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A Review of Solar Thermal Applications using Polymer Materials

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A review of solar thermal applications using polymer materials

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Abstract

The construction of solar thermal collectors has traditionally relied on the use of materials such as such as copper, aluminium and glass, which are heavy or expensive, or both. Manufacturing processes require labour-intensive individual assembly of components, and because of their weight, installation is awkward, requiring specialist operators and equipment. These factors incur additional expense. With rising prices of metals, there is increasing interest in alternative materials, such as polymers. These lend themselves readily to mass-production manufacturing and assembly methods, to produce cheaper and lighter solar collectors, which would also make them more attractive to a wider market, especially in temperate climates. This paper presents a review of polymer materials (plastics) in solar thermal applications, including recent advances in material properties. Design and manufacturing developments are examined, both for all-polymer systems and for substitution of other materials in key components, and the potential for future developments is assessed.

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Introduction

Traditionally metals such as copper and aluminium (because of their very high thermal conductivity) and glass (because of its high transmissivity to solar radiation) have been used as materials for the key components of a solar collector. However, copper and aluminium prices have been rising rapidly over the past few years (see figure 1) and glass is heavy, and so it requires at least two people to handle and install a solar collector. These materials also imply designs which require complex assembly by hand. Therefore, there is an imperative to investigate lower-cost materials and improved designs to reduce assembly costs, especially for countries with low solar potential.

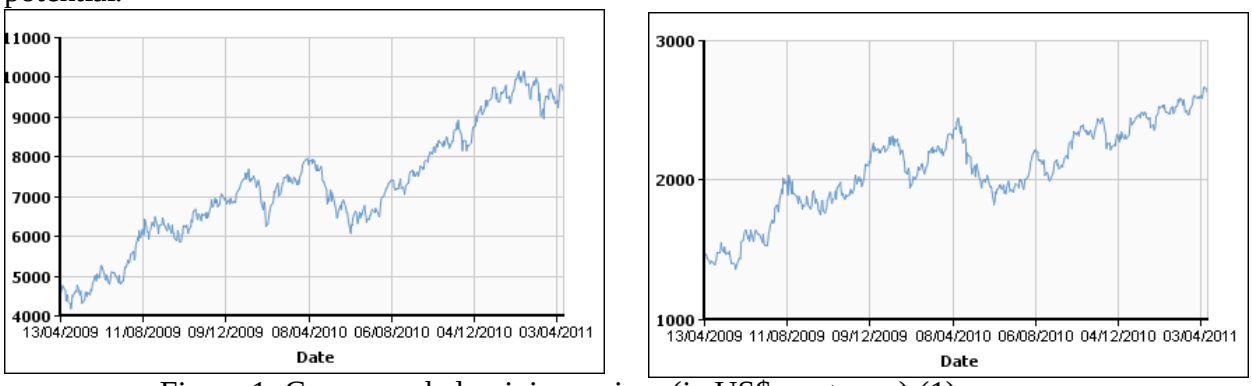

Figure 1: Copper and aluminium prices (in US$ per tonne).(1)

The price of polymer materials depends on the price of oil, the raw material for most polymers. The thermal, mechanical and other properties of the material depend on the complexity of the material itself, which in turn affects the price, as shown in figure 2.

