Thermal Evaluation and Modeling of a Double-pass Solar Collector For Air Heating

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ABSTRACT: This paper shows the experimental study of the thermal efficiency of a double-pass solar air heater that was designed and manufactured at INENCO, National University of Salta, and the theoretical thermal model developed to describe its thermal behavior. The solar collector has a useful collection area of $2m^2$, and a channel size of 0.025m high. The edge and bottom surfaces are thermally insulated with a 0.05 m thick glass wool layer. The air flow is forced by a tangential fan installed in a 0.18m diameter pipe that is connected to the flow outlet. The collector was mounted with a slope of 34° facing north, in order to maximize the intensity of solar irradiance during winter. The experimental tests were performed during December, 2011. The results show a temperature rise of 35 °C with respect to the inlet air temperature, for a solar irradiance on the collector plane around 900 W/m². An average daily efficiency of 34% was measured. A thermal model was developed in order to simulate the air temperature at the collector outlet under different outdoor climatic conditions. Experimental results and the predictions of the theoretical model were found to be in good agreement.

Keywords: solar air collector, double pass collector, solar energy

INTRODUCTION
The global energy crisis and the consequences on the environment of the greenhouse gases due to fossil fuel burns, call both, for technology to produce clean energy and for measures to reduce the energy demand. Renewable energies can provide part of the solution, and a great effort is currently made in this field. In Argentina, and according to the Greenhouse Effect Gases Inventory, for the year 2000, 91% of CO2 emissions from the energy sector were originated by fuel burning, the remaining 9% was due to fugitive emissions. Residential sector was responsible for 14.4% of those emissions. Between 1990 and 2000 there was a 28% emissions’ increase, with an accumulated annual rate of 2.5%. The two sectors with higher shares in the total net consumption were the residential one (which rose from 13.6% CFT – total final consumption – in 1970 to 19.4% in 2003) and the commercial and public one (2.6% in 1970 to 6.7% in 2003). These consumption rates are directly related to meeting energy household and services’ needs and they had increased, mostly, due to the use of natural gas, which substituted other sources and increased the specific consumption related to caloric use (cooking, water heating, air heating). Regarding fuels’ share in CO2 emissions in the residential sector, natural gas takes up 81.1%. In the last years, the high consumption levels of natural gas during winter caused a strong restriction, between 20 and 50%, of the gas delivered to the industrial sector and to the power stations, in order to supply it to the top priority residential sector. In this context, the use of renewable energies to provide air heating to buildings is of great importance, linked to an improvement of the thermal conditions in the households, both efforts being still incipient in Argentina. The situation is worst for those regions away from the local electrical and gas grids.

The evolution of collector’s study, allowed getting a better relationship between thermal efficiency and cost. There are several types of solar collectors, from which the double-pass type showed to be efficient. Efficiency values over 75% in normal operating conditions were found by [1] for a double-pass solar air heater. Several studies were conducted in order to increase the heat transferred to the working fluid, by enhancing the turbulence with flaps, barriers and baffles fixed to the absorber plate [2-5]. The obtained efficiencies were also above 75% [6]. Transpired collectors that not include a cover glass have lower construction costs and were studied by several authors giving also good results [7-11]. The comparison between the thermal efficiency of single-pass and double-pass air heaters were made by [12] with and without matrix absorber on the second channel. They found that the thermal efficiency of a solar air collector of double pass is 10% higher that of a single pass, and that the double pass collector with absorber matrix is 25% higher that collector without matrix. The authors found that for solar radiation levels...
ranging from 550 W/m² to 850 W/m², the efficiency varies between 65% and 75% for a double-pass collector with matrix absorber, between 45% to 50% for a double-pass collector without matrix, and between 35% to 40% for a single pass collector, they all evaluated at the temperatures and solar irradiation conditions.

A great effort was conducted by the researchers of INENCO in the last decades. Several collector types were developed, mainly for agro-industry [13, 14, 15] and households [16, 17]. The purpose of this paper is to describe the experimental study of the thermal efficiency of a double-pass solar air heater that was designed and manufactured at INENCO, National University of Salta, and the theoretical thermal model developed to describe its thermal behavior. The experimental tests were performed during December, 2011.

