Experimental and Theoretical Evaluation of the Overall Heat Loss Coefficient of a Vacuum Tube Solar Collector

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Abstract

The overall heat loss coefficient (U-value) of a vacuum tube solar collector is investigated experimentally and theoretically with regard to the pressure of the remaining gas inside the evacuated glass envelope. A number of collector tubes of same geometry are randomly selected from an installation of a solar based air-conditioning system and tested individually in the laboratory for the determination of the U-value. Measurement results indicate that most of the examined collector tubes have higher overall heat loss coefficients than expected corresponding to a significant varying amount of gas inside the glass envelope. For the same conditions, an approximate theoretical model is also developed for the evaluation of the U-value. The theoretical model is validated against the experimental results for a collector tube having air inside the glass cover at atmospheric pressure and found to be in close agreement. Then, the influence of gas pressure is studied for various gases. Possible presence of air, hydrogen, helium and argon is discussed.

1. Introduction

The quality of the vacuum is decisive for the effective suppression of the heat transfer inside vacuum tube solar collectors. the gas pressure inside the glass cover must be reduced to considerably below atmospheric pressure in order to achieve a reduction of the U-value in the collector [1]. Typical inner pressures are around 10^{-5} mbar, which effectively eliminates the gas convection and conduction heat loss. Vacuum durability becomes an important issue for collectors operating under such ambitious vacuum conditions.

Previously, Window and Harding [2] have reviewed the material problems in evacuated collectors and found that despite the use of efficient sealing techniques, gas pressure inside the glass envelope can still increase during the lifetime of the collector as a result of joint leakage, desorption from the hot selective layer, and diffusion from atmosphere. The increase is strongly temperature dependent. Moon and Harding [3] have described evacuation and degassing processes for all glass tubular evacuated tube solar collectors and then the deterioration of the vacuum in each collector was observed after aging. A significant proportion of the small amount of gas detected probably is due to permeation of atmospheric helium through the borosilicate glass, but no deterioration of the properties of the selective surface was observed after aging. Beikircher et al. [4] have studied the heat losses by gas conduction of an evacuated flat-plate solar collector for a preset value of absorber temperature and different values of gas pressure. They also developed a formula for the pressure dependency of the thermal conductivity of gas covering the entire pressure range, and then validated experimentally for air and argon. A similar investigation was carried out for an evacuated plate-in-tube solar collector [5], where pressure dependency of thermal losses was measured for pressures ranging from10^{-2} to 10^{4} Pa. It was concluded that an inner gas pressure below 0.1 Pa is sufficient to suppress gas heat conduction. Watanabe [6] analyzed experimentally the degassing rate of hydrogen from pure copper into a vacuum chamber. It was found that vacuum cast pure copper can attain degassing rate of 10^{-12}Pa m/s after 100°C bakeout. The rate increases when the bakeout temperature exceeds about 250°C.

In the present work, heat loss from vacuum collector tubes is measured and the unknown gas pressure inside the glass envelope is predicted using a simplified model of the collector tubes. An experimental strategy is devised to find the overall heat loss coefficient (U-value) of an individual vacuum collector tube in the laboratory. The purpose is to estimate the overall heat loss coefficient for every vacuum tube to observe whether each tube has the same thermal behaviour and the vacuum inside of the tubes is still intact. A number of vacuum collector tubes are selected randomly and taken out of the collector array used for the solar cooling system. The collectors have been in operation for 6-8 years.

2. Collector Specification and Experimental Setup

A particular type of vacuum tube collector with a flat absorber sheet welded to a co-axial pipe structure is used for the study. The specifications and typical values of all the relevant parameters and constants used in this study are mentioned in table 1.

