Design and Development of an all Polymeric Solar Water Heating System

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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.

In addition to polymer material costs being less than traditional materials another key factor in reducing overall system cost is the reduction in manufacture and assembly costs. An all polymer solar water heater would use significantly less parts and therefore be easier to assemble and dis-assemble after its useful life.

Another barrier is the aesthetic appeal of water heaters. Traditional solar water heaters are not deemed aesthetically pleasing on the rooftops. Any new design would need to have a lower profile to be attractive to the market.

This work evaluates a number of possible concepts for the design of a new low cost all polymer solar water heating system with a low profile that will meet the existing standard and exhibit similar thermal efficiencies to traditional solar water heaters.

This required a thorough detailed comparison of performances, possible materials and production methods.

Comparative efficiencies of traditional v polymer systems were reviewed by way of a developed computer model and also by experimental results including testing of a design prototype.

Although traditional systems exhibited slightly higher thermal efficiencies than those of the less expensive polymer systems, the all polymer solar water heater fully satisfied all the design specifications and at a significantly lower cost.

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TABLE OF CONTENTS

APPENDICES

LIST OF ILLUSTRATIONS AND DIAGRAMS

TABLES.

STATEMENT OF SOURCES

DECLARATION

I declare that this thesis is my own work and has not been submitted in any form for another degree or diploma at any university or other institution of tertiary education. Information derived from the published or unpublished work of others has been acknowledged in the text and a list of references is given.

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Signature   Date

1 INTRODUCTION

Solar water heating is arguably the most energy-efficient way of producing domestic hot water, as the primary energy source “sunlight " is free, clean, abundant and renewable.

Solar water heating has been used for many years in warm sunny climates, but it can work in locations as far north as Canada and Northern Europe. While the equipment has a higher initial cost than other types of water heaters, the energy savings can more than offset the cost over the life of the system.

The aim of this research is to design and develop a low cost aesthetically pleasing solar water heater that has a thermal efficiency comparable to conventional solar thermal water heaters. This water heater is to be aimed primarily at the DHW (Domestic water heating market) but with the possibility of extension into multi domestic water heating and commercial water heating.

One of the major barriers to the uptake of solar heating is the initial cost of traditional systems. The use of polymers, as an alternative to the commonly used metal and glass structure, could lead to significant reductions in the actual cost of solar water heating systems.

This introduction chapter includes sections on the background of traditional commonly used collectors, highlights why the world needs alternative energy sources, and reviews literature relating to research in flat plate solar water heaters.

The sun’s energy is the primary source for most energy forms found on the earth. Solar energy has tremendous potential (Tian & Zhao, 2013) to fulfill the world’s demand that is currently being met mainly by the burning of fossil fuels. The efficient and exhaustive use of solar energy can reduce the intensity of global warming and climate change that is being created by the larger and faster consumption of fossil fuels (Souliotis, Singh, Papaefthimiou, Lazarus, & Andriosopoulos, 2015).

The conversion of solar energy by the thermal route is highly efficient, more environmentally friendly and economically viable when compared to other routes such as fossil fuels (Roberts & Forbes, 2012) .

1.1 World Energy Consumption

The world urgently needs to consider alternative renewable energy sources such as solar. Not only is there currently an over reliance on fossil fuels but as shown below in Figure 1 (Outlook, 2010) this is predicted to increase and continue to add to the worlds pollution difficulties.

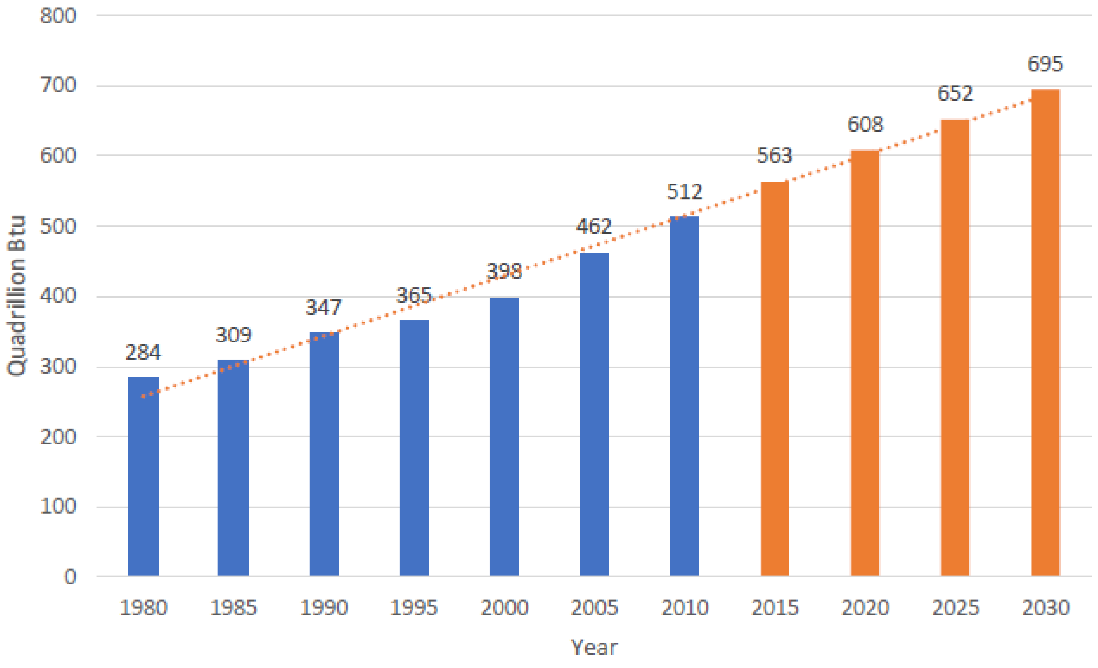


Figure 1 World Marketed Energy Consumption 1980-2030 (2015-2030 are projections)

The main reason behind the increases in Carbon Dioxide in the atmosphere is the continued reliance on fossil fuels. Carbon Dioxide is the most abundant human-caused greenhouse gas in the atmosphere (Outlook, 2010) Atmospheric concentrations of carbon dioxide have been rising at a rate of about 0.6 percent annually in recent years, and that growth rate is likely to increase. As a result, by the middle of the 21st century, carbon dioxide concentrations in the atmosphere could be double their pre-industrialization level.(Outlook, 2010)

Because human caused emissions of Carbon Dioxide result primarily from the combustion of fossil fuels for energy, world energy use has emerged at the centre of the climate change debate. In the *IEO2008* reference case, world carbon dioxide emissions are projected to rise from 28.1 billion metric tons in 2005 to 34.3 billion metric tons in 2015 and 42.3 billion metric tons in 2030. See projected growth in emissions shown in Figure 2 (Outlook, 2010) .

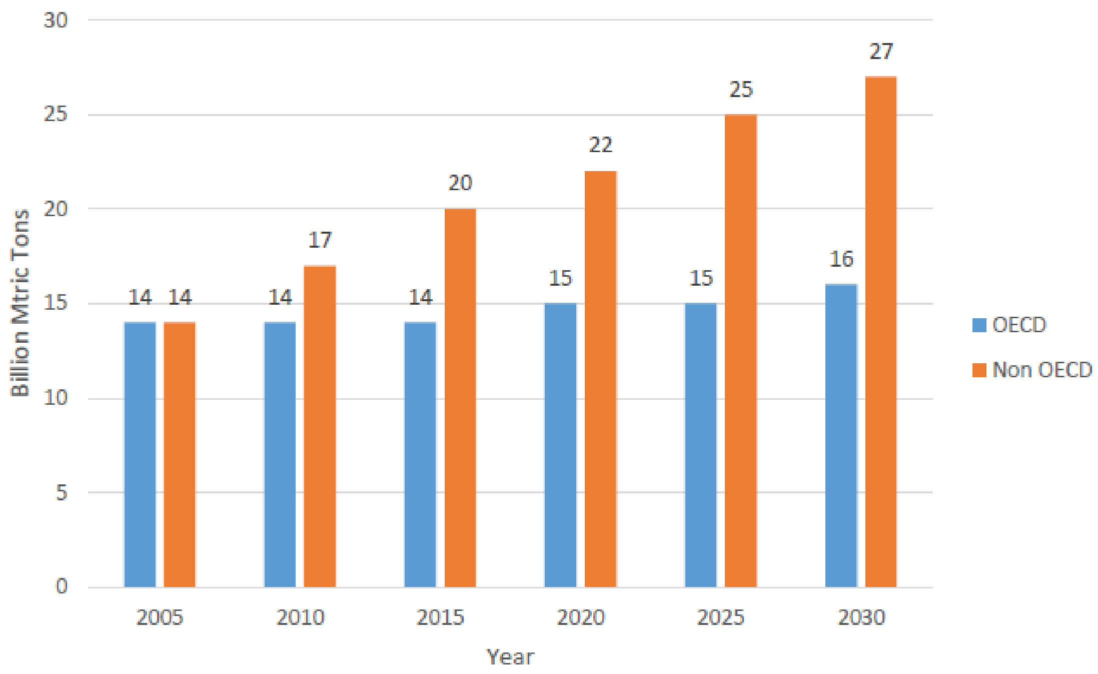


Figure 2 World Energy – Related Carbon Dioxide Emissions, 2005-2030

Renewable energy and coal are the fastest growing energy sources, with consumption increasing by 2.1 percent and 2.0 percent, respectively. Projected high prices for oil and natural gas, as well as rising concern about the environmental impacts of fossil fuel use, improve prospects for renewable energy sources. Coal's costs are comparatively low relative to the costs of liquids and natural gas, and abundant resources in large energyconsuming countries (including China, India, and the United States) make coal an economical fuel choice

The first oil crisis in 1973 prompted many countries to reduce their dependence on oil and fossil fuels as a method of generating electricity. The continued rising price of oil, the introduction of the Kyoto Protocol and a growing awareness of environmental issues has prompted the development of many alternative energy sources.

OECD Europe, where many countries are obligated to reduce greenhouse gas emissions under the Kyoto Protocol treaty, remains a key market for wind power, adding 8,554 megawatts of new capacity in 2007 alone. The European Union (EU) has set a target of increasing the renewable energy share to 20 percent of gross domestic energy consumption by 2020, including a mandatory minimum of 10 percent for biofuels. Most EU member countries offer incentives for renewable energy production, including subsides and grants for capital investments and premium prices for generation from renewable sources. Installation of wind-powered generating capacity has been particularly successful in Germany and Spain, which had 22,247 megawatts and 15,145 megawatts of installed capacity, respectively, at the end of 2007. (Köhl, Meir, Papillon, Wallner, & Saile, 2012) .

This particular thesis will concentrate on the use of solar energy for water heating. Solar water heating systems have reached a technical maturity and are already used in many countries.

Most commercially available solar water heaters have a separate energy collector and a hot water storage tank that can be close coupled or remote. The water heated in the collector can be circulated to the tank either by thermosiphon effect or mechanical pumping. [A more detailed description of these water heaters is included in section 1.3].

In general these types of water heaters are efficient enough but are too expensive are not aesthetically pleasing to householders.

More recently there has been significant support from governments, manufacturers and consumers to support this industry and product. There has been significant investment in research and development of innovative new systems replacing existing water heating methods.

The international market has shown strong development these last years. Especially in China, USA and Europe the manufacturing and commissioning of solar thermal systems has grown rapidly. According to a survey by Fawer (2011) there are 70 million households with a solar hot water supply and current market forecasts suggest that there will be a considerate number of additional systems in the years to come. Despite this overall positive impression of significant growth in sales of solar thermal water heaters, the take up of the technology is inconsistent worldwide. The market penetration is not homogeneous and varies a great deal with, not only, ecological awareness but also due to climatic and political conditions.

Whereas some country have already acted on environmental concerns others have put less effort into paving the way for renewable heat with the result being a low or non-existent solar thermal involvement.

The cost of energy produced by solar water heaters depends on the cost of the various materials that make up the collector, maintenance costs and the amount of energy collected. The solar collector cost represents around 50% of the initial investment cost for a conventional solar water heater. This high cost for the heater is due to the use of expensive materials and expensive manufacturing methods. (Cristofari, Notton, Poggi, & Louche, 2002). It is important therefore to develop new designs of collectors that have acceptable thermal efficiencies and conform to the relevant standards such as AS/NZS 2535.1

These new designs have to cost significantly less than conventional collectors to encourage greater market uptake. Traditional systems use a mix of different materials with a large number of individual components that often require expensive fabrication methods. Not only does the use of multiple materials lead to high manufacture and assembly costs it also makes the finished water heater environmentally unfriendly. If dissimilar materials cannot be separated it makes future recycling of materials difficult. Therefore the aim of this research is to design and develop a solar water heater that minimises the number of individual components used and also ensures that the heater can be recycled when its useful life as a water heater has expired.

1.2 Research Objective

A number of possible concepts were evaluated before a prototype of the low cost polymer heater was fabricated. This required a thorough detailed comparison of performances and possible materials and production methods.

A computer model was developed to predict performance of the new design and make comparisons with traditional collectors with metallic absorbers. The computational model was based on Hottel and Whillier's original work in this area. (Hottel & Whillier, 1955)

The theoretical results of the design were validated by experimental analysis and use of Finite Element Analysis and Computational Fluid Dynamics.

This experimental testing also allowed comparison between performances of traditional solar water heaters with the prototype low cost polymer one. The experimental testing used the procedures outlined in AS/NZS 2535.1.

This thesis focuses on the non-concentrating flat plate type that uses solar power for water heating and in particular the development of a low cost solar water heater manufactured solely from polymer.

1.3 Background Collector types.

This section covers some history regarding the development of solar water heaters and includes a brief overview of solar thermal collector types.

The basic principle of solar water heater is to collect solar energy and then to transfer this energy to domestic hot water. Given the time lag between solar resource and domestic hot water loads, a storage volume is used to ensure the availability of hot water outside periods of sunshine.

Solar domestic hot water systems are the most widely used worldwide, and many different concepts and product are available depending on climatic conditions, regulations, and regional/national industry history. Usually systems are classified as:

- Integrated collector storage (ICS) systems, where the tank and the collector are combined.
- Thermosiphon systems, where density differences of the circulating fluid causes water with a higher temperature to rise up the collector and into storage.
- Forced circulation systems where the circulating fluid flows through the collector and into storage by means of a pump.

There are two main types of solar water heating systems, active, which uses a pump to circulate the water between the tank and the collectors, and passive, which relies on natural convection to circulate the water.

Active systems can be either direct circulation or indirect circulation. Direct circulation systems circulate domestic water through the collectors and to the storage tank. These are best-suited for mild climates where temperatures seldom drop below freezing.

Indirect circulation systems circulate a non-freezing heat transfer fluid through the collectors and then through a heat exchanger in the storage tank. These are preferred in cold climates where the pipes in a direct circulation system might freeze.

Passive systems are usually less expensive but less efficient. They can be either integral collector/storage systems or thermosiphon systems. The integral collector/storage type is typically used to preheat water for a conventional water heater, and is best-suited to climates where temperatures seldom fall below freezing.

Thermosiphon systems rely on natural convection to circulate the water, so the tank must be located higher than the collector panels - the heated water from the panel's flows upward to the tank and the cooler water returns to the collector for heating.

1.3.1 Flat Plate Collector

This consists of an absorber, a transparent cover, a frame and insulation. Only very little of the heat emitted by the absorber escapes the cover. With the frame, the cover protects the absorber from adverse weather conditions.

Usually glass is used as a transparent cover with the frame materials from aluminium, galvanized steel or fiberglass-reinforced plastic. Insulation is usually of polyurethane foam or mineral wool, though sometimes mineral fibre insulating materials like glass wool, rock wool, glass fibre or fiberglass are used.

Transmission, reflection and absorption at front glass plane: Incident solar radiation with wavelength (lambda) shines on the front glass plane. By passing the cover approximately 8% of the solar radiation is lost due to reflection. Another 2% is absorbed by the cover. (Köhl et al., 2012)

One crucial attribute of the absorber is the absorptivity of the absorber. The higher the absorptivity the more solar radiation can be converted into heat. Typical values are around 93% resulting in reflection of around 7% of the incoming radiation. (This is discussed in more detail in chapter 2)

The absorber is heated up by absorbed solar radiation. This resulting in temperature difference between the absorber and the glass located over the absorber. Owing to this temperature difference, free convection is developing between the two surfaces, leading to a heat transfer from the hot absorber to the cold glass.

In cases of significant wind speed of the ambient air additional forced convection is induced on the outside surface of the collector. Especially for uncovered collectors and flat plate collectors this effect can lead to a significant reduction of the collector efficiency due to increased heat losses.

A second physical process resulting from the temperature difference between the absorber and the transparent cover is the radiative heat transfer. The radiation heat transfer takes place between the absorber and the transparent cover as well as between the transparent cover and the sky.

1.4 An Australasian Perspective

Since this research has been conducted in New Zealand an overview of water heating and the uptake of solar water heating in New Zealand is discussed. A breakdown of the various methods of water heating in New Zealand is shown in Figure.3.

