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EXPERIMENTAL AND THEORETICAL ANALYSES ON THERMAL PERFORMANCE OF A SOLAR AIR COLLECTOR

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Abstract

The present contribution describes the investigation of a solar air collector for space heating in order to develop more efficient and cost effective energy process. Various configurations of absorber and different air flows through the collector were tested. The influence of the air mass flow on the air outlet temperature and thermal efficiency has been studied. The thermal efficiency, fluid outlet temperature, heat increase and heat losses of the collector are calculated depending on the collector geometry, fluid properties, fluid inlet temperature, air flow rate, solar insulation and ambient temperature.

Key words: solar air collector, solar radiation, thermodynamic performance

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1. Introduction

The combustion of fossil fuels has caused the production of greenhouse gases (CO_2, SO_2, NO_x), higher levels of acid rain and air pollution, ozone layer depletion and global warming. The global problem is amplified by future expectations of a considerable increase in power and heat demand. The energy demand associated with heated air for different sectors is quite significant. Solar air heaters have been developed with the aim of reducing the consumption for conventional fuels.

The residential and commercial sectors are larger consumers of fossil fuel. Therefore, the heating and air conditioning of residential and commercial buildings generate an important amount of CO_2. Energy required to heat and air-condition buildings can also be reduced by using renewable sources as alternative to fossil fuel (Sanjay and Vilas, 2014).

Solar air heating is a technology where the energy from the sun, solar radiation, is trapped by an absorbing medium and used for air heating. It is a technology that uses renewable energy for air conditioning or heating in buildings or for different processes (Omajaro and Aldabbagh, 2010). Solar air heaters are the most cost-effective solar technologies, widely used due to their simplicity in space heating, drying of timber, industrial products, vegetables and fruits. They may be also used in combination with photovoltaic panels forming so called photovoltaic thermal hybrid solar collectors (hybrid PV/T systems or PVT) to generate heat and electricity.

The main advantages of solar air collectors are: the working fluid does not freeze or boil, they have noiseless, safely and low cost operation, they do not produce any kind of wastes and have long life cycle (Abdullah and Bassiouny, 2014). The solar air collectors have the following disadvantages: low density, low thermal capacity and small heat conductivity of air which lead to low thermal efficiency, high cost of production and installation and non-uniform flow (Öztop et al., 2013).

Due to their low thermal efficiency and high capital investment cost there are many studies focused on heat transfer enhancement and construction of low cost collectors (Abdullah and

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Bassiouny, 2014; Alvarez et al., 2004; Bilgen and Bakeka, 2008; Gill et al., 2012).

Solar air collectors can be classified according to many criteria, such as: cover type, absorber materials, shape of absorber, absorber flow pattern and flow shapes, active and passive types implying natural and forced convection (Bilgen and Bakeka, 2008; Öztop et al., 2012). A simple air solar collector consists of a selective absorbent surface, which absorbs solar radiation and transfers the absorbed heat to the flowing air by convection. The air heated in this way is introduced into the building for space heating.

The opportunity of partial or total replacement of conventional heating installations depends mainly on the heating load, climatic conditions, technological difficulties and fuel prices, economic considerations being ultimately decisive (Esen, 2008; Sopian et al., 2009).

A solar air heating system consists of three components: a solar collector, a fan and an air distribution system within the building. Depending on the application, the solar air heating systems can reduce the conventional energy consumption in three ways: by active solar heating of air supply in buildings; by recovering the waste heat of equator-facing walls during the winter (heat lost through the building walls is recovered by the air and reintroduced in building); and by the stratification of air inside the tall buildings. The scientific literature is focused on single or double-pass channel of flat-plate solar air heater with roughness elements or fins on the absorber plates (Filiz et al., 2009; Raheleh et al., 2014; Sunil et al., 2012).

The objective of the present work was to search the feasibility to develop a higher performance solar air collector of the above mentioned features including the use of thermodynamics methods and test of low costing materials for absorber. The cost of commercial solar air collectors varies between 1000 and 1900 $, meanwhile the cost of a recycling solar air collector is about 80 $ (http://www.aurorapower.net/products/list/1/categoryid/7/level/a.aspx).