**DESIGN AND CONSTRUCTION OF SOLAR COLLECTOR**

![Figure 1: Scheme of the studied double-pass solar air collector.](image)

The scheme of the studied solar air double flow collector is shown in Fig. 1. The useful area is 0.83m x 2.4m, giving a collection area of 2m². The air inlet channel has a rectangular shape (0.025m high and 0.78 wide) and it has a low density air-filtering foam to prevent dust to enter the collector. The collector cover is a 4mm transparent polycarbonate alveolar sheet, while the absorber plate is a metal sheet treated with a black paint for high temperature. Air enters from the outside and warms up as it moves along the channel. The air circulates between the transparent cover and the absorber plate (upper channel) and then it turns back flowing between the absorber plate and the collector base (bottom channel). The air flow is forced by a tangential fan (220V and 2750 rev/min) installed in a 0.18m diameter pipe that is connected to the flow outlet. The edge and bottom surfaces of the collector were thermally insulated with a 0.05 m thick glass wool layer. The cover was designed so as to be easily removable for cleaning.

**INSTANTANEOUS EFFICIENCY OF THE SOLAR COLLECTOR**

The instantaneous efficiency of a solar collector is defined as the ratio of the useful gain to the incident solar energy, that is:

$$\eta_i = \frac{Q_u}{A_c G_T}$$  \hspace{1cm} (1)

where $Q_u$ is the useful gain in W, $A_c$ is the collector area in m², and $G_T$ is the solar irradiance on the collector plane in W/m² [18].

The useful gain $Q_u$ is calculated from inlet and outlet air temperatures and mass flow:

$$Q_u = m c_p (T_o - T_i)$$ \hspace{1cm} (2)

where $T_i$ and $T_o$ are the inlet and outlet air temperatures in °C, $m$ is the mass flow in kg/s, and $c_p$ is the specific heat at constant pressure in J/(kgK).

If the air enters the collector at the outdoor temperature $T_o$ and the air flows through a gap of area $A_g$ (m²), then from (1) and (2) we find that

$$\eta_i = \frac{\rho v_i A_g c_p}{A_c} \left( \frac{(T_o - T_i)}{G_T} \right)$$ \hspace{1cm} (3)

where $v_i$ is the instantaneous air velocity in the collector channel (m/s), and $\rho$ is the air density at the mean temperature between inlet and outlet in kg/m³. Eq. (3) shows a linear relationship between $\eta_i$ and $(T_o - T_i)/G_T$, with a positive slope given by $(\rho v_i A_g c_p)/A_c$.

The efficiency of the collector can also be written as a function of its thermal coefficients [18]:

$$\eta_i = F_R \left[ (\tau \alpha)_{av} - U_L \frac{(T_o - T_i)}{G_T} \right]$$ \hspace{1cm} (4)

where $U_L$ is the overall heat loss coefficient in W/(m²K), $(\tau \alpha)_{av}$ is the effective transmittance-absorptance product, and $F_R$ is the collector heat removal factor that relates the actual useful energy gain to the useful gain if the whole collector surface were at the fluid inlet temperature.

Another common way of expressing $\eta_i$ is the European practice that calculates the instantaneous efficiency by using $T_{aw}$, the arithmetic average of the fluid inlet and outlet temperatures [18]. Thus, Eq. (3) can be alternatively written as:
\[
\eta_i = \frac{v_i A_g \rho \varepsilon_p}{A_e} 2 \left[ \frac{(T_{av} - T_a)}{G_T} \right] 
\]  

(5)

Again, there is a linear relationship between \( \eta_i \) and the variable \( (T_{av} - T_a)/G_T \). In this case, the slope is twice the slope of the straight line defined by Eq. (3).

When \( T_{av} \) is used, the equivalent expression of Eq. (4) is

\[
\eta_i = F_{av} \left( \tau \alpha - U_L \frac{(T_{av} - T_a)}{G_T} \right) 
\]  

(6)

where \( U_L \) is the overall heat loss coefficient in W/(m²K), \( \tau \alpha \) is the transmittance-absorptance product, and \( F_{av} \) is the collector heat removal factor that relates the actual useful energy gain to the useful gain if the whole collector surface were at the average temperature \( T_{av} \).

**METHODOLOGY**

The collector was mounted in the INENCO experimental campus, with a slope of 34° facing north, in order to maximize the intensity of solar irradiance during winter. The experimental tests were performed during three cloudless days on December, 2011.