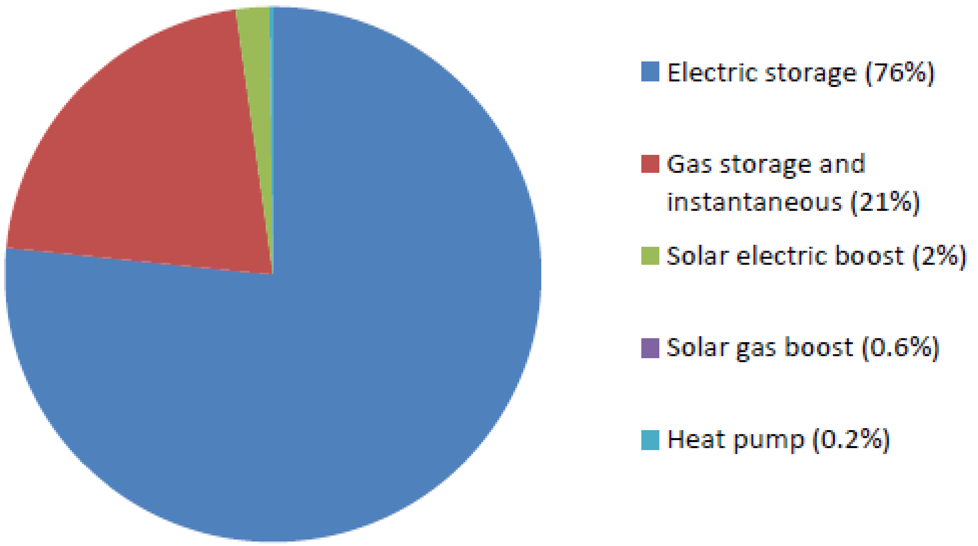


Figure 3.Estimated New Zealand water heater stock (Gillingham, 2009)

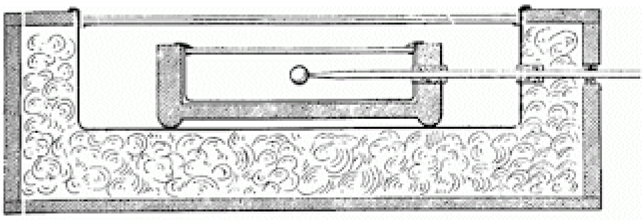
Water heating in Australia and New Zealand is a major contributor to energy use in the residential and commercial sectors. Solar water heaters provide an opportunity for both households and businesses to save energy, save money and reduce greenhouse gas emissions over the life of the system when compared to most other water heating technologies. In addition heating water with less electricity or gas improves energy productivity and hence improves economic prosperity.

Nearly 12% of all electricity generated in New Zealand is used to heat water in New Zealand homes and replacing much of this electricity with sunlight is obviously a very attractive proposition.

In 2012 solar water heaters made up around 12% of the installed water market in Australia. Of these around 77% are boosted by electricity and 23% by gas. In New Zealand water is heated predominately by electricity with Solar Water Heaters having a relatively low market share of 1.6% .(Gillingham 2009)

1.5 Literature Review

The use of use of solar power for water heating water is not new. A pre curser to present day designs was invented by Horace de Saussure, a noted Swiss naturalist, when he invented the hot box back in 1760 (Hirst, 1981). However it was only after the 1973 oil crisis that demand for solar water heating increased significantly.



Rendering of Langley's "Hot Box", similar to Sausure's model

Figure 4. Langley's Hot Box.

Current technology for solar thermal system is based primary upon metals and glass, with 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. One possible avenue to achieve lower manufacturing cost 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.

In addition, polymers tend to be significantly less expensive than metals such as copper and aluminium that are more frequently utilised in domestic water heating. In the light of this a polymeric domestic solar water heater may be developed and sold for significantly less than existing technology. This would address the initial cost of such systems which has been highlighted as a limiting factor in the uptake of solar energy devices.

Polymers offer a wide range of adaptable features, highly automated manufacturing can be very inexpensive and innovative processing can produce multiple integrated features in a single step. Previous results in solar thermal and in analogous cost/weight reduction in other areas indicate that this promise might be achievable, leading potentially to new low-cost market niche for solar thermal systems and multi-functional collectors with additional use, for the building technology.

Since the 1970s there has been considerable efforts made to design low cost water heaters both for industrial and commercial applications. Big commercial systems were developed during the 1970s that consisted simply of big low cost plastic bags resting on a layer of thermal insulation. (Tsilingiris, 1997) developed a similar design but utilising rigid enclosure that incorporated thermal insulation. The use of polymer absorbers has been studied by Van Niekerk et al (1996) with the aim of evaluating polymer parallel tubes. One outcome from his work was to conclude that the best configuration for parallel tubes was obtained from tubes that had zero spacing between them. They further concluded that it is the configuration of the collector that had the greatest influence on collector performance.

The basis for much of the research conducted on solar domestic water heaters since the 1970s has been based on studies conducted by Hottel and Whillier (Hottel & Whillier, 1955). An empirical equation for determining the heat loss coefficient from the top was developed by Klein (Klein, 1975) that follows the same basic procedure of Hottel. These empirical equations are used as the basis for the iterative theoretical computer model used in this thesis to model thermal performance of the benchmark system and the proposed design.

Further work by (Matrawy & Farkas, 1997) compared three different configurations of collector, twin parallel plate, serpentine and parallel tubes and concludes that the two parallel plates collector can be used with high efficiency for solar water heating systems. Under the same ambient and performance conditions, its efficiency increases by about 6% more than the serpentine tube collector and by about 10% more than the parallel tubes one. It is noted that Matrawy's work was conducted using metallic absorber plates with conductivity of 211 W/mK.

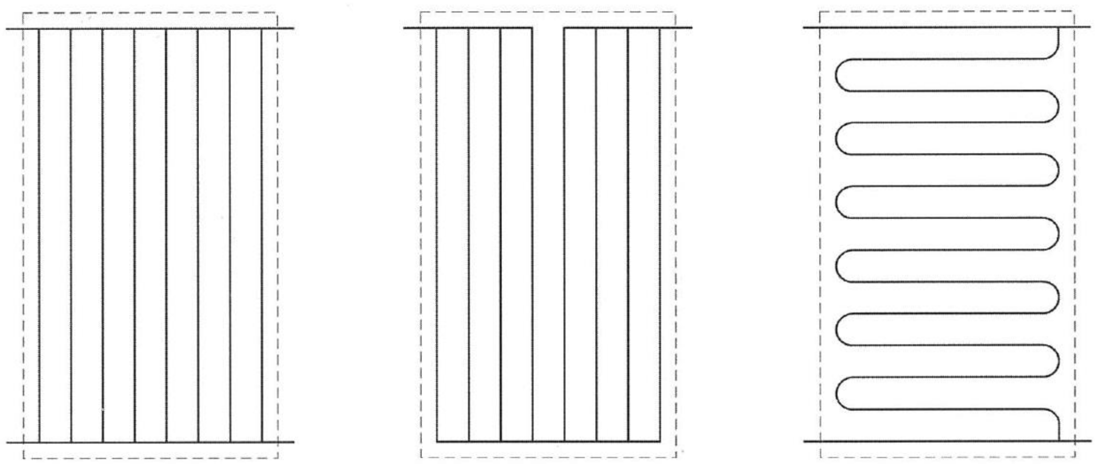


Figure 5 Different hydraulic arrangements inside the collector.

It is typical that most flat plate collectors have their back and sides insulated by rock wall or similar. When new and dry the thermal conductivity is around 0.035-0.06 W/mK. According to work by Beikircher et al (2014) for an insulation thickness of 40-60mm rear side losses are around 1 W/m^2K. However this type of insulation has a number of serious disadvantages. 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. In cases of high moisture content values of thermal conductivity can be increased by a factor of 20 (Ochs, Heidemann, & Müller-Steinhagen, 2008). This raises the question as to whether insulation is absolutely necessary for solar flat plate collectors.

Further work by (Elsherbiny, 1996) suggests that eliminating insulation altogether and keeping only an air gap of 15-20mm does not significantly reduce the thermal efficiency of the collector. This work is examined in more detail in section 5.2

As discussed earlier most conventional absorbers in flat plate collectors are manufactured as finned tubes. The design is often referred to as fin and tube construction. (Duffie & Beckman, 1980) refer to a fin efficiency factor F_R and define it as the actual useful energy gain of a collector to the virtual useful energy gain that would result if the collector absorbing surface had been at the local fluid temperature. F_R has a strong and direct influence on the overall collector thermal efficiency as can be seen from the equation 1.1

$$ή = F_R \left(\tau\alpha - U_L \, \frac{T_m - T_a}{I} \right) \qquad (1.1)$$

Where F_R = Fin efficiency factor

U_L = Total heat losses

T_m = Fluid mean temperature

T_a = Ambient temperature

$\tau\alpha$ = Collector transmittance-absorptance product (see section 2.1.1 for more detail of this product).

Clearly a low fin efficiency factor will directly lower the collector's thermal efficiency. This is an important observation and directly impacts the proposed design in this thesis.

With a conventional copper fin and tube collector a typical value for the fin efficiency would be in the range of 0.87-0.95. The best may reach 0.97 using small fin widths and high flow rates (Frey, Frei, Brunold, Prüf, & Forschungsstelle, 1995).

In an attempt to move away from conventional fin and tube collector design the collector efficiency factor for an absorber with rectangular duct-like fluid channels contacting the entire surface of the fluid was investigated by (Rommel & Moock, 1997). They concluded that the fin efficiency for rectangular duct style collectors can have higher thermal efficiency factors than fin and tube. This will vary with duct height as shown in Figure 6.

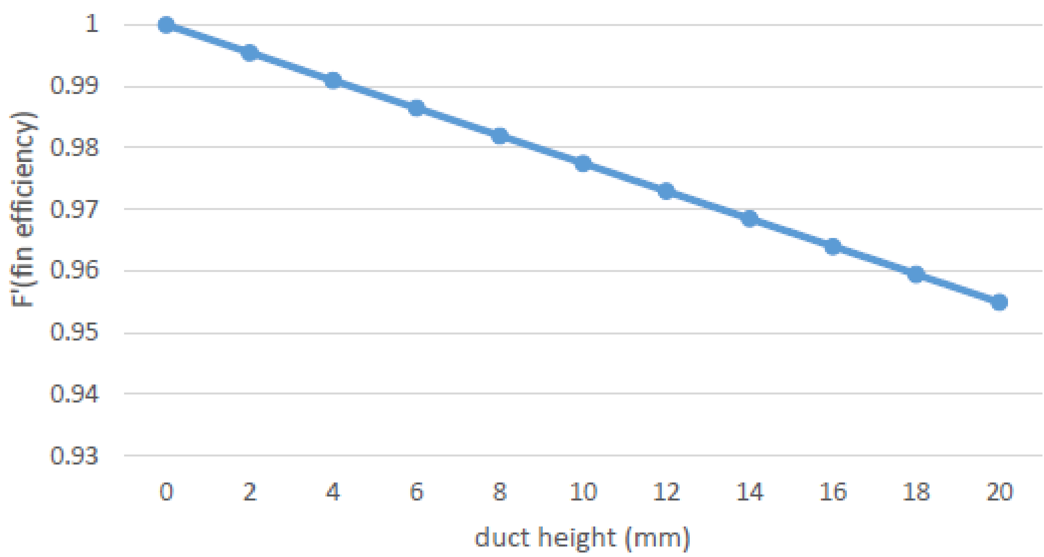


Figure 6. Fin efficiency v Duct height.

Rommel's work was conducted on an idealised absorber which was essentially constructed of two parallel metal plates with parallel channel across the whole width of the absorber sheet. He theorised that a serpentine configuration with duct width of around 15-20mm may have been more suitable for production but accepted that the pressure drop across the collector would increase.

(Matrawy & Farkas, 1997) compared twin parallel plate collectors (TPPC) with a parallel tube collector (PTC) and a serpentine collector. (STC) Under the same ambient and performance conditions, efficiency of the TPPC is, respectively, 6% and 10% greater than STC and PTC efficiencies.

More recently the European group ‘Scoop’ in conjunction with Aventa and Fraunhofer Institute and other European Universities have been developing various projects with polymer collectors (Hansen, Sørensen, Byström, Collins, & Karlsson, 2007) . They have reached a stage with one project that has reached a stage of commercialisation. This utilises Polyphenylene Sulphide (PPS). This polymer which is well known for its high thermal and chemical resistance is an ideal candidate for solar thermal application. The Aventa design uses extruded twin wall sheets of PPS for the absorber. (Rekstad, Meir, & Aventa, 2015)

While the extrusion process is extremely cost effective for producing the absorber this design and material are not suitable candidates for the aims of this thesis i.e. ‘a low cost all polymer collector’. The material, PPS, is a high performance polymer and costs around five times as much as standard commodity polymers. Also the extruded flat absorber requires two headers to be attached to top and bottom. Not only does this involve two extra parts but also a joining process. Aventa have experimented with welding and bonding.

It is interesting to note that the latest ‘Scoop’ projects are focused on producing a low cost all polymer collector that uses a low cost commodity polymer. No further details are currently available.

Similar to the latest endeavors at ‘Scoop’ the aim of this research is to design and develop a new low cost solar water heating system utilising solely polymeric materials. Despite the low conductivity of the absorber material the thermal efficiency of the all polymer collector must compare well against that of traditional metal absorber plate collector. This design is likely to be a combining of the earlier research of Hottel and Whillier, Matrawy and Farkas and Rommel et al.

However, before proceeding to investigate possible materials and configurations it is necessary to establish the feasibility of a low cost all polymer collector. This examination of the feasibility is covered in Chapter 2 where a computer model simulation compares the performance of a traditional parallel tube and fin collector with an all polymer collector with absorber of same configuration.

2 Feasibility

The attractiveness of a low cost polymeric solar water heater is obvious given that cost is a major driver for customer selection of method for water heating. (Hewitt, 1999). However first it needs to be demonstrated that this is a possible proposition. This chapter examines the feasibility of an all polymer solar water heater.

Before commencing the design and development of a new novel all polymeric collector it is necessary to establish that the performance, in terms of thermal efficiency, of a polymeric collector is comparable with that of a conventional metallic collector.

A measure of collector performance is the collection efficiency, defined as the ratio of the useful gain over a time interval to the incident solar energy over the same time interval as shown in equation 2.1.

$$\mu = \frac{\int Qu.dt}{Ac \int Gt.dt} \qquad (2.1)$$

The design of a solar water heating system is concerned with obtaining minimum cost energy. Therefore it can be acceptable to design a polymeric collector with efficiency slightly lower than that can be achieved with conventional collectors that utilise a metallic absorber.

Hence in order to be a viable design it is important that a low cost all polymer collector not only meets the reduced cost targets but also can operate at efficiencies similar or slightly lower than to that of conventional collectors.

In order to demonstrate the feasibility of an all polymer collector a simulation comparison of conventional collector was carried out. The performances were evaluated using a computer simulation model developed from Hottel and Whillier's original work in this area. (Hottel & Whillier, 1955).

This chapter compares the performance of a conventional collector with a solar thermal collector fabricated completely from polymer materials.

A computer simulation model programme was written based on the theoretical work of Duffie and Beckman (Duffie & Beckman, 1980) and (Van Niekerk, du Toit, & Scheffler, 1996)

The formers work was developed originally for conventional parallel tube flat plate solar thermal collectors and is used in this project as a benchmark for the performance of polymer solar thermal collectors.

2.1 Benchmark System

Conventional solar water heaters are often of the parallel tube type design and manufactured from many different materials with the absorber plate of metallic material. This absorber plate is commonly black to enhance the solar energy absorbing capabilities when transferring the absorbed energy to the fluid in the parallel tubes. Theoretical thermal performance is already well established. (Duffie & Beckman, 1980)

As a basis of benchmarking the thermal performance of an all polymer design against a traditional solar water heater the theoretical approach used by Duffie with conventional parallel tubes was used as a basis to develop a computer model to predict the theoretical performance of parallel tube solar water heater. From a theoretical perspective, the thermal efficiency of a flat plate solar connector 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 2.2.

$$\eta = Fr.(\tau\alpha) - Fr.Ul(\frac{Ti-Ta}{G''}) \qquad (2.2)$$

The programme will determine the theoretical performance using a one-dimensional steady state thermal model based on the Hottel - Whillier-Bliss equations presented by Duffie and Beckman.