The investigation of the air solar collector has involved: setting of solar collector power, air flow rate (the air fan selection); use of energy analysis to find out the appropriate configuration and optimal operation mode; test set up; apparatus adjustments; collector testing by varying absorber design and operating conditions.

2. System description

Experimental studies targeted a solar air collector whose absorber is made of recycled aluminum cans. This type of collector was designed with the idea of using waste aluminum cans to build an absorber at a price as low as possible. Absorber was placed in a wooden cabinet, thermal insulated and covered with a glass plate with a thickness of 5 mm (transparent surface) to reduce convective heat loss to the environment. The characteristics of solar air collector are given in Table 1.

Table 1. Characteristics of solar air collector

Collector dimensions	2 x 0.8 x 0.1 m
Cover	Low Iron Solar Glass Glass thickness = 5 mm Transmittance = 91% Reflectance = 8%
Absorber area	1.6 m^2
Diameter of air flow channel	0.065 m
Absorber material	Aluminium
Absorber coating	Black paint Absorptivity =(0.95-0.97) Emissivity = (0.95-0.97)

The collector was tested in the courtyard of the Thermal Systems and Environmental Engineering Department, "Dunarea de Jos" University of Galati, Romania (latitude 45°26'N, longitude 28°03'E). The experiments were conducted for various air mass flow rates between 0.025 kg/s and 0.045 kg/s, the air being vehiculated by 12 V, 0.6 A fan with a total cost for power needed less than 0.50 EUR per month. The highest thermal efficiency was obtained for the air mass flow rate of 0.045 kg/s.

The solar air collector has simple design and easy maintenance. The main factors affecting the efficiency of solar air collectors are the collector length and depth, type of absorber, transparent cover, wind speed etc. (El-Sebaii et al., 2007). Increasing the absorber surface will increase the heat transfer to air that circulates through the collector leading to the increase of pressure drop in the collector and increase in energy consumption to circulate air through the collector (Aldabbagh et al. 2010; Ho et al. 2007). The efficiency of the air solar collector with absorber made of aluminum cans was determined by experimental measurements.

The absorber has painted in black to increase the absorption and to lower the emissivity of solar radiation. Collector thermal losses through the housing which take place by conduction through the insulation and convection due to wind are considered to be negligible (due to low temperature inside the collector). The absorber which is the most important part of the solar collector consists of 10 channels made of 130 aluminum cans.

The thermal efficiency of solar air heaters has been found to be generally poor because of their inherently low heat transfer capability between the absorber plate and air flowing in the duct. To make the solar air heaters economically viable, their thermal efficiency needs to be improved by enhancing the heat transfer coefficient (Ebru and Fatih, 2010; Giovanni, 2011).

The heat transfer coefficient for the air flowing through the pipes in the solar air collector tends to be limited due to the fluid boundary layer near to the pipe wall that is stagnant or moves at slow speed, thus acting as an insulating layer (Fatih et al.

2013). In order to break or reduce the thickness of the boundary layer in the pipeline were introduced turbulators by partially cutting the bottom part and removing the top cover of every cans for each column. These cuttings create turbulent flow which reduces the thickness of the boundary layer and thus increases the heat transfer coefficient (Anil and Manish, 2014). The collector was tested in outdoor conditions. Air temperature at the collector inlet and outlet were measured using two thermocouples type I. The wind speed was measured with digital anemometer type Lutron YK-2005.

The solar radiation on the collector surface was measured with a Kipp & Zonen CMP3 pyranometer type. The temperature of absorber surface was measured using an infrared thermacam model FLIR Fluke Ti10 Thermal Imager W/IR Fusion. Measured parameters (air temperature at inlet and outlet of the collector, ambient temperature, absorber temperature, wind speed and air mass flow rate) were recorded every 10 minutes. All tests started at 8:30 AM and ended at 18:00 PM.