Table 1. Values of geometrical parameters and constants used in the calculation

Description	**Specification**
Glass Cover	D_{og}, D_{ig}= (65, 62)mm L_g=1700mm Emissivity of glass, ε_g= 0.88
Absorber Plate and Pipe (Material: Copper, Surface Coating: Cu/TiNoX)	L_{ab}, W_{ab}, t_{ab} = (1700, 60, 0.2)mm D_o, D_i = (12, 10.4)mm Emissivity of surface coating, ε_p = 0.05 Emissivity of copper, ε_c = 0.03 $(mc_p)_{cu}$ = 252 J/K ± 20 J/K
Water inside the tube	$(mc_p)_{water}$ = 593 J/K ± 11 J/K

A transient method was used. The basic idea is to monitor the cooling down of the collector in a controlled surrounding, and by this determine the thermal losses. Before the start of the experiment, boiling water was made to flow in and out continuously through the inner and outer absorber pipe of the vacuum tube for a certain time, so that the whole length of the absorber reaches a uniform initial temperature. The inner absorber pipe then was taken out and the outer absorber pipe of the vacuum tube was refilled with hot water, placed horizontally and allowed to cool down in the laboratory environment. Fig. 1 shows the schematic of the experimental setup. Temperature readings (PT100) of two positions in the fluid and the ambient (see Fig. 1) were recorded for every second and then evaluated to find the overall heat loss coefficient (W/m^2.K) of the collector tube. The uncertainty of the temperature measurement was ±0.1K.

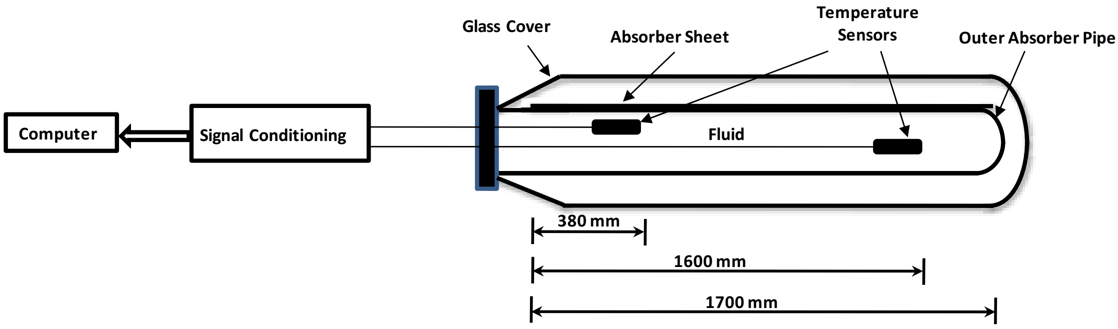

Fig. 1. Schematic of the experimental setup

In order to estimate the heat loss of the fluid, the following assumptions are made:

- Absorber sheet and fluid in the pipe are cooled down at the same rate
- Mass and thermal effects of temperature sensor wires inserted inside the fluid are neglected
- The uncertainties of the geometrical parameters are neglected

Heat loss of the fluid (Q_{loss}) at a particular instant is defined as:

$$Q_{loss,i}(t_i) = \frac{[(mc_p)_{water} + (mc_p)_{cu}](T_{f\_ti} - T_{f\_tf})}{\Delta t} \tag{1}$$

Where T_{f_ti} and T_{f_tf} are the fluid temperatures at time instants t_i and t_f with an interval of Δt (sec).

The overall heat loss coefficient (U-value) of the collector tube is:

$$U_i = \frac{Q_{loss,i}}{A_{ab}(T_{f\_t,i} - T_{a\_t,i})} \tag{2}$$

Where A_{ab} is the absorber area and $T_{a\_t,i}$ is the ambient temperature at time instant t_i. Basically, this loss coefficient is temperature and therefore, in the present experiment, time–dependent. However, the dependency is only weak (see Fig. 3). A series of experiments was conducted for the selected tubes and repeated several times to verify the results for various setup conditions.

3. Theoretical Model

A theoretical model based on an iterative procedure [7] is used to estimate the U-value of a vacuum tube collector for a fluid at rest in the tube. The model assumes a quasi-steady state condition in each collector component. For calculating the overall heat loss coefficient from the absorber to ambient, we have to face a non-symmetric situation. First the radiant temperatures above and below the collector may be different. Second, remaining gases in the space above the absorber are heated from below which can lead to free convection. Gases below the absorber are heated from above and consequently only conduction occurs. Therefore the vacuum tube is divided into two parts and the heat loss coefficient for the top and bottom side of the absorber plate is calculated separately as described in fig. 2. The top and bottom heat losses from the absorber each have to flow through the gas and the glass and from glass to the ambient. We account for radiation (index r) separately from conduction and convection (index c). As a simplification we assume that air temperature and radiation temperature is equal to T_a on both sides.

