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Experimental Measurements of Evacuated Enclosure Thermal Insulation Effectiveness for Vacuum Flat Plate Solar Thermal Collectors

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Abstract**—**Encapsulating the absorber of a flat plate solar thermal collector in vacuum by an enclosure that can be evacuated can result in a significant increase in collector performance and achievable operating temperatures. This is a result of the thermal insulation effectiveness of the vacuum layer surrounding the absorber, as less heat is lost during collector operation. This work describes experimental thermal insulation characterization tests of prototype vacuum flat plate solar thermal collectors that demonstrate the improvement in absorber heat loss coefficients. Furthermore, this work describes the selection and sizing of a getter, suitable for maintaining the vacuum inside the enclosure for the lifetime of the collector, which can be activated at low temperatures.

Keywords**—**Vacuum, thermal, flat-plate solar collector.

I. INTRODUCTION

THE use of flat evacuated enclosures as a means of thermal insulation can greatly enhance the efficiency and operational temperature range of flat plate (FP) solar thermal collectors. Such collectors, known as vacuum flat plate (VFP) collectors, would exhibit collector efficiencies similar to evacuated tube (ET) collectors, in terms of absorber area, whilst filling a larger proportion of the gross collector area [1]. Only a thin vacuum layer is needed surrounding the collector solar absorber; subsequently the collector could be shallow, architecturally versatile and capable of providing clean thermal energy efficiently for a range of applications.

Conventional FP solar thermal collectors are typically configured as shown in Fig. 1. In Fig. 1, it can be seen that these collectors utilize an air gap (depth 5-10 cm) to insulate the absorber on the top. The bottom surface of the collector is insulated via a layer of backing insulation. The overall depth of a conventional solar thermal collector can thus be in the region of ~10-15 cm [2]. A VFP collector however, needing only a thin vacuum layer to effectively insulate the absorber, can be much shallower (depth 1-3cm) in comparison; a conceptual depiction of a VFP collector is shown in Fig. 2. As can be seen a VFP collector requires a number of additional components such as a hermetic periphery seal that joins the glass cover to the rear metal housing of the collector and an array of evenly spaced supporting pillars to withstand atmospheric pressure forces [3].

For this work, a prototype of a VFP solar thermal collector has been fabricated and is thermally characterized to determine the level of thermal insulation provided by the high vacuum, less than 0.1 Pa, within the enclosure. Such collectors, with a configuration consistent with Fig. 2, comprise of a flat front glass cover, rear metal housing, internal solar absorber and an array of supporting pillars. The collector aperture is 500 mm by 500 mm in size with the glass cover bonded to the rear metal housing via a tin or indium based solder alloy to form the hermetic seal around its periphery. The solar absorber integrated into the collector vacuum enclosure utilizes inlet/outlet ports also insulated by a vacuum layer to reduce heat transfer to the rear metal housing [4].

Temperature measurements were made of the glass cover and rear metal housing while circulating warm water at temperatures of approximately 45 °C and 55 °C through the absorber, for cases in which the internal pressure of the collector enclosure is at a) high vacuum (<0.1 Pa) and b) at atmospheric pressure. Experimental measurements are compared to a thermal-electrical analogy network model of the collector and the impact of different absorber emissivity's are analyzed to determine the effect on collector performance.

In ET solar collectors a getter is required in order to maintain the vacuum level within the vacuum tubes over the service life of the collector; and the same is true for VFP collectors. In this work the gas load of a VFP collector over its predicted lifetime (up to 30 years) is estimated as well as getter sizing. Suggestions for activation of a suitable getter material at low temperatures within the vacuum enclosure are discussed.

VFP solar thermal collectors are versatile and competitive with conventional solar thermal collectors in terms of efficiency, achievable operating temperatures and use of available installation area. This work describes the thermal characterization of a prototype collector and demonstrates the effectiveness of the vacuum layer in insulating the solar absorber. A getter material is selected and sized for maintenance of the vacuum layer over the collector's lifetime.