Under these conditions the useful heat gain can be calculated using equation 2.3.

$$Q = A.Fr.[(\tau\alpha).G" - Ul.(Ti - Ta)] \qquad (2.3)$$

In this equation the useful heat gain (*Q*) is represented by a function of the collector area (A), the heat removal efficiency factor (*Fr*), the transmittance-absorbance product of the photovoltaic collector($\tau\alpha$), 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 2.4 which also accounts for the mass flow rate in the collector (*m*) and the specific heat of the collector cooling medium (*Cp*).

$$Fr = \frac{m.Cp}{Ul.A}[1 - e^{-(A.Ul.F'/m.Cp)}] \qquad (2.4)$$

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 2.5.

$$F = \frac{tanh(M\frac{W-D}{2})}{M\frac{W-D}{2}} \qquad (2.5)$$

This equation 2.5 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 2.6.

$$M = \sqrt{\frac{Ul}{K.t}} \qquad (2.6)$$

As such, the corrected fin efficiency (F') can be calculated using Equation 2.7.

$$F' = \frac{1/Ul}{W[\frac{1}{Ul(D+(W-D)F)}+\frac{1}{\pi.Dh.Hf}]} \qquad (2.7)$$

In Equation 2.8 the overall heat loss coefficient (*Ul*) of the collector is the summation of the collector's edge, bottom and top losses. The bottom loss coefficient is given by Equation 2.10, the inverse of the insulations R-value (i.e. *Kb/Lb*), the edge losses are given by Equation 2.9 where p is the collector perimeter and t is the absorber thickness

$$Ul = Ut + Ue + Ub \qquad (2.8)$$

Where Ue is the edge heat loss and Ub is the back heat loss:

$$Ue = \frac{Kb.p.t}{Le.A} \qquad (2.9)$$

$$Ub = \frac{Kb}{Lb} \qquad (2.10)$$

The top loss coefficient, due to reflections and wind, can be calculated using Klein's empirical equation as given by Duffie and Beckman:

$$Ut = \left\{\frac{N}{\frac{c}{Tpm}\left(\frac{Tpm-Ta}{N-f}\right)^{e}} + \frac{1}{Hw}\right\}^{-1} + \frac{\sigma(Tpm+Ta)(Tpm^2+Ta^2)}{(\varepsilon p+0.00591.N.Hw)^{-1}+\frac{2N+f-1+0.133\varepsilon p}{\varepsilon g}-N} \qquad (2.11)$$

Where coefficients *c*, *f* and *e* are:

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

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

$$e = 0.430\left(1 - \frac{100}{Tpm}\right) \quad (2.12)$$

$$Tpm = Tin + \frac{Q/A}{Fr.Ul}(1 - Fr) \quad (2.13)$$

Tpm is mean absorber temperature.

From these equations it is then possible to calculate the useful heat gain by the solar collector. Furthermore, by rearranging Equation 2.1 we can develop an equation for determining the thermal efficiency of the collector. This equation is expressed in the form shown in Equation 2.14

$$\eta = Fr.(\tau\alpha) - Fr.Ul(\frac{Ti - Ta}{G"}) \quad (2.14)$$

The required design parameters listed in Table 1 can be input and the computer model will determine the theoretical thermal efficiency of the collector.

Table 1. Parameter for comparison of polymer v copper collector with same configuration

Parameter	Symbol	Metal	Polymer
Number of covers	N	1	1
Emittance of plate	ε_p	0.95	0.92
Emittance of cover	ε_c	0.88	0.9
Number of tubes	n	38	38
Collector Length	L_C	1.3m	1.3m
Collector Breadth	B	1.04m	1.04
Absorber thickness	t	.0005m	.0005m
Tube hydraulic data	D_h	10mm	10mm
Tube spacing	W	20mm	20mm
Insulation conductivity	K_b	.045W/mK	.045W/mK
Back insulation thickness	L_b	50mm	50mm
Edge Insulation thickness	L_e	25mm	25mm
Absorber conductivity	K	385W/mK	0.4 W/mK
Transmissivity-Absorptance	*Ta*	0.8	0.71
Solar radiation	G	1000W/mK	1000W/mK
Wind heat transfer	H_w	11W/m^{2}K	11W/m^{2}K

To ensure a reasonable comparison to be made the size and the style of collectors are made the same in order to compare like with like. The hydraulic arrangement of both is the parallel tube type connected by inlet and outlet headers.

Figure 7 shows the inner tube diameter (D_H) and tube spacing (W)

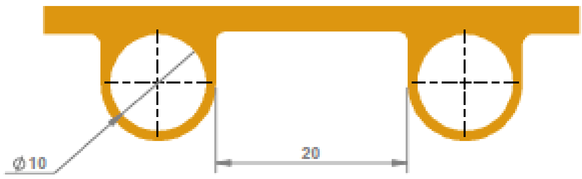


Figure 7. Tube and Fin

2.1.1 Collector Transmittance and Absorptance

The efficiency of solar collectors is significantly dependent on the absorptance and the emittance of the absorber surface, where the incoming solar radiation is converted to thermal energy. Before the performance of the benchmark polymer collector can be modelled the collector's transmittance-absorptance product τα requires evaluation. Of the parameters shown in equation 2.2 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 glass (or plastic) top cover. The absorptance (α) component can be determined from knowing the reflectance (ρ) of the absorber and using equation 2.15.

$$\alpha = 1 - \rho \qquad (2.15)$$

The reflectance of HDPE is shown in Figure 8 (Wang, Chen, & Zhang, 2013)

The transmittance of the acrylic top cover is shown in Figure 9. (Altuglas, 2014)

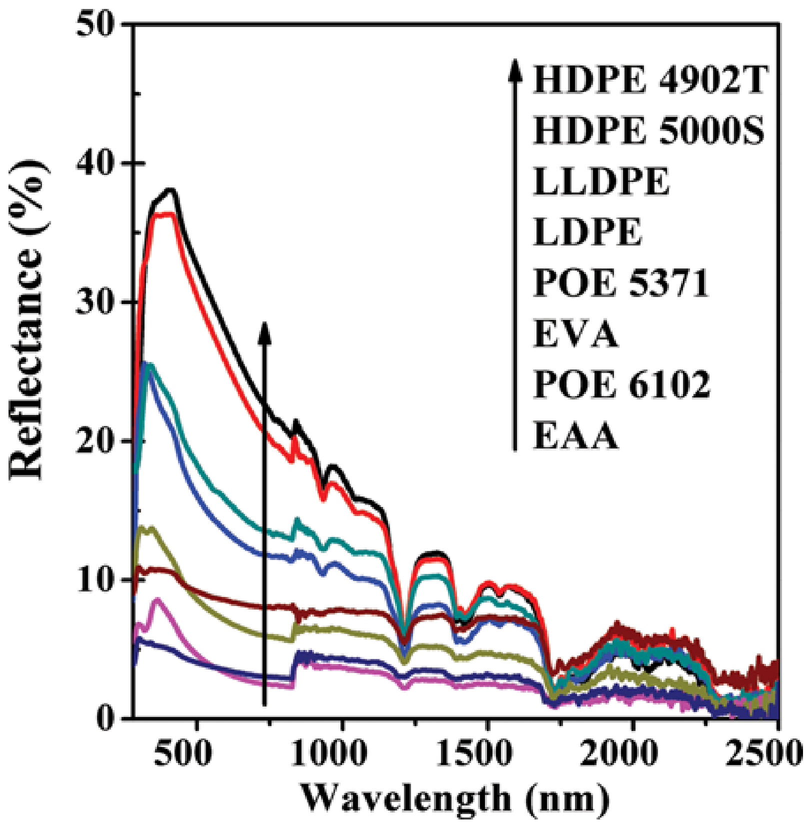


Figure 8. HDPE Reflectance (Wang et al., 2013)

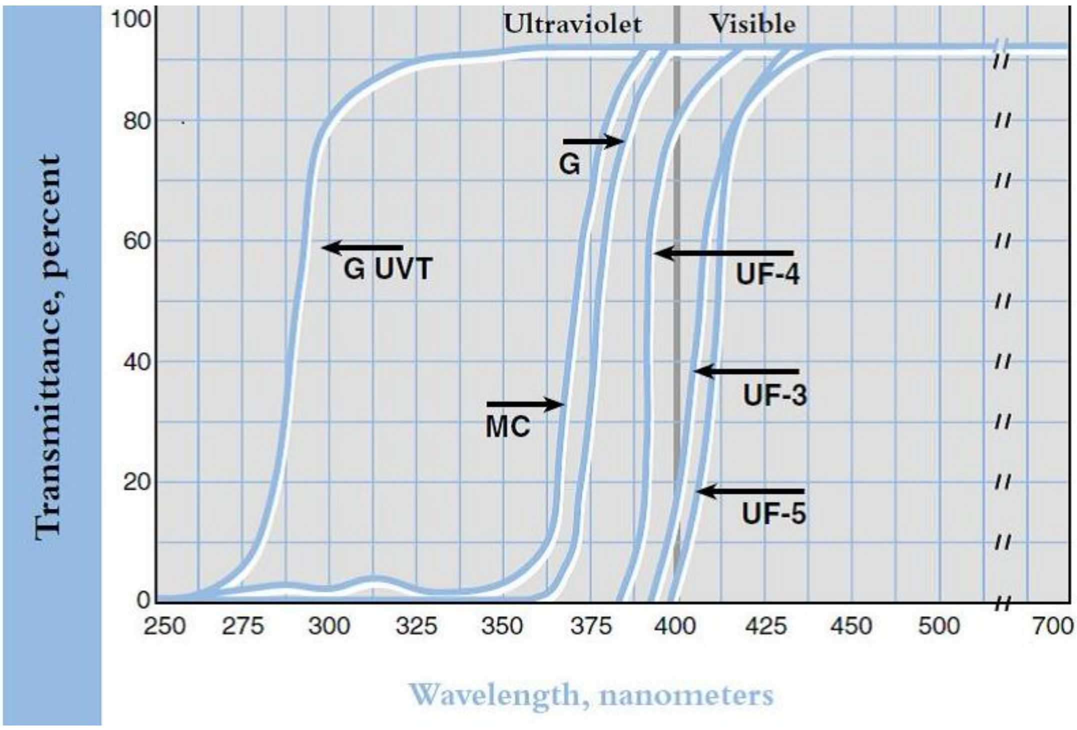


Figure 9 Acrylic Transmittance Characteristics (Altuglas, 2014)

The transmittance-absorptance product is a property of a cover-absorber rather than a product of two properties. The solar transmittance of the cover system and the solar absorptance of the absorber plate are functions of wavelength and the angle of incidence and can be established from equation 2.16.

$$\tau\alpha(\Theta) \;=\; \frac{\int_0^\infty \tau_\lambda.(\Theta).\alpha_\lambda.(\Theta).I_{\lambda i}.(\Theta).d\lambda}{\int_0^\infty I_{\lambda i}\,.(\Theta).d\lambda} \qquad (2.16)$$

$$\tau\alpha \;=\; \frac{\int_0^\infty \tau_\lambda.\alpha_\lambda.I_{\lambda i}.d\lambda}{\int_0^\infty I_{\lambda i}\,.\,d\lambda} \qquad (2.17)$$

Figure 10 shows the transmittance curves for the acrylic top cover and the absorptivity curves for the HDPE absorber. By integrating these values over the AM1.5 spectrum the transmittance-absorptance product for the polymer collector can be established.

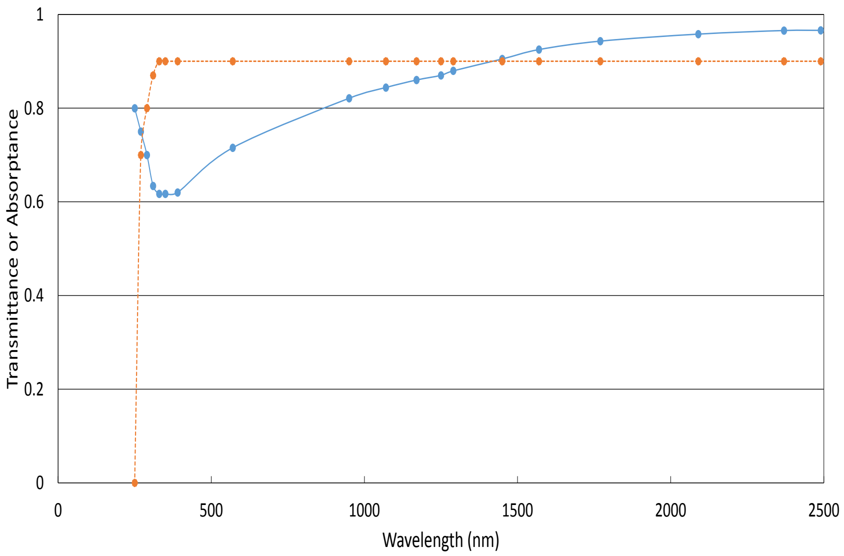


Figure 10. Polymer transmittance- absorptance Curves.

The conventional collector has a glass front cover with a transmittance-absorptance product of 0.8. The polymer collector has a transmittance-absorptance product of 0.71

The conventional collector has a metallic absorber plate with 38 copper tubes welded to a copper absorber plate of 0.0005m thickness. The polymer one is of extruded high density polyethylene with 38 parallel tubes of 0.0005m wall thickness. This should really be around 3mm but to ensure a direct comparison is made will be identical to the copper collector but since according to (Van Niekerk et al., 1996) thermal efficiency is only slightly dependent on wall thickness it will allow a valid comparison.

The inside diameters of the tubes are the same 10mm for both copper and polymer absorbers. Insulation material and thickness is the same for both. Collector area is the same for both. Distance from bottom of top cover to top of absorber is the same for both. Duffie and Beckman advise an optimum distance of 25mm (Duffie & Beckman, 1980) . Plate thermal conductivity of copper absorber is 385 W/mK and for polyethylene absorber 0.4 W/mK

Ambient temperature was assumed at 293 K

Wind speed assumed at 2 m/s for both.

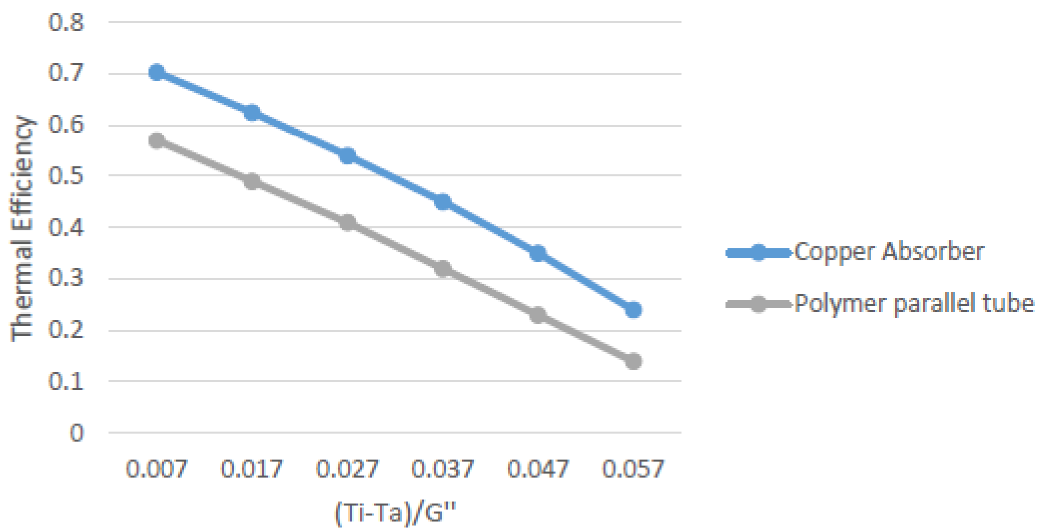


Figure. 11. Comparative thermal efficiencies of copper v polymer collectors

Figure 11 illustrates the comparison of thermal efficiencies of traditional v polymer collectors. These studies and the calculation of a first polymer collector design show that efficiencies comparable to conventional metallic designs can be obtained. This study demonstrates that the project to design and develop a low cost all polymer solar water heater to be worth pursuing and further work to develop optimum design will continue.

So in conclusion to this chapter the feasibility of an all polymer collector is proven to be comparable to that of traditional collectors so investigation into possible configurations and materials can proceed. Before proceeding to develop and evaluate concepts it is necessary to consider the market requirements. The next chapter draws on a number of worldwide sources to give a guide to market preferences.

3 Market Analysis

The market for water heaters can be segmented into two parts.

- The purchases of new water heaters
- Replacement water heaters into existing houses.

In the first case it follows that volume of sales of water heaters is directly linked to the sales of new homes. This cannot be consistently relied upon as the new house market is a very volatile market. The uptake of solar water heaters in the replacement market is also inconsistent, being linked to the rate of existing system failure. In Australia in 2012, 70% of water heating sales were in the replacement market, 20% for new dwellings and 6% were linked to renovation. (Shrapnel, 2012)

The greatest cost of solar water heating occurs at the time of purchase. The maintenance and running costs of a solar water heater are generally low. (Pilgaard, 2006). The capital cost of a solar water heater is typically significantly higher than of other types of heaters (see table 2). The average installed cost of solar water heater in New Zealand is NZ$7,000 (Roulleau & Lloyd, 2008)

Table 2: Average capital cost in Australia by water heater type 2008-2012. (Shrapnel, 2012)

	2008	2010	2012	% change 2008-2012
Electric Storage	$1,300	$1,151	$1,105	-15%
Gas storage	$1,300	$1,328	$1,105	-3%
Gas instant	$1,350	$1,140	$1,378	+2%
Heat pump	N/A	$2,543	$1,904	N/A
Solar	$3,700	$3,018	$3,070	-17%
Average	$1,620	$1,814	$1,796	+11%

The data in table 2 indicates that despite a 17% reduction in the installed cost of solar water heaters between 2008 and 2012 they are still more expensive than alternative water heating systems. Therefore in order for growth in sales of solar water heaters a considerable price reduction is required in order to make them attractive to the market.

According to (Wüstenhagen & Bilharz, 2006) the most important drivers influencing the sales of Solar Water Heaters are:-

- Capital cost compared to other systems
- Access to reticulated gas
- Financial incentives and rebates
- Regulations.
- Consumer perceptions of energy prices.

3.1 Customer Requirements

All solar water heaters installed in Australia and New Zealand must meet the Australian and New Zealand AS/NZS2712:2007. This standard sets out the minimum requirements for collectors for use in solar water systems regarding performance, materials and installation. These functional requirements are the basis for development of the detailed design specification of this new all polymer solar water heater.