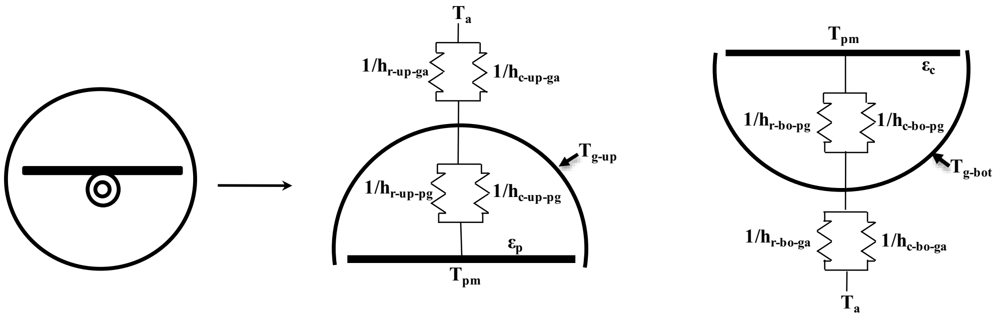

Fig. 2. Geometrical simplification for the calculation of overall heat transfer coefficient

Top and bottom heat loss coefficients for the gas inside the glass envelope of the collector are given as:

$$U_{t/b} = \frac{1}{\left(h_{r-up/bo-pg} + h_{c-up/bo-pg}\right)^{-1} + \left(h_{r-up/bo-ga} + h_{c-up/bo-ga}\right)^{-1}} \tag{3}$$

The overall heat loss coefficient then results by simply adding: $U = U_t + U_b$ (4)

Details of the complete theoretical model including all assumptions, simplifications and correction factors used for estimating the respective heat transfer coefficients will be presented in another paper.

4. Results and Discussion

The whole cooling down procedure takes several hours. Therefore a time interval (Δt), of 1 minute is used as resolution. The resulting temperature dependent U-value is plotted for 14 different collector tubes against the difference of mean fluid and ambient temperature (T_f-T_a) in fig. 3. One of the tested tubes (tube-14) had no vacuum and there was air present at atmospheric pressure.

