ANALYSIS OF A PHOTOVOLTAIC/THERMAL SOLAR COLLECTOR FOR BUILDING INTEGRATION

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ABSTRACT

The idea of combining photovoltaic and solar thermal collectors (PVT collectors) to provide electrical and heat energy is not new, however it is an area that has received only limited attention. With concern growing over energy sources and their usage, PVTs have become a focus point of interest in the field of solar energy research. Although PVTs are not as prevalent as solar thermal systems, the integration of photovoltaic and solar thermal collectors into the walls or roofing structure of a building could provide greater opportunity for the use of renewable solar energy technologies in domestic, commercial and industrial applications. As such, the design of a novel building integrated photovoltaic/thermal (BIPVT) solar collector is theoretically analysed through the use of a modified Hottel-Whillier model. The thermal efficiency under a range of conditions was subsequently determined and results showing how key design parameters influence the performance of the BIPVT system are presented.

KEYWORDS:

Photovoltaics; solar thermal; photovoltaic/thermal; BIPVT

INTRODUCTION

The utilisation of solar energy has traditionally been divided into two fields; solar thermal and photovoltaics. Solar thermal research is, as the name suggests, concerned with the utilisation of solar radiation to provide useful heating. Typical examples include passive solar heating of houses and solar water heating. Photovoltaics, on the other hand, are concerned with the conversion of solar energy to electricity, mainly through the use of silicon based solar cells.

Solar thermal energy has a long history and is used extensively for water and space heating. A survey by the International Energy Agency Solar Heating and Cooling programme (IEA SHC) (2006) found that, in 2004, there was approximately of 141 million m^2 of solar thermal collectors in its 41 member countries. This survey also found that the solar thermal collector market in Australia and New Zealand was growing at a rate of 19% per annum. Furthermore, it showed that the use of solar thermal energy made significant reductions in the use of energy from other sources.

In contrast, photovoltaic devices have a much shorter history than solar thermal systems; however they too have received significant attention. Furthermore, over the last decade, the photovoltaic market has made significant moves away from their traditional application as standalone off-grid power sources to grid connected systems, thus opening the technology to a wider market.

Although both photovoltaics and solar thermal are mature technologies in their own rights, there are significant opportunities to combine the two elements into one device. The idea of combining photovoltaic and solar thermal collectors (PVT collectors) to provide electrical and heat energy is not new. However, with concern growing over energy sources and their usage, PVTs have started receiving more attention.

Van Helden et. al. (2004) noted that PV collectors absorb 80% of the incident solar radiation but convert only a small portion of this to electrical energy, the remainder being dissipated as thermal energy. Furthermore, they noted that the temperatures reached by PV cells are higher than the ambient temperature and that the efficiency of PVTs is greater than the combined sum of separate PV and thermal collectors. In light of this, they suggest that PVT systems offer a cost effective solution for applications where roof area is limited.

Although PVTs are not as prevalent as solar thermal systems, Florschuetz (1979) provided perhaps the earliest theoretical analysis of a PVT solar collector through the use of a modified Hottel-Whillier model. Bergene and Lovvik (1995) also conducted a theoretical examination of a flat plate solar collector with integrated solar cells based on the Hottel-Whillier model. They developed a series of algorithms which they utilized in calculating both the thermal and electrical efficiency of a PVT system. They suggested that such systems might be useful as pre-heaters for domestic hot water services.

More recently, Tripanagnostopoulos et. al. (2002) conducted tests on hybrid PVT systems using pc-Si and a-Si PV cells. They found that the cooling provide by the thermal integration assisted in improving the efficiency of the PV cells by approximately 10%. Additionally, they found that water cooling provided better cooling than air circulation. Finally, they suggested that the performance of these systems could be further improved through the use of diffuse reflectors or through glazing. However, glazing the collectors would improve thermal performance to the detriment of the electrical efficiency.