In addition to meeting these basic requirements it is important to consider the actual customer requirements and drivers affecting sales of solar water heaters.

Studies by Hewitt conducted for the US Department of Energy (Hewitt, 1999) highlight clearly the most important (must have) features required by stakeholders. These studies included home buyers surveys and focus groups that were held with homebuyers, homebuilders, and architects. The primary areas of concern to consumers are:-

- Low total installation costs
- High reliability of systems
- High system performance with significant energy savings. With payback within four years.

These consumer concerns outweighed any concerns for the environmental or aesthetics of the solar heating system. Since Hewitt's study there has been a considerable increase in environmental impact of all products, not just those related to energy usage. Companies are keen to develop products that enhance their clean green environmental image (see chapter 7). A growing number of consumers of all products are beginning make purchasing decisions with environmental considerations in mind. Legislation relating to product performance, materials used. Likewise consumers would prefer their solar water heater to be aesthetically pleasing.

Using KANO analysis to assist in developing a product that not only meets the required operation requirement of AS/NZS2712:2007 but is also attractive to consumers. Considering the product 'must haves' as:-

- Low total installation costs
- High reliability of systems
- High system performance with significant energy savings. With payback within four years.

And the 'delighters' to be

- High system performance with significant energy savings. With payback within four years.
- Aesthetically pleasing
- Environmentally friendly.

4 Design Considerations

The designs of the all polymer solar water heater are guided by a number of factors. Firstly and most important the design and performance must satisfy the Australian standard AS/NZS2712:2007. Secondly the thermal efficiency of collector must be similar to conventional collectors. Other important considerations are reliability, cost and aesthetics. Other relevant design considerations are shown in a Design Objective Tree in Figure 12.

In meeting the standard the choice of possible polymer options is restricted to polymers that can operate at elevated temperatures. The choice of possible polymer options is further limited by processing methods. There is a ‘trade off’ to be made here, the most ideal polymers for meeting performance requirement cannot be manufactured by the most cost effective production process. Possible polymers that could meet requirements are detailed in section.

This chapter uses a formal design process adapted from (Pahl & Beitz, 2013). The customer needs and market analysis have been described previously in chapter 3. An objective tree identified and prioritised design objectives and the method of QFD (Quality Function Deployment) was used to provide an objective evaluation of design, materials and production processes.

In addition to these customer needs and requirements there are additional design requirements such as those stated by (Cristofari et al., 2002) that the collector material must have an absorber with copolymer material that satisfies the following constraints.

- To be UV protected
- To have a high thermal conductivity.
- To be water resistant
- To have good thermal range of utilisation (-10^{o}C to 150^{o}C)

The information from the design objective tree (Figure 12) and the QFD analysis (Figure 13) are combined and given weighted importance in the concept evaluation matrix. (Table 3).

This provides an objective method for comparison of possible concepts and allows design and development of the concept that meets most of the design objectives.

The QFD chart also gives a competitive analysis of the new all polymer design against a traditional collector design and the Aventa design.

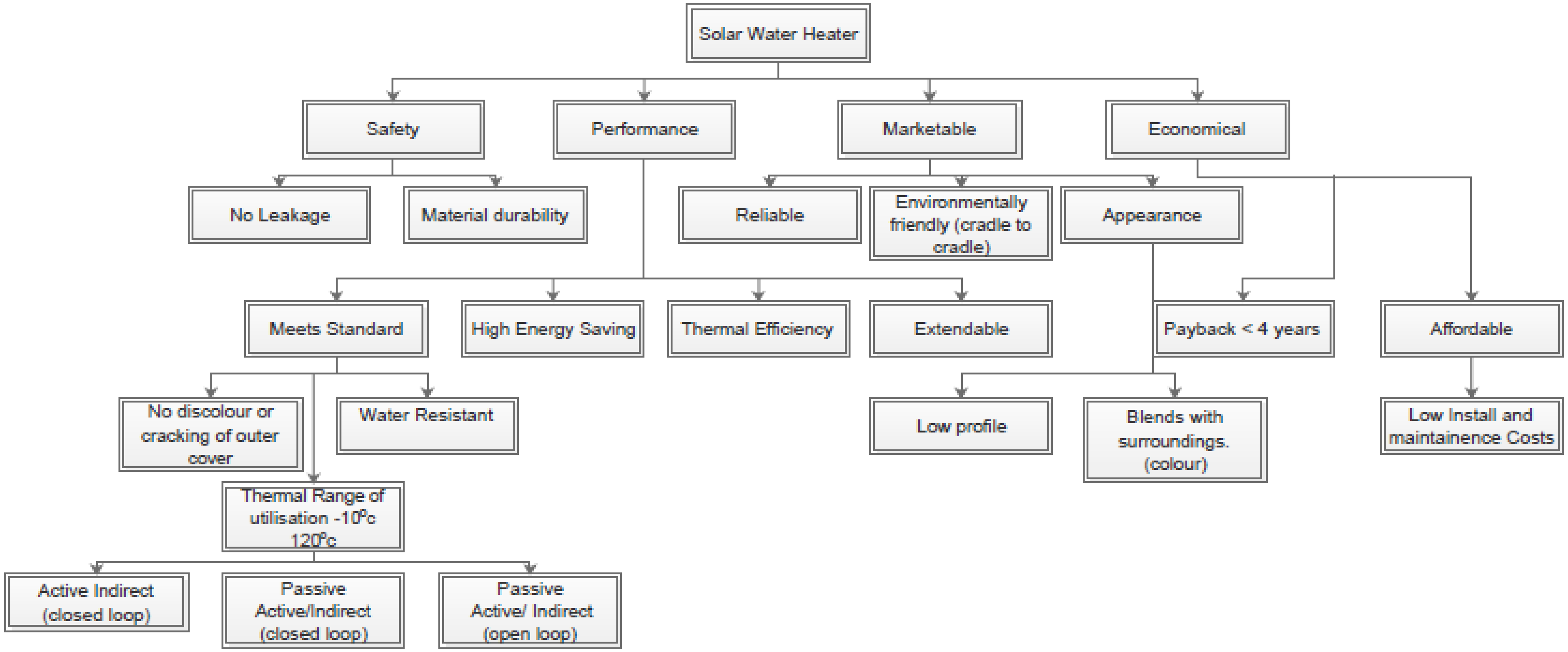


Figure 12 Design Objective Tree

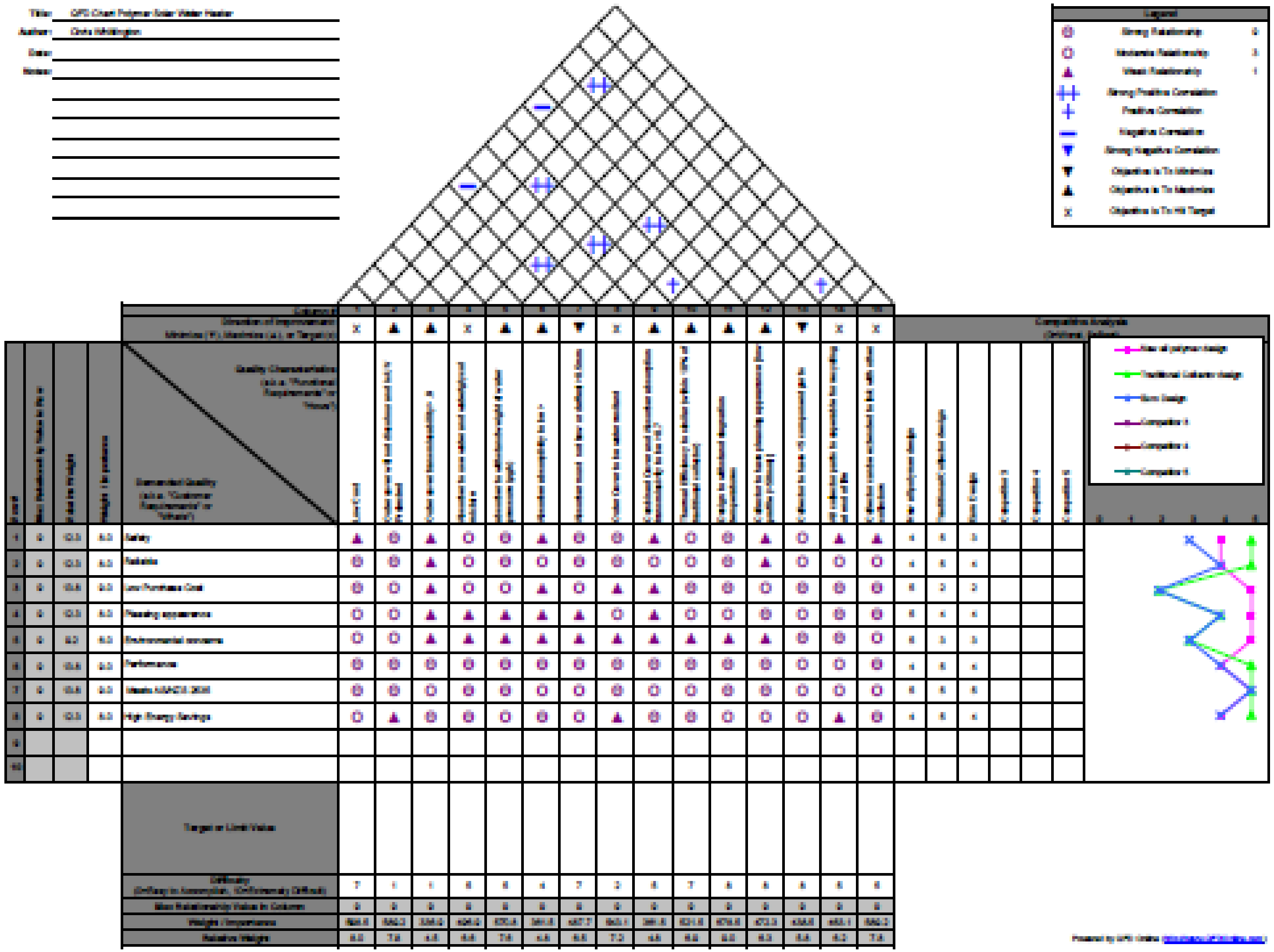

Safety
Low Purchase Cost
Pleasing appearance
Environmental concerns
Performance
High Energy Savings
Target or Limit Value
Weight / Importance
Relative Weight

Table 3 Evaluation of Concepts

Concept Design		Low Cost	Outer Cover UV protection	Suitable for water and water/glycol	Absorber strength	Absorptivity Tranmissivity Product	Water resistance of collector	Thermal Efficiency of collector	Not fail at stagnation temperature	Collector aesthetics	Collector Number of parts	Ease of recycling	Ease of Assembly	Sum
Weighting Factor		0.11	0.10	0.06	0.09	0.06	0.09	0.09	0.11	0.08	0.07	0.08	0.07	1
Extruded Parallel Absorber (High performance polymer absorber)	**Rating**	4	9	9	9	9	9	6	9	6	6	3	3	
		0.45	0.87	0.50	0.78	0.54	0.80	0.51	1.00	0.47	0.45	0.23	0.22	6.82
Extruded Parallel Absorber (Engineering Thermoplastic Absorber)	**Rating**	7	9	9	9	9	9	6	6	6	6	3	3	
		0.78	0.87	0.50	0.78	0.54	0.80	0.51	0.67	0.47	0.45	0.23	0.22	6.82
Rotor Molded Pillow Type (with insulation)	**Rating**	6	9	9	8	9	9	7	7	7	7	8	8	
		0.67	0.87	0.50	0.69	0.54	0.80	0.60	0.78	0.55	0.52	0.61	0.59	7.73
Rotor Molded Pillow Type (with no insulation)	**Rating**	9	9	9	8	9	9	6.5	8	9	9	9	9	
		1.00	0.87	0.50	0.69	0.54	0.80	0.56	0.89	0.70	0.67	0.69	0.67	8.59
Rotor Molded Outer with separate cover sheet	**Rating**	7	9	9	7	9	6	7	5	6	6	6	6	
		0.78	0.87	0.50	0.61	0.54	0.54	0.60	0.56	0.47	0.45	0.46	0.45	6.81

4.1 Evaluation of Concepts

The possible designs evaluated in section 4.3 are described in more detail in this section. The possible configurations that could meet some/ all the requirements include:-

4.1.1 Extruded parallel tube absorber with high performance polymer absorber.

Scored 6.82 in the concept evaluation table. This is similar to the design of the Aventa as part of an IEA SHC project. (Rekstad et al., 2015). (Figure 14)

Figure 14. Aventa Design

This design will no doubt have thermal efficiency comparable with traditional collectors and will certainly have no problem with stagnation temperatures but will certainly not be low cost. The design uses extruded PFS. The fact that the main body of the absorber is extruded means that the design has open ends. Each end requires an injection molded header and footer manifold, these are required to be joined to the main body. Possible methods of joining the headers to the absorber have included adhesives and laser welding. In addition to the polymers used being too expensive the initial tooling costs are high.

4.1.2 Extruded parallel tube absorber with engineering thermoplastic absorber.

Scored 6.82 in the concept evaluation table.

This design is similar to the previous one but in this case it uses an engineering thermoplastic as the absorber and headers. Thermal efficiency would be comparable with traditional collectors. This design would require some extra measures to be taken to protect against stagnation temperatures.

The extruded main body would be produced cost effectively but the design will again suffer from requiring manufacture and joining of top and bottom manifolds. Not only are these additional parts but the joining methods could prove problematic over the life cycle of the collector.

4.1.3 Pillow type (with insulation)

Scored 7.3 in the concept evaluation table.

This design uses a HDPE absorber with internal supports. It approximates to the parallel plate design advocated by Matrawy et al. (See Figure 15). Again the thermal efficiency would be comparable with conventional collectors. The absorber would a complete one piece roto-molding so therefore no separate manifolds are required to be manufactured or joined. Measures to guard against stagnation temperatures are required. Possibly a drain back method.

Figure 15 Pillow type absorber with insulation

4.1.4 Rotor molded pillow type (with no insulation)

Scored 8.59 in the concept evaluation table.

Thermal efficiency would be comparable with conventional collectors. The absorber would be a complete one piece rotor-molding so therefore no separate manifolds are required to be manufactured or joined. This is a major advantage since it minimises number of component parts and requires no joining or bonding. The absence of the insulation component not only means one less part to assemble/disassemble but can provide protection against stagnation temperatures.

4.1.5 Rotor molded pillow type with separate cover.

Scored 6.82 in the concept evaluation table. Again thermal efficiency would be comparable with conventional collectors. This design benefits from the outer cover and bottom of the absorber being manufactured very efficiently by rotor-molding and the air gap provided some insulation.

However it would require the top absorber plate and top cover to be joined to the main body, probably by adhesive. Given the extreme condition that the collectors are exposed to during their life time use of adhesives is currently not proven.

5 Proposed Design

The type of collector to be developed will therefore be based on the rotor-moulded pillow type with no separate insulation component. A typical conventional collector could consist of around 40 parts; some of these would have been welded or brazed together. Not only would this assembly process been costly it would make separation and recycling of materials difficult at the end of collectors useful life.

The proposed design dramatically reduces the components down to two main components. The outer cover and the absorber. Both can be easily assembled and disassembled therefore providing the opportunity to recycle materials at the end of useful life.

This design eliminates the need for insulation in line with the earlier research of Elsherbiny et al. This is discussed further in section 5.2.

The outer cover will be in one piece and perform the functions of top cover and in addition rear and side panels. The requirements for material are discussed in section 5.1.1

The absorber will be of a twin parallel plate type based on Matrawy's and Rommel's (1997) work but from an acceptable polymer. The material requirements are discussed in section 5.1.2.

This design of absorber maximises the wetted area and has a wall thickness as thin as possible. This creates material and design challenges. In attempting to minimise the wall thickness it is important to consider the effects of hydrostatic pressure on the absorber. The weight of the water will attempt to bulge the collector in the areas shown in figure 16.

The collector design will also have to consider how to avoid reaching stagnation temperature.

