SOLAR AIR HEATER WITH HEAT STORAGE

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ABSTRACT

Experimental investigations of solar air heater with box-type absorber and with heat storage unit has been performed. The heat storage unit was filled with a commercial grade paraffine wax and its phase changes were applied to store the heat during operation of the air heater. Amounts of energy delivered by this air heater as well as by similar air heater but without heat storage unit were measured. Initial results revealed that the energy amounts delivered by solar air heater with heat storage unit are bigger than those delivered by solar air heater without heat storage unit.

INTRODUCTION

Solar air heaters have many advantages over liquid heaters regarding problems of corrosion, boiling and freezing. Air heaters have been, therefore, finding increasing application in agricultural and residential fields. One of the most promising applications of solar air heaters is the supply of hot air for drying of agricultural products like grain, hay, foods etc.

Thermal efficiency of solar air heaters is relatively low due to poor convective heat transfer coefficients between the absorber plate and the air which results in the absorber temperature much higher than the air stream temperature and greater heat losses to the surroundings. Another disadvantage inherent solar air heaters is limited storage capabilities resulting from low thermal capacity of the air. In order to enhance the thermal efficiency of the air heaters different modifications are suggested and applied. These modifications include means leading to increased heat transfer area between the absorber plate and the air and augmented heat transfer coefficient. It has been found that the main thermal resistance to the convective heat transfer is due to formation of boundary layer on the transferring surface. Efforts for enhancing heat transfer have been directed towards artificially destroying or disturbing this boundary layer. Artificial roughness in form of wires and various arrangements have been used to create turbulence near the wall or to break the boundary layer [1,2]. Enhanced heat transfer coefficient can also be obtained in corrugated solar air heaters [3,4].

In order to enhance the efficiency of the solar air heaters a greater heat transfer area between the absorber plate and the air is often introduced in different ways. The increased heat transfer area can be obtained by using a finned absorber, box-type absorber or V-corrugated absorber [5,6]. Greater heat transfer area is also obtained in a suspended plate, double flow solar air heaters. In this case the air to be heated flows on either side of the absorber plate [7].

Enhanced thermal performance is also obtained in matrix-type air heaters by using a porous absorber which improves heat transfer from the absorber to the airstream. The collector channel formed by transparent cover and bottom and side walls is filled with iron or aluminium or glass chips. The porous absorber absorbs the solar radiation "in depth", so that the absorber temperature is relatively low and the heat losses occurring from the absorber to the surroundings are low. The large surface area of the packing material and the turbulence producing air flow path through the bed provide high rate of the heat exchange [8]. Further reduction of heat losses at the front cover can be achieved by using two glass covers [9] instead of one. The ambient air can be forced to flow between the covers before passing through the absorber. In such a manner energy extracted from the glass cover is used to preheat the air. However the porous absorber enhances the thermal efficiency of the air heater significantly, but there is a substantial increase in pressure drop and, consequently, a higher mechanical power requirement to move the air.

It is often desirable that solar energy utilization system also have a heat storage effect in order to compensate for the irregular supply of solar radiation or to prolong heated air supply in case when solar radiation falls significantly due to clouds or sunset. Thermal energy could be stored, in general, in the form of either sensible or latent heat.

Heat storage capacity of packed bed filled with metallic chips is unsatisfactory for solar drying systems due to low heat capacity. In order to alleviate this problem rock beds have been proposed [10]. In case of nontransparent packing (rocks, porcelain beads, metal chips) the highest temperature is on the top surface in the first period of heating and becomes gradually more uniform till steady state is reached since a large portion of the incident radiation is absorbed around the top of the bed and the heat absorbed there is transferred to the bottom of the bed by thermal conduction or convection. In case of semitransparent packing the temperature peak is observed within the bed [11].

The solar air heaters may be connected in parallel, series or a combination of the two. A series connection would result in a long system but higher discharge air temperature system, whereas a parallel connection would result in a shorter system but lower discharge air temperature. The efficiency of such systems depends upon the physical design of the solar air heaters, heat losses, air circulation rates, and prevailing ambient conditions.

SOLAR AIR HEATER WITH BOX-TYPE ABSORBER AND HEAT STORAGE UNIT

A scheme of a solar air heater with a box-type absorber and heat storage unit is shown in Fig. 1. The absorber consists of two metallic plates, top and back ones. The plates are joined to each other by means of equidistant slates. The plates and the slates are made of aluminium, copper or steal. Top and back plates and the slates form flow channels. The slates and the back plate improve the air heater efficiency. Firstly, as it was already mentioned, they increase the heat transfer area exposed to flowing air. This area includes the top plate, the slates and the back plate. Secondly, as a result of the heat conduction through the slates from the absorbing surface that receives the solar energy, to the absorber back plate. The resulting decrease of the top plate temperature lowers the top heat losses, whereas the increase of the back plate temperature and back losses are very small.