He et. al. (2006) recently studied a hybrid PVT system which used natural convection to circulate the cooling water. They found that their system showed a combined efficiency in the order of 50%, with the thermal efficiency contributing approximately 40%. Although they found that the thermal efficiency was less than a conventional thermosyphon solar water heater they note that the energy saving efficiency was greater.

Chow et. al. (2006) also examined the hybrid PVT system of He et. al. (2006) and developed a dynamic thermal model. They suggested that this system could be improved by placing the PV cells on the lower portion of their collector. They noted that there was a larger temperature gradient between the water entering the thermosyphon tubes and the PV cells in this region and so the electrical and thermal efficiency could be improved by placing the cells there.

Many of the systems mentioned however have only focused on stand alone PVT water heating devices with little integration into buildings. Bazilian et. al. (2001) presents a comprehensive examination of PV and PVT in built environments. In their study they highlight the fact that PVT systems are well suited to low temperature applications. Furthermore they note that the integration of PV systems into the built environment can achieve “a cohesive design, construction and energy solution” (p.57). Finally, they note the need for further research to be undertaken before combined PVT systems become a successful commercial reality.

Given the research that has been conducted to date, it is apparent that there is still a large amount of work that needs to be undertaken before PVT systems can be successfully implemented and integrated into domestic and commercial building applications.

BIPVT OVERVIEW

The system examined in this study is unique in a number of ways. Unlike many of the systems that have been proposed, this system is directly integrated into the roof of a building, in this case a standing seam or troughed sheet roof. Standing seam and troughed sheet roofs are typically made from aluminium or coated steel, although copper or stainless steel could be used. They are rolled or pressed into a shape that gives the roof product stiffness, strength and when assembled are weather proof. This system utilises the high thermal conductivity materials used in these roofing systems to form the BIPVT collector. During the manufacturing process in addition to the normal troughed shape, passageways are added to the trough for the thermal cooling medium to travel through.

In essence, a cover having PV cells laminated to its surface is bonded into the trough. The passageways formed in the trough are subsequently enclosed by the cover; thus forming a tube to which heat can be transferred. The flow ways have an inlet and outlet at opposite ends of the trough as shown in Figure 1. In addition the design allows a glass or polymer glazing to be added to the collector to create an air gap between the outer surface of the PV module and laminate surface and the ambient air. This could be used to increase the temperature of the BIPVT to improve the thermal efficiency of the collector.

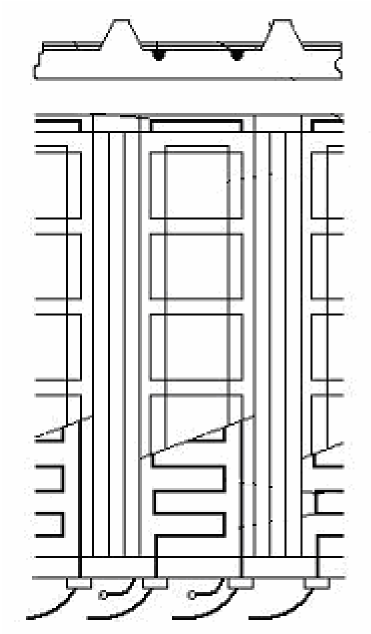

Figure 1: BIPVT Collector

As the PV cells are exposed to sunlight they absorb radiation and generate electricity, however, silicon PV cells tend to convert only short wavelength radiation to electricity while the longer wavelengths result in heating of the laminate. As such, in the BIPVT collector there is heat transfer from the cells through the laminate to the fluid passing underneath. The fluid is pumped along the flow paths and output through a manifold and pipes and fed to a heat exchanger that removes the heat from the fluid. The system is continuous so that the cooler fluid enters the passageways and is heated by the PVs and so on. The heating of the fluid reduces the temperature of the PV cells, thereby increasing their efficiency under high temperature and radiation conditions.