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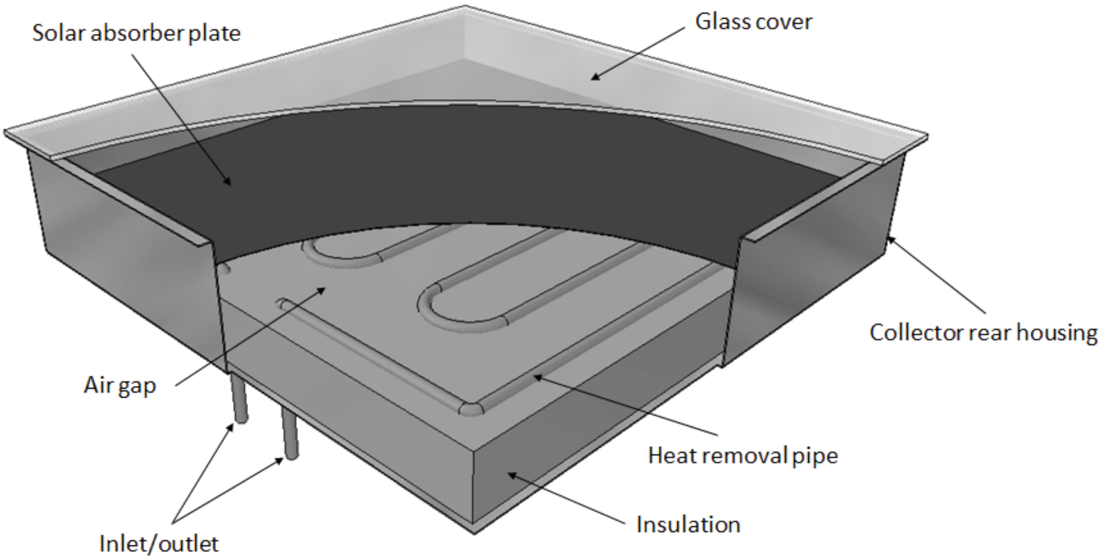

