The design and performance of a novel low cost all polymer flat plate solar collector

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Abstract

One of the major barriers to the uptake of solar water heating is the initial cost of these systems. The use of polymers as an alternative to the commonly used metal and glass structure could lead to significant reductions in the cost of solar water heating systems. Therefore, this study explores the design and development of a new low cost polymer solar collector.

It shows that in addition to polymer material costs being less expensive than traditional materials, a reduction in the cost of manufacture and assembly may be achievable by using fewer parts. In this respect, the design uses significantly fewer components than a traditional collector, and is simple to assemble and disassemble. This means the parts are easily separated and therefore available for re-use once the collector's life is over, this 'cradle to cradle' approach to the design of solar water heaters has not previously been previously discussed in the literature.

Furthermore, it shows that by rethinking the traditional fin-tube design used in metallic collectors, with a view to maximising the wetted area, the issue of the low thermal conductivity of polymers can be effectively eliminated.

Finally, experimental testing of the polymer collector demonstrates that their efficiency is not significantly different from a traditional flat plate solar collector and so do present a feasible alternative to the current technology.

1. Introduction

Traditional flat plate solar collectors use a mixture of different materials and a large number of individual components that often require expensive fabrication methods. In addition, the use of multiple materials can result in high manufacturing and assembly costs while also leading to difficulties in separating these materials at the end of the collector's useful life.

The current state of technology for flat plate solar collectors is based primarily upon metals, (multiple copper tubes with an aluminium or copper absorber fin and aluminium or steel casing), glass (sometimes with an anti-reflective layer) and mineral wool insulation with the associated processing methods and cost. The costs of these conventional systems are unlikely to be reduced significantly in the future as the current technologies have nearly exhausted the most possible cost reductions.

As such, one possible avenue to achieving lower manufacturing costs is to manufacture collectors from polymers and with fewer parts. This seems to be a realistic alternative, providing relevant standards are met, and thermal efficiencies are broadly similar to traditional collectors.

Polymers have previously been used as low cost material for unglazed solar collectors in low temperature water heating applications, such as pool heating. The reason for this is that these materials tend to have poor thermal conductivities that can lead to relatively low collector efficiencies. However, despite the poor thermal conductivity of polymers a number of studies have shown that collectors made from polymers can achieve thermal efficiencies comparable to “standard” flat plate glazed solar water heaters.

Since the 1970s there has been considerable efforts made to design low cost water heaters both for industrial and commercial applications. A number of systems were developed during the 1970s that consisted simply of large low cost plastic bags resting on a layer of thermal insulation. In a 1997 study, Tsilingiris developed a similar design but utilised a rigid enclosure that incorporated thermal insulation. (Tsilingiris, 1997). The use of polymer absorbers has also been studied by Van Niekerk et al (1996) with the aim of evaluating polymer parallel tubes. One outcome from this work was to conclude that the best configuration for parallel tubes was obtained from tubes that had zero spacing between them. Further work by Matrawy & Farkas (1997) compared three different configurations of collector: twin parallel plate, serpentine and parallel tubes and concluded that a twin parallel plate collector can deliver a high efficiency for solar water heating systems.

Now although flat plate solar collectors are a relatively mature technology, and a number of studies have demonstrated the technical feasibility of polymer flat plate solar collectors, there is very little discussion in the literature about the disposal of solar collectors. It is becoming increasingly important to consider how materials can be re-used after a products useful life has ended and this ‘cradle to cradle’ (Braungart, McDonough, & Bollinger, 2007) approach has already been adopted by the automotive industry. In this respect, The End of Life Material Directive (Kanari, Pineau, & Shallari, 2003) introduced by the European Union, that requires a minimum of 95% of the average weight per vehicle be reused and recovered, and is likely to be the forerunner of a whole new approach to design and manufacture of all products in the very near future. In this respect materials need to easily separated at the end of their life and not mixed with other materials (for example; how does one easily separate a laser welded aluminium fin absorber from a copper riser tube). In this respect, “design-for-disassembly” will enable the materials to be up-cycled and have a full new life after the original life of the part is over.