Experimental studies were conducted in the period 01.05.2011-15.09.2011 under clear sky conditions. The collector slope was adjusted to 45˚, which is considered adequate for geographical location of Galati city. A schematic view of experimental setup of the constructed solar air collector is shown in Fig. 1.

3. Thermal performance analysis

The theoretical model used to study solar air collector that works in non-stationary regime is described by the balance equation (1):

$$\dot{Q}_u = I_0 - \dot{Q}_p \quad (1)$$

where: $\dot{Q}_u$ - heat output of collector, kW; I_0 - absorbed solar radiation, kW; $\dot{Q}_p$ - heat lost, kW.

Heat output of collector is expressed by the balance equation (2):

$$Q_u = \dot{m} \cdot c_p \cdot (T_{a,out} - T_{a,in}) \quad (2)$$

where: $\dot{m}$ – air mass flow rate, (kg/s); c_p – air specific heat at constant pressure (kJ/kg·K) (Eq. 3);

$$c_p = 0.97034 + 0.6789 \cdot 10^{-4} T + 1.657 \cdot 10^{-7} T^2 - 6.786 \cdot 10^{-11} T^3 \quad (3)$$

where: $T_{a,in}$ - air temperature at collector inlet (K); $T_{a,out}$ – air temperature at collector outlet (K).

Solar radiation absorbed by collector is given by Eq. (3):

$$I_0 = \eta_o \cdot I \cdot A_c \quad (4)$$

where: η_o – optical efficiency; I – solar radiation (kW/m^2); A_c – area of collector absorber (m²)

Lost heat is described by Eq. (5):

$$Q_p = U_c (T_{p,med} - T_{amb}) A_c \quad (5)$$

where: U_c - coefficient heat losses by convection (kW/m^{2}K); $T_{p,med}$ – average temperature of collector (K); T_{amb}- ambient average temperature (K).

Equation (1) can be re-written using the equations (2)-(5) as Eq. (6):

$$\dot{m} \cdot c_p \cdot (T_{a,out} - T_{a,in}) = \eta_0 \cdot I \cdot A_c - U_C \cdot (T_{p,med} - T_{amb}) \cdot A_C \quad (6)$$

Optical efficiency (η_o) and heat loss coefficient (U_c) are parameters that characterize the behaviour of the solar collector (Ozgen et al., 2009). Optical efficiency is the fraction of solar radiation absorbed by the collector and depends basically on the transmittance of transparent cover and absorbance (Prashant et al., 2011).

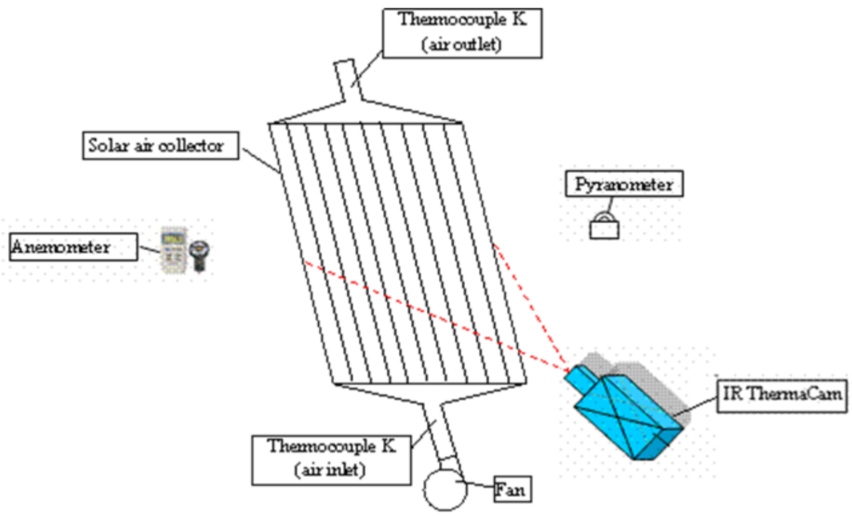

Fig. 1. Schematic view of experimental set-up

The heat loss coefficient includes losses through transparent cover, lateral and bottom sides of collector (Tchinda, 2009). The thermal efficiency of the solar collector (η) is defined as the ratio of energy collected (useful energy) and solar radiation incident on the collector plane (Eq. 7) (Ramadan et al., 2007):

$$\eta = \frac{\dot{m} \cdot c_p (T_{a,out} - T_{a,in})}{I \cdot A_C} \tag{7}$$

4. Results and discussions

Fig. 2 shows the hourly variation of the temperature difference during the experiments for mass flow rates of 0.045 kg/s.