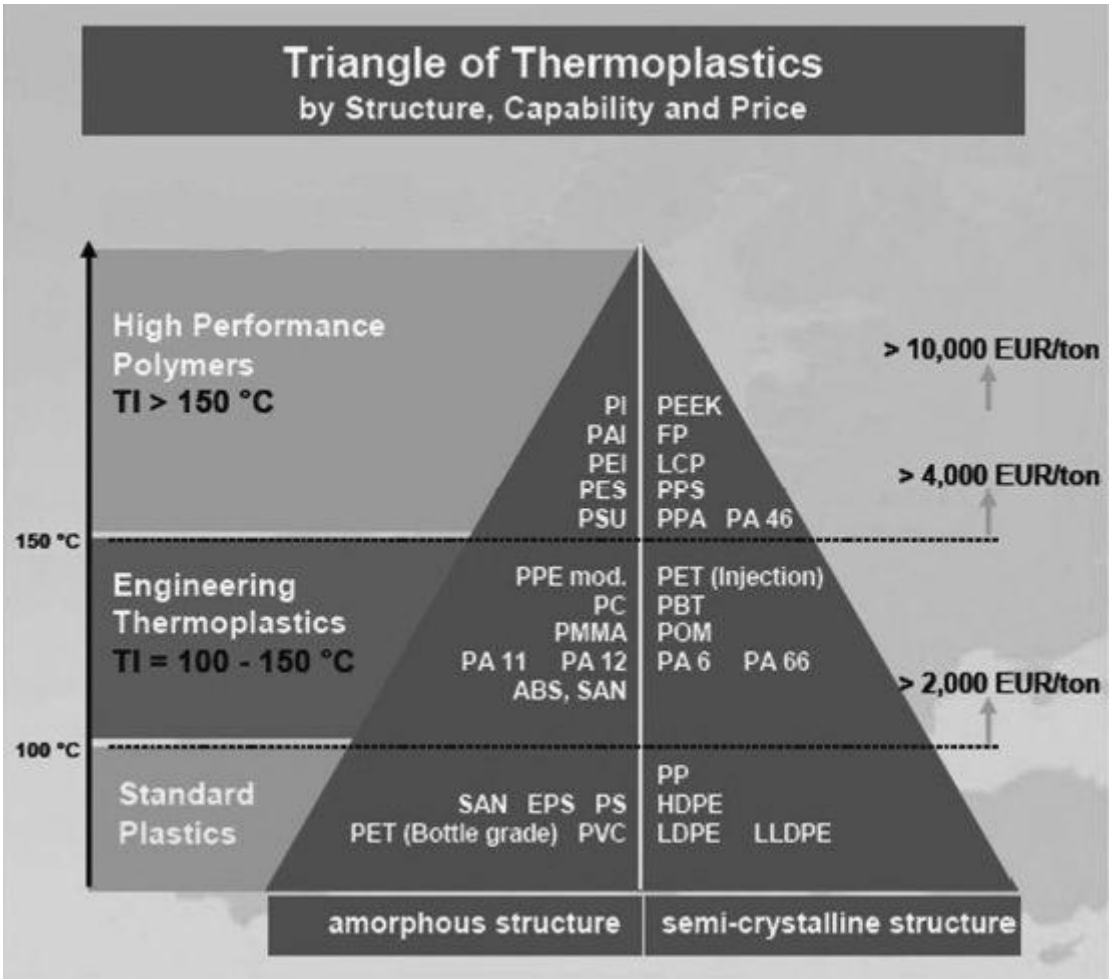

Figure 2: Properties and prices of thermoplastic polymers. (2)

Theoretical work

The International Energy Agency (IEA) established the Solar Heating and Cooling Programme as one of its first programmes in 1977. Of special interest is Task 39 – Polymeric Materials for Solar Thermal Applications, whose objective was to assess the cost reduction potential of thermal systems using polymeric materials (3). The outcomes of this study have been reported in various media.

Kahlen et al studied the aging behaviour of some polymeric materials used as absorbers in solar thermal applications. Polymers studied included polycarbonate (PC), polyamide (PA), polyphenylene ether polystyrene blend (PPE +PS), polyethylene and polypropylene. According to their work, polycarbonate has very good optical properties but is prone to physical and chemical aging through exposure to hot water, making it suitable for air collectors and glazings only (4), (5). According to Kohl (6) PC exhibits optical clarity and excellent impact strength but yellows and becomes brittle under the influence of ultraviolet (UV) radiation. Thus there is need for a UV stabilized version (such as the Bayer APEC 5393, which is both UV and heat stabilized).

Polyamide (PA) and polyphenylene ether polystyrene blends (PPE+PS) are excellent candidates for glazed solar collectors, though a mechanism is required to protect against internal overheating. Kahlen et al. (7) considered polypropylene (PP) and polyethylene (PE) as good candidates for solar thermal applications under certain circumstances (northern climate, low stagnation temperatures with overheating protection).They identified the need for further prototyping and study for more conclusive results.