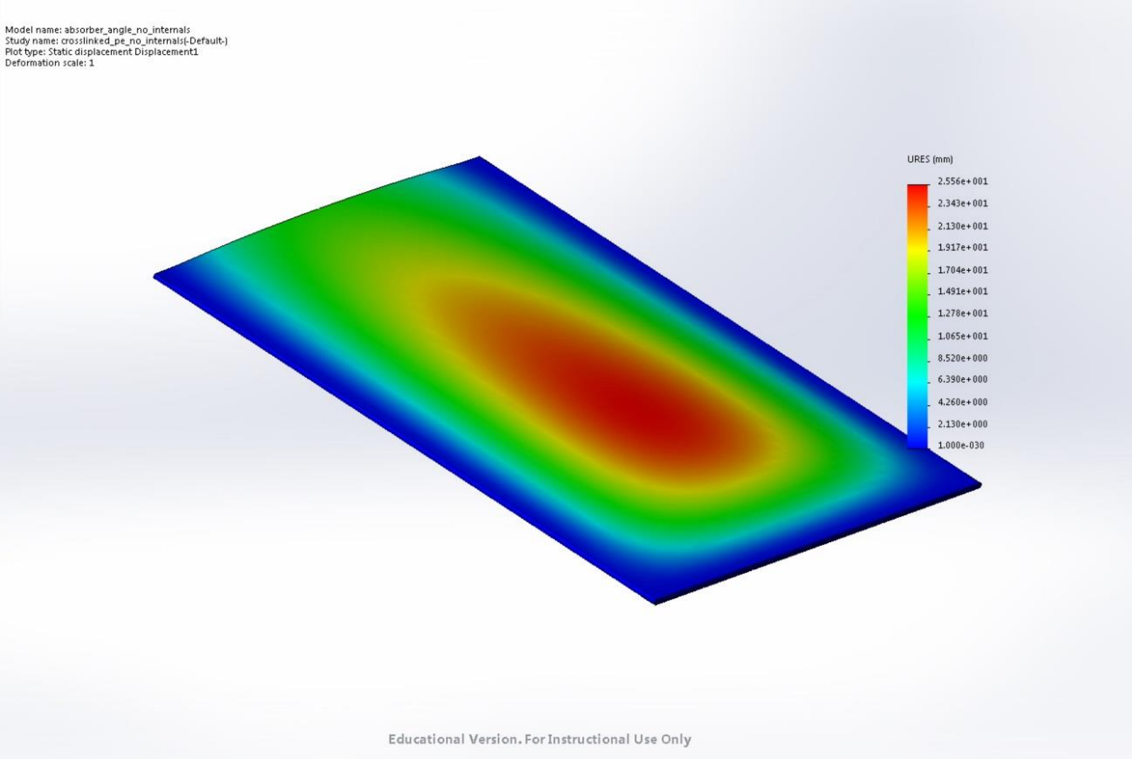


Figure 16. Deflection of unsupported absorber due to water at 30º inclination

5.1 Material Selection

Before moving on to the design calculations and production processes the polymer material for the cover and the absorber is discussed in this section. There are compromises to be made here as some possible polymers that satisfy the design criteria and low cost for the absorber may not have a suitable manufacture and assembly process.

In selecting the materials, their manufacture and assembly methods it is important to note that the aim of this project is to design a low cost polymer collector. This automatically excludes the use of 'high performance polymers' and limits selection to either 'standard commodity plastics or 'Engineering Thermoplastics'. See figure 17 for details of common polymers by structure, capability and price.

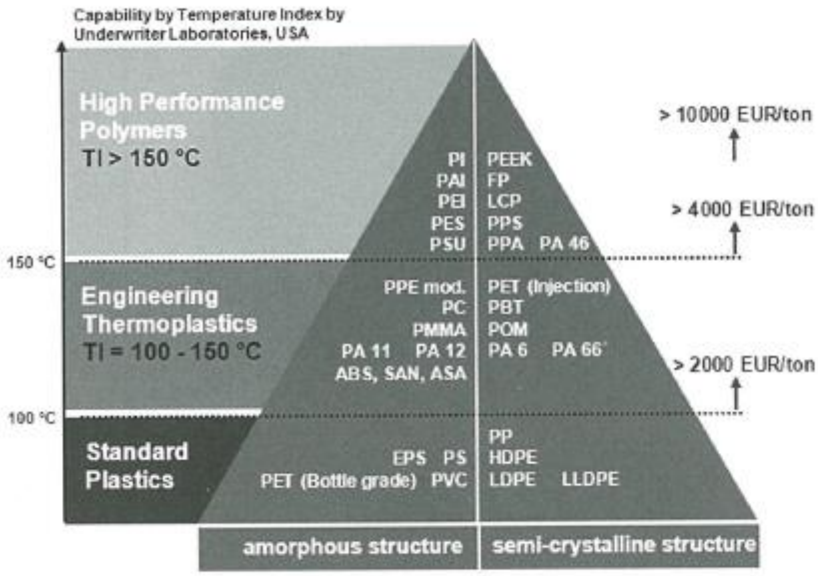


Figure. 17. Polymer structure and price (PlasticsEuropeGroup, 2011)

Since this projects proposed design does not require an insulation component there are only two components to consider, the cover and the absorber. Insulation is discussed in 5.2.

5.1.1 Cover

A conventional solar thermal collector would typically have a transparent cover made of solar glass (low iron content for a high transmission of solar radiation). To further reduce thermal losses, some collectors use double glazing. In order to further improve solar transmission an antireflective coating can be applied to the inner and outer surfaces. Solar transmission of the glazing can be increased from 90% to 93% with one side coated to 95% with both sides coated. (Köhl et al., 2012).

The polymer used to replace the glass cover would be required to exhibit similar transmissivity properties. The optical transmittance, measured in accordance with ASTM E424, Part A shall not decrease by more than 10% as a result of exposure.

The polymer cover must be durable and capable of withstanding any loadings to be imposed (e.g. hailstones). Also able to withstand and loadings from animals and birds.

The tensile strength of the material must not decrease by more than 20% as a result of exposure to the elements measured in accordance with ASTM D882.

In selecting a polymer for the cover of a polymeric solar collector a key challenge is to maintain adequate system performance and assure the required durability over extended lifetimes.

After an extensive trial of 58 possible polymer glazing material types two were singled out as the most important groups, Polycarbonate (PC) and Polymethylmethacrylate (PMMA) (Köhl et al., 2005). These two are currently widely used for glazing materials for many applications.

Comparisons between PMMA and PC show that both exhibit similar transmissivity and strength performance at the beginning of use, however material degradation occurs in PC despite UV inhibiters being used. This leads to a yellowing and loss of strength when exposed for extended periods (Ram, Zilber, & Kenig, 1985).

In contrast PMMA exhibits excellent weathering properties similar to glass. Good transmittance and strength values were exhibited even after samples had been exposed for twenty years. (Davis & Sims, 1983).

Based on this previous research PMMA will be used as the cover material for this projects design. PMMA sheet is not only as transparent as the finest optical glass but also 50% lighter than glass. Importantly it also exhibits higher impact strength than glass.

Other considerations now involve the thickness of cover and the fabrication methods. Fabrication methods are discussed in section 6.2. The thickness of the cover will be influenced by the requirement to withstand impact loading as described above.

In this design a 4mm thick sheet will meet all requirements of ASTM D882. And the impact load of hailstones or similar.

5.1.2 Absorber

A conventional solar thermal collector would commonly have a copper construction. This is due to its high thermal conductivity, mechanical strength and resistance to corrosion. Other metals also used are stainless steel, aluminium and mild steel (Lenel & Mudd, 1984).

The key challenges here are to satisfy the requirements of the standard, maintain similar thermal efficiencies of conventional collectors yet be manufactured totally from polymeric materials thus ensuring cost reduction.

This presents a considerable challenge when designing the absorber plate. There is a trade-off between material properties and their processability. The technical challenge is find a material that is compatible with the fluids and can withstand the high pressure and temperatures encountered.

One of the primary aims of this project was to reduce costs yet still meet the thermal efficiencies of conventional SWH. Costs can be reduced by replacing glass and metal parts with less expensive, lighter weight polymeric components. Weight reduction can also lead to reduced shipping, handling and installation costs. The use of polymeric materials will also allow the benefits and cost savings associated with well-established manufacturing processes, along with savings associated with improved fastening, reduced part count and a considerable reduction in assembly tasks.

Since the primary aim of the project was to produce a low cost all polymer collector the material selected for the first design will be a commodity polymer, cross linked polyethylene. With an absorber manufactured with this type of polymer there are restrictions on upper operating temperature. Other areas for design consideration are strength of the absorber to withstand internal working pressures and also optimise the flow patterns of the fluid through the collector. (The flow patterns are discussed in section 5.3.1.)

Polymers also offer the potential advantages of resistance to corrosion, reduced weight and better integration with other polymer components.

Polymeric absorber materials must withstand elevated temperature, exposure to UV from the sunlight, contact with the heat collection fluid and internal pressures.

Suitable design requirements stated by (Raman, Mantell, Davidson, Wu, & Jorgensen, 2000) are that the absorber material be compatible with hot water and propylene glycol, exhibit stable properties over an operating range of 0^{o} C to 105^{o} C and have good long term mechanical performance at high temperature.

The long term mechanical performance is characterised by the burst strength and creep. The burst strength is discussed in section where the Blach (1990) method and Finite Element Analysis are used to evaluate the hydrostatic burst pressure of the absorber.

Creep is also an important concern for absorber materials. Severe deformations may result in elevated stress concentrations that can result in cracking. Also if the absorber bulges reach the glazing, then thermal performance can negatively affected.

For high temperature applications Hemmerich et al proposed that the maximum permissible design stress is 20% of the tensile strength at 82^{o}C (Hemmerich, Rose, & Stubstad, 1998) . Since there is insufficient data available for the effects of creep at the temperatures and pressures typical in solar absorbers Hemmerich estimates long term strength to be of cross linked Polyethylene to be 4.0 MPa. (20% of the tensile strength at 82^{o}c which is 20MPa.) . Hemmerich concludes that of the non-reinforced polymers , Cross- linked-Polyethylene (PEX), Polyphenylene sulphide (PPS) and Polyvinylidene fluoride (PVDF) can be assumed to be the most ‘‘stable’’ mechanically. The PEX is borderline commodity plastic/ engineering plastic and therefore would be suitable for a low cost collector. The PPS and PVDF are both high performance polymers and therefore would be too expensive for this design of low cost all polymer collectors.

Work by Raghu Rahman et al recommends that High Temperature Nylon (HTN) Polypropylene (PP) and Cross linked Polyethylene (PEX) are best suited for solar absorbers (Raman et al., 2000)

Combining the comments of both the above researchers the material selected for this design is PEX. Possible manufacturing processes for PEX are discussed in chapter 6.

The primary consideration in material selection for polymeric absorbers is in defining the expected operating and stagnation temperatures for the collector design. Researchers at NREL have modeled a glazed collector with polymeric absorber. Their results indicated a maximum absorber temperature of 101^{o}C for normal operation and 140^{o}C for stagnation. (Burch & Thornton, 2006).

This means that this design will require protection against reaching stagnation temperature. This is discussed in chapter 6.

5.2 Insulation.

Heat is lost to the environment from the solar collector as the temperature of the absorber plate rises and collector gets warm. The rear side of the absorber plate is typically insulated in such a way that minimum heat is lost to the surroundings as most of the heat lost is from the rear side, though heat is also lost from the other two sides also. Traditionally most commonly used materials are Mineral wool, Rockwool or Styrofoam.

An evacuated chamber insulation is found to be most efficient but it is very costly to create and maintain a vacuum.

Flat plate collectors are usually insulated by a 40-60mm thick mineral wool layer. Under dry conditions typical thermal conductivities are between 0.035 and 0.060 W/m K depending on absorber temperature. (Ochs & Müller-Steinhagen, 2005). For a typical insulation thickness of 40-60mm, the rear side collector losses in operation can be in the region of 1 W/ (m^2 K). However this insulation material absorbs moisture from ambient air and its insulation properties can deteriorate significantly as operating temperatures increase.

If moisture is present the thermal conductivity of mineral wool increases rapidly. In case of high moisture content thermal conductivity can increase by a factor of 20.(Ochs et al., 2008).

One significant difference between mineral wool and insulation foams is the pore structure. Foams mainly have closed pore structures while mineral wools are open. This results in mineral wools being open to absorption of moisture. The effective heat transfer in an open pored material is the result of the combined reactions of thermal radiation and thermal conduction. The effective heat conduction increases with rising humidity in the pores. This is due to the higher heat conductance of water over air and the heat migration due to diffusion.

The design of all polymer flat plate collector proposed in this thesis eliminates the insulation completely. There is a slight trade off in thermal efficiency but the advantages of reducing the part count outweigh the slightly lower thermal efficiency. Beikircher et al (2014) demonstrate theoretically and experimentally that the height and width of collectors can be significantly reduced with only small reduction in thermal efficiency. If the insulation is removed altogether then any humidity problems disappear. Instead, free reverse air convection and free radiation will occur between absorber and the outer cover.

The convective heat loss coefficient for the absorber can be obtained from equation 5.1

$$Uconvection \ = Nu(Ra).\frac{\lambda}{d} \qquad (5.1)$$

Where Nu is Nusselt number, Ra is the Rayleigh number, λ the thermal conductivity of the air and d the distance between the bottom of the absorber plate and the bottom cover.

The Rayleigh number can be obtained from equation 5.2

$$Ra \ = \frac{gM^2p^2d^3C_p\Delta T}{\mu\lambda R^2T^3} \qquad (5.2)$$

M is the molar mass, p the air pressure, g the gravity constant. Convection starts if Ra.cosβ > 1708, where β is the slope of the collector. (Duffie & Beckman, 1980)

Beikircher discusses various methods of establishing the correlations of Nu and Ra. Citing methods of (Hollands, Unny, Raithby, & Konicek, 1976), (Buchberg, Catton, & Edwards, 1976) and (Elsherbiny, 1996). The work of the first two groups was predominantly considering heat loss from bottom up or heat loss by convection through the front cover. (Elsherbiny, 1996) considered the heat transfer through the rear and side covers experimentally for various angles of inclination (β) between 0^oC and 60^o C as shown in equation 5.3.

$$Nu(\beta^o) = \ Nu(0^o) + \frac{\beta}{60^o}[Nu(60^o) - Nu(0^o)] \qquad (5.3)$$

With

$$Nu(0^o) = \{1 + (0.212Ra^{.136})^{11}\}^{\frac{1}{11}} \qquad (5.4)$$

$$Nu(60^o) = \{1 + (0.0566Ra^{.332})^{4.76}\}^{\frac{1}{4.76}} \qquad (5.5)$$

Figure 18 shows rear and side losses due to convection depending on the distance between the absorber and outer cover to the rear and side of the outer cover. This will change with the temperature difference between absorber and the outer cover temperature. In this case an absorber temperature of 343K and outer cover temperature of 303K was used. It can be seen that with a distance of around 15mm between absorber and outer cover is used the losses due to convection from rear and sides will be around 1.8 W/m^2K.

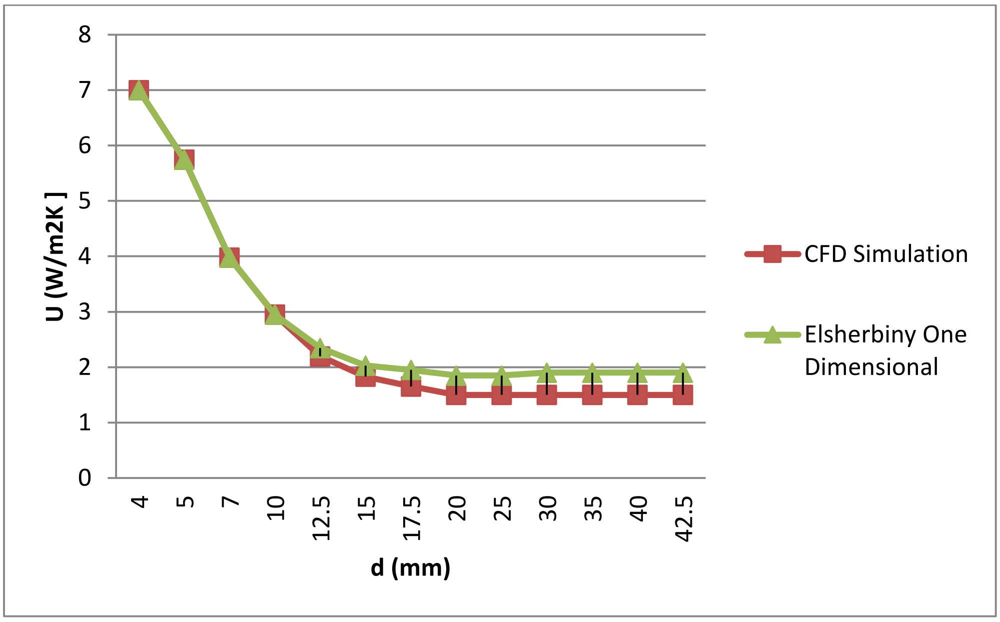


Fig. 18. Loss coefficient U the absorber due to rear and side convection.

Eliminating the requirement for insulation completely also satisfies one of the stated customer requirements for improved aesthetics of collectors. The collector will have a lower profile without insulation and therefore be more aesthetically pleasing and have similar profile to that of PV panels.

5.3 Absorber Design Considerations

The key challenges are to satisfy the requirements of the standard, maintain similar thermal efficiencies of conventional collectors yet be manufactured totally from polymeric materials thus ensuring cost reduction.

This presents a considerable challenge when designing the absorber plate. There is a trade-off between material properties and their process ability. The technical challenge is find a material that is compatible with the fluids and can withstand the high pressure and temperatures encountered.

The wall thickness of the absorber has been minimised and the wetted surface maximised in order to improve the thermal efficiency of the collector.

Since the primary aim of the project was to produce a low cost all polymer collector the material selected for the first design will be a commodity polymer, cross linked polyethylene. With an absorber manufactured with this type of polymer there are restrictions on upper operating temperature. The importance of avoiding stagnation temperature has already been discussed later in this chapter. Other areas for design consideration are strength of the absorber to withstand internal working pressures and also optimise the flow patterns of the fluid through the collector.

5.3.1 Flow Patterns

It is important that the water flows as evenly as possible upwards through the collector with no ‘dead spots’ or areas of no flow. If this situation were to continue, water in that stagnant flow area would continue to absorb energy and heat up but could stay in that area. Different design configurations and their resulting patterns of flow were evaluated by CFD in order to establish an optimal flow pattern. The most effective flow pattern is shown in figure.19. It shows good even flow across the whole collector with no serious ‘dead spots’ where there is no flow velocity.