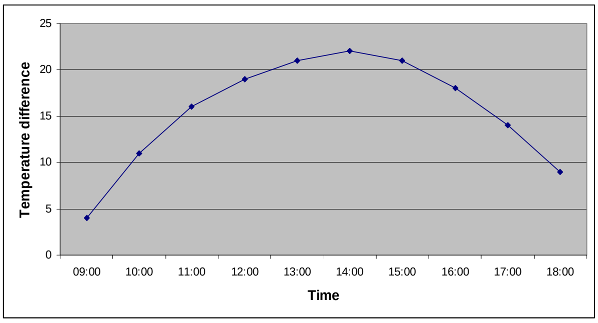

Fig. 2. Temperature difference for the air mass flow rate of 0.045 kg/s

In Fig. 3 are shown the values of solar radiation measured. The highest measured value of daily solar radiation was 1056 W/m². As expected in the morning it increases to peak at noon and then began to fall in the evening. Average hourly solar radiation was 806.26 W/m². Daily average absorber surface temperature was 51.166°C. The difference between the average daily air temperature at the collector inlet and outlet ($T_{a,in}$ and $T_{a,out}$) measured for air mass flow rate 0.045 kg/s was 15.7˚C.

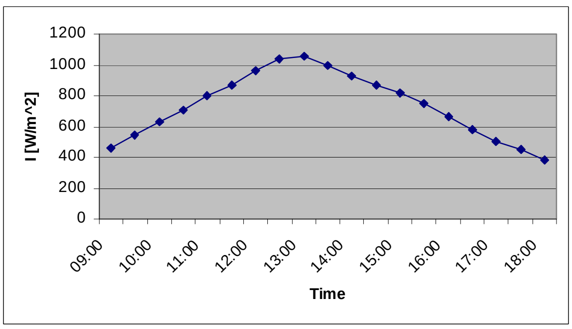

Fig. 3. Hourly variation of solar radiation

Fig. 4 shows the hourly variation of the air temperature difference during the experiments for air mass flow rate of 0.025 kg/s. Maximum solar radiation was 964 W/m². Average hourly solar radiation was 794.13 W/m². Daily average temperature of absorber surface was 59.26°C. The difference between the air daily average temperature entering and leaving the collector ($T_{a,in}$ and $T_{a,out}$) measured for air mass flow rate of 0.025 kg/s was 23.8˚C.