Therefore the aim of this work is to discuss the design and performance of a polymer solar water heater that minimises the number of components and materials used in its construction with a view to ensuring that it can be recycled when its useful life as a water heater has expired.

2. Design Concept

As has been highlighted, one means of achieving a robust “whole of life” design is through a significant reduction in parts, thus allowing for easy assembly and disassembly. This process requires suitable structuring of assemblies to allow an economic dismounting of the product without damaging the parts. This can also be aided by selecting joints which can be easily accessed and separated (Beitz, 1993).

In addition, the goal of a new polymer design is to use materials that are intended for real re-use and up-cycling at the end of the collector’s life cycle. In terms of polymers that meet this criteria, high density polyethylene (HDPE) and poly-methyl methacrylate (PMMA or acrylic) offer appropriate characteristics for the absorber/casing and glazing respectively, as it has been demonstrated that both HDPE (Boldizar, Jansson, Gevert, & Möller, 2000) and PMMA (Kikuchi, Hirao, Ookubo, & Sasaki, 2014) can be up-cycled with no loss of original material properties.

In maintaining this philosophy, it is envisaged that conceptually, a collector could be realised that consists of only two main parts, an acrylic outer cover and a HDPE absorber plate. In such a configuration the outer cover could be fabricated from acrylic sheet that folds around the absorber and functions as the top cover as well as the side and bottom panels. The absorber could be achieved in a single piece of rotationally moulded HDPE, with a "pillow" absorber type configuration. This would be a move away from the traditional fin and tube style of absorber typically used in current systems, and is similar to the rectangular duct channels investigated by Rommel and Moock (1997). By moving to this style of design the wetted area is maximised, and despite having a lower conductivity, a polymer absorber of this type could potentially achieve similar efficiencies to that of a conventional collector. Further, the problem of stagnation temperatures, that have limited the use of some commodity polymers in the past, could be dealt with in a number of ways; such as venting, drain back, shades or even by trading efficiency against heat loss to maintain the cost effectiveness.

3. Experimental Testing

Having developed a conceptual design for an all polymer solar collector, it was decided to undertake a comparative assessment of three flat solar collectors: firstly a commercially available collector with a copper fin-tube absorber, secondly a commercially available collector with an aluminium housing, polymer glazing and absorber and finally a prototype HDPE polymer collector with acrylic glazing.

The prototype, shown in Figure 1a, consisted of three components, a folded acrylic cover, a rotationally moulded pillow type absorber (Figure 1b) and a layer of insulation to provide support to the absorber.