The flow 0.06kg/s used here is the same as that of the experimental prototype.

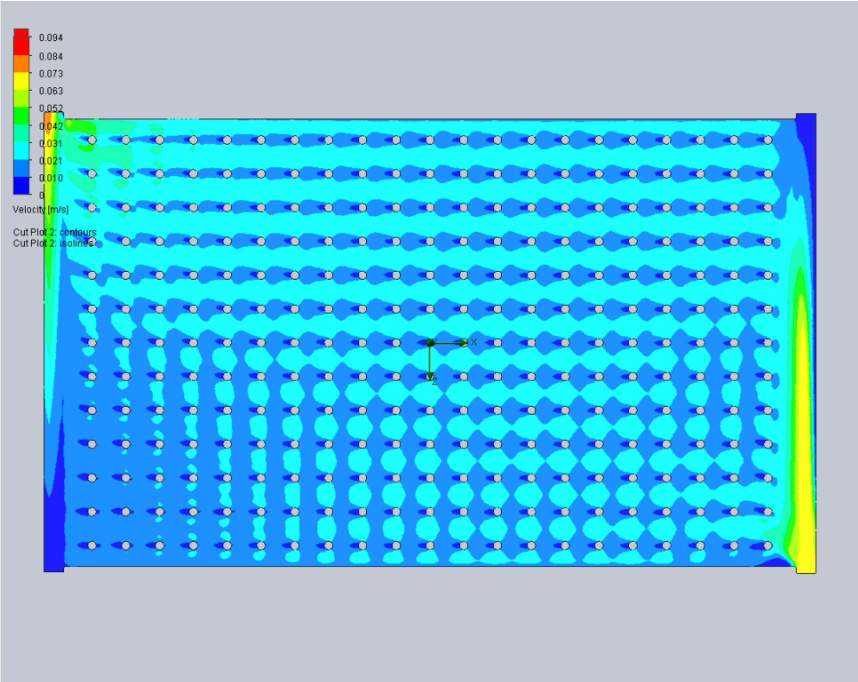


Figure. 19. CFD Prediction of flow velocities

Work by (Blach, Hoa, Kwok, & Ahmed, 1990) on small deflections of rectangular vessels of finite length was used to determine the required strength and thickness of the absorber cover to withstand the internal hydrostatic pressure caused by weight of water inside the absorber. (More detail of this work applied to the new design can be found in section 5.3.2.

The problem of ‘stagnation temperature’ is a big one for polymer absorbers. The possibility of occasional elevated temperatures limits the use of some commodity polymers for this application. This dealt with in a number of ways such as venting, drain back and shades. In this project design the fact that there will be no insulation around the absorber will be sufficient to lose heat if high temperatures are experienced. The heat loss from the absorber dramatically increases at higher temperatures. As the collector temperature rises, the insulation of the air layers decreases dramatically by higher convection due to greater convective heat loss. The additional heat loss passively act to prevent the absorber reaching extreme stagnation point. This works well at average ambient temperatures. Convective heat losses ensure that stagnation temperatures are not exceeded. (Beikircher, Berger, Osgyan, Reuß, & Streib, 2014). This is illustrated and discussed further in chapter 5

It is clearly more advantageous to use a stiffer polymer that can operate at higher temperatures. However these so called high performance polymers are considerably more expensive and are more difficult to manufacture by low cost production processes such as rotor-moulding, blow moulding and vacuum moulding.

5.3.2 Internal Working Pressure

Firstly considering the internal working pressure. The collector is essentially an unreinforced rectangular pressure vessel that is subjected to a non- uniform internal pressure. This internal hydrostatic pressure will be caused by the pressure of the water (ρgh) and will vary with height. The collector will be inclined at 30^{o} C to the horizontal. The bottom surface of the absorber will be supported by two longitudinal ribs that rest against the outer cover.

The effect of this pressure will attempt to push the two parallel surfaces apart in the area shown red in figure 20.

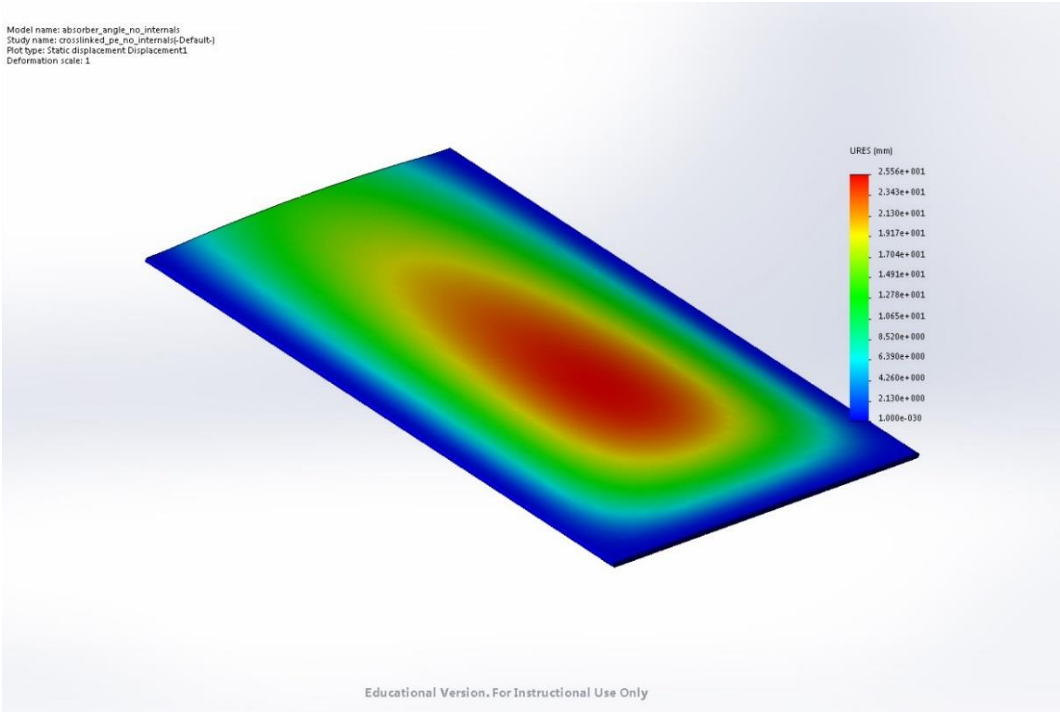


Figure. 20. Deflection of Absorber with no internal supports

If the bottom surface is not supported it will sag downwards reducing the insulation air gap between absorber bottom and the external rear cover. Figure 20 indicates that the surface will bulge by 2.6mm and likely burst either immediately or continue to creep until bursting.

Since the bottom surface will be fully supported by two longitudinal ribs the internal pressure will potentially cause a of the top absorber surface central to the red area. This has the potential to immediately cause the absorber to burst in this area, or instigate a more gradual move towards failure by way of creep. The latter could also be exacerbated by higher operating temperatures.

There are a number of methods that can be applied to the determination of these stresses including finite element analysis, superposition methods or the ASME Boiler and Pressure Vessel Code. Of the available methods however, (Blach et al., 1990) large deflection analysis demonstrates probably the best prediction of stress values in rectangular cross section pressure vessels.

Two methods are used here to ensure that the absorber can meet operating requirements. The Blach method and FEA. These will determine wall thickness and support to ensure integrity of absorber.

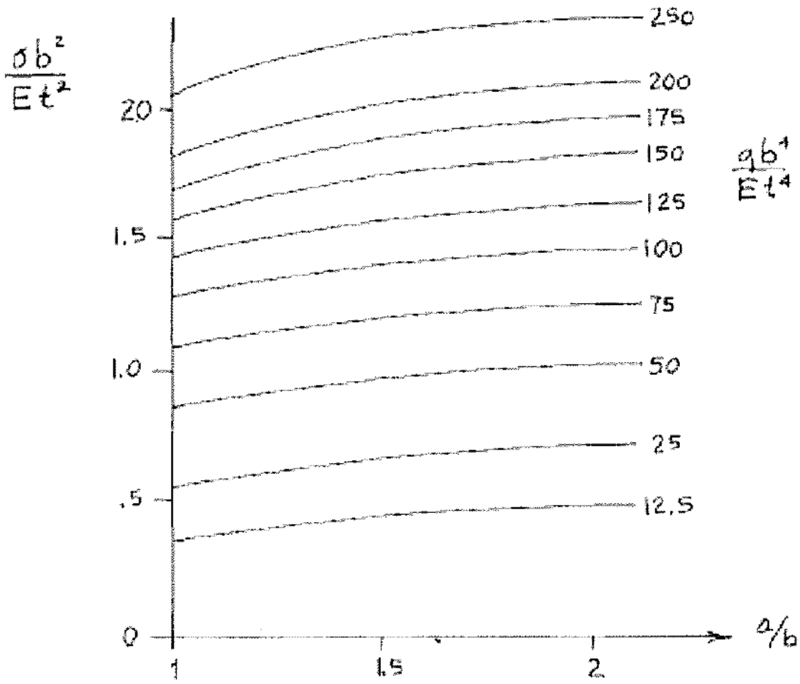


Figure 21 Total Stress coefficients (Adapted from Blach et al. 1990)

To determine the stress in the absorber, it is assumed that the stress at the centre of the tube surface (i.e. the top of absorber plate). This is not exactly true since the area of greatest stress is central but toward the bottom half of absorber due to the inclination.

The length of the absorber is 1.5m and the width 0.8m. The thickness of absorber is 3mm and the maximum allowable combined bending and membrane stress (δ) of 20MPa. Using figure 21 we have:-

$$\frac{a}{b} = \frac{1200}{800} = 1.5$$

$$\frac{\delta b^2}{Et^2} = \frac{20.10^6.060^2}{1.7.10^9.003^2} = 4.7$$

From chart in figure 21 it can be seen that this value corresponds to $qb^4/Et^4=25$

$$\frac{qb^4}{Et^4} = 25$$

Solving for q gives maximum working pressure of 2.5MPa

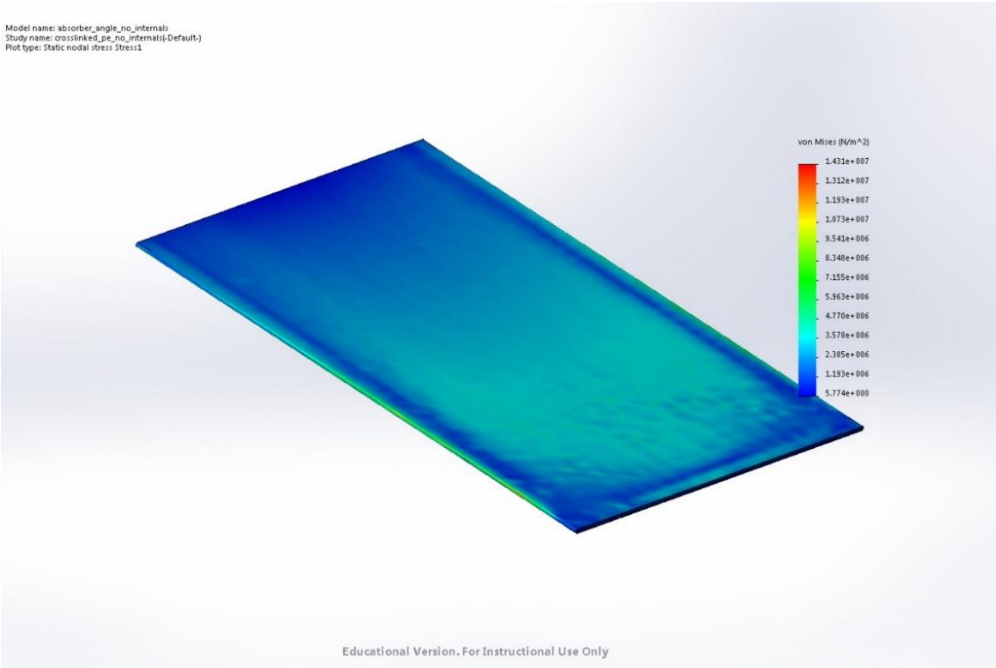


Figure 22 HDPE Absorber – Two Parallel Flat plates with no internal supports

Figure 22 shows a FEA study of two parallel flat plates with no internal supports. The internal pressure at the highest stressed point is around 5MPa with a deflection of 2.6mm. This is greater than the maximum working pressure derived from the Blach analysis. To ensure the absorber does not fail internal supports are required. The absorber will be of a pillow type with top and bottom surfaces joined by 'dimples' as shown in figure 23.

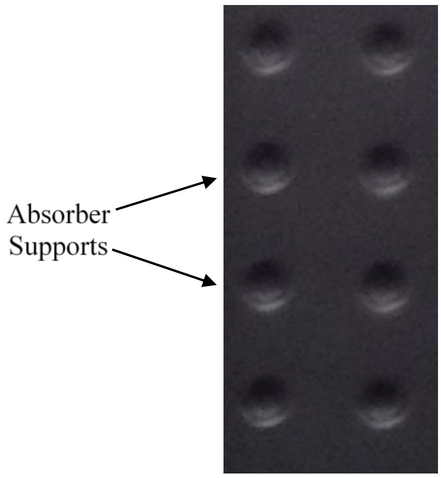


Figure 23 Absorber support pattern

Figure 24 shows a FEA study of the pillow type collector with support as shown in Figure 23. This study indicates a maximum internal working pressure of only 70kPa which is within the operating limits of the absorber with 3mm wall thickness.

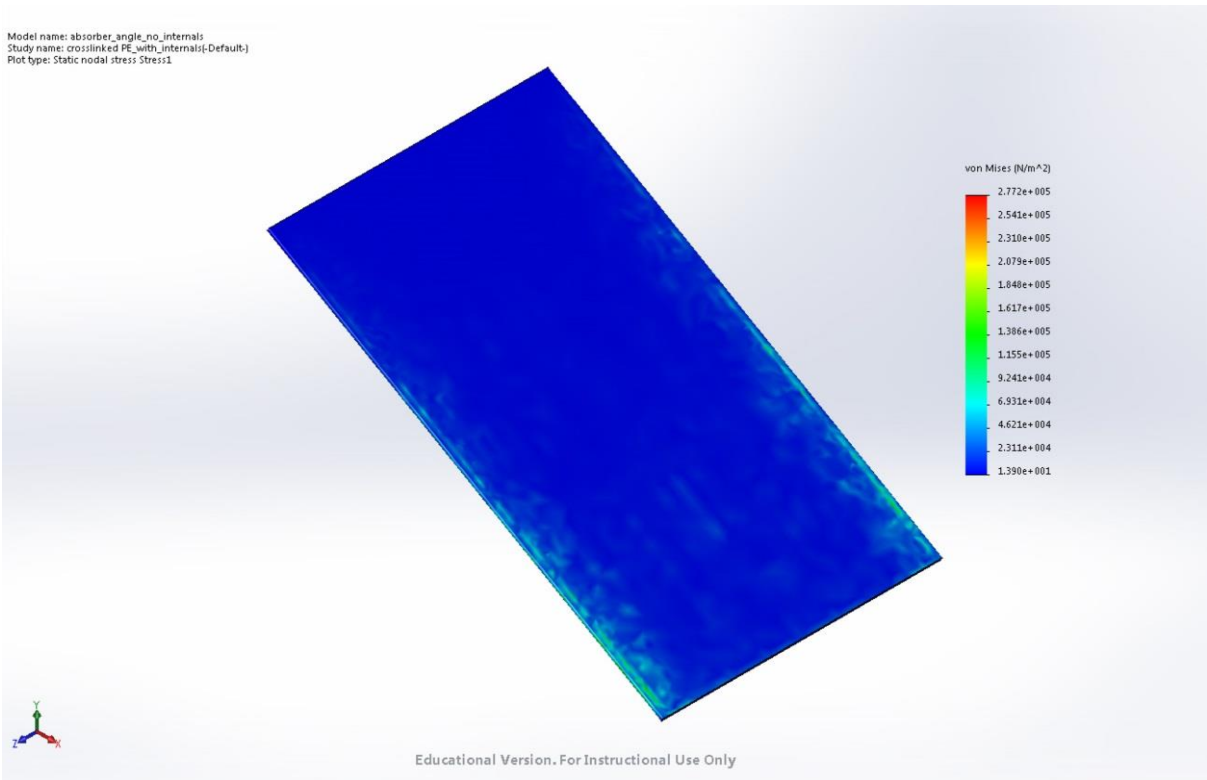


Figure 24 HDPE Absorber – Two Parallel Flat plates with internal supports

6 Production Methods

6.1 Absorber

The option of using extrusion as a production method is discounted as this would require two additional headers and a joining process.

Absorber could possibly be made by three methods.

- Blow Moulding
- Vacuum / Blow Moulding
- Rotational Moulding

6.1.1 Rotational Moulding

Since the original aim of this project was to design a low cost solar water heater the design of this projects absorber will be from a rotor-moulded high density cross linked polyethylene. An article by (Tamboli, Mhaske, & Kale, 2004) describes the cross linking process well and demonstrates that the properties of this material as being suitable for this application.

Rotational moulding is a highly versatile manufacturing process that allows for virtually unlimited design possibilities, and offers design advantages over other moulding processes, parts that are usually assembled from several pieces can be moulded as one. This reduces fabrication and assembly costs. The process also has a number of inherent design strengths, such as consistent wall thickness and strong outside corners that are virtually stress free. If additional strength is required, reinforcing ribs can be designed into the part.