METHODOLOGY

In order to analyse the thermal performance of the PVT it was decided to use a 1 dimensional steady state thermal model. In this model it was assumed that the collector could be represented as a flat plate thermal collector. As such a modified from of the Hottel-Whillier-Bliss equations presented by Duffie and Beckman (2006) were used.

Under these conditions the useful heat gain was calculated using Equation 1.

$$Q = AF_R\left[(\tau\alpha)_{PV}.G - U_{loss}(T_{in} - T_a)\right] \tag{1}$$

In this equation the useful heat gain (Q) is represented by a function of the collector area (A), the heat removal efficiency factor (F_R), the transmittance-absorbtance product of the photovoltaic collector ($\tau\alpha_{PV}$), the solar radiation (G), the collector heat loss coefficient (U_{loss}) and the temperature difference between the cooling medium inlet temperature(T_{in}) and the ambient temperature(T_a).

The heat removal efficiency factor (F_R) can be calculated using Equation 2, which also accounts for the mass flow rate in the collector (m) and the specific heat of the collector cooling medium (C_p).

$$F_R = \frac{mC_P}{AU_{loss}}\left[1 - e^{-\frac{AU_{loss}F'}{mC_P}}\right] \tag{2}$$

In order to obtain the heat removal efficiency factor however, it is necessary to calculate a value for the corrected fin efficiency (F’). This is done by first calculating the fin efficiency (F) using Equation 3.

$$F = \frac{\tanh\left(M\frac{W-d}{2}\right)}{\left(M\frac{W-d}{2}\right)} \tag{3}$$

This equation determines the efficiency of the finned area between adjacent tubes by taking into account the influence of the tube pitch (W) and the tube diameter (d).

The coefficient (M) is a term which accounts for the thermal conductivity of the absorber and PV cell and is represented by Equation 4.

$$M = \sqrt{\frac{U_{loss}}{K_{abs}L_{abs} + K_{PV}L_{PV}}} \tag{4}$$

As such, the corrected fin efficiency (F’) can be calculated using Equation 5.

$$F' = \frac{\frac{1}{U_{loss}}}{W\left[\frac{1}{U_{loss}(d + (W-d)F)}\right] + \frac{1}{Wh_{PVA}} + \frac{1}{\pi d h_{fluid}}} \tag{5}$$

In Equation 5, the overall heat loss coefficient (U_{loss}) of the collector is the summation of the collector's edge, bottom and top losses and h_{PVA} and h_{fluid} are a "quasi" heat transfer coefficient to account for the bond resistance between the PV cell and the absorber (Zondag et. al., 2002) and the forced convection heat transfer coefficient inside the cooling passage respectively. Further, the bottom loss coefficient is given by the inverse of the insulations R-value (ie. K_b/L_b), the edge losses are given by Equation 6, where p is the collector perimeter and t is the absorber thickness.

$$U_{edge} = \frac{K_{edge} pt}{L_{edge} A_{collector}} \quad (6)$$

The top loss coefficient, due to reflections and wind, can be calculated using Klein's empirical equation (Equation 7) as given by Duffie and Beckman (2006).

$$U_{top} = \left\{ \frac{N}{\frac{c}{T_{pm}}\left(\frac{T_{pm}-T_a}{N-f}\right)^e} + \frac{1}{h_w} \right\}^{-1} + \frac{\sigma\left(T_{pm}+T_a\right)\left(T_{pm}^2+T_a^2\right)}{\left(\varepsilon_p + 0.00591Nh_w\right)^{-1} + \frac{2N+f-1+0.133\varepsilon_p}{\varepsilon_g} - N} \quad (7)$$

Where:

$$c = (520 - 0.000051\beta^2) \qquad f = (1 + 0.089h_w - 0.1166h_w\varepsilon_p)(1 + 0.07866N)$$

$$e = 0.430(1 - \frac{100}{T_{pm}}) \qquad T_{pm} = T_{in} + \frac{Q / A_{collector}}{F_R U_{loss}}\left(1 - F_R\right)$$

β is the collector mounting, σ is the Stefan-Boltzmann constant, N is the number of covers or glazing layers, ε_g the emittance of the cover or glazing, ε_p the emittance of the plate and h_w is the convection heat transfer due to the wind.