The measurement equipments were a photovoltaic pyranometer LI-200 for measuring solar radiation, HOBO U12 data-loggers to measure inlet and outlet air temperatures, and a TSI 8345 hot wire anemometer with temperature compensation for measuring air velocity at the collector inlet. The pyranometer was placed on the plane of the collector to sense the global solar radiation incident on this plane. Records of temperature and solar radiation and temperatures were registered automatically at 5 minutes timesteps, while measurements of air speed were taken manually at three points in the collector inlet (Fig. 2) to obtain an average value.

**EXPERIMENTAL RESULTS**

The experimental results for December 20\textsuperscript{th} to 22\textsuperscript{nd} are shown in Figures 4 and 5. Figure 4 shows the solar irradiance \( G_T \) on the collector plane, the outdoor air temperature \( T_a \), and the difference \( (T_{av} - T_a) \) between outlet and inlet air temperatures. Solar irradiance on the collector plane reached maximum values between 900 and 950 W/m\(^2\) at solar noon, with outdoor air temperatures between 30 and 40°C. The air at the collector outlet is heated around 35°C. Figure 5 shows the air velocity \( v_i \). It is observed a considerable variability of air velocity during the tests.

![Figure 2: Side view of the collector with points where air velocity was measured (left) and photo of the collector (right). The inlet channel was extended through a cardboard in order to minimize turbulence caused by the wind.](image)

![Figure 4: Measured solar irradiance \( G_T \) on the collector plane, the outdoor air temperature \( T_a \), and the outdoor temperature \( T_{av} \).](image)

Fig. 6 shows the instantaneous efficiency \( \eta_i \) calculated for the experimental data through Eq. (3) versus \([(T_{av} - T_a)/G_T] \). The obtained values of \( \eta_i \) lies between 0.25 and 0.55. The dots were calculated by using instantaneous values of air velocity, while the triangles were calculated using an average air velocity. In the first case, there is observed a wide dispersion of the experimental points that can be explained by the inaccuracies and variability found in the manual measures of the instantaneous air velocity, which had low values and was also highly influenced by the local wind speed. When an average air velocity was used, the dispersion was minimized and the linear relationship derived, with an \( R^2 \) value of around 0.98. The linear obtained expression is:

\[
\eta_i = 6.36 \left( \frac{T_0 - T_a}{G_T} \right) + 0.06 
\]  

(7)

By following the same procedure, the experimental data can be plotted against \((T_{av} - T_a)/G_T\), as shown in Fig. 7.

When an average air velocity was used, the linear obtained expression is:
Naming the slope of Eq.(8) $a=12.72$ and its origin $b=0.06$ and using Eqs. (3), (6) and (8) we find that $T_o$ can be expressed as:

$$T_o = T_a + \frac{\lambda G_T b}{(1 + \lambda a/2)}$$

(9)

with $\lambda$ given by

$$\lambda = \frac{A_v}{\nu A_s \rho C_p} = \frac{A_v}{m C_p}$$

(10)

Eqs. (9) and (10) provides the way to calculate the outlet air temperature as a function of the solar irradiance $G_T$ on the collector plane and the outdoor air temperature $T_a$, by knowing the collector parameters $a$ and $b$. In this case, a substitution of the values of $a$, $b$ and $\lambda$ in Eq. (9) gives that the outlet temperature can be estimated as

$$T_o = T_a + 0.043 G_T$$

(11)

These results are valid for the working conditions of the tested collector. The predictions of Eq. (11) were tested against experimental data, and the results are shown in Figure 8. The maximum difference between predicted and modeled values is around 5°, that is, an error of around 5%.

**CONCLUSIONS**

The experimental study of the thermal efficiency of a double-pass solar air heater that was designed and built...
at INENCO, National University of Salta, and the theoretical thermal model developed to describe its thermal behavior, were described.

Air outlet temperatures reached 80°C at solar noon, with a daily average temperature rise of 35 °C with respect to the inlet air temperature, for cloudless days when solar irradiance on the collector plane was around 900 W/m² at solar noon. An average daily efficiency of 34% was measured with maximum values reaching 40%. These values are low when compared with the 70% efficiencies reached in the literature [12]. The low values of efficiency were caused by low air mass flow rates and they are expected to increase with a powerful fan. Preliminary results with air velocities twice the values used in this paper showed increases of the efficiency up to 46%.

The thermal model was developed in order to predict the air temperature at the collector outlet for known values of the outdoor temperature and solar irradiance on the collector plane. Experimental results and the predictions of the theoretical model were found to be in good agreement, with a maximum error of 5%. In the future, experiences with an extended range of inlet air temperatures will improve the obtained model.

REFERENCES