Rotational moulding is very cost-effective when compared to injection and blow moulding for large parts such as absorber plates. Injection mould tools are typically more expensive than rotor moulding tools. Injection moulded shells have been developed by Aventa as part of an IEA SHC project. (Rekstad et al., 2015) These are then welded or glued together.

Production costs for product conversions are reduced because lightweight plastics replace heavier, often more costly materials. This makes rotational moulding as cost effective for individual prototypes as for large production runs.

Reduction of cycle times is an important factor for the rotor-moulding process, it has been seen as a key disadvantage of the process, however a recent report by (Abdullah, Bickerton, Bhattacharyya, Crawford, & Harkin-Jones, 2009) have demonstrated cycle time reductions of around 70% thus making rotor-moulding a viable process for producing this new design of absorber for this project

6.1.2 Blow Moulding

Blow moulding and a combination of blow moulding and vacuum forming, known as Twin Sheet Moulding were considered as possible production processes but not considered suitable for the selected design. Both are better suited to polymers with better flow characteristics than the PEX material used in this design. The twin sheet process would be to produce a twin sheet parallel absorber but not with the internal supports that join top and bottom sheets. (Processing & Jones, 1995)

6.2 Top and outer cover

The combination of the top cover and the outer cover represents a major shift from conventional design where they were separate parts assembled from dissimilar materials. This design eliminates number of parts and reduces assembly operations.

The choice of possible polymers is guided by the requirement for good transmissibility, resistance to degradation by UV and exposure to the elements. Many possible clear polymers ‘yellow’ with time degrading their transmissibility and some become brittle with UV exposure.

The sheet polymer selected here is produced by extrusion. The manufacturing operation performed to fabricate our proposed combined outer cover and top cover requires a simple series of folding.

7 Design for Sustainability and Aesthetics

7.1 Sustainability

A major feature of this design is the significant reduction in parts allowing for easy assembly and disassembly. Designing for ease of disassembly (DFD). A suitable structuring of assemblies allows 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) .

Not only will this lead to significant reduction in costs it is also an eco- friendly design. It is becoming increasingly important to consider how materials can be re used after the products useful life has ended. This ‘cradle to cradle’(Braungart, McDonough, & Bollinger, 2007) approach has already been adopted by the automotive industry. The End Of Life Material Directive (Kanari, Pineau, & Shallari, 2003) introduced by the European Union is likely to be the forerunner of a whole new approach to design and manufacture of all products in the very near future. As from 1st January 2015, for all end-of life vehicles, the reuse and recovery is to be a minimum of 95% by an average weight per vehicle. Separation of automotive materials is often difficult and costly and often results either in disposing of materials or down cycling of materials. Already cars are being designed with this directive in mind. Materials need to easily separated at end of life and not mixed with other materials. This will enable the materials to be up cycled and have a full new life after the original life as an automotive part is over.

The proposed all polymer design can be defined as eco-effective and is in line with the ‘cradle to cradle’ approach as opposed to the previous traditional collector design that was more ‘cradle to grave’. Traditional collectors were difficult to disassemble and involved mixed materials often joined by welding or brazing. Being difficult to dispose of they were more often disposed of rather than re used. Some materials could be recycled but it is something that they were not designed for and they are likely to be down-cycled, a downgrade in material quality which limits usability and maintains the cradle to grave material flow system.

The goal of the new polymer design is to use a design and materials that are intended for real re-use and up cycling at the end of the collector’s life cycle.

It has been demonstrated that both HDPE (Boldizar, Jansson, Gevert, & Möller, 2000) and PMMA (Kikuchi, Hirao, Ookubo, & Sasaki, 2014) can be upcycled with no loss of original material properties.

7.2 Aesthetics

It was common in the late 1970’s and early 1980’s to mount solar water heaters at a steeper angle than the roof pitch in order to maximise energy collection. These were not aesthetically pleasing. (Pollard, Zhao, Efficiency, & Authority, 2008)

Integrated solar water heaters and close coupled solar water heaters also have a high profile and can look unattractive on roofs.

The proposed design will have a low profile and can be mounted on or be mounted flush with the roofing system. It could also be advantageous for the panel to be designed with a colour that blends with the roofing material. There is now considerable interest in installing solar panels as part of the façade of buildings. (Anderson, Duke, & Carson,

2010) and there are possibilities to develop this all polymer design for this type of application. This all polymer design gives the opportunity to have different coloured absorbers that could prove aesthetically pleasing to architects when designing buildings of the future. This is an area explored by (Anderson et al., 2010) and (Tripanagnostopoulos, Souliotis, & Nousia, 2000)

8 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 (Figure 27), secondly a commercially available collector with an aluminium housing, polymer glazing and polymer absorbers (Figure 28) and thirdly a prototype all polymer collector with a HDPE absorber and with a one piece acrylic outer cover (Figure 25).

The prototype, shown in Figure 25, consisted of three components, a folded acrylic cover, a rotationally moulded pillow type absorber (Figure 26) and a layer of insulation to provide support to the absorber.

Figure 25 Prototype Collector with insulation

Figure 26 Prototype absorber

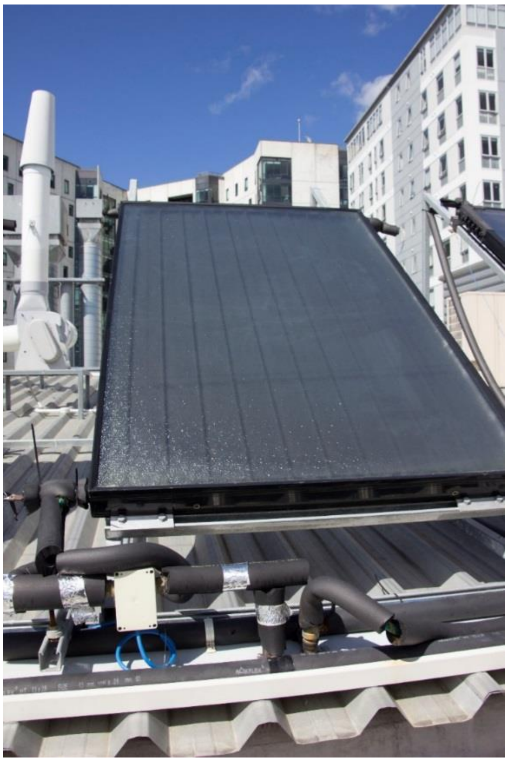


Figure 27 Traditional Copper Absorber

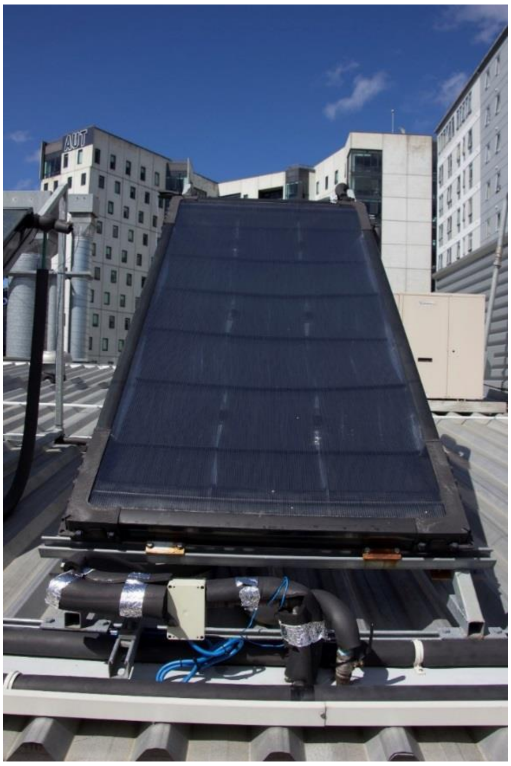


Figure 28. Polymer Collector

For this study, a steady state outdoor thermal test setup similar to that recommended in AS/NZS 2535.1-1999 and shown in Figure 29 was used to determine the efficiency characteristics of the collectors.

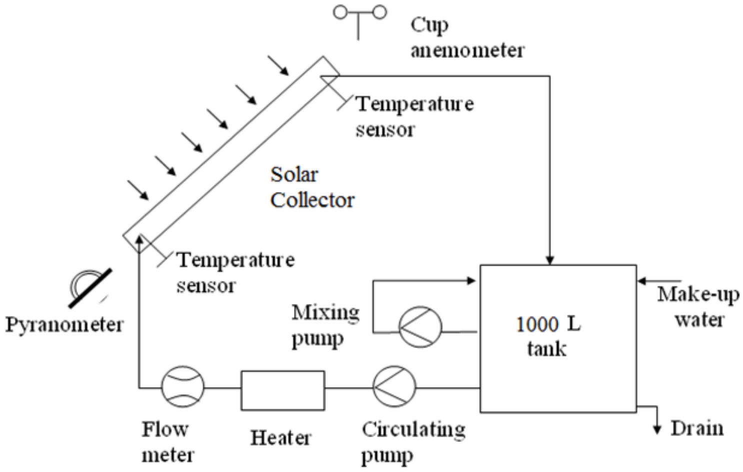


Figure 29 Test Set Up

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.

8.1 Experimental Results

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. It is interesting to note was that the performance of all the collectors was broadly similar as shown by Figure 30. 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 and the frosted glazing. 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.

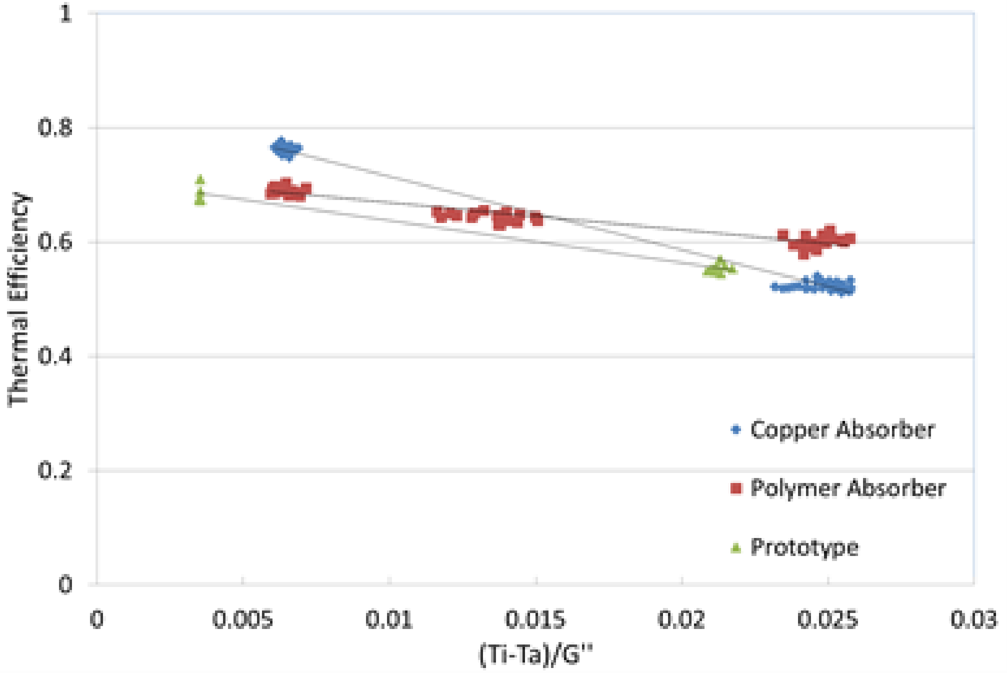


Figure 30 Experimental Test results

9 Design Modelling

In this chapter the efficiency of the new all polymer collector is compared using experimental results of traditional collectors and also against computer simulation models.

In order to better understand the thermal performance of the selected 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. This is a similar model to that used in chapter two for the original feasibility study. 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 31, and that there was a thin wall between these "tubes".

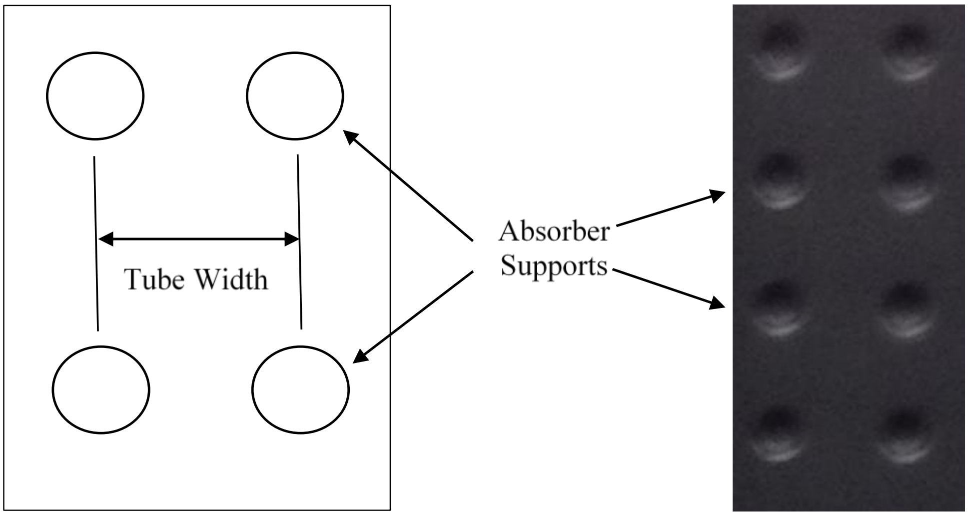


Figure 31 Absorber tube width

9.1 Modelling Results and Discussion

Having developed a simplified representation of the pillow absorber as shown in Figure 34 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 32 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 computer simulation model in refining the design of an all polymer collector.

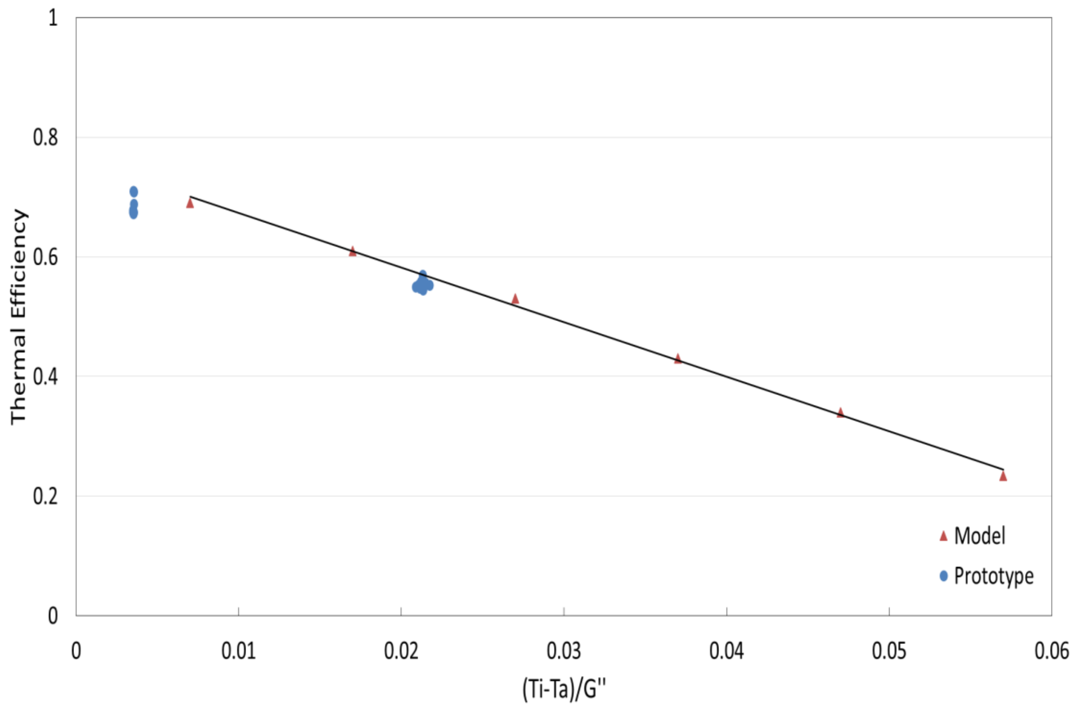


Figure 32 Modelled v experimental efficiency

Two computer simulation model programmes were written, one for the proposed new design and one for a parallel tube polymer absorber based on previous work of and Duffie and Beckman. (2006).

Table 4 Parameters for prototypes v benchmark model.

Parameter	Symbol	Metal	Polymer	Polymer Sandwich with no insulation
Number of covers	N	1	1	1
Emittance of plate	ε_p	0.95	0.92	0.92
Emittance of cover	ε_c	0.88	0.9	0.9
Number of tubes	n	38	12	12
Collector Length	L_C	1.3m	1.3m	1.3m
Collector Breadth	B	1.04m	1.04m	1.04m
Absorber thickness	t	.0005m	.003mm	.003mm
Tube hydraulic diameter	D_h	10mm	6mm *	6mm *
Tube spacing	W	20mm	35mm	35mm
Tube width	D	10.001mm	70mm	70mm
Insulation conductivity	K_b	.045W/mK	.045W/mK	NA
Back insulation thickness	L_b	50mm	50mm	NA
Edge Insulation thickness	L_e	25mm	25mm	NA
Absorber conductivity	K	385W/mK	0.4 W/mK	0.4 W/mK
Mounting angle	β	30^O	30^O	30^O
Transmissivity-Absorptance	*Ta*	0.8	0.71	0.71
Solar radiation	G	1000W/mK	1000W/mK	1000W/mK
Wind heat transfer	H_w	$11W/m^2K$	$11W/m^2K$	$11W/m^2K$

* Hydraulic Diameter of rectangular duct = 2x width x height / (width + height)

Using a prototype polymer collector the performance of such a system was shown to be comparable with commercially available collectors. See Figure 33.