From these equations it is then possible to calculate the useful heat gain by the solar collector. Furthermore, by rearranging Equation 1, we can develop an equation for determining the thermal efficiency of the BIPVT. This equation is expressed in the form shown in Equation 8.

$$\eta_{thermal} = F_R(\tau\alpha)_{PV} - F_R U_{loss}\frac{T_{in} - T_a}{G} \quad (8)$$

Additionally, it is possible to analyse the thermal performance of PVT collectors by the inclusion of a packing factor. In practical terms, it is not always possible to have complete coverage of a panel with photovoltaic cells. As such Equation 1 can be modified to account for this packing factor (S) and the transmittance-absorbtance product of the collector material ($\tau\alpha_T$) on which the PV cells are mounted, as shown in Equation 9. By rearranging Equation 9, it is also possible to determine the thermal efficiency.

$$Q = S\left[AF_R\left[(\tau\alpha)_{PV}.G - U_{loss}(T_{in} - T_a)\right]\right] + \left(1-S\right)\left[AF_R\left[(\tau\alpha)_T.G - U_{loss}(T_{in} - T_a)\right]\right] \quad (9)$$

Having established the methodology for calculating the performance of a PVT solar collector, some typical design values were chosen, as shown in Table 1, to examine their performance.

Table 1: PVT physical characteristics

Parameter	Symbol	Value	Unit
Number of covers	N	1	
Ambient Temperature	T_a	293	K
Emittance of plate	ε_p	0.95	
Emittance of cover	ε_c	0.88	
Number of tubes	n	66	
System flow rate	m	2	l/s
Collector Area	$A_{collector}$	100	m^2
PV Trans/Abs	$\tau\alpha_{PV}$	0.74	
Thermal Trans/Abs	$\tau\alpha_T$	0.82	
Absorber thickness	t	0.5	mm
PV thickness	L_{PV}	0.4	mm
PV conductivity	K_{pv}	84	W/mK
Tube Hydraulic Diameter	d	9.7	mm
Tube Spacing	W	0.1	m
"Quasi" heat transfer coefficient from cell to absorber (Zondag et. al. 2002)	h_{PVA}	45	W/m^2K
Insulation Conductivity	K	0.045	W/mK
Back insulation thickness	L_b	0.1	m
Edge Insulation Thickness	L_{edge}	0.025	m
Absorber Conductivity	K_{abs}	50	W/mK

RESULTS

From the physical characteristics given in Table 1, it was apparent that a number of variables could be modified in order to improve the thermal efficiency of the BIPVT system. As such a sensitivity analysis was conducted to determine how some of these variables would affect the thermal efficiency of the system relative to the ratio between the reduced temperature (T_{in} –T_a) and the global radiation incident of the collector surface (G").

Typically, heat transfer is controlled by the Reynolds number which is a function of flow rate; as such flow rate was varied to examine its effect on the thermal efficiency. In Figure 2 it can be seen that it has negligible impact in this regard, however, it does improve heat transfer meaning that electrical efficiency does increase marginally.