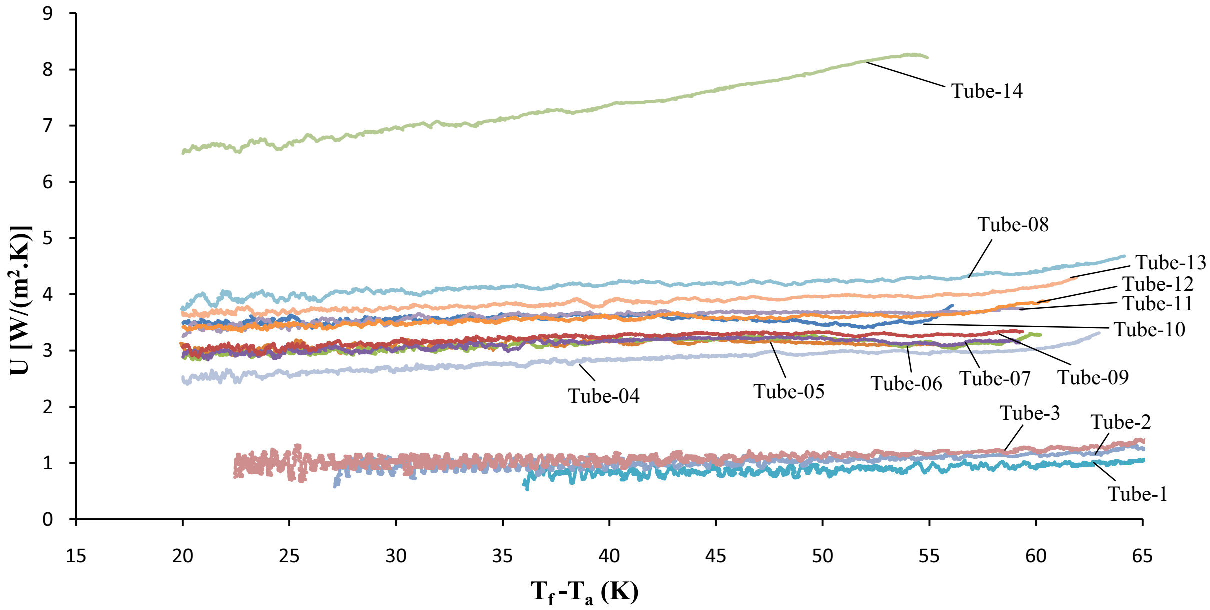

Fig. 3. Experimentally obtained U-values versus fluid-ambient temperature difference

For comparison, fig. 4 shows the experimentally obtained U-value curves along with the error margin for vacuum tubes-1, 7 and 14. It is seen from fig. 3 that the tested tubes show a range of variation of overall heat loss coefficients. Tube-14 having atmospheric air inside the glass envelope of course shows the largest value of heat loss coefficient. Tubes 1, 2 and 3 have the lowest heat loss coefficient varying between 0.8 and 1.3 $W/m^2.K$. Most of the vacuum tubes fall into the range of 2 to 4 $W/m^2.K$. Assuming negligible degradation of radiation properties (Emissivity etc.) of the collector materials [3], it can be concluded that the vacuum is deteriorated in these cases and there is an individual, non-zero gas pressure inside the glass envelope of the tubes, which has given rise to such a variation of U-values for the individual tubes.

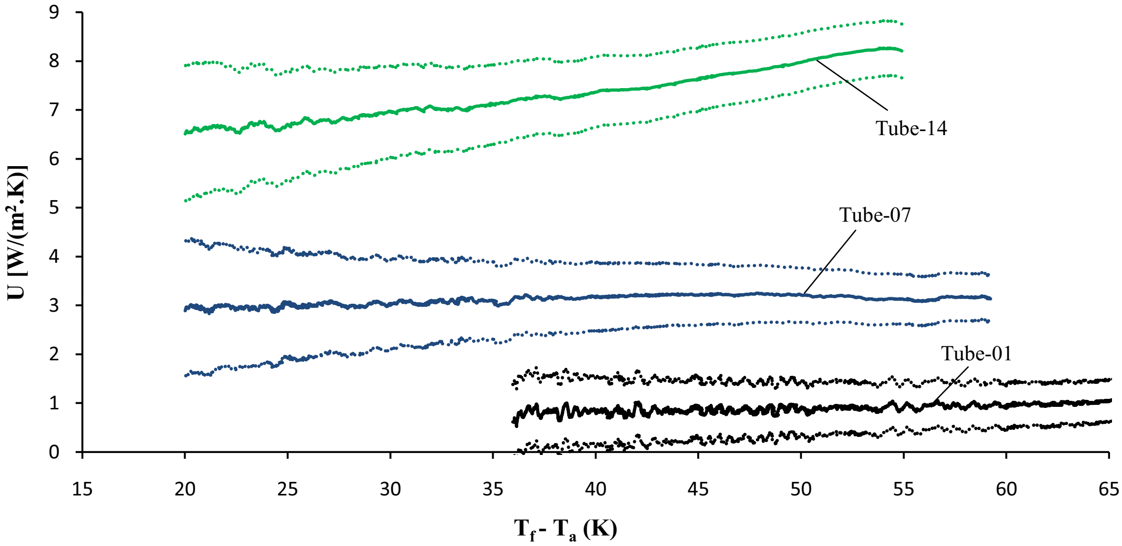

Fig. 4. Estimated measurement error in U-values

Based on the theoretical model mentioned above, the U-value is computed initially for a collector tube with air present at 1 atm inside the glass envelope at different fluid and ambient temperatures. Fig. 5 shows the comparison of experimental and theoretical results. It has to be mentioned that one fitting parameter was used to account for the geometry of the tubes.