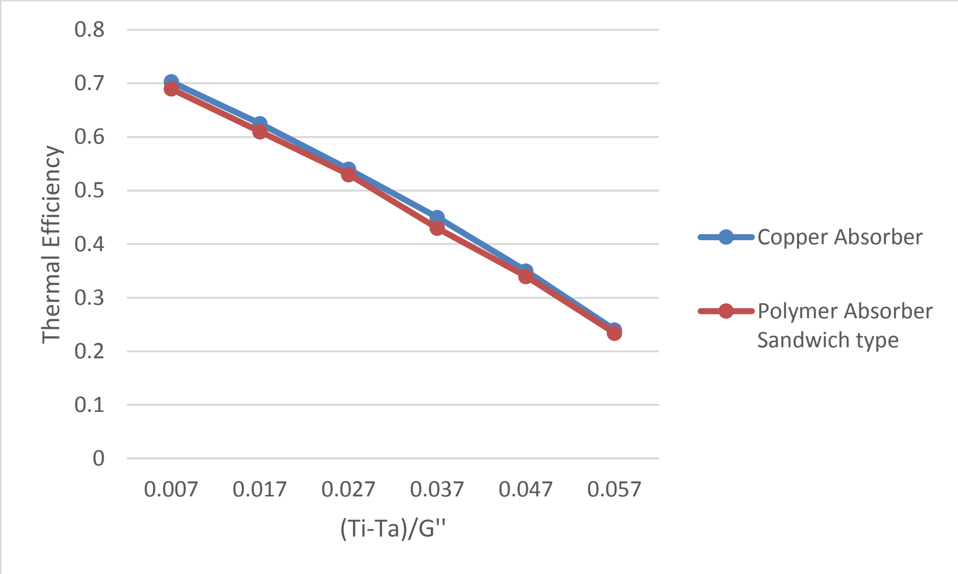


Figure 33. Modelled efficiencies of benchmark copper v polymer absorber sandwich type

Further, a design model was developed that showed that the system could be simplified further, by removing the insulation without dramatically affecting the performance.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 et al., 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/m2K. 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 34 it can be seen that if the insulation is removed altogether, there is a reduction in the thermal efficiency 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.

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.

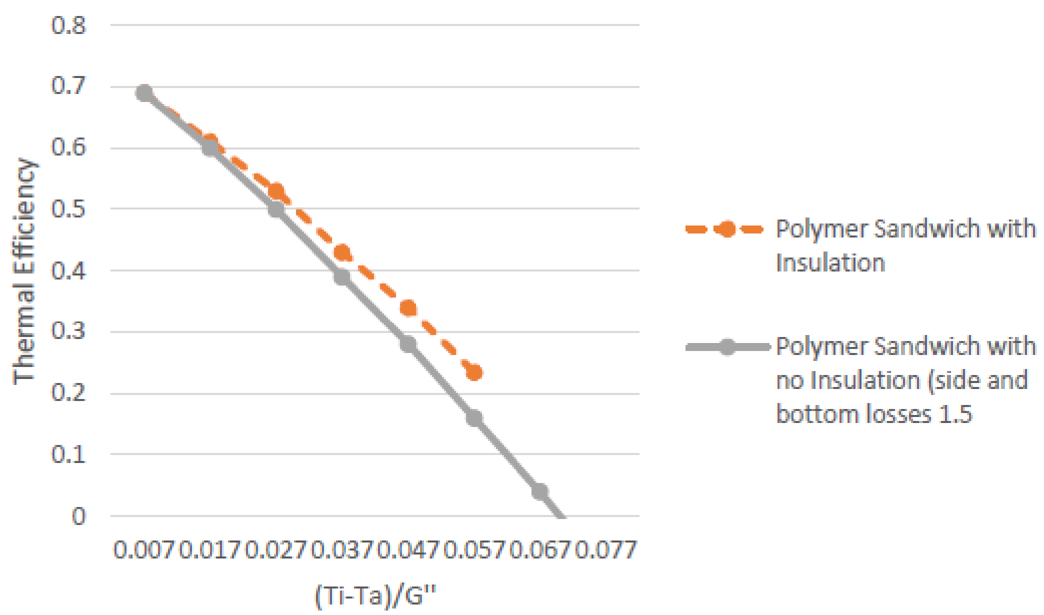


Figure 34 Modelled efficiencies of polymer absorber sandwich type with insulation and without insulation.

10 Discussion and 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.

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. Designing a collector without insulation has benefits in addition to reducing part count and improving design from an environmental viewpoint. Without an insulation component the collector can be prevented from reaching stagnation temperature due to there being a greater heat loss at higher temperatures. As the collector temperature rises, the insulation of the air layers decreases dramatically due to greater convective heat loss. The additional heat loss passively acts to prevent the absorber reaching extreme stagnation point. This works well at average ambient temperatures.

One area of further work would be to investigate the effectiveness of no insulation at high ambient temperatures.

Another area of possible future work that relates to avoiding stagnation temperatures is the use of thermotropic layers. This was not included in the scope of this work but a brief explanation of this method is included for completeness in the appendix.

Further work should also be considered into the combination of the material science of the absorber and the absorbers production process. The possibility of using blow moulding rather than roto-moulding would produce a similar one piece absorber at a lower cost but would require better flow characteristics than the cross linked HDPE used in this design.

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Abdullah, M. Z., Bickerton, S., Bhattacharyya, D., Crawford, R., & Harkin-Jones, E. (2009). Rotational molding cycle time reduction using a combination of physical techniques. *Polymer Engineering & Science, 49*(9), 1846-1854.

Altuglas. (2014). Acrylic Optical and Transmission Characteristics.

Anderson, T. N., Duke, M., & Carson, J. K. (2010). The effect of colour on the thermal performance of building integrated solar collectors. *Solar energy materials and solar cells, 94*(2), 350-354.

Beikircher, T., Berger, V., Osgyan, P., Reuß, M., & Streib, G. (2014). Low-e confined air chambers in solar flat-plate collectors as an economic new type of rear side insulation avoiding moisture problems. *Solar energy, 105*, 280-289.

Beitz, W. (1993). Designing for ease of recycling. *Journal of Engineering Design, 4*(1), 11-23.

Blach, A., Hoa, V., Kwok, C., & Ahmed, A. (1990). Rectangular pressure vessels of finite length. *Journal of pressure vessel technology, 112*(1), 50-56.

Boldizar, A., Jansson, A., Gevert, T., & Möller, K. (2000). Simulated recycling of post-consumer high density polyethylene material. *Polymer Degradation and Stability, 68*(3), 317-319.

Braungart, M., McDonough, W., & Bollinger, A. (2007). Cradle-to-cradle design: creating healthy emissions–a strategy for eco-effective product and system design. *Journal of cleaner production, 15*(13), 1337-1348.

Buchberg, H., Catton, I., & Edwards, D. (1976). Natural convection in enclosed spaces—a review of application to solar energy collection. *Journal of Heat Transfer, 98*(2), 182-188.

Burch, J., & Thornton, J. W. (2006). High Temperature Issues for Polymer-Based Solar Thermal Systems. *ANTEC, Charlotte, NC*.

Cristofari, C., Notton, G., Poggi, P., & Louche, A. (2002). Modelling and performance of a copolymer solar water heating collector. *Solar Energy, 72*(2), 99-112. doi: 10.1016/S0038-092X(01)00092-5

Davis, A., & Sims, D. (1983). *Weathering of polymers*: Springer Science & Business Media.

Duffie, J. A., & Beckman, W. A. (1980). *Solar engineering of thermal processes* (Vol. 3): Wiley New York etc.

Elsherbiny, S. M. (1996). Free convection in inclined air layers heated from above. *International Journal of Heat and Mass Transfer, 39*(18), 3925-3930.

Frey, R., Frei, U., Brunold, S., Prüf, S., & Forschungsstelle, S. (1995). Bestimmung des Kollektorwirkungsgradfaktors F'an flüssigkeitsführenden Solarabsorbern *Report by: Solarenergie Prüf-und Forschungsstelle* (Vol. 10).

Gillingham, K. (2009). Economic efficiency of solar hot water policy in New Zealand. *Energy Policy, 37*(9), 3336-3347.

Gladen, A. C., Davidson, J. H., & Mantell, S. C. (2015). The Effect of a Thermotropic Material on the Optical Efficiency and Stagnation Temperature of a Polymer Flat Plate Solar Collector. *Journal of solar energy engineering, 137*(2), 021003.

Hansen, J., Sørensen, H., Byström, J., Collins, M., & Karlsson, B. (2007). *Market, modelling, testing and demonstration in the framework of IEA SHC Task 35 on PV/thermal solar systems.* Paper presented at the Proceedings of the 22nd European Photovoltaic Solar Energy Conference and Exhibition.

Hemmerich, K., Rose, J., & Stubstad, J. (1998). 'Preventing Plastic Part Failure. *Department of Engineering Professional Development, University of Wisconsin at Madison*.

Hirst, E. (1981). A golden thread: 2500 years of solar architecture and technology: by Ken Butti and John Perlin Cheshire Books, distributed by Van Nostrand Reinhold Company, New York and London, 1980, 304 pp, [pound sign]11.95. *Energy Policy, 9*(2), 167-167.

Hollands, K., Unny, T., Raithby, G., & Konicek, L. (1976). Free convective heat transfer across inclined air layers. *Journal of Heat Transfer, 98*(2), 189-193.
Hottel, H., & Whillier, A. (1955). *Evaluation of flat-plate solar collector performance.* Paper presented at the Trans. Conf. Use of Solar Energy;().
Kanari, N., Pineau, J.-L., & Shallari, S. (2003). End-of-life vehicle recycling in the European Union. *Jom, 55*(8), 15-19.
Kikuchi, Y., Hirao, M., Ookubo, T., & Sasaki, A. (2014). Design of recycling system for poly (methyl methacrylate)(PMMA). Part 1: recycling scenario analysis. *The International Journal of Life Cycle Assessment, 19*(1), 120-129.
Klein, S. (1975). Calculation of flat-plate collector loss coefficients. *Solar Energy, 17*(1), 79-80.
Köhl, M., Jorgensen, G., Brunold, S., Carlsson, B., Heck, M., & Möller, K. (2005). Durability of polymeric glazing materials for solar applications. *Solar Energy, 79*(6), 618-623.
Köhl, M., Meir, M. G., Papillon, P., Wallner, G. M., & Saile, S. (2012). *Polymeric Materials for Solar Thermal Applications*: John Wiley & Sons.
Lenel, U., & Mudd, P. (1984). A review of materials for solar heating systems for domestic hot water. *Solar Energy, 32*(1), 109-120.
Matrawy, K., & Farkas, I. (1997). Comparison study for three types of solar collectors for water heating. *Energy Conversion and Management, 38*(9), 861-869.
Ochs, F., Heidemann, W., & Müller-Steinhagen, H. (2008). Effective thermal conductivity of moistened insulation materials as a function of temperature. *International Journal of Heat and Mass Transfer, 51*(3), 539-552.
Ochs, F., & Müller-Steinhagen, H. (2005). Temperature and moisture dependence of the thermal conductivity of insulation materials. *NATO Advanced Study Institute on Thermal Energy Storage for Sustainable Energy Consumption (TESSEC), Izmir, Cesme*.
Outlook, A. E. (2010). Energy Information Administration. *Department of Energy*.
Pahl, G., & Beitz, W. (2013). *Engineering design: a systematic approach*: Springer Science & Business Media.
Pilgaard, O. (2006). Solar Thermal Action Plan for Europe (Brussels: ESTIF, 2007); Janet L. Sawin,"Solar Industry Stays Hot,". *Worldwatch Institute, Vital Signs, 2007*, 38.
PlasticsEuropeGroup. (2011). Plastics- The Facts.
Pollard, A. R., Zhao, J. X., Efficiency, E., & Authority, C. (2008). *The Performance of Solar Water Heaters in New Zealand*: BRANZ.
Processing, P., & Jones, D. M. (1995). Chapman & Hall. *New York*.
Ram, A., Zilber, O., & Kenig, S. (1985). Life expectation of polycarbonate. *Polymer Engineering & Science, 25*(9), 535-540.
Raman, R., Mantell, S., Davidson, J., Wu, C., & Jorgensen, G. (2000). A review of polymer materials for solar water heating systems. *Transactions-American Society of Mechanical Engineers Journal of Solar Energy Engineering, 122*(2), 92-100.
Rekstad, J., Meir, M., & Aventa, A. (2015). Description: Low cost simple design thermosiphon concepts based on polymer structured sheets have been patented and developed. One concept is presented. Date: May 2015.
Resch, K., & Wallner, G. M. (2009). Thermotropic layers for flat-plate collectors—A review of various concepts for overheating protection with polymeric materials. *Solar Energy Materials and Solar Cells, 93*(1), 119-128.
Roberts, D., & Forbes, A. (2012). An analytical expression for the instantaneous efficiency of a flat plate solar water heater and the influence of absorber plate absorptance and emittance. *Solar Energy, 86*(5), 1416-1427.
Rommel, M., & Moock, W. (1997). Collector efficiency factor F'for absorbers with rectangular fluid ducts contacting the entire surface. *Solar energy, 60*(3), 199-207.
Roulleau, T., & Lloyd, C. (2008). International policy issues regarding solar water heating, with a focus on New Zealand. *Energy Policy, 36*(6), 1843-1857.
Shrapnel, B. (2012). The Household Appliance Market in Australia 2012: vol. 4 hot water systems: BIS Shrapnel, Australia.

Souliotis, M., Singh, R., Papaefthimiou, S., Lazarus, I., & Andriosopoulos, K. (2015). Integrated collector storage solar water heaters: survey and recent developments. *Energy Systems*, 1-24.

Tamboli, S., Mhaske, S., & Kale, D. (2004). Crosslinked polyethylene. *Indian journal of chemical technology, 11*(6), 853-864.

Tian, Y., & Zhao, C.-Y. (2013). A review of solar collectors and thermal energy storage in solar thermal applications. *Applied Energy, 104*, 538-553.

Tripanagnostopoulos, Y., Souliotis, M., & Nousia, T. (2000). Solar collectors with colored absorbers. *Solar Energy, 68*(4), 343-356.

Van Niekerk, W. M. K., du Toit, C. G., & Scheffler, T. B. (1996). Performance modelling of a parallel tube polymer absorber. *Solar Energy, 58*(1), 39-44. doi: 10.1016/0038-092X(96)00052-7

Wang, S., Chen, S., & Zhang, J. (2013). Characterization, solar reflectance, and crystal properties of polyethylene and ethylene copolymer after thermal treatment. *International Journal of Polymer Analysis and Characterization, 18*(4), 257-268.

Wüstenhagen, R., & Bilharz, M. (2006). Green energy market development in Germany: effective public policy and emerging customer demand. *Energy Policy, 34*(13), 1681-1696.

Appendix1 Thermotropic stagnation temperature protection

Another method of avoiding stagnation temperatures that provides an interesting solution is that of using thermotropic layers for overheating protection. These layers permit the light and energy flux to be adapted dynamically to climatic demands. (Resch & Wallner, 2009) discuss the suitability of this method of overheating protection for flat plate collectors state that the temperature switching properties of thermotropic systems with fixed domains (TSFD) can be tailored easily to the desired application and provide adequate protection, although they admit further research is required for optimal solution.

An example given by (Gladen, Davidson, & Mantell, 2015) relates to a thermotropic protection layer with a solar weighted reflectance greater than 52% to protect a Polypropelyne absorber which has a maximum service temperature of 115^{o}C

Figure 15 shows a typical switch over from clear to translucent state when the selected upper temperature is reached.

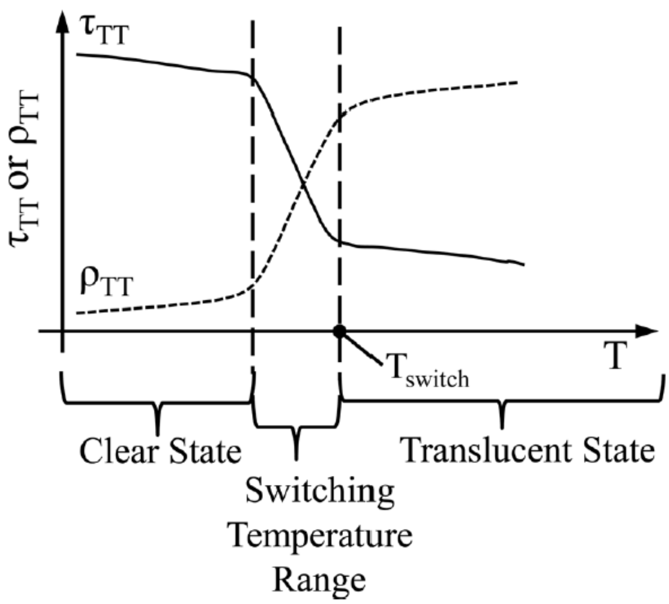

Figure 15 Temperature dependency of the optical properties of thermotropic materials.