According to Kohl et al (8) it has been observed that the most common mode of failure of polymers used for glazing materials is the yellowing that is caused from exposure to UV radiation. Therefore a protective coating is considered necessary for polymer glazing materials. Glazings must have high transmittance across the solar spectrum and withstand long term exposure to ultraviolet light. Glazings can be considered in a number of forms including thin film, rigid sheet and multichannel constructions. A measure of performance to quantify degradation is hemispherical transmittance as a function of exposure time weighted by a terrestrial air mass 1.5 global solar spectrum. In their work it has been reported that

- Measurements of hemispherical transmittance indicate that a 3.35 mm PC sheet with a thin film acrylic UV screen provides good performance without excessive degradation - high transmittance across the solar spectrum, and long-term resistance (10-20 years) to elevated operating temperatures (55-90 ^{o}C) and UV light.

- Polyethylene teraphthalate (PET) films have high optical clarity, low cost and have good mechanical properties, but the continuous-use temperature of PET is low (90 ^{o}C) and UV resistance is poor. Incorporating UV blockers into bulk films do not prevent deterioration at the surface.

- Polyethylene Naphthalate (PEN) is a more expensive alternative to PET with better thermal, mechanical properties and UV stability, but its optical transmittance is questionable under UV exposure.

- Fluoropolymers in general have excellent UV stability and UV resistance but are more expensive, so tend to be used in thin film form in order to reduce costs.

- Acrylic is UV resistant, but is sensitive in temperatures developed in collector glazings. Furthermore it is brittle and therefore sensitive to impacts.

- Korad acrylic and Tedlar films could be used as a UV screening layer on substrates such as PET and PC. Of the two Korad is a more effective UV screen and is more durable.

In general, commodity plastics are low cost materials, but their weathering resistance is not good. Nevertheless, under certain circumstances, they can provide viable options.

More recently, Weiss and Mauthner (9) have identified several different types of polymers that could fulfil the requirements of solar thermal applications. These include low cost commodity plastics that have been stabilised with suitable fillers or additives as well as the more expensive engineering polymers.

Other studies

Apart from the IEA task 39, other research includes the work of Tsilingiris (10,11,12,13). He determined that extruded polymer absorber plates seem very suitable for large, all-polymer, low-cost collector modules, and that back plate absorbers have efficiencies of 20% greater than top plate absorbers over a wide range of operating conditions . He confirmed that polymer glazing materials are often partially transparent to the near and far infra-red radiation, which leads to increased radiation losses from the absorber to the sky. Furthermore polymers have very low thermal conductivities compared to metals, but this can by counteracted by using

collector designs with a larger area of contact between the absorber the transfer liquid. That design is known as a fully wetted absorber design. From his analysis he concludes that the absorber plate conductance, which he defines as the thermal conductivity by the polymer plate thickness ratio, is a very important parameter in the design of the polymer absorber. If the absorber plate conductance is lower than a certain critical value, the collector efficiency factor decreases dramatically.

Cristofari et al (14) modelled the performance of a copolymer solar water heating collector in Ajaccio, Corsica, with theoretical yearly mean efficiencies of 56.5% for wind speeds of 0 m/s and 49% for wind speeds of 5 m/s, which is comparable with other collectors using more traditional materials. Furthermore they report a reduction of 50% in weight in a direct comparison with a traditional flat plate collector.

According to Kaushika et al, (15) polycarbonate used in a honeycomb array to act as a transparent insulation material shows very good promise to increase the overall thermal performance of collectors in working temperatures up to 80 ^{o}C. Therefore, they identify the need to investigate transparent insulation materials for higher working temperatures and lower manufacturing costs. They propose further investigation in cellular honeycomb arrays with non-convective air layers and selective covers as well as in parallel slat arrays. The honeycomb arrays hold more promise for less heat loss without affecting solar transmittance, whereas the slat configuration enhance solar transmittance.

Abdullah et al (16) did an experimental investigation of the performance of a flat plate solar collector outfitted with honeycomb of different arrangements. The honeycombed unit they used was constructed from polycarbonate sheet of 16mm thickness and six different arrangements were tested. They indicate that the gap between the sheet and the flat plate is crucial regarding the heat loss coefficient and find that the arrangement of single honeycomb with bottom gap of 3 mm is the optimum, as it offers the highest efficiency between all the arrangements and the lowest heat loss coefficient among the other honeycomb arrangements

When it comes to fabrication costs Liu et al (17) concluded that a conventional absorber plate made from Nylon was almost 80% of the cost of a comparable unit made from copper.