Fig. 1 Schematic diagram of a conventional FP solar thermal collector

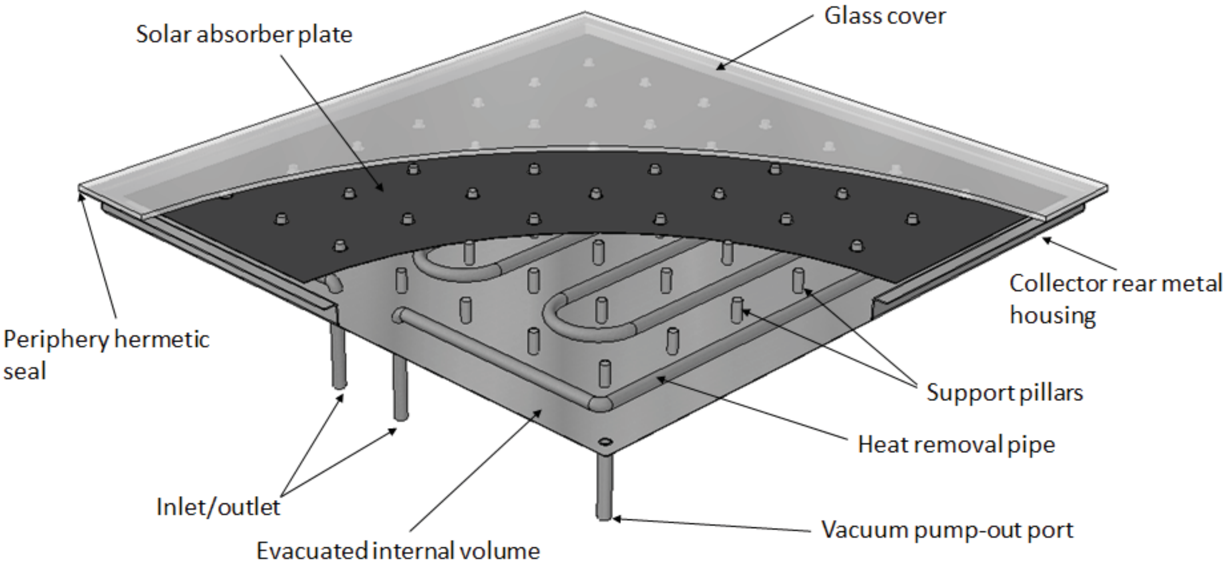

Fig. 2 Conceptual depiction of a VFP solar thermal collector

II. BACKGROUND

The idea of using an evacuated or low pressure enclosure to improve the thermal performance of FP solar collectors dates back to the 1970s [5]. At that time FP solar thermal collectors had poor performance at elevated temperatures: efficiencies were typically less than 40% for absorber plate temperatures greater than 100 °C. Use of a moderate vacuum layer (~150-3,500 Pa) between the absorber plate and enclosure glass cover was expected to allow the collector to operate efficiently at temperatures exceeding 150 °C [5]. The advantage of attaining higher temperatures of 100-150 °C would be that it allows FP collectors to be considered as viable sources of heat for industrial processes [6].

The moderate vacuum pressure range is effective at suppressing convective heat transfer between the absorber plate and the collector glass cover but does not suppress gaseous conduction which can account for several W/m^2 of total power loss from a solar collector [7]. A vacuum pressure between the absorber plate and glass cover of less than 0.1 Pa, however, results in a molecular mean free path larger than the plate-to-cover spacing and thus suppresses both convection and gas conduction heat loss. This is the desired level of vacuum in vacuum glazing which bears many similarities to VFP collectors. Vacuum glazing is a building window component in which two glass panes are bonded together via a hermetic seal around the periphery of the glazing. In-between the two glass panes is an array of very small glass support pillars that allow the glazing structure to withstand atmospheric pressure forces [8].

Attaining and maintaining enclosure pressures below 0.1 Pa for an adequate product lifetime (20-30 years), represents a significant challenge for a VFP collector enclosure and is

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especially the case for vacuum glazing in which the vacuum layer volume is very small. In vacuum glazing the vacuum layers are typically less than 0.5 mm thick resulting in a maximum evacuated volume of 0.5 liters per m^2 of glazing area [9]. A VFP collector can expect to have a much larger volume per m^2 of gross collector area (> 10 liters). This gives VFP collectors an advantage over vacuum glazing as it has a much larger volume to internal surface area ratio (> 9 liters/m^2 compared to 0.25 liters/m^2); a larger ratio means that gasses desorbing in to the enclosure from the internal surfaces will be able to occupy a larger volume and therefore pressure will rise more slowly.

In isolated vacuum systems gasses will be desorbed from the internal surface of the system into the evacuated volume over time while the system remains isolated. Gas molecules and volatiles can be present on and within the walls of the system structure and if the majority are not removed prior to the final evacuation and sealing of the system significant degradation of the internal vacuum and subsequent service life of the system will occur. These gas molecules and volatiles can be largely, but not completely, removed via suitable cleaning and baking out of the system prior to final evacuation. Another source of gas ingress into an isolated vacuum system is directly through the walls of the vacuum enclosure. Some gasses are able to permeate and slowly diffuse through certain materials, for example Helium is found to be able to slowly diffuse through the glass of vacuum glazing [10]. Thus there will always be a source of gas ingress into a VFP collector, however, this can be compensated for over the service life of the collector, via the use of a getter. A getter is a material, such as some Zirconium based alloys, that can be a pellet/pill within the vacuum enclosure or coated on to the enclosures walls. The getter reacts with a wide range of gasses such that gas molecules that come in to contact with the getter are trapped on the getter surface. Thus the getter can capture and restrain much of the residual gas still present within the volume and structure of the VFP collector over its service life as long as it is correctly sized. Once the pressure of the system has been reduced to required levels the getter is activated, via heating to drive off already trapped gas molecules, after which the system can be sealed. Getters are used in ET collectors [11] and vacuum glazing [9].