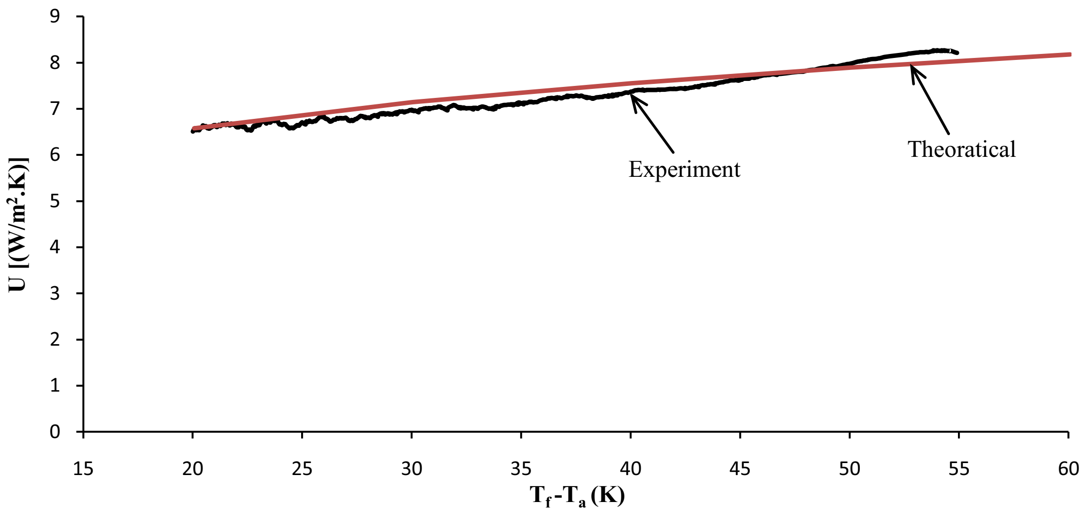

Fig. 5. Variation of U-value computed theoretically and experimentally for air at 1atm inside glass envelop

The mean deviation between the theoretical and mean experimental U-value curve is approximately 1.2%, which is estimated as the arithmetic mean of the individual deviations calculated for the considered temperature range.

The model is then further used without additional fit parameters to compute the U-value for various gases at lower pressures, and the possible presence of those gases is discussed here. As the thermal and production history of the collector tubes is not well known, the calculations are carried out for air, hydrogen, helium and argon, which can be the potential cause of vacuum deterioration and resultant increase of heat loss of the collector tubes [2, 3, 6 and 8]. Fig. 6 and 7 shows the resulting loss coefficients at different gas pressures for air and hydrogen along with the experimental curves for tested collector tubes.