Van Niekerk et al (18) selected a conventional solar collector design and replaced the copper tubes used for the heat transfer liquid with tubes made from polypropylene. The found that the heat conversion efficiency is inversely proportional to the tube pitch. A metallic backplate can only increase the collector efficiency if the tube pitch exceeds a minimum threshold

Dorfling et al (19) investigated the fabrication of lightweight, all-plastic, solar collectors with the absorber plate being made from a material analogous to a micro-scale multi-tube extrudate. This material is termed as microcapillary film (MCF) and consists of an extruded flexible, plastic film with a parallel array of hollow capillaries running along the film's length, very similar to a honeycomb design. The material used for the absorber plate was low density polyethylene (LDPE) and glazings from polyethylene or fluorinated ethylene propylene (FEP) were investigated. Initial research investigating the heat transfer performance of MCFs demonstrated that, despite their plastic construction, their overall heat transfer performance was comparable to other metal-based micro-scale heat exchangers. Further research,

verified these measurements and also highlighted the usefulness of the MCF's mechanical flexibility with the ability to exchange heat easily from three-dimensional surfaces. Concerning the glazings it was found that the losses, in the still air of the laboratory environment, brought about by the combination of absorption and reflection of the incident radiation by the additional plastic cover were more significant than the reduction in heat loss that it achieved for the range of heat transfer fluid temperatures investigated. In a commercial application, however, they propose that a glazing layer would have to be incorporated.

Some polymer-based designs consisting of polypropylene hollow fibres have achieved overall heat transfer coefficients of up to 1300 W m^{-2} K^{-1} by Zarkadas, Sirkar (20). These devices present an interesting alternative to metallic heat exchangers in the temperature range where polypropylene has sufficient mechanical strength to contain the pressure generated by the fluid flow within the fibre bundle.

Zaheed et al (21) investigated some high performance polymers suitable for solar thermal applications along with more conventional ones. These candidate polymers included include polyvinylidene fluoride (PVDF), polytetrafluoroethylene (PTFE), polyphenylene sulphide (PPS), polyphenylene oxide (PPO) in addition to more familiar polymers such as polyethylene (PE), polypropylene (PP) and polycarbonate (PC).

Martinopoulos et al (22) used computational fluid dynamics (CFD) in order to model a polymer solar collector and compare it's results with the experimental ones. The polymer collector used had of all the usual components of a typical solar collector. The main difference was that instead of a metal absorber they incorporated the use of a black fluid to act both as an absorber and a heat carrier. That fluid flows in a transparent polymer honeycomb construction. The polymer used was a single sheet of transparent, UV stabilized, honeycombed, LEXAN sheet of 10 mm thickness. The upper and lower collector channels were made of semi-transparent acrylic. A solution of black Indian ink in water was used as heat transfer fluid. The glazing consisted of a 3 mm thick solid, transparent, UV stabilized LEXAN sheet while the back insulation consisted of a nanogel filled honeycombed LEXAN sheet of a 10 mm thickness. They reported an experimentally measured average efficiency similar to that of the low-cost flat plate commercially available collectors. Furthermore, the collector was modeled using CFD techniques, in order to obtain a more detailed inside look in the flow field development and the temperature distribution. The experimental and CFD results comparison showed that there was a reasonably good agreement regarding the collector efficiency while, at the same time, significantly similar flow patterns and temperature distributions were observed. Thus, it can be concluded that the computational model is capable of providing reliable results both qualitatively and quantitatively. Both the experimental set up and the CFD computations revealed that there were large problematic regions inside the solar collector which decrease its efficiency, suggesting that the CFD model is a useful tool for further investigations and optimisation of the collector.

Olivares et al (23,24) state that the most critical operational demand of a solar absorber is the avoidance of leaks in the heat transfer fluid and that the mechanical

integrity of the polymeric absorber has been identified as a very significant factor in order to determine its service life. They investigated a solar collector with a double wall polycarbonate sheet as glazing and an extruded sheet of NORYL, which is an amorphous polyphenylene/ polystyrene (PPE/PS) blend, for the absorber plate. According to their findings, thermal aging has been identified as the main cause for deterioration of the polymeric absorber, as long exposure times to high temperatures produce a transition in the material's properties, from ductile to brittle. This is considered crucial for the absorber service life, since a brittle material has a greater risk to cause leaks due to the low ductility to absorb mechanical impacts and stresses. The service life results from their study suggest that the polymeric absorber is able to achieve a prolonged service life when the solar collector system is designed for supply of large demand of domestic hot water and thus is suitable for that kind of applications.

