cuboid Shaped collector. The efficiency of both low and high mass flow rates for Cuboid Shaped and Dimpled Shaped was almost equal.

7. Conclusion

The study proved that the solar air heaters with Cuboid Surface Roughness Geometries as absorber plate promote turbulence, exhibited high heat transfer coefficient and efficiency. For the same air flow rate (45 kg/m²h), the average efficiency of the Plane Shape is 26%, whereas that of the Dimpled Shape was 55%. The instantaneous efficiency recorded while the collector reached its maximum temperature, was 88%. The maximum temperature difference was 54.l°C for a flux of 930 W/m2.

The results exemplified, as expected, that a surface roughness with maximum barricades, the absorber plate performed better. The additional electrical power required to push the air through the Cuboid Shaped Surface Roughness.

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