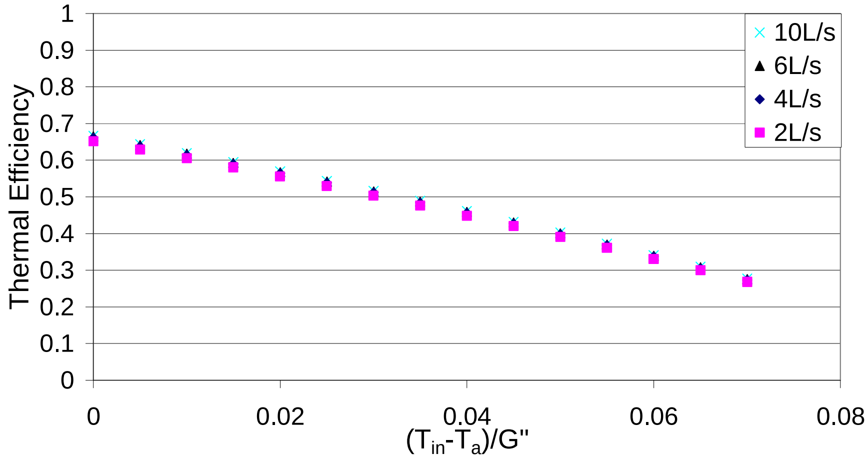

Figure 2: BIPVT thermal efficiency at varying flow rates

Furthermore, it may be possible to vary the material from which the collector is made. In Table 1 it was assumed that the collector was made from steel, however, by using aluminium or copper it is possible to increase the thermal conductivity and hence transfer within the panel. However, as shown in Figure 3, the material from which the collector is made does not significantly improve the thermal efficiency. Similarly the thermal resistance of the PV cells was varied to examine if this was influencing the thermal efficiency, however this also did not influence the efficiency significantly.

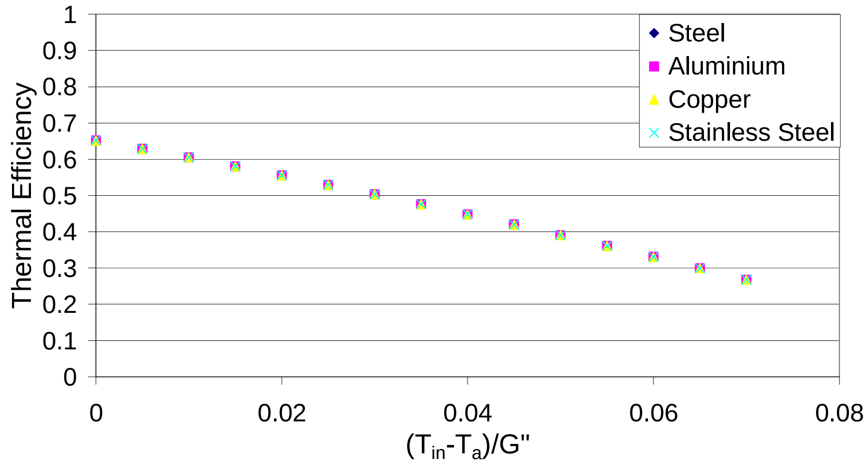

Figure 3: BIPVT thermal efficiency for varying collector materials

Another way in which heat transfer can be improved is by increasing the thermal conductivity between the PV cells and the absorber plate. In Table 1 a value of 45 W/m^{2}K (h_{PVA}) was used as a "quasi" heat transfer coefficient between the PV cells and the absorber plate rather than the bond resistance normally used in the Hottel-Whillier-Bliss equations (the experimental derivation of this value was reported and discussed by de Vries (1998) and Zondag et.al. (2002)). However, this value could be increased by the use of thermally conductive adhesives to join the cells to the absorber. In Figure 4 it can be seen that by increasing the value of this "quasi" heat transfer coefficient to 135 W/m^{2}K, that the maximum thermal efficiency is improved by approximately 5%. As such, it would be prudent to ensure that thermal conductivity between these bodies is maximised.