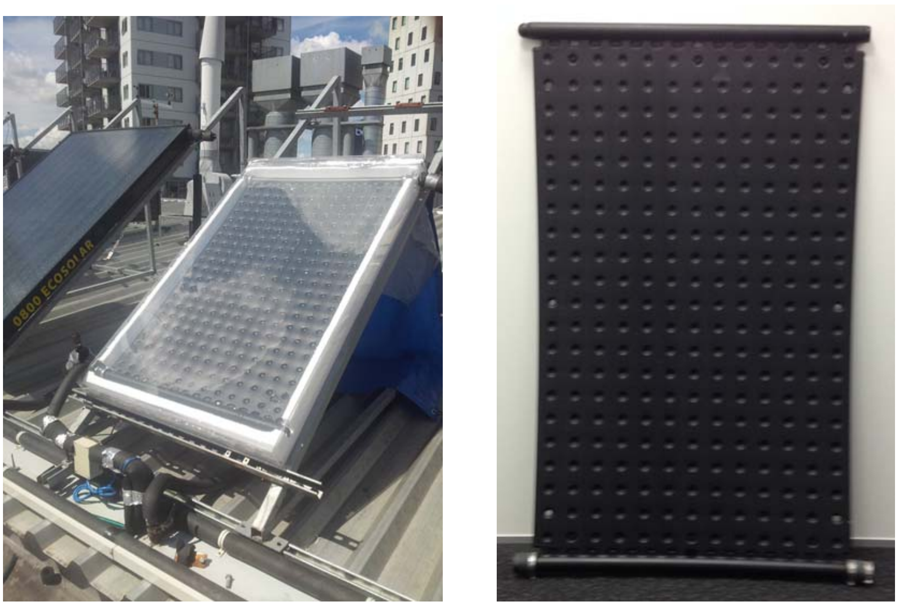

Figure 1. (a) Prototype collector, (b) pillow absorber in prototype collector

For this study, a steady state outdoor thermal test setup similar to that recommended in AS/NZS 2535.1-1999 and shown in Figure 2 was used to determine the efficiency characteristics of the collectors.

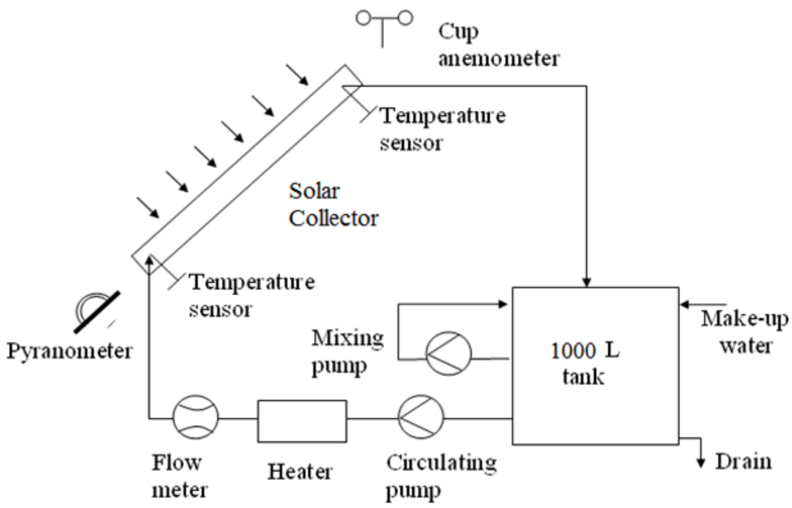

Figure 2. Experimental test system

In order to test the prototype and commercial collectors, an unimpeded north facing test location on the Auckland University of Technology's School of Engineering building was chosen. To quantify the performance of the collector the global incident solar radiation on the collectors was measured using a LI-COR LI-200 silicon pyranometer mounted in line with the collectors at an angle equal to the local latitude. T-type thermocouples (±0.3K), were used to measure the inlet and outlet temperatures to the collectors and also the ambient temperature, while a cup anemometer was used to monitor the wind speed adjacent to the collectors. The flow of water through the collector was set at a constant rate and measured by a vortex flow sensor (Grundfos VFS1-20) that was calibrated by manually measuring the time taken for a known volume of water to pass through the collector.

For each test all data was logged at 20 second intervals and the collectors were given at least 15 minutes at the beginning of each test condition in which to reach a quasi-steady state. Steady state was taken as being the conditions that met the requirements of AS/NZS 2535.1-1999. Additionally, any data points that satisfied these criteria but were more than 30 degrees either side of solar noon were eliminated to avoid including incident angle modifier terms.

4. Experimental Results

Now, when analysing the collectors, the instantaneous collector efficiency can be determined from the experimental results, simply defined as the ratio of heat transfer in the collector to the product of the collector area and the global solar irradiance. What was interesting to note was that the performance of all the collectors was broadly similar as shown by Figure 3. From this it can be seen that all the collectors had a similar overall heat loss coefficient, as indicated by the slope of their efficiency curve.

A noticeable difference however was in the optical performance of the collectors. It can be seen that the optical efficiency, where the efficiency curve intersects the vertical axis, of the copper absorber is significantly higher than the polymer absorbers and is likely the result of the higher absorptance of the copper absorber coating. However, broadly speaking, the difference in the efficiency of the collectors was relatively small and thus validates the case for entirely polymer collectors, and their further development.

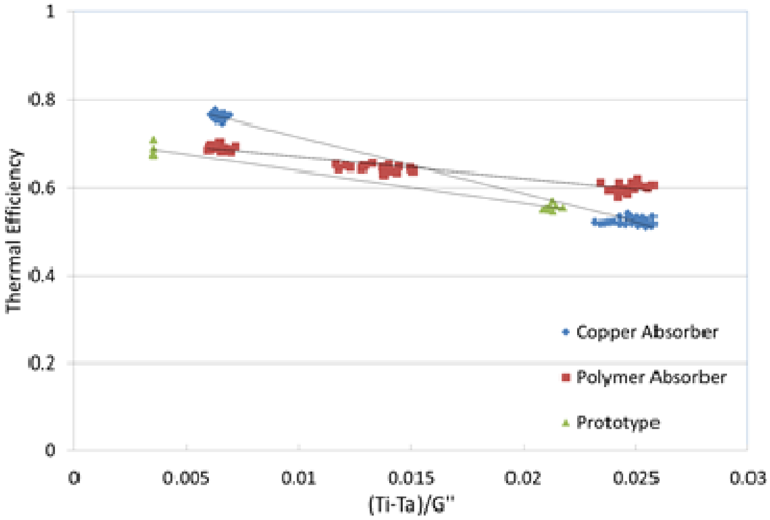

Figure 3. Efficiency of tested collectors

5. Design Modelling

In order to better understand the thermal performance of the all polymer design, and the opportunities to improve its performance, a one-dimensional steady state thermal model based on the Hottel-Whillier-Bliss equations outlined by Duffie and Beckman (2006) was developed. In doing this it was assumed that the pillow absorber design concept could be treated as a conventional parallel tube collector. However, to achieve this, it was assumed that the width of the tubes corresponded to the distance between the supports of the pillow absorber, as shown in Figure 4, and that there was a thin wall between these “tubes”.

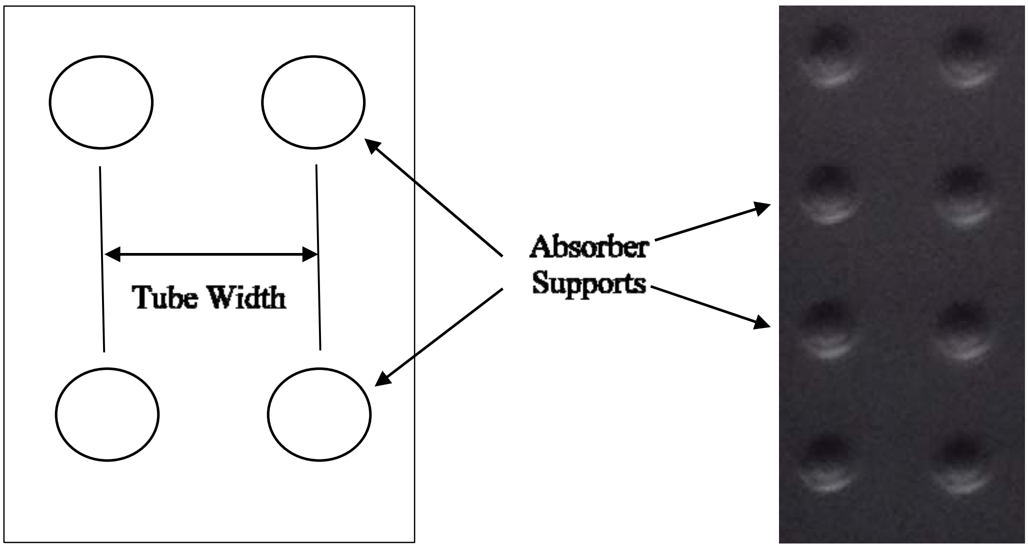

Figure 4. Absorber “tube” width

From a theoretical perspective, the thermal efficiency of a flat plate solar collector can be represented by a relationship between the collectors heat removal factor (*Fr*), the collector heat loss coefficient (*Ul*), the inlet (*Ti*) and the ambient temperature (*Ta*), solar radiation (*G”*) and the collector transmittance-absorptance product ($\tau\alpha$) as shown in equation 1.

$$\eta = F_r(\tau\alpha) - F_r U_l \left(\frac{Ti - Ta}{G''}\right) \quad (1)$$

Of the parameters shown in equation 1, the transmittance-absorptance product is the only one based on the physical properties of the collector materials. The absorptance provides a measure of the proportion of the radiation captured by the absorber surface while the transmittance component measures the portion of the radiation transmitted by the top cover.

As such, the transmittance-absorptance product is a property of a cover-absorber combination rather than just a product of two properties. The solar transmittance of the cover system and the solar absorptance of the absorber plate are both functions of wavelength and so the transmittance-absorptance product can be established from equation 2.

$$\tau\alpha = \frac{\int_0^\infty \tau_\lambda . \alpha_\lambda . I_{\lambda i} . d\lambda}{\int_0^\infty I_{\lambda i} . d\lambda} \quad (2)$$

Now for, “standard” collectors the range of transmittance-absorptance product is well known, however for the proposed concept this needs to be determined. Figure 5 shows the absorptance and transmittance curves for the HDPE absorber (Wang et al, 2013) and acrylic top cover Altuglas (2014). By integrating these values over the AM1.5 spectrum the transmittance-absorptance product for the polymer collector can be established.

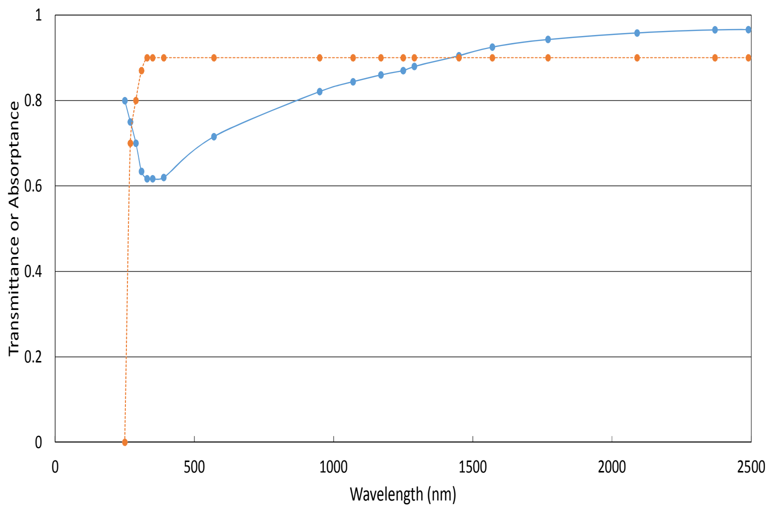

Figure 5. Optical characteristics of HDPE and acrylic

Returning to the steady state thermal model, under these conditions the useful heat gain can be calculated by equation 3:

$$Q = AF_r . [(\tau\alpha)G'' - U_l(Ti - Ta)] \quad (3)$$

where the useful heat gain (*Q*) is a function of the collector area (*A*), the heat removal efficiency factor (Fr), the transmittance-absorbance product of the collector (*τα*), the solar radiation (*G''*), the collector heat loss coefficient (*Ul*) and the temperature difference between the cooling medium inlet temperature (*Ti*) and the ambient temperature (*Ta*).

The heat removal efficiency factor (*Fr*) can be calculated using Equation 4, which also accounts for the mass flow rate in the collector (*m*) and the specific heat of the collector cooling medium (*Cp*).

$$Fr = \frac{m.Cp}{Ul.A}\left[1 - e^{-(AU_l F' / m.Cp)}\right] \quad (4)$$

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 5.

$$F = \frac{\tanh\left(M\frac{W-D}{2}\right)}{M\frac{W-D}{2}} \qquad (5)$$

Equation (5) 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 is represented by Equation 6

$$M = \sqrt{\frac{Ul}{K.t}} \qquad (6)$$

As such, the corrected fin efficiency (*F'*) can be calculated using Equation 7.

$$F' = \frac{1/Ul}{W\left[\frac{1}{Ul(D+(W-D)F)} + \frac{1}{\pi.D_h.h_f}\right]} \qquad (7)$$

Now in Equation 7 the overall heat loss coefficient (*Ul*) of the collector is the summation of the collector's edge, bottom and top losses as shown in Equation 8. The bottom loss coefficient is given by the inverse of the insulations R-value (i.e. Kb/Lb) and the edge losses are given by Equation 9, where p is the collector perimeter and t is the absorber thickness

$$Ul = Ut + Ue + Ub \qquad (8)$$

$$Ue = \frac{Kb.p.t}{Le.A} \qquad (9)$$

The top loss coefficient, can be calculated using Klein's empirical equation as given by Equation 10:

$$Ut = \left\{\frac{N}{\frac{c}{Tpm}\left(\frac{Tpm-Ta}{N-f}\right)^{e}} + \frac{1}{Hw}\right\}^{-1} + \frac{\sigma(Tpm+Ta)(Tpm^2+Ta^2)}{(\varepsilon p+0.00591.N.Hw)^{-1}+\frac{2N+f-1+0.133\varepsilon p}{\varepsilon g}-N} \qquad (10)$$

Where coefficients c, f and e are:

$$c = (520 - 0.000051\beta^2)$$

$$f = (1 + 0.089Hw - 0.166Hw.\varepsilon p)(1 + 0.07866N)$$

$$e = 0.430\left(1 - \frac{100}{Tpm}\right)$$

And *Tpm* is the mean plate temperature as shown in Equation 11

$$T_{pm} = Ti + \frac{Q/A}{Fr.Ul}(1 - Fr) \qquad (11)$$

From these equations it is then possible to calculate the useful heat gain by the solar collector as suggested by Equation 3 and the thermal efficiency of the collector as given by Equation 1.

6. Modelling Results and Discussion

Having developed a simplified representation of the pillow absorber, the efficiency of the prototype was modelled using the properties of the materials used in the prototype as well as the characteristic dimensions. In Figure 6 it can be seen that, despite the simplifying assumptions that were made about the flow in the collector, the experimentally measured efficiency corresponds well with the model prediction. On this basis there is scope to utilise this model in refining the design of an all polymer collector.

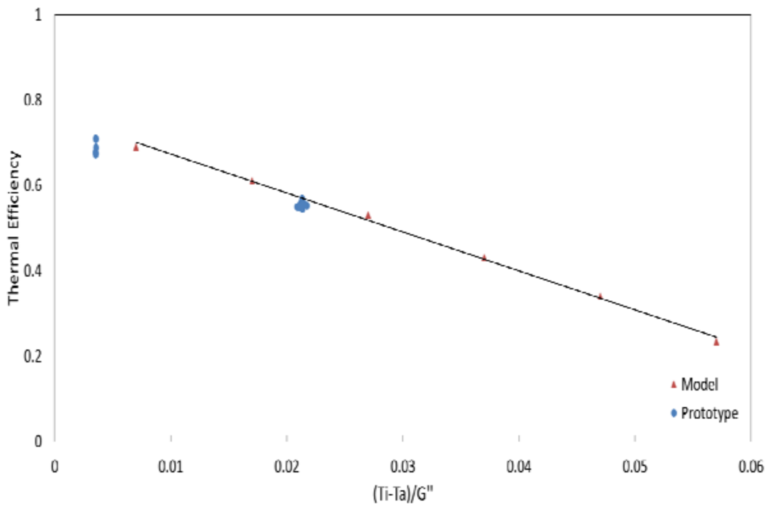

Figure 6. Modelled v experimental efficiency

Now, as described earlier, one of the key principles of designing for "whole of life" lies in the reduction of the number of parts and sub-assemblies, as well as attempting to minimize the potential for materials to end up as waste. Considering the prototype that was tested, the collector was mounted on polystyrene foam as a means of support and also insulation. However, as polystyrene is generally recognised as being a poor candidate for reuse or recycling it raised the issue of alternative means of insulating the absorber.

Typically, flat plate collectors have their back and side surfaces insulated by mineral wool insulation. However, this type of insulation has a number of disadvantages in that the handling during production can be difficult and, during operation moisture is absorbed from the ambient air. If the mineral wool becomes wet, the thermal conductivity increases rapidly and in cases of high moisture absorption, the thermal conductivity of the insulation can be increased by a factor of 20 (Ochs, Heidemann, & Müller-Steinhagen, 2008). However, work by (Elsherbiny, 1996) suggests that eliminating insulation altogether and maintaining an air gap of 15-20mm would not significantly reduce the thermal efficiency of the collector.

Based on Elsherbiny's (1996) work it was noted that it may be possible to construct a collector without insulation and that under these conditions, the value of the overall heat loss coefficient (*Ul*) would only be increased by 1.5W/m^{2}K. Thus by modifying the overall heat loss coefficient in the model it was possible to determine the impact this would have on the collector efficiency. In Figure 7 it can be seen that if the insulation is removed altogether, there is a reduction in the thermal efficiency but the efficiency is still comparable with the insulated prototype. As such, it suggests that insulation would not necessarily be required if developing an all polymer collector. Further when the insulation is removed altogether there will be a greater heat loss at higher temperatures. If the collector temperature rises, the insulation of the air layers decreases dramatically due to greater convective heat loss. The additional heat loss passively act to prevent the absorber reaching extreme stagnation temperatures.

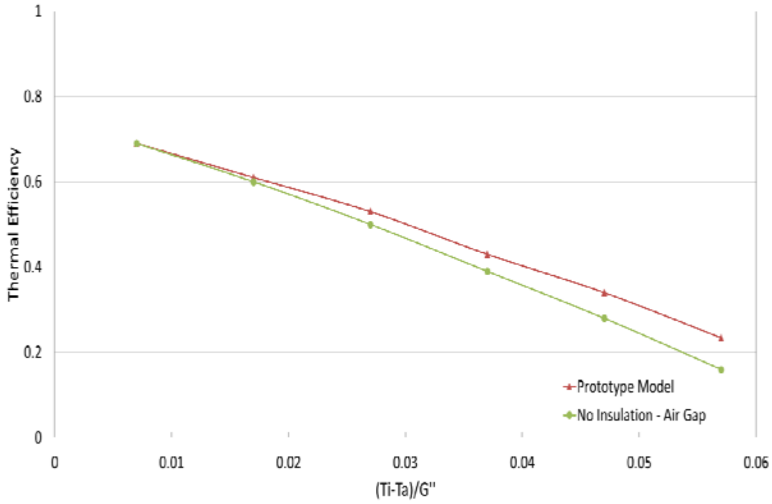

Figure 7. Efficiency of an un-insulated collector

Based on this finding, it may be possible to further reduce the number of materials used in the development of a polymer collector. In turn this would reduce costs and improve the ease of disassembly and the prospects for recycling of the materials at the end of the collector life.

7. Conclusion

One of the main obstacles to the greater uptake of flat plate solar collectors is their capital cost. This work has shown that there is significant potential to utilize lower cost engineering polymers such as high density polyethylene and acrylic to form flat plate collectors. In doing this, there is significant opportunity to reduce the number of components and hence steps in the manufacture of collectors.

Using a prototype polymer collector the performance of such a system was shown to be comparable with commercially available collectors. Further, a design model was developed that showed that the system could be simplified further, by removing the insulation without dramatically affecting the performance.

As such, there is a clear opportunity for low cost polymer collectors to be developed. By adopting a cradle-to-cradle/whole-of-life view to the design of flat plate collectors it is apparent that a far more limited number of components and materials than are currently used can deliver adequate performance. Moreover, this simplification makes the disassembly and reprocessing of the collector materials far easier when its useful life is over and is an area that will no doubt become more significant to solar collector manufacturers in the future.

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