It is important in such vacuum systems to properly characterize the volatile and residual gasses likely to be present within the evacuated enclosure and size the getter to maintain the vacuum below the minimum pressure for the service life of the product. Koebel et al. [12] describe a pressure balance model for the accurate estimation of service life of vacuum glazing. Given the similarities of VFP collectors with vacuum glazing it is likely that similar analyses can be performed.

III. COLLECTOR PERFORMANCE AND THERMAL MODEL

Previous research has predicted that the total heat loss coefficient (U_L) for a VFP collector can range between 1-2 W/m^2·K depending on operating temperature (ambient to 200 °C) [13], [1]. Compare this to conventional FP collectors for which U_L typically varies between 4-6 W/m^2·K [14], [1]. This results in VFP collectors being capable of operating with efficiencies 20-40% higher than FP collectors at elevated temperatures. The total loss coefficient is calculated as:

$$U_L = U_t + U_b + U_e \tag{1}$$

where U_t is the top loss coefficient, U_b is the bottom loss coefficient and U_e is the edge loss coefficient. It is arguable that the top loss coefficient is most critical as the other loss coefficients can be improved via the use of additional insulation; while use of insulation on the top glass cover of the collector would inhibit its operation.

In order to estimate the thermal characteristics of a prototype VFP collector and simulate the time varying temperature of its glass cover a transient lumped capacity thermal model was created utilizing a thermal-electrical analogy network analysis as is described in [15] for the calculation of heat transfer coefficients. In this case the network only considers the temperature of the glass cover (T_c), assuming the temperature of the absorber plate (T_p) and the ambient temperature (T_a) are known from experimental data.

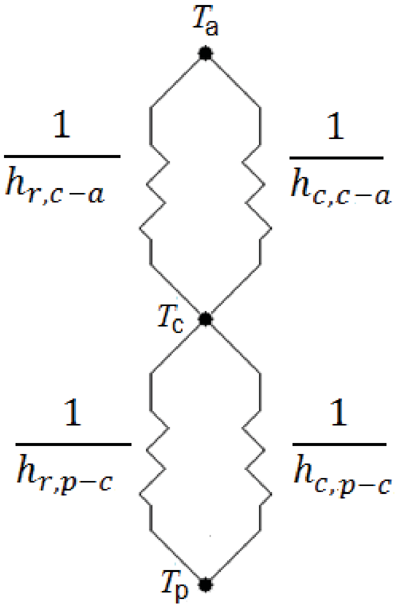

Fig. 3 Thermal-electrical analogy network for VFP collector.

Fig. 3 shows the thermal-electrical analogy network for a VFP collector when the enclosure is not evacuated. In Fig. 3, $h_{r,\,c-a}$ and $h_{c,\,c-a}$ are the radiative and convective hear transfer coefficients between the glass cover and ambient and $h_{r,\,p-c}$ and $h_{c,\,p-c}$ are the radiative and convective hear transfer coefficients between the absorber plate and the glass cover. In the thermal-electrical analogy network shown in Fig. 3 there are no thermal conduction heat transfer processes due to it being assumed that the absorber plate is suspended inside the enclosure with small conductive contact with the other collector components. Also in this model thermal contact between the glass cover and rear metal housing is neglected. When the enclosure is evacuated the thermal network will change with the convective heat transfer coefficients between the absorber plate and the glass cover/rear metal housing becoming negligible ($h_{c,p-c} = 0$).

The heat transfer coefficients in the thermal-electrical analogy networks are estimated for given experimental values of T_p and T_a at different times determined by the time parameter n and are based on the characteristics of the prototype VFP collector (listed in Table I). With estimated values of the heat transfer coefficients the temperature of the glass cover node at a particular time (n+1) is estimated via:

$$T_c^{n+1} = T_c^n + \left(\frac{\Delta t}{C_c M_c}\right)\cdot\left(A_p h_{p-c}\left(T_p^n - T_c^n\right) - A_c h_{c-a}\left(T_c^n - T_a^n\right)\right) \quad (2)$$