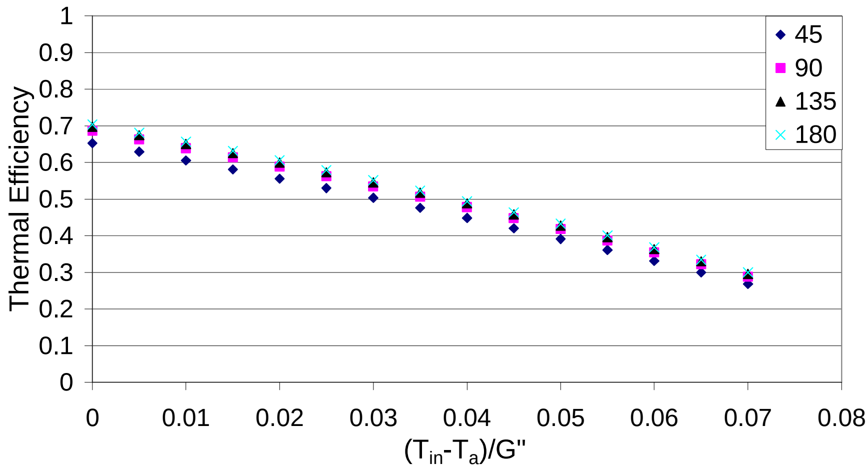

Figure 4: BIPVT thermal efficiency for varying PV to absorber conductivities

In addition to improving the heat transfer between the absorber and the PV cells, it may be possible to improve the optical efficiency of the BIPVT system. In Table 1, a value of 0.74 was specified for the transmittance/absorptance product for the PV cells. De Vries (1998) derived this value from a theoretical optical analysis of a photovoltaic laminate; however, Coventry (2004) found that for his concentrating PVT system that the transmittance/absorptance product was 0.82. This difference can be explained by the differing lamination methods and materials and the method of practical implementation that were analysed by these authors. De Vries analysed a “typical” PV laminate using EVA encapsulation, whereas Coventry used Silicone encapsulation. Moreover, Santbergen and van Zolingen (2006) suggested a number of modifications that could be made to PV cells in order to increase the transmittance/absorptance product for PVT collectors. The effect of varying this parameter is clearly illustrated in Figure 5.

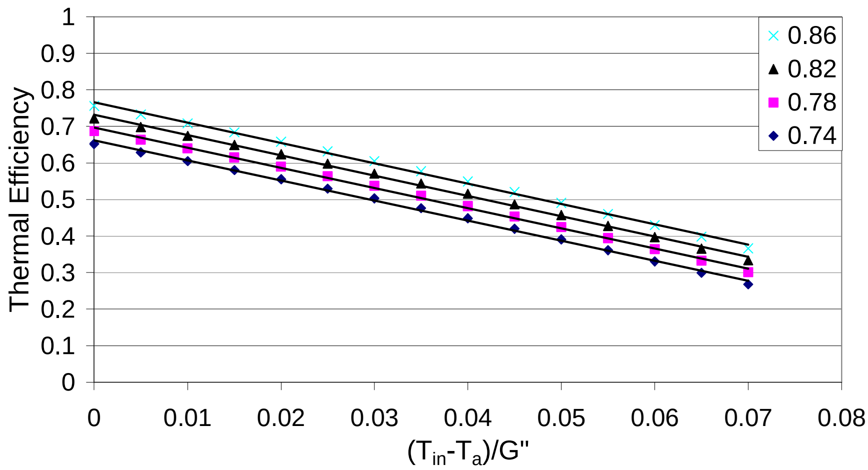

Figure 5: BIPVT thermal efficiency for varying transmittance/absorptance products

From Figure 5 it is clear that by increasing the transmittance/absorptance product, that the thermal efficiency can be improved. The reason for this improved performance is related to the spectral absorption characteristics of PV cells, typically these respond well to short wavelengths, in the range from 400nm up to approximately 1200nm. The solar spectrum however continues to approximately 2500nm and these long wavelengths tend to be reflected from PV cells, whereas they are absorbed by solar thermal collectors. The modifications suggested by Santbergen and van Zolingen were aimed at increasing the absorption of these longer wavelengths, while the use of a silicone encapsulant by Coventry meant that a greater portion of the longer wavelengths were absorbed by the silicone whose spectral properties were shown to absorb longer wavelengths.