Davidson et al (25) found that scale formation on polymer tubes is 30% less than that on copper tubes after 2 months exposure to flowing tap water, leading ultimately in lower maintenance costs. Furthermore they state that successful use of polymer components in solar collectors requires a method of predicting material degradation in water. This degradation from oxidation can be delayed through the use of antioxidant additives.

Riazi et al (26) measured performances and rates of heat transfer for three different types of tubes in solar water heaters with thermosyphonic flow. The tubes investigated were copper, polypropylene and steel. The comparison of experimental data showed that performance of copper tubes is better than polypropylene tubes, whereas both of them are significantly better than steel ones. The say that some of the advantages of using polypropylene tubes are that they are lightweight, cost less, have a high resistance to corrosion and there is no need for electrical equipment in the system since polypropylene acts as an electrical insulator.

Commercial designs of polymer collectors

Pool heating is one of the applications that polymer collectors have proven to be effective. The basic principle behind these types is a simple modular design, unglazed with an absorber plate made from black high density polyethylene (HDPE). Indicative companies that have developed collectors of this type include ROTH, UMA solar, Heliocol and Sunstar. (27),(28),(29),(30)

AES Solar (31), based in Scotland, have been producing solar collectors using polymer glazings. Their current model uses as glazing a is a 10mm twinwall polycarbonate sheet with a solar transmittance of 85%, protected to withstand deterioration and yellowing due to UV exposure and weathering, guaranteed with a ten year warranty. On previous models, AES Solar have been using standard Tedlar transparent films by DuPont at a width of 75 microns, which are no longer produced, but found that they were more easily damaged by impacts, and so no longer offer this option.

Aventa (32) is a Norwegian manufacturer, who in collaboration with Chevron Phillips Chemicals has produced an all-polymer collector with an absorber plate made from a proprietary blend of polyphenylene sulphide (PPS). Other all-polymer collectors were made by ALTEN collectors with their ALTEN 1 and ALTEN 2A collectors (33) and a further model was the Solarnor plastic absorber (34)

Future challenges

The challenges that have to be overcome are largely concerned with the material properties. Issues for glazing materials include:

- Materials should have high transmittance across the solar spectrum and offer resistance to long term exposure to UV light
- Resistance to long term (10-20 years) elevated operating temperatures (55-90 ^{o}C) and high stagnation temperatures
- Materials should be durable and able to withstand weathering effects (wind, rain, hail)

For absorber materials the obstacles that have to be overcome include:

- An absorber must have a high thermal conductivity. This can be overcome by increasing the effective area of the absorber
- Ability to withstand high temperatures for long periods of time and high stagnation temperatures. For northern climates a suitable absorber material will face maximum operating conditions of 80 ^{o}C in water up to 16,000 hours. Stagnation conditions can be 140 ^{o}C in air up to 500 hours. Extreme operating conditions could be up to 130-140 ^{o}C, and extreme stagnation could be up to 200 ^{o}C, especially in southern climates.
- For direct heating systems without heat exchangers (for example thermosyphoning systems, common in some parts of Southern Europe), leaching of the material to the water is possible. In this case it will be necessary to use food grade plastics.
- Hydrolysis of the material. This is turn causes polymer degradation changing the material's mechanical properties such as tensile strength, shape etc.

The thermal conductivity of polymeric materials can be increased significantly by using carbon black can be used as an additive. Carbon black is a very fine form of carbon powder, produced during the incomplete combustion of heavy oils. According the Scottish Plastics and Rubber Association the thermal conductivity of thermoplastics can be increased by up to 1000 times, from values of around 0.3 W m^{-1} K^{-1} to values as high as 350 W m^{-1} K^{-1}. However, such high values are achieved using expensive grades of carbon fibre, but cheaper carbon black fillers can still give up to 10-fold increases in thermal conductivity, measured at room temperatures. Furthermore, elastomers are available in commercial grades with high loadings of carbon black which give 3 to 5 times increase in thermal conductivity. (35)

Conclusions

There have been several studies and many attempts to incorporate polymers into the main components of solar thermal collectors, but these have been mostly unsuccessful because of poor thermal conductivity and a tendency to degrade under prolonged exposure to sunlight and elevated temperatures. Nevertheless, