DESIGN AND TECHNO- ECONOMIC ANALYSIS OF A SOLAR MATRIX COLLECTOR FOR DRYING APPLICATION

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Keywords

- Solar thermal
- Solar air heater
- Wire mesh collector
- Dryer
- Economic analysis

ABSTRACT

In the current world energy scenario, use of renewable energy is found to be exponentially increasing every year. India, being in the tropical region, has very good solar energy resource with nearly 300 sunny days on average. Many Solar PV and Thermal installations have been done to utilize the same. Hot air generation through solar air heaters is considered as one of the prominent applications of utilizing solar energy. Few developments have been taken place to utilize solar air heaters for applications like drying, process heating etc. This paper explains the development of a solar air heater with wire mesh as absorber, with nominal porosity for flow of air through it. The main advantage of this type of design is the hot air will not have contact with the glazing and hence top loss coefficient is minimized. The performance of the air heater is studied using a dryer as the end application. Thermal analysis of the air heater was done to determine its efficiency. Products, used in dryer, are different types of vegetable, say bitter guard and hence the study was done to compare the open sun dried and the solar dried samples. Economic analysis for the drying application was also investigated.

1 INTRODUCTION

Solar energy is the primary energy source and all other energy sources are derived from solar energy. Direct utilization of solar energy can be done by two technologies, solar Photo Voltaic and Solar Thermal. Solar PV can used for direct conversion of solar energy to electricity whereas solar thermal can be used for converting solar energy to thermal energy or electrical energy by means of thermal power generation. Generating power from solar thermal technology requires concentrated technologies like Fresnel lens, parabolic dishes, parabolic troughs, concentration towers etc, which can produce high temperate of more

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than 400°C based on their concentration ratio. Fluid heating is the most commonly used solar thermal application.

Either water or air is the most commonly used fluid. Much innovation has been come for solar water heater with different technologies like Flat Plate Collectors (FPC), Evacuated Tube Collectors (ETC) and Evacuated Tube Heat Pipes (ETHP). Unlike water, air doesn’t have good thermodynamic properties and hence the efficiency will not be on par with solar water heaters (Kurtbas and Turgut, 2006). But solar air heaters are less complicated than solar water heaters because of less impact of corrosion and leakage. Solar air heaters are mostly used for crop drying, process heating, timber seasoning, space heating and other applications. Solar air heaters are mostly classified as active and passive systems. Passive systems will not have a driving device like fan or blower and are used for mostly space heating applications whereas active system work with a blower or fan for getting the required conditions. Fig. 1 shows the schematic diagram of a solar air heater.

Many researchers have come forward with different innovations to improve the performance of the air heater. Irfan and Emre (2006) experimentally investigated the efficiency and exergy loss of a solar air heater with free and fixed fins. Results show that the exergy loss is directly affected by the efficiency and the temperature difference of the fluid. It is also found that fixed fins are more effective than the free fins because of the higher outlet temperature and pressure drop they produce. Saravanakumar et al. (2012) studied the behaviour of flat plat collectors with and without thermal storage using a mathematical model and found that the efficiency is 5 to 10% greater for system with thermal storage. The results were validated experimentally.

Walid et al. (2012) studied the performance of a forced convection solar flat plate air heater with energy storage. Experimental and theoretical results show that the mass flow rate and solar radiation are the major parameters which determine the performance of the collector. For getting a particular temperature for applications like drying, mass flow rate is to be optimized. Hematian et al. (2012) explained the working of a flat plate air heater for free and forced flow and found that heat loss is lesser for forced flow even though the temperature rise obtained is lower. The contact area for convection was increased using Venetian formation in the absorber plate Research on improving the efficiency of the flat plate collectors were done by Yeh and Lin (1996) by dividing the air channel using parallel barriers, as shown in Figure 2, thereby creating sub-channels for air flow. Experiment was repeated for different locations of the barriers and hence optimized the best barrier location for the design.
Verma et al. (1992) optimized the solar air heater design for ten configurations of absorber plates and reported the optimum mass flow rate for each configuration and the thermal efficiency is found for the optimum conditions as shown in figure 3. Double flow configuration with a single glazing is found to give the best performance.

Esen (2008) studied on the energy and exergy efficiencies of a double pass air heater with different types of absorber plates for wide range of working conditions. Obstacles in the absorber plate is found to
increase the heat transfer area and hence the efficiency. Similar studies were done by Ebru and Fatih (2010) for different types obstacles in the absorber plate. Improvement in thermal efficiency of air heater using fins is studied by comparing the performance with and without fins by Chabane et al (2013). The results show an increase in efficiency of the air heater for finned collectors, which will depend on the solar intensity, mass flow rate and surface geometry of the collector. Basharia et al. (2012) used two types of air heater, flat plate absorber with porous medium and V-grove absorber, both having double flow mode, to study the effect of mass flow rate and geometry of the collector on the thermal performance of the collector. Thermal efficiency of the V-grove type is found to be 4-15% more than the flat plate with porous medium. Cost benefit analysis also shows that the cost for V-grove type is less than that of flat plate with porous medium because of the higher pumping required for the later.

Kapardar and Sharma (2012) investigated the performance of solar air heater with porous medium as collector, for different mass flow rates and different type of materials like glass wool and steel wool and found that the efficiency is increasing with increasing mass flow rate. There is also a noted increase in efficiency of about 10% for glass wool and 26% for steel wool. Thermal performance analysis is done using a mathematical model for an air heater with absorber plate having improved roughness using V-down discrete rib (Karwa and Srivastava, 2013). There is an increase in thermal efficiency of 6-26% for roughened duct air heater than smooth duct air heaters. The mass flow rate need to be varied based on the change in solar intensity for constant temperature output. A roof top solar air heating system for drying applications has been designed and is performance has been analysed using a batch drier by Sreekumar (2010). The batch drier is used to dry pineapple slices with initial moisture content of about 82% to less than 10% in 8 hours. Economic analysis was done using three methods namely, annualized cost, present worth of annual savings, and present worth of cumulative savings. Tyagi et al. (2012) reviewed about solar air heating system with and without thermal energy storage with energy and exergy analysis of the sir heaters and discussed about a hybrid PV/T Solar air heater system for better utilization of solar energy.

Mohanraj and Chandrasekhar (2009) performed an analysis on an indirect solar drier for chilli drying which uses gravel as heat storage medium. The heat storage helped to increase the working time to nearly 4 hours with thermal efficiency nearing 21%. Prakash and Kumar (2013) reviewed the development of solar drying technology with design and working principle of various types of dryers which are evolved during the development. Use of PV systems to power the active systems was motivated to reduce the dependence of conventional energy sources. Stiling et al. (2012) demonstrated the effect of adding mobile concentrating solar panels (CSP) to a mixed mode solar drier and found the temperature and relative humidity is higher for the CSP than normal ones. This results in the reduction of drying time. Theoretical evaluations of solar driers are also well explained.

Many researchers studied the performance of air heater with wire mesh absorber. Wire mesh is normal wire woven or cross rod to form net like sheet with pores in them through which fluid can pass through. This type of flow over the wire will increase the convection heat transfer from the collector to the fluid as shown in figure 4. Former researches reveal usage of wire mesh bed for improving heat transfer. In using wire mesh, the dimensions of the wire and the porosity of the wire mesh play a vital role in the performance of the solar fluid heaters. Tong and London (1957) explained the heat transfer phenomenon in woven screen and cross rod matrices. Algebraic equations for and graphical representations were given for
interpolation and for tentative usage. The effect of porosity on the heat transfer and friction factor is well explained.

![Diagram of wire screen used as packing element](image)

**Fig. 4 Schematic of wire screen used as packing element**

Design of a matrix air heater with longitudinal flow and its thermal performance was studied by Bharadwaj et al. (1981). The efficiency was found to be decreased from 38.9% to 27.4% for a gap of 20 days. Al-Nimr (1993) generated a mathematical formulation to explain the transient behaviour of the matrix solar collector for sudden changes in the solar radiation and in inlet air temperature. Ahmad et al. (1996) experimentally studied the effect of geometry of the matrix geometry, inlet temperature and mass flow rate on the thermo hydraulic performance of a packed bed solar air heater. The efficiency is found to increase for increase in mass flow rate and once reaching a maximum value it declines with further increase in mass flow rate. Varshney and Saini (1998) experimentally investigated the effect of geometry of the wire mesh bed on the heat transfer and friction factor by developing correlation for Colburn J-factor and friction factor. Development of a metal matrix solar air heater to reduce the problems of conventional air heaters were done by Kolb et al. (1999) for copper matrix with different type of selective coatings. The pressure loss in the air heater is found to depend only on the mass flow rate and not on the matrix composition and coating.

Thakur et al. (2003) carried out experimental investigation on the heat transfer and friction factor correlations for a low porosity packed solar air heater for different no. of layers. The findings shows that geometric parameters of the wire mesh packed bed have direct impact on heat transfer and friction factor. Mittal and Varshney (2006) studied the thermal performance of a wire mesh packed bed solar air heater, as shown in figure 5, with bed of different porosity and optimized the parameters which can affect the performance of the collector like mass flow rate, geometry of the wire mesh, etc.

Velmurugan and Ramesh (2011) proposed a wire mesh solar air heater with 20 mm wire mesh packed between the second glass cover and the absorber plate. The study shows an increase of 5% in overall efficiency when compared with conventional one.
2 PERFORMANCE ANALYSIS

2.1 Solar Air Heater

For the performance analysis, all properties of air, viz. Density, viscosity, specific heat, Prandtl No. etc., are calculated for the arithmetic mean of air inlet and outlet temperature. The heat transfer rate, \( Q \) to the air from the collector is given by the eqn 1

\[
Q = FR \cdot A_p \cdot [(τα)_e \cdot I - U_L \cdot (t_p - t_o)]
\]

where \( F_R \) is the collector heat removal factor, \( A_p \) is the collector area, \( (τα)_e \) is the product of transmittance the glass plate and the absorptivity of the collector material, \( I \) is the solar irradiance per unit area, \( U_L \) is the heat losses, \( t_p \) is the collector temperature and \( t_o \) is the ambient temperature.

For calculating the collector heat removal factor \( F_R \), rather than the collector area \( A_p \), wetted area or heat transfer area \( A \) of the collector is used which can found using the eqn 2.

\[
A = \frac{4A_pL(1-P)}{d_w}
\]

where \( L \) is the length of the duct, \( P \) porosity of the wire matrix and \( d_w \) is the wire diameter of the mesh wire.

The efficiency \( η \) can be given by

\[
η = \frac{Q}{I} = \frac{m_a c_p(t_p - t_o)}{I}
\]

where \( m_a \) is the mass flow rate of the air, \( c_p \) is the specific heat of air, \( t_p \) is the collector temperature and \( t_o \) is the ambient temperature.

2.2 DRIER

Drying is nothing but removal of moisture. Moisture content in any material is expressed in wet and dry basis. Mostly for agricultural products moisture is expressed in wet basis as

\[
X_w = \frac{m_w}{m_{w} + m_d}
\]
where, $m_w$, is the mass of moisture /mass of wet solid in kg and $m_d$, is the mass of moisture /mass of dry solid in kg.

The moisture content in the samples was found by drying them using an electric oven at 105±10 C until constant weight is reached. The initial mass $m_i$ and the final mass $m_f$ are found out using an electronic weight gauge. The moisture content, $M_w$ is found for a regular interval using the following equation

$$M_w = \frac{m_f-m_i}{m_i} \times 100 \%$$

(5)

Drying Rate, DR for the sample depends on its initial moisture content, $m_i$, and the equilibrium moisture content, $m_e$, and is given is given by

$$DR = \frac{dM}{dt} = -k (m_i - m_e)$$

(6)

where $k$ is the drying constant.

The thermal efficiency of the drier can be given as,

$$\eta_{th} = \frac{m_w h_{fg}}{m_a C_p (T_o - T_i) + BP} \times 100 \%$$

(7)

3  METHODOLOGY

3.1 Experimental Setup

The solar collector was designed using normally available materials with required properties. The collector was designed for an area of 2 m\(^2\) with 2 m length and 1 m width. The absorber plate is a GI wire mesh with a wire diameter of 1 mm and a pitch of 3.175 mm. The absorber plate has two layers of wire mesh with divider in between of 2mm diameter to maintain the gap. The absorber plate is inclined along the length of the collector as shown in Figure 6.

Fig. 6 Schematic of the wire mesh solar air heater
The inclination helps in proper flow of air through the wire mesh and hence the hot air does not get in contact with the glazing, hence reducing the convection loss. The wire mesh and the back plate are painted with selective coating with absorptivity of 0.95. The glazing is of toughened glass of 4mm thickness (transmissivity =0.90). The sides and bottom part of the collector are made of 50mm PUF sandwich of low thermal conductivity (0.16 W/mK). Three such collectors are connected in parallel. The outlet from the collector panels are connected to centrifugal blower. The centrifugal blower has the capacity suck air through the solar collector panels at the required flow rate.

\[ \text{Fig. 7 Experimental Setup} \]

The mass flow rate of centrifugal blower is 500m\(^3\)/hr, powered with a 0.5 H.P. motor. The output of the blower is fed to a drier of 30 Kg capacity. The walls of the drier are made with 50mm PUF sandwich with SS304/GI as inside/outer layers respectively and have 10 trays each of 3Kg capacity. There is a mixer space provided as shown in the figure so as to distribute the air evenly to the drying area. In the mixer chamber, there are baffles provided to distribute air evenly to the drying chamber.

### 3.2 Working principle

When the solar radiation falls on the collector, the absorber gets heated up. Good absorptivity of the black chrome coating on the wire mesh collector helps in increasing the absorption capacity of the wire mesh. The glazing having high transmissivity helps in allowing the incoming short wave radiations to pass through and reflects back the long wave radiations from the absorber and back plates. The incoming air gets in contact with the absorber wire mesh and the heat is transferred by convection to the hot air. The air will pass through the wire mesh and gets heated up. Once it passes through the wire mesh, the hot air has very less chance of getting in contact with the glazing. This helps in reducing the heat loss due to cooling effect of the glazing. Further, the air will also get heated up by convection from the back plate.

The centrifugal blower provides the pressure drop inside the collector panels to suck air from atmosphere and also to pump the air into the drying chamber. The hot air is allowed to pass through the trays where the product to be dried. The air circulation is maintained using baffles which diverts the air uniformly to all sides. The hot air absorbs the water vapour from the product and exits into the atmosphere.
3.3 Instrumentation

The temperature sensors used are RT100 sensors, placed at required points, connected to a digital display with a selector. A digital weighing machine is used to measure the weight of the samples. A sophisticated LP 471 Pyranometer with an accuracy level of 1° was used to measure solar radiation intensity.

4 RESULT AND DISCUSSION

A set of experiments were carried out at Solar Thermal Energy Laboratory of Pondicherry University to determine the thermal behaviour of developed system. Experiment was done by keeping the mass flow rate constant. Performance of air heater and the drier was studied by loaded and no-loaded condition. The parameters (Ambient Temperature Ta, Inlet Temperature Tin, Absorber plate Temperature Tp, Outlet Temperature Tout, Solar Radiation I) measured when operated without load is shown in the Figure-8. The maximum output air temperature recorded was 700°C, when an intensity solar radiation of 767.2 W/m², measured at 12:00 pm. The mass flow rate was maintained at 500 m³/hr. The high outlet air temperature than the absorber material is the black coated back plate, which enhances the heat addition.

Similarly parameters (Ambient Temperature Ta, Inlet Temperature Tin, Absorber plate Temperature Tp, Outlet Temperature Tout, Solar Radiation I) recorded when operated with load is shown in Figure-9. It shows the highest temperature of 74°C at 1:10 pm, when the solar radiation available was 829.5 W/m².

![Fig. 8 Temperature & Solar Radiation Vs Time (Without Load).](image)

From both the figures, it is clearly found that there will be a rise in temperature of the output air when there is higher solar radiation. In the first case, the ambient temperature is found to be varying from 32°C to 35°C, whereas in the later, the ambient temperature was varying from only 29°C to 32°C. But the outlet air temperature of the later was found to be higher. This is well explained by the higher solar radiation available when operating with load.
Fig. 9 Temperature & Solar Radiation Vs Time (With Load).

Fig. 10 Drying Curve for the sample

Fig. 11 shows the comparison between open sun drying and the solar drying with the moisture retained in the sample after every hour is marked against time. The graph shows a little higher drying rate in solar drying than open sun drying.

Also the Fig. 11 shows the quality of drying in both the cases. The sample from solar drying shows a better quality of drying, with the retaining of its natural color, whereas the open sun drying sample shows a lesser quality because of its dark patches in them due to direct sun.

5 CONCLUSION

A wire mesh solar air heater for drying application was designed and tested. The importance is given to the solar air heater. It is tested with and without load and the variations in performance are studied. It is found that the highest temperature of 74 °C is attained when operated with load. Even though there is only little variation from solar and open sun drying, the quality of the product dried is comparatively much better. The natural colour of the product is retained in solar drying whereas in open sun drying, there is a discolouration. Also due to exposure to atmosphere, there is a risk of contamination due to dust and other
materials, which can be completely eliminated in solar drying. 90% of the moisture content is removed in 5 hours, then the drying rate is constant because there will be some residual moisture in the sample.

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References