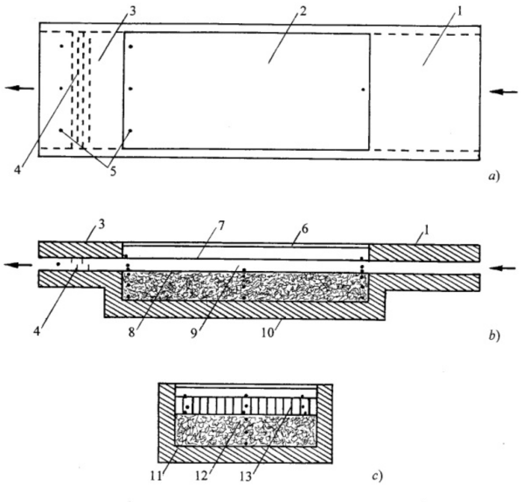

Fig. 1. Schematic presentation of solar air heater with box-type absorber and heat storage unit;
1 – inlet section, 2 – test section , 3 – outlet section, 4 – mixing section, 5 – thermocouples, 6 – glazing, 7 – top plate of box-type absorber, 8 – back plate of box-type absorber, 9 – collector channel, 10 – heat storage unit, 11 – insulation, 12 – paraffinic wax, 13 – slate

The absorber was made of 1.5 mm aluminium sheets. The absorber was 2 m long and 0.85 m wide. The top and the back plates were at a distance 0.025 m apart. The number of the slates was equal to 18, and the distance between two successive slates was 0.05 m.

The air heater was instrumented with NiCr – Ni thermocouples for measuring temperature distributions in the absorber and in the heat storage unit and of the air in the collector channel. Figure 1 shows also the location of the thermocouples. In Fig. 1a are shown only locations of the thermocouples measuring the air temperature. Three thermocouples arranged span-wise were located at the exit of the absorber. Another three thermocouples were arranged span-wise behind the mixing section of the outlet duct. The mixing section was provided with four baffles for purpose of mixing the hot air coming out of solar air heater channel to obtain a uniform temperature of air (bulk mean temperature).

HEAT STORAGE UNIT

From an energy storage point of view, latent heat thermal energy is an efficient and suitable means of heat storage, and has advantages of large thermal capacity with constant storage (melting) temperature.

The major advantages of the phase change heat stores are their large heat storage capacity and their isothermal behaviour during charging and discharging processes. Particularly large latent heat and consequently high energy density have salt hydrates like sodium sulphate and calcium chloride. However, they show several disadvantages after repeated cycling. Because of incongruent melting, segregation may occur, moreover, large subcooling effects hamper their application. Due to these difficulties organic phase change materials such as paraffine waxes and fatty acids has gotten widespread attention.

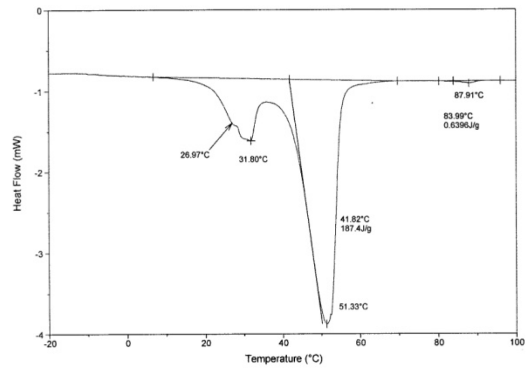

Fig. 2. DTA curve of paraffinic wax used in the experiment

As a phase changing material to heat storage a low melting commercial paraffinic wax marketed by Fabryka Parafin Naftowax Sp. z o.o. in Trzebinia was used. The melting and solidyfing properties of the wax were measured by means of calorimetric Differential Thermal Analyzer. The response of the DTA measurement is given in Fig. 2. Two peaks were found. This is typical for most paraffines and waxes. The change of enthalpy of the wax in the range of the temperature from 15 to 60ºC is equal to 187 kJ·kg-1. In main melting range of the wax in the temperature range from 35 to 60ºC enthalpy change is equal around 148 kJ·kg-1 . The wax shows solid-solid phase change transition in the range around 15 to 35ºC and appropriate enthalpy change is equal around 40 kJ·kg-1.