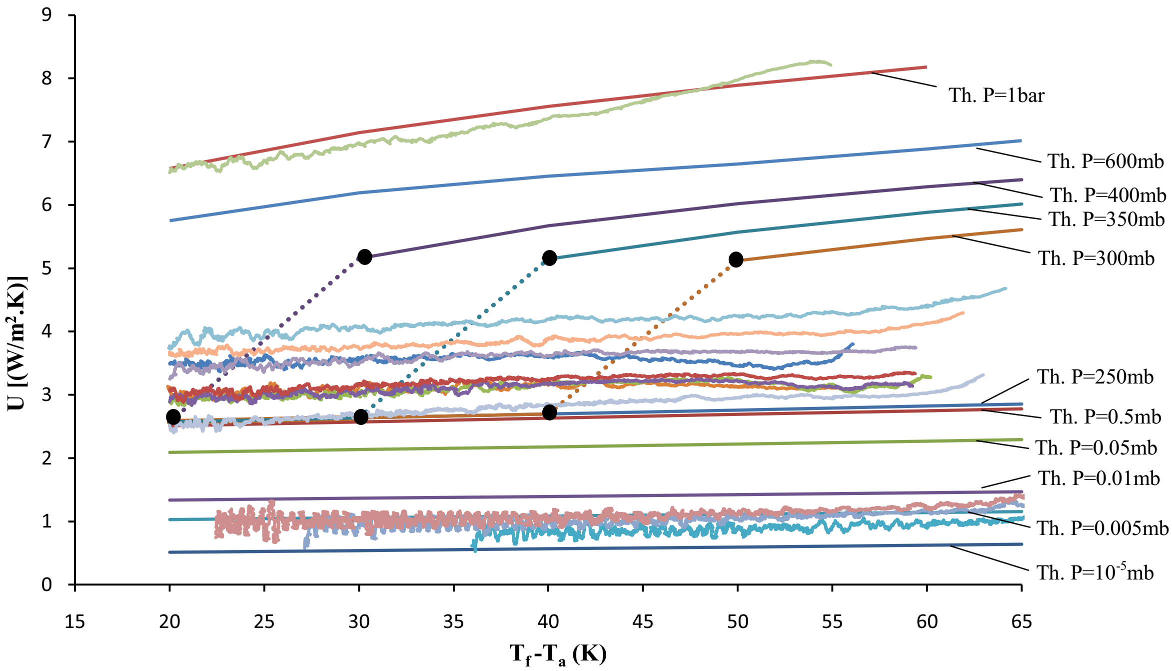

Fig. 6. Experimental and theoretical overall heat loss coefficient for air inside glass

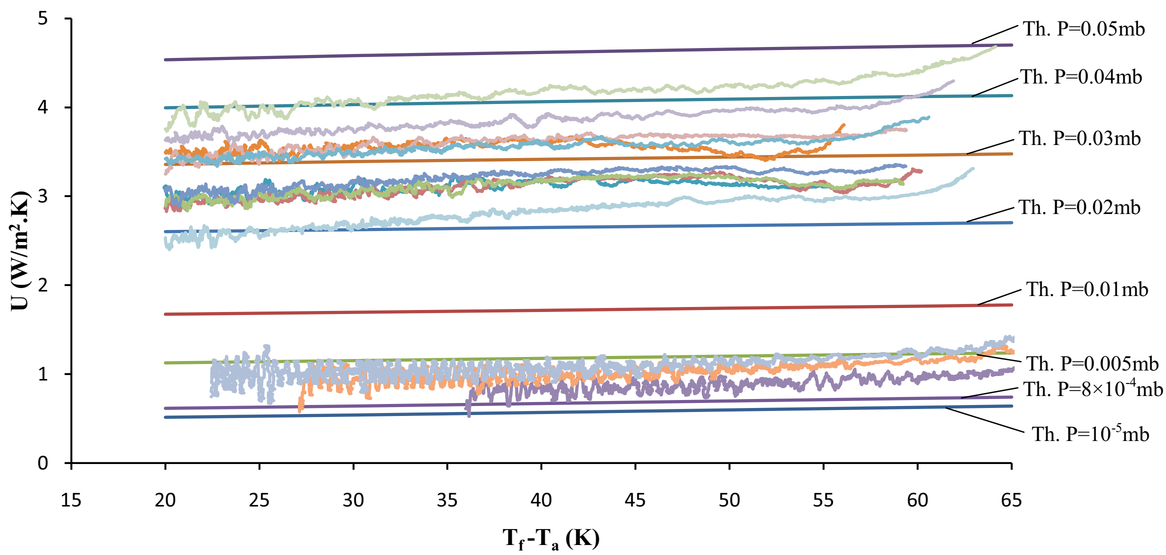

Fig. 7. Experimental and theoretical overall heat loss coefficient for H_2 inside glass

The following observations are made with reference to fig. 6 and 7:

- For perfect vacuum (P=10^{-5}mbar) inside the glass envelope, theoretically calculated U-value is in the range of 0.5-0.6W/m^2.K for the considered temperature range.