where T^n_c is the current temperature of the glass cover, T^n_p is the current temperature of the absorber plate, T^n_a is the current ambient temperature, Δt is the time between samples of experimental data, C_c is the specific heat capacity of the glass cover, M_c is the mass of the glass cover, A_p is the area of the absorber plate and A_c is the area of the glass cover. The heat transfer coefficients h_{p-c} and h_{c-a} are given by:

$$h_{p-c} = h_{r,p-c} + h_{c,p-c} \quad (3)$$

$$h_{c-a} = h_{r,c-a} + h_{c,c-a} \quad (4)$$

The top loss coefficient is given by:

$$U_t = \left(\frac{1}{h_{p-c}} + \frac{1}{h_{c-a}}\right)^{-1} \quad (5)$$

IV. Experimental Setup

The prototype VFP collector fabricated in this work is shown in Fig. 4.

The prototype of the VFP collector, seen in Fig. 4, is constructed based on the design of Fig. 2 and has the following properties:

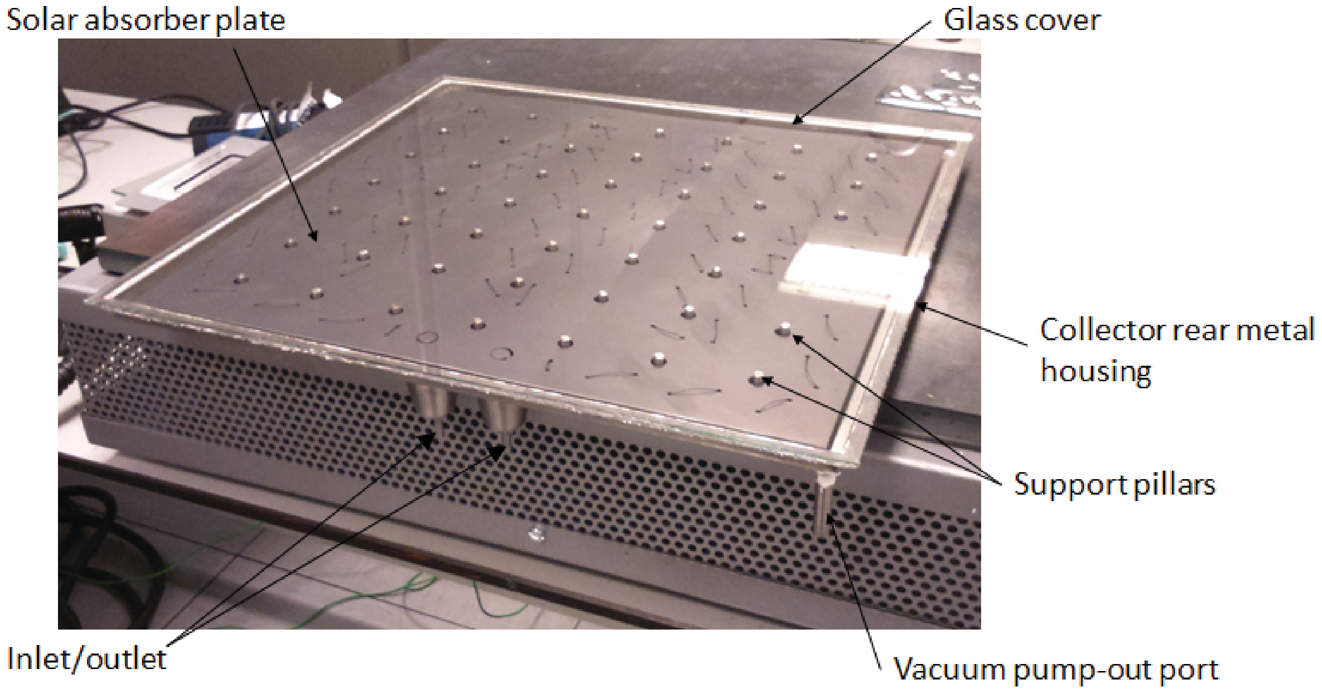

Fig. 4 Prototype of VFP solar thermal collector

TABLE I
Properties of Prototype VFP Collector

Collector Property	Value	Unit
Absorber area (A_p)	0.22	m^2
Glass cover area (A_c)	0.25	m^2
Mass of glass cover (M_c)	2.5	kg
Specific heat capacity of glass cover (C_c)	880	J/kg·K
Emissivity of absorber plate	0.5	--
Emissivity of glass cover	0.9	--
Absorber plate to glass cover/metal housing spacing	7	mm