As an alternative method for improving the thermal efficiency it is possible to vary the area that is covered by PV cells. In Table 1 a value of 0.82 was specified as the transmittance/absorptance product for the absorber to which the PV cells were mounted, as this was greater than the unmodified PV cells with a transmittance/absorptance product of 0.74 it is apparent that by decreasing the area covered by PV cells that the thermal efficiency increases. In Figure 6 it can be seen that increasing the amount of area covered by PV cells does reduce the thermal efficiency. Obviously, however, reducing the area covered by PV cells also means that the overall electrical output is reduced.

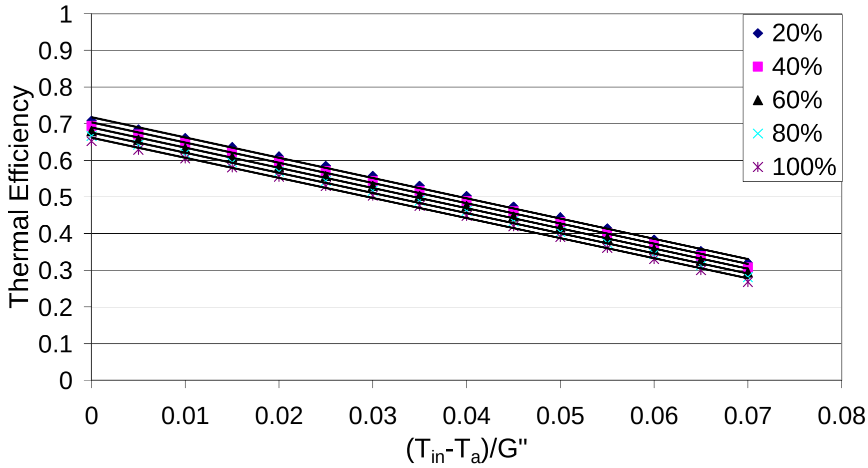

Figure 6: BIPVT thermal efficiency for varying PV area coverage

Previously it was noted that the transmittance/absorptance product of 0.74 could be improved by altering the lamination method and the PV cells. Another simple method is to remove the glazing (cover) from the PVT panel. The presence of glazing means that not all the available radiation is transmitted to the PV cells as some is absorbed or reflected by the glazing. As such removing the glazing should improve the maximum efficiency. De Vries (1998) suggested that an unglazed PVT would have a transmittance/absorptance product of 0.78.

However, it should also be noted that in an unglazed situation the thermal efficiency of the collector is strongly related to the external wind speed. In essence, a glazed collector has a “pocket” of air trapped between the absorber plate and the glazing that suppresses the heat loss due to forced convection by the wind. As this layer of air is not present in an unglazed collector the forced convection heat loss from the wind tends to dominate the performance of the collector. As such, in Figure 7, it can be seen that the maximum thermal efficiency is higher than for the previously illustrated cases but reduces significantly at increasing wind speeds.