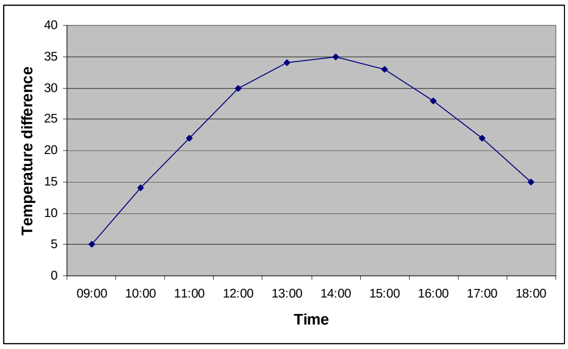

Fig. 4. Temperature difference for air mass flow rate of 0.025 kg/s

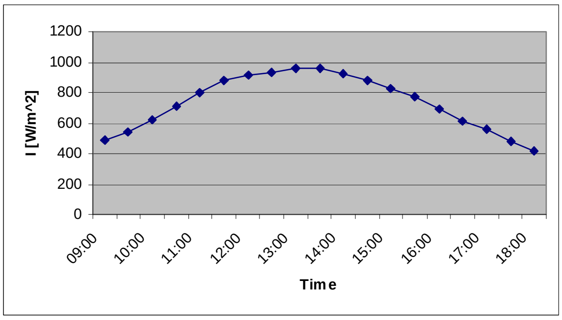

Fig. 5. Hourly variation of solar radiation

Variation of thermal efficiency in time for different air mass flow rate is shown in Fig. 6. As can be seen in the figure, the efficiency increases to a maximum value in the interval 12:30 to 1:30. PM then decreases towards evening. Air mass flow rate is very important in collector efficiency calculations. The results show that the collector efficiency increases with air mass flow rate and solar radiation increasing. The average efficiency calculated for air mass flow rate 0.045 kg/s is 0.63. The average efficiency calculated for air mass flow rate 0.025 kg/s is 0.47.

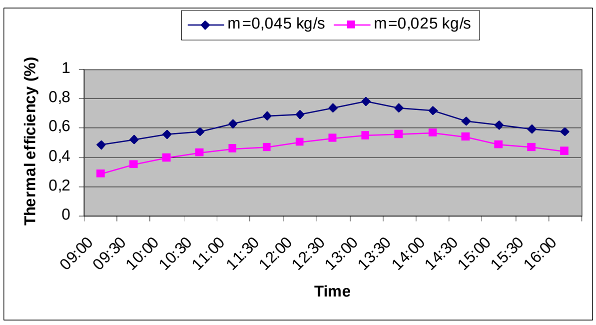

Fig. 6. Thermal efficiency variation in time for different air mass flow rates

It can be seen in Fig. 7 the temperature field on the surface of collector absorber measured by the infrared thermal imager.

Fig. 7. Temperature measure on the absorber surface with FLIR Fluke Ti10 Thermal Imager W/IR Fusion

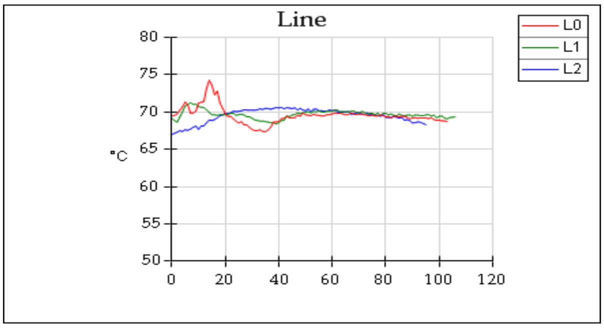

Fig. 8. Variation of temperature on absorber surface

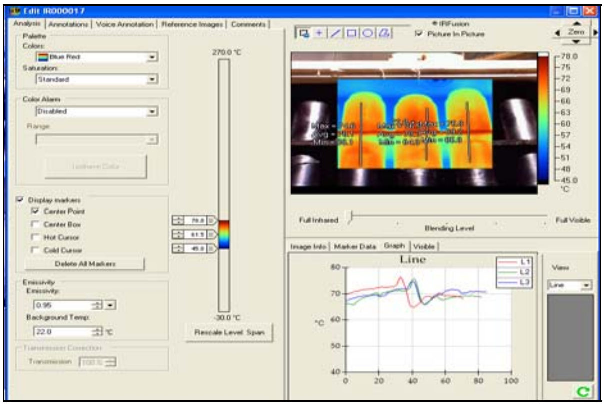

Fig. 9. Visualization of temperature variation on absorber surface in area of support elements

Fig. 8 shows the temperature variation on the absorber surface for three adjacent tubes. It can be observed that the temperature on the surface has slightly variation, meaning that the air is distributed roughly equally in the pipes. Figs. 9 and 10 show the heat loss by conduction from the absorber to the supports of aluminum cans. A lower temperature (with about 10 degrees) is observed in the joining area of tubes with wooden frame.

The temperature variation on absorber surface near the support elements is shown in Fig. 11. It can be observed in Fig. 12 that the maximum temperature difference between central tubes and the surface of the four lateral tubes is up to 3°C, which also shows an uniform heating and even distribution of air in all collector tubes.