- For air, the heat loss coefficient decreases with decreasing air pressure inside the glass. The suppression of convection is dependent not only by the gas pressure but by the temperature difference also. Between 600 and 275mbar heat transfer due to convection is completely suppressed (Ra<1700) only at some lower fluid temperature and then a sudden drop in U-value is observed, as shown by the dotted lines in fig. 7. This region between the circular marks is the transition zone, where the heat transfer mode is changing from convection to pure conduction and the exact variation of U-value in this region cannot be traced. At 250mbar the convection is totally suppressed in the respective temperature range and only heat transfer due to air conduction takes place for the whole considered temperature range. This heat conduction is independent of pressure till 1mbar. Below 1mbar the continuum effects start to vanish and the loss coefficient decreases with decreasing pressure. At 8×10^{-4}mbar gas heat conduction is almost fully suppressed.
- For argon, a similar pattern as for air is observed. Experimental U-values for the tested collector tubes, in the range of 2-4 $W/m^2.K$, have not shown such a pattern of sudden drop in U-value.
- For Hydrogen and helium, heat transfer occurs only due to gas conduction as the Rayleigh number is always below the critical value for the whole considered temperature and pressure range. As shown in fig. 8 for hydrogen, the loss coefficient decreases rapidly with decreasing pressure below 1mbar and fits reasonably well with the experimental curves in the range of (0.05-0.0005)mbar. Helium can only permeate from atmosphere through the glass and the maximum achievable pressure inside glass cover would be 0.00533 mbar (i.e., partial pressure of helium in atmosphere) and at that pressure the corresponding theoretically calculated U-value is approximately $1W/m^2.K$, which is below then the 2-4 $W/m^2.K$ range.

5. Conclusion

An experimental strategy is described to measure the overall heat loss coefficient of a vacuum tube collector. It is found that randomly selected vacuum collector tubes from the same collector field have shown different values of heat loss coefficient under similar conditions. Most of the tested tubes fall into the range of (2-4) $W/m^2.K$. A steady state model based on simplifying geometrical assumptions is developed to calculate the U–value of the collector tubes and to estimate the unknown gas pressure inside the glass cover. The model agrees well to the experiments.

No experimental U-value curves for the tested tubes have shown a sudden drop of loss coefficient at a certain lower fluid-ambient temperature difference, as predicted from the model for the case of air or argon. It can be concluded that presence of hydrogen at a very low pressure range (0.0005-0.05) mbar can give rise to U-value in the range of (2-4) $W/m^2.K$. Thermal and manufacturing history would be required for precisely estimating the presence of a particular gas or mixture of gases inside the glass envelope.

6. Nomenclature

A_{ab}	Absorber Area (m^2)	T_{f_ti}	fluid Temperature at time t_i (°C)
D_o, D_i	Outer and inner diameter of copper pipe (mm)	T_{f_tf}	Fluid Temperature at time t_f (°C)
D_{og}, D_{ig}	Outer and inner diameter of glass cover (mm)	T_{a_ti}	Ambient Temperature at time t (°C)
$h_{r-up-pg}$, $h_{r-bo-pg}$	Radiative heat transfer coefficient from top and bottom of absorber to upper and bottom portion of glass cover, respectively. ($W/m^2.K$)	Δt	Time interval (sec)
		T_{g-up}	Glass cover temperature of the top portion above the absorber sheet (°C)
$h_{r-up-ga}$, $h_{r-bo-ga}$	Radiative heat transfer coefficient from upper and bottom portion of glass cover to ambient, respectively. ($W/m^2.K$)	T_{g-bo}	Glass cover temperature of the bottom portion below the absorber sheet (°C)
$h_{c-up-pg}$, $h_{c-bo-pg}$	Convective heat transfer coefficient from top and bottom of absorber to upper and bottom portion of glass cover, respectively.	T_{pm}	Mean absorber plate temperature (°C)
		t_{ab}	Thickness of absorber sheet (mm)

	(W/m^2.K)	U	Overall heat loss coefficient (w/m^2.k)
$h_{c\text{-}up\text{-}ga}$, $h_{c\text{-}bo\text{-}ga}$	Convective heat transfer coefficient from upper and bottom portion of glass cover to ambient, respectively. (W/m^2.K)	U_t	Top heat loss coefficient (w/m^2.k)
		U_b	Bottom heat loss coefficient (w/m^2.k)
L_g, L_{ab}	Length of glass tube and absorber sheet, respectively. (mm)		
$(mC_p)_{water}$	Thermal capacitance of water (J/K)	**Greek Symbols**	
$(mC_p)_{cu}$	Thermal capacitance of copper (absorber pipe and sheet) (J/K)	ε_g	Emissivity of the glass
Q_{loss}	Heat loss of the fluid (Watts)	ε_p	Emissivity of the absorber surface coating
Ra	Rayleigh number		
		ε_c	Emissivity of the copper (Polished)

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