For organic materials, like paraffinic waxes, the thermal conductivity lies in the range of 0.1÷0.2 W·m-1·K-1, both for solid and liquid. These low values allow only a small heat transfer rate when a solidified layer of wax has been formed on the heat exchanger surface during heat extraction. In the case of heating the waxes, the melted liquid shows natural

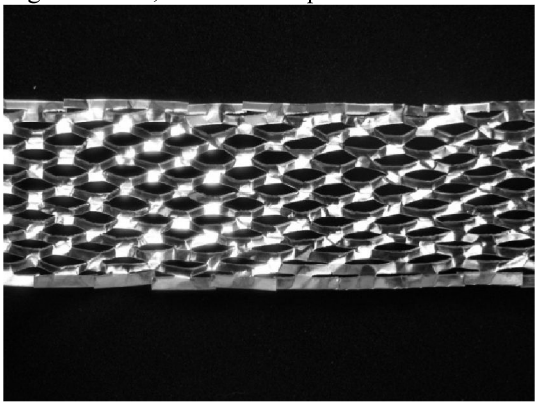

Fig. 3. Aluminium thin strip matrix

convection effects and conduction is less essential. To improve on the conduction heat transfer aluminium thin strip matrix structures were embedded into the wax. The aluminium matrices were glued to the back plate of the absorber with special high thermal conductivity glue. The aluminium thin strip matrix structure is shown in Fig. 3. Its thickness was 0.09 mm, the width of the strips was approximately 4 mm. The improvement in thermal conductivity due to introduction of the aluminium strip matrix was found to be approximately linearly related to the volumetric percentage p of the matrix in the heat storage unit [12]. The effective thermal conductivity of the wax with the aluminium structure embedded in it is given by the following experimental relationship:

$$\lambda_{eff} = (1+1{,}85p)\lambda_w \qquad (1)$$

The volumetric percentage of the aluminium structure in heat storage unit was equal to 1.3% and the effective thermal conductivity estimated from Eqn (1) is equal $0.4 \div 0.7\ W \cdot m^{-1} \cdot K^{-1}$.

EXPERIMENTAL SETUP

The experimental test facility was designed and fabricated according to the guidelines given in ASHRAE Standard 93-1983 [13] for testing of solar collectors using an open loop system. The test facility included solar air heater and inlet section and outlet section. A 0.93 m long inlet duct was used to stabilize the flow at the air heater inlet. A 0.75 m long outlet section was provided to reduce any downstream effect of the section. The average of the temperatures measured by the three thermocouples located behind the baffles was the temperature of the air at the solar air heater outlet. Separate thermocouple which measured the ambient air temperature was kept in a shelter to protect the sensor from direct sunlight.

The absorber was blackened with black, mate paint on the side facing solar radiation. Low iron glass pane of 4 mm thickness has been used as a cover over the absorber. Under the absorber was situated the heat storage unit. The heat storage unit was a cuboid vessel partially filled with the wax. Part of the vessel was left free from the wax in order to allow it to expand during melting. Volume change of the wax during phase changes reaches around 15%. The upper wall of the vessel was at the same time the back plate of the absorber. The depth of the heat storage unit was equal to 60 mm. The heat storage unit was insulated from outside by 50 mm polyurethane foam. The sides and the back of the air heater were also insulated by polyurethane.

The outlet section was provided with bell-shaped transition section.

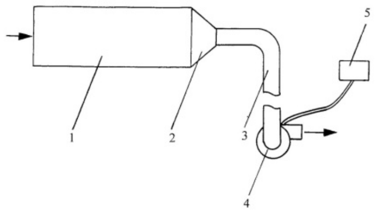

Fig. 4. Schematic diagram of the experimental setup; 1 – solar air heater, 2 – bell-shaped transition section, 3 – tube, 4 – centrifugal blower, 5 – frequency changer

The scheme of the experimental setup is shown in Fig. 4. The solar air heater was facing south and its inclination to the horizontal was varied between 40 to 60º. The solar air heater was on the suction side of a centrifugal blower of 550 W. Two Kipp&Zonen pyranometers were used to measure solar global and diffused irradiance the air heater aperture. The air flow rate was measured by means of hot-wire anemometer in the tube behind bell-shaped transition section. The air mass flow rate in the air heater was calculated from air flow velocity at the outlet tube and known duct area. Air flow rate was controlled by means of a frequency changer. The air mass flow rate per unit area of the absorber was varied between 0.013 to 0.025 $kg \cdot m^{-2} \cdot s^{-1}$ (flow Reynolds number ranging from around 2000 to 3800).