In experimental testing, the absorber of a prototype VFP collector is heated via passing hot water through the absorbers heat transfer tubes using a Julabo (F25-ME) controlled temperature circulator. The temperature of the inlet and outlet were measured, as well as the temperature of the glass cover, via T-type thermocouples monitored by a DataTaker 800 series data acquisition system which sampled temperature every second (Δt = 1 second). The glass cover temperature was monitored via two thermocouples with one placed at the center of the panel and the other centrally aligned placed 125mm from the edge. The internal pressure of the prototype VFP collector was monitored via a Kurt J Lesker 392 wide range pressure gauge. An Edwards (T-station 75) vacuum pump was used to maintain the internal pressure of the VFP collector at less than 0.1 Pa during testing. In separate tests the VFP collector was heated at different temperatures (~45°C and ~55 °C) while the internal pressure was either standard atmospheric pressure (high pressure) or less than 0.1 Pa (low pressure). Each test was ran for a 1 hour period to allow the collector to approach thermal equilibrium.

V. EXPERIMENTAL AND MODEL RESULTS

The experimental results of this study are presented in Figs. 5 and 6.

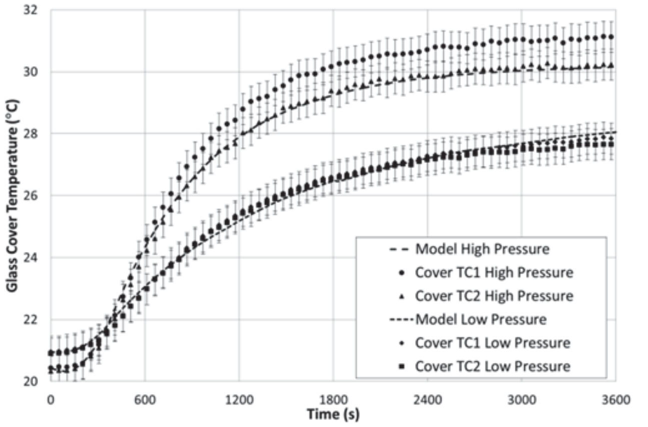

Fig. 5 Temperature of glass cover when passing 45°C water through the absorber plate

In Fig. 5, the temperature of the prototype VFP collectors glass cover is seen to increase and approach thermal equilibrium over the course of the 45 °C heating test. This is seen for both the high pressure and low pressure cases. The insulating effect of the vacuum layer surrounding the absorber plate is clearly seen with the low pressure temperature profiles being significantly lower than those for high pressure. It is interesting to note that for the high pressure case the thermocouple temperatures are different where as they are very similar in the low pressure case. This may be due to the absorber plate having a more uniform temperature profile over its surface in the low pressure case in comparison to the high pressure case. A similar situation is also seen in Fig. 6 for the 55°C heating tests. It should be noted that each test did not start with the same ambient temperature. Also, plotted in Figs. 5 and 6 are the glass cover temperatures as estimated via the thermal model for each of the cases. For each model instance the absorber temperature is taken as the average of the measured inlet and outlet temperatures. It can be seen that there is reasonable agreement between experimental and model results. This suggests that the heat transfer coefficients estimated by the model for each of the cases is a good representation of the actual heat transfer processes occurring in the prototype VFP solar collector. Using the thermal model, the top loss coefficient for each case was estimated.