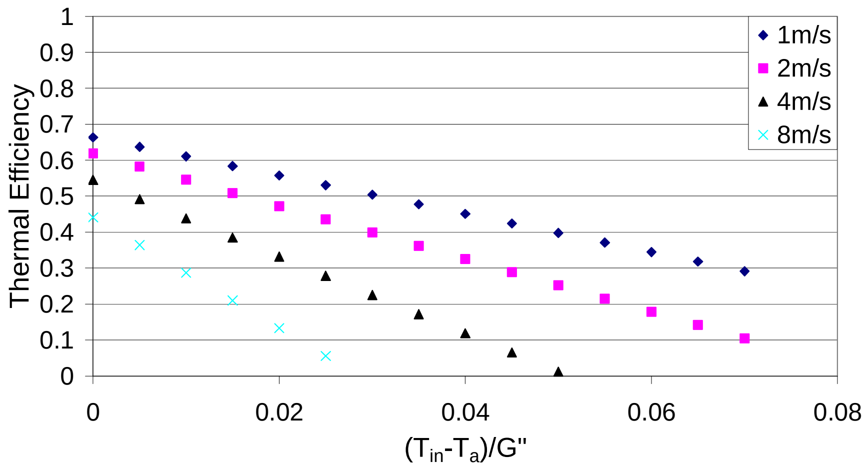

Figure 7: Unglazed BIPVT thermal efficiency

Furthermore, it should be noted that the reduced thermal efficiency is not necessarily an entirely negative point. In fact if the system were to be coupled with a heat pump system, such as that discussed by Anderson et. al. (2002), the lower inlet temperatures, typically below ambient in the evaporator of a heat pump, would mean that the efficiency characteristics of the BIPVT would be advantageous as its thermal, and electrical, efficiency would increase at temperatures below ambient.

Finally, the analysis that has been presented has treated the BIPVT collector as a typical solar collector, however, it should be remembered that it is in fact also a roofing or façade element. In New Zealand it is common for buildings to use insulation at the ceiling level rather than at the rear of the roof and so it was decided to examine the effect of varying the insulation thickness at the rear of the panel. In Figure 8 it can be seen that by treating the BIPVT as a "stand-alone" solar collector, that reducing the thickness of insulation reduces the thermal efficiency. However, it can also be seen that the 100 mm of insulation specified in Table 1 is equivalent to having 100mm of static air trapped behind the collector.

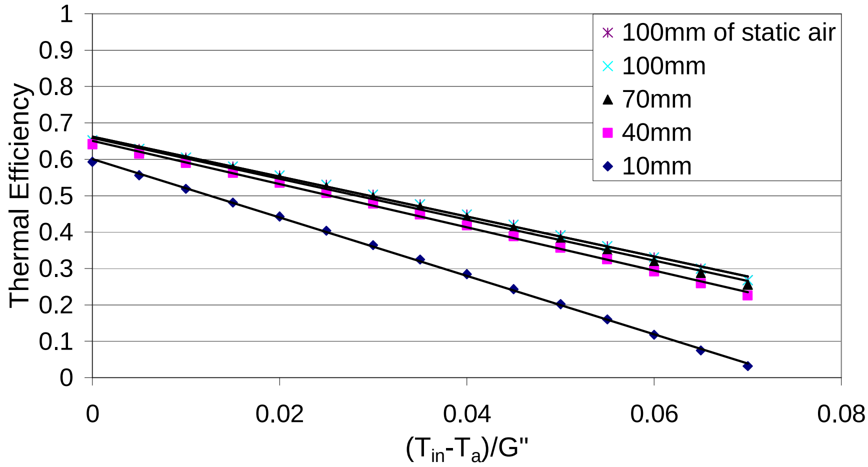

Figure 8: BIPVT thermal efficiency for vary levels of insulation

Given that air could provide the same level of insulation as an insulating material there is obvious scope for reducing the cost of materials in the construction of BIPVT by doing this. At the most basic level it may be possible to rely on natural convection in attic spaces or wall cavities to provide a degree of insulation, however this requires further examination.

CONCLUSION

From the results presented it has been shown that there are a number of parameters that can be varied in the design of a BIPVT collector such as that discussed. The fact that collector material made little difference to the thermal efficiency of the BIPVT suggests that lower cost materials, such as steel, could be utilised for these systems.

Further, it was highlighted that good thermal contact between the PV cells and the absorber needs to be made; this could be achieved using thermally conductive adhesives. Additionally, any modifications that can be made to improve the absorption of long-wave radiation should be made. As was shown, increasing the transmittance/absorptance product results in perhaps the greatest increase in performance of any parameter discussed. Furthermore the use of unglazed BIPVT systems in conjunction with heat pumps could present interesting possibilities.

Finally, there appears to be significant potential to replace the insulation material at the rear of the BIPVT with an air-gap, thus reducing materials costs. In order to accurately quantify this effect for a typical roof-integrated BIPVT, there is a need to understand and develop correlations to describe the natural convection heat transfer in attic spaces. As such, it is suggested that this should serve as the basis for future work in this area.

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