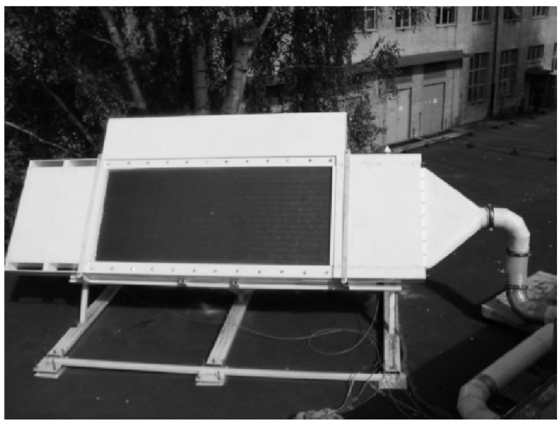

Figure 5 shows the investigated solar air heater with the heat storage unit.

RESULTS AND DISCUSSION

Average air heater efficiency

To evaluate the utilizability of solar air heaters equipped with heat storage units their thermal efficiency η_{av} averaged over several hours is measured [14]. If the average efficiency is measured from the sunrise to the sunset then the daily average air heater efficiency is obtained. The average air heater efficiency is defined as follows:

$$\eta_{av} = \frac{c_p \dot{m} \int_{t1}^{t3} (T_{out} - T_{in}) dt}{A \int_{t1}^{t2} G(t) dt} = \frac{Q}{H} \qquad (2)$$

The average thermal efficiency is also measured in case of solar air heaters without heat storage units. In case of the air heater without the heat storage unit $t_3 = t_2$. At the time t_1 irradiation of the air heater begins and at the time t_2 the irradiation completes. If the measurements of the average efficiency are to be performed during part of daytime the aperture of the air heater should be initially shielded from the solar radiation by means of solar reflecting cover. At the time t_1 when the measurement begins the cover should be removed. When the measurement is to be completed, at the time t_2, the movable cover should be put on the air heater. At the same time the measurement of the temperature rise of the air between the inlet and the outlet may also be finished. In the air heater with heat storage unit part of heat released in the absorber is transferred to the air and part is lost to the surroundings, the rest is transferred to the wax into the heat storage unit. To take into account the heat recovered from the heat storage unit the measurements of the average thermal efficiency are continued after shielding the solar air heater from the solar radiation (at time t_2), until the temperature of the air at the outlet is higher than the ambient air by more than 5 ºC. As soon as the elevation of the air temperature at the outlet reaches around 5 ºC, at the time t_3, the measurements are completed. As a result, in Eqn (2) referring to the solar air heater with heat storage unit $t_2 < t_3$.

The measurements of the average collector efficiency η_{av} were usually performed between around 10:00 a.m. to 2:00 p.m. The following measurements were made:

- the global and diffuse solar irradiance at the air heater aperture,
- air temperatures at the air heater inlet and at the air heater outlet,
- temperature distributions along the absorber and the heat storage unit,
- air flow rate in the air heater.

The average air heater efficiency as a function of air flow rate is shown in Fig. 6.

Solar air heaters with heat storage unit

The thermal conductivity of the heat storage material influences the efficiency of solar air heater. In order to estimate this influence the average efficiencies were measured for solar air heaters equipped with:

- heat storage unit filled with wax,
- heat storage unit filled with wax and aluminum matrix structure embedded in it.

The influence of the thermal conductivity of the heat storage material on the air heater average efficiency was investigated at air mass flow around 0.015 $kg \cdot m^{-2} \cdot s^{-1}$. The measured average efficiency of the air heaters with both types of the heat storage units and the air heater without heat storage are shown in Fig. 6. Both air heaters with heat storage units operate at better efficiency than the air heater without heat storage units.

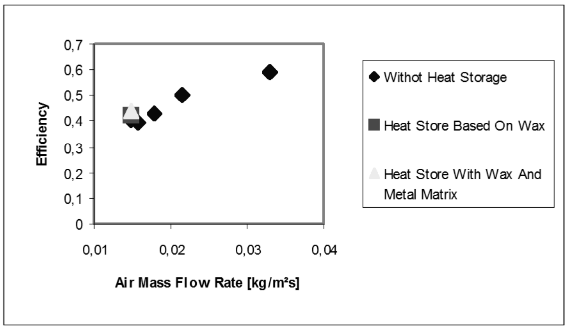

Fig. 6. The efficiency of the air heater with box-type absorber without heat storage unit as a function of air mass flow rate per unit area of the absorber. Average air heater efficiency of solar air heaters with heat storage units filled with wax and aluminum matrix structure and without aluminum matrix structure.