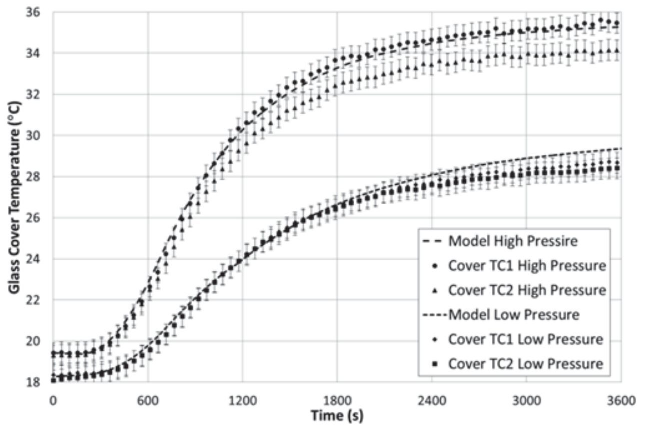

Fig. 6 Temperature of glass cover when passing 55°C water through the absorber plate

TABLE II
TOP LOSS COEFFICIENT ESTIMATES FOR EXPERIMENTAL CASES

Heating Temperature	45°C	55°C
Low Pressure	U_t = 2.3 W/m^2·K	U_t = 2.4 W/m^2·K
High Pressure	U_t = 3.8 W/m^2·K	U_t = 3.9 W/m^2·K

The estimated top loss coefficients presented in Table II shows that the presence of the vacuum layer between the absorber plate and the glass cover has a significant insulating effect. Approximately 40% reduction in heat lost from the absorber plate to the glass cover is seen.

The values of top loss coefficient seen in Table II are relatively high for what would be expected from a VFP collector and is likely due to the high emissivity value of the absorber plate and glass cover. This can be improved via the use of better materials in a VFP collector and can be demonstrated via the use of the thermal model. For example, the emissivity of the absorber plate could be reduced, via a selective coating, to 0.1. For the 55 °C heating case this would result in the glass cover temperatures seen in Fig. 7.

In Fig. 7, there is a clear reduction in glass cover temperature for the low pressure case when the absorber emissivity is reduced to 0.1 in comparison to the other cases. The top loss coefficient estimate in this case is much smaller at ~ 0.6 W/m2·K. Assuming similar values for the bottom and edge loss coefficients, this suggests that with appropriate selection of materials and coatings in VFP solar thermal collectors, efficiencies consistent with those predicted in the literature are achievable.

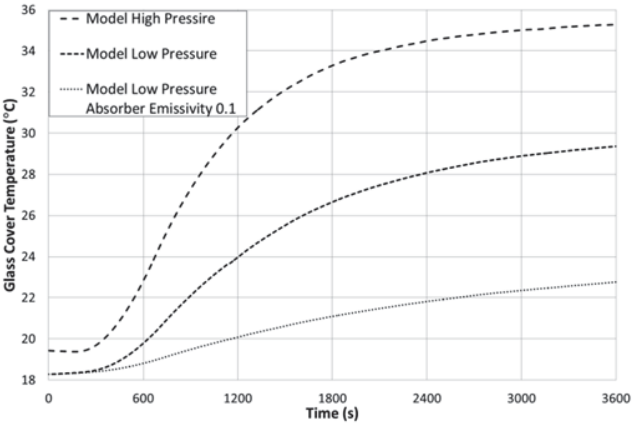

Fig. 7 Modeled temperature of VFP collector glass cover temperature in 55°C test

VI. GETTER SIZING AND ACTIVATION

The selection, sizing and activation of an appropriate getter within the enclosure of a VFP solar thermal collector is essential to ensuring the collector performs consistently over its service lift time, which could be up to 30 years. The getter should be sized for the expected gas load likely to occur over this time and is dependent on the manufacturing process of the collector as well as the materials used to construct the collector.

In this work, a getter is selected and sized for the VFP collector of Fig. 4. A primary driver for the selection of a getter for this collector is its ability to be activated at low temperatures (< 300 °C). This is important as the activation of the getter, via heating, should be conducted in a manner that safe guards the periphery hermetic seal of the collector. The hermetic seal material may be indium, which is a known hermetic sealing material in vacuum glazing [16], or a tin based solder. Indium has a melting temperature of ~154 °C and appropriate tin based solders have melting temperatures between 210 °C and 250 °C.