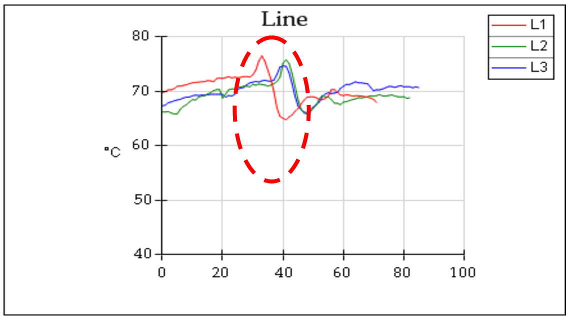

Fig. 10. Temperature variation on absorber surface due to heat loss by conduction

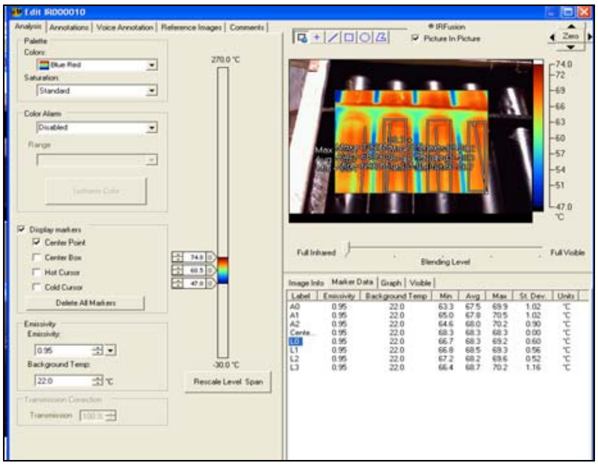

Fig. 11. Visualisation of temperature variation on absorber surface for lateral tubes

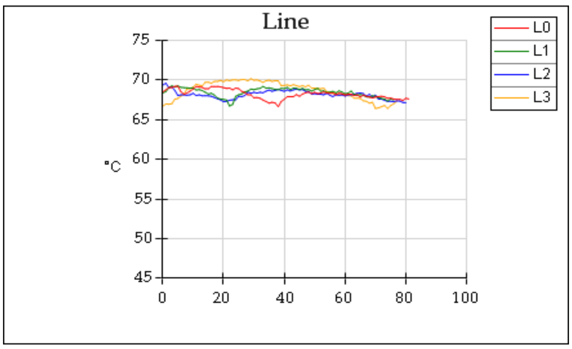

Fig. 12. Visualisation of temperature variation on surface of lateral tubes

5. Conclusions

The key case in this report was to construct a simple and cheap solar air collector using recycled materials and to investigate and to perform possible optimizations of it. Investigation was achieved to evaluate the thermal efficiency of a solar air collector made of aluminum cans subjected to varying operating conditions.

Measurements concerning collector like air flow, temperature of air in the collector and additionally parameters describing weather like wind speed, solar radiation and outdoor temperature were performed. Secondly in order to check the performance of the collector the heat balance and efficiency is determined and in order to optimize the performance the internal shape of the pipe it has been changed in order to make turbulent flow.

It was observed that increasing the air velocity trough the absorber tubes with the increase of air mass flow rate, the thermal efficiency increases significantly. The cause of this significant increase in thermal efficiency is attributable to changing conditions flow from laminar to turbulent regime and consequently to the heat transfer enhance. The maximum collector efficiency was obtained for an air mass flow rate of 0.045 kg/s.

The air solar collector performance can be enhanced by the following ways: use of a good thermal insulation to reduce the heat losses; use of a cover with high transmittance and low absorptance and thermal conductivity; use of a low cost absorber with high absorptions and thermal conductivity; constructing of a flow duct with low pressure losses and use of a fan with a proper $P(\dot{V})$ (power-flow rate) characteristic.

Using solar air collector the conventional heat reduction is 40-70% and panel generates over 625 W of heat energy with little cost (0.5 Euro/month) in a sunny day.

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