TEMPERATURE DISTRIBUTIONS ALONG THE ABSORBER AND THE HEAT STORAGE UNIT

Temperature distributions along the absorber and the heat storage unit give important information about the air heaters complementary to the measured average efficiencies. Two exemplary temperature distributions measured in the solar air heater with heat storage unit for two air flow rates and one temperature distribution measured in air heater without the heat storage unit are given in Table 1. An analysis of the obtained data of temperature distributions suggests means that should be undertaken to improve the efficiency of the heat storage.

It was found that the temperature of the back plate of the absorber in the section situated behind the air inlet has never surpassed much 40ºC. This temperature is well below the temperature range where melting of the wax performs. As a result it is impossible to fully utilize heat storage capacity of the wax placed under this section of the absorber. This finding suggests that there is no need to place the wax under the entrance section of the absorber. Current length of the heat storage unit may be shorten by around 1/4÷1/3 and it should adhere to middle and exit sections of the absorber. However, further experimental investigation should be performed to determine influence of the hotter heat storage unit on the efficiency of the air heater

Tab. 1.Exemplary temperature distributions in solar air heaters with heat storage unit and without heat storage unit.

air mass flow rate [kg/m²s]	average global irradiation [W/m²]	ambient air temperature [°C]	absorber temperature at air inlet [°C]		temperature in heat storage unit under air inlet into absorber [°C]			absorber temperature in the middle of its length [°C]		temperature in heat storage unit in the middle of its length [°C]		
			back plate	top plate	*	**	***	back plate	top plate	*	**	***
0.013	820	24.0	39.6	42.2	32.9	24.5	19.9			47.1	31.3	19.9
0.015	940	25.6	35.8	37.9	30.6	24.8	21.5			43.9	32.5	25.2
0.015	930	26.8	50.6	53.2				70.0	73.9			

air mass flow rate [kg/m²s]	average global irradiation [W/m²]	ambient air temperature [°C]	absorber temperature at air exit [°C]		temperature in heat storage unit under air exit from absorber [°C]			air temperature at the exit of air heater [°C]
			back plate	top plate	*	**	***	
0.013	820	24.0	73.9	76.4	50.3	37.8	25.7	58.4
0.015	940	25.6	65.2	68.0	47.1	37.7	28.9	50.6
0.015	930	26.8	77.5	82.7				61.6

* at the absorber
** in the middle of the depth of the heat storage unit
*** at the back wall of the heat storage unit

CONCLUSIONS

Initial experimental results has shown that the solar air heater with box-type absorber and equipped with heat storage unit based on wax operates at better efficiency than similar air heater without heat storage. Solar air heater average efficiency is effected by thermal conductivity of phase change material. The higher is the conductivity the better is the efficiency. Conductivity of the phase changing material used in the heat storage unit was improved by embedding thin aluminium strip matrix structures into the wax. The average efficiency of the solar air heater without heat storage unit was equal to 0.40, the efficiency of solar air heater with heat storage unit filled with the wax was equal to 0.42 and the efficiency of solar air heater with heat storage unit filled with the wax and thin aluminium strip matrix structures was equal to 0.44 (10% better than in case of air heater without any heat storage unit). The investigated air heater was able to deliver warm air which temperature elevation over ambient air was at least equal 5ºC during more than 1 h after the solar irradiation was ceased. The experimental investigations will be continued for higher air mass flow rates.

The analysis of the temperature distributions in the investigated solar air heaters suggests application of the heat storage unit shorter than the absorber. The wax should adhere to the back plate of the middle and exit sections of the absorber.

NOMENCLATURE

- A air heater aperture area, m^2
- c_p specific heat of air, $J \cdot kg^{-1}$
- G(t) global solar irradiance at the air heater aperture, $W \cdot m^{-2}$
- H total irradiation at the air heater aperture, J
- $\dot{m}$ air mass flow rate, $kg \cdot s^{-1}$
- p volumetric percentage of the matrix in the heat storage unit, %
- Q useful energy extracted, J
- T_{in} temperature of the air at the air heater inlet, K
- T_{out} temperature of the air at the air heater outlet, K
- t time, h, s

Greek symbols

- λ_w wax heat transfer coefficient, $W \cdot m^{-1} \cdot K^{-1}$
- λ_{eff} effective thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$
- η_{av} average air heater efficiency

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