The initial outgassing rate (q_0) of pre-cleaned and degreased surfaces of glass and stainless steel can be around 10^{-6} mbar cc s^{-1} cm^{-2} [17]. This can be improved with prior baking out of the collector enclosure at temperatures dependent on the hermetic seal material. The outgassing rate (q) of the collector will typically decrease over time (t), which can generally be described via [18]:

$$q = q_0 t^{-\nu} \tag{6}$$

where ν is time factor specific to the type of gas (is estimated to have a value of 0.5 for gasses that desorb by diffusion in to the enclosure volume from the bulk of the enclosure structure [18]). The total gas load per unit internal surface area of the collector (Q) can be described as [18]:

$$Q = q_0 \frac{t^{1-\nu} - 1}{1-\nu} \tag{7}$$

The volume of the prototype VFP collector is estimated to be ~1.6 liters and the internal surface area of the collector is estimated to be ~0.7 m^2. Assuming an initial outgassing rate of 10^{-6} mbar·cc·s^{-1}·cm^{-2}, the gas load of the collector over a 30 year period is predicted to change as plotted in Fig. 8.

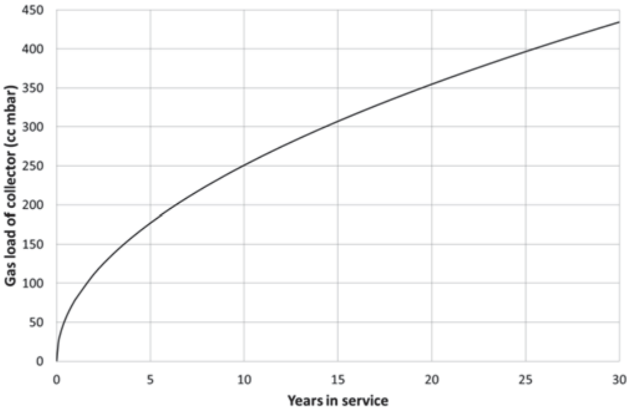

Fig. 8 Estimated gas load of prototype VFP collector over service life

From Fig. 8, it is predicted that the prototype VFP collector would have a gas load of ~450 cc·mbar after a 30 year period. This constitutes a pressure increase inside the collector enclosure of ~0.3 mbar (30 Pa) which would significantly impact the performance of the collector over time if not dealt with via a getter. A suitable getter, recommended by a getter manufacturer [19], is the St2002/10-3 non-evaporable getter. These getters come as pills with each pill capable of absorbing a gas load of ~125 cc·mbar suggesting that 4 pills would be sufficient to cope with the collectors outgassing over its service life. More pills can be added to provide additional margins of safety with regard to collector performance. An additional advantage of this getter is that it can be activated at relatively low temperatures. The lowest recommended activation temperature is 250 °C which the getter must be heated to and kept at for several hours to achieve a sufficient level of activation. Depending on whether the solder alloy used to create the periphery hermetic seal is solid at 250 °C, the entire collector enclosure could be heated to this temperature or the getter must be heated locally inside the collector. For the latter case it would be advisable to locate the getter pills in the center of the enclosure, far removed from the periphery seal during getter activation.

VII. CONCLUSION

VFP solar thermal collectors are considered to be capable of exceeding the performance of conventional solar thermal collectors. This is a result of the insulating vacuum layer that surrounds the solar absorber plate within the collector's vacuum enclosure as well as the solar absorber filling a large proportion of the available gross area.

In this study a prototype FP vacuum solar thermal collector was thermally characterized in terms of its top loss coefficient for cases when the absorber was heated to 45 °C and 55 °C with the collector enclosure either being evacuated to a low pressure or at standard atmospheric pressure (much like a conventional FP collector). For each of the low pressure cases a 40% reduction in top loss coefficient is observed over the high pressure cases. A model used to predict the thermal behavior of the prototype collector is used to demonstrate further reductions in top loss coefficient due to better material or selective coating selections for the solar absorber plate. Finally, a getter is selected and sized for the prototype collector with recommendations made with regard to activating the getter at temperatures similar to the melting temperature of the collectors' periphery hermetic seal material.

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