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Experimental and theoretical evaluation of the overall heat loss coefficient of vacuum tubes of a 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 amount of gas inside the glass envelope.

For the same conditions, an approximate theoretical model is 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.

Keywords: Overall heat loss coefficient; Vacuum tubes; Convection; Gas pressure

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 significant reduction of the *U*-value of the collector. Typical inside 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 (1984) 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. Harding and Window (1981) investigated the thermal conduction in an evacuated concentric glass tubular solar collector. They used a technique where the total heat flux is measured between absorber and glass envelope as a function of absorber temperature. Then the envelope seal was broken and the gases inside the glass were evacuated to measure the radiant heat flux only. In their experiment, the absorber was heated electrically and the power needed to maintain the absorber temperature at a certain level corresponded to the heat loss of the collector. The difference between radiant and total heat flux gives gas heat conduction. Harding and Moon (1982) have described evacuation and degassing processes for all glass tubular evacuated tube solar collectors and then the deterioration of the vacuum in

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Nomenclature

A_{ab}	absorber area (m^2)
A_g	glass cover area (m^2)
C_p	specific heat of gas (J/kg K)
f	number of degrees of freedom of each gas molecule (–)
$F_{p\text{-}g}$	view factor from absorber to glass (–)
$h_{r\text{-}t/b\text{-}pg}$	radiative heat transfer coefficient from absorber to glass cover from top or bottom (W/m^2 K)
$h_{r\text{-}t/b\text{-}ga}$	radiative heat transfer coefficient from glass cover to ambient from top or bottom (W/m^2 K)
$h_{c\text{-}t/b\text{-}pg}$	convective heat transfer coefficient from absorber to glass cover from top or bottom (W/m^2 K)
$h_{c\text{-}t/b\text{-}ga}$	convective heat transfer coefficient from glass cover to ambient from top or bottom (W/m^2 K)
$h_{c\text{-}t/b\text{-}h}$	convective heat transfer coefficient from top or bottom horizontal face (W/m^2 K)
$h_{c\text{-}t/b\text{-}v}$	convective heat transfer coefficient from top or bottom vertical face (W/m^2 K)
Kn	Knudsen number
k_o	thermal conductivity of gas in the continuum range (W/m K)
k_p	thermal conductivity of gas at pressure p (W/m K)
$L_{t/b}$	characteristic length, i.e. spacing b/w parallel plates (m)
$(mC_p)_w$	thermal capacitance of water inside copper pipe (J/K)
$(mC_p)_{cu}$	thermal capacitance of copper (pipe and absorber) (J/K)
M	molar mass of gas (kg/mol)
p	gas pressure (Pa)
Q_{loss}	heat lost of the fluid (W)
R	universal gas constant (J/mol/K)
Ra	Rayleigh number (–)
T	mean gas temperature (K)
T_{f_ti}	temperature of fluid at time t_i (°C)
T_{f_tf}	temperature of fluid at time t_f (°C)
T_{a_ti}	ambient temperature at time t_i (°C)
Δt	time interval (s)
T_a	ambient temperature (K)
$T_{g\text{-}t/b}$	glass cover temperature of the top or bottom portion above or below the absorber (K)
T_{pm}	mean absorber plate temperature (K)
ΔT_{pg}	temp. difference b/w absorber and glass cover (K)
U	overall heat loss coefficient (W/m^2 K)
$U_{t/b}$	top or bottom heat loss coefficient (W/m^2 K)
Y	area correction factor (Eq. (5)) (–)

Greek symbols

ε_g	emissivity of the glass (–)
ε_p	emissivity of the absorber surface coating (–)
ε_c	emissivity of the copper (–)
α_{red}	reduced thermal coefficient (–)
μ	dynamic viscosity of gas (kg/m s)
β	collector slope (deg)
σ	Stephen Boltzmann constant (W/m^2 K^4)

each collector was observed after aging. A small quantity of helium was detected due to diffusion from atmosphere, but negligible deterioration of the radiative properties of the selective surface was observed. Beikircher et al. (1995) have studied the heat losses by gas conduction of an evacuated flat-plate solar collector for known quantities of air and argon, using a similar technique as described by Harding and Window (1981). They also derived 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 (Beikircher et al., 1996), where pressure dependency of thermal losses was measured for pressures ranging from 10^{-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 (2001) analyzed experimentally the degassing rate of hydrogen from pure copper into a vacuum chamber. It was found that vacuum cast pure copper can attain a degassing rate of 10^{-12} Pa m^3/s after 100 °C bakeout. The rate increases when the bakeout temperature exceeds about 250 °C.

In the present work, a novel experimental strategy is devised to find the overall heat loss coefficient (U-value) of an individual vacuum collector tube in the laboratory. The procedure is simple and does not require the aid of sophisticated measurement apparatus like electric heaters, vacuum diffusion pump, mass spectrometer or gas analyzer. A number of vacuum collector tubes are selected randomly and taken out of a collector array which is used for a solar cooling system. The collectors have been in operation for 6–8 years. The purpose of the experiments 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. The proposed method, due to its simplicity, can be employed at any time during the operational life of vacuum tube collectors in the field. Moreover, the unknown gas pressure inside the glass envelope is predicted using a numerical model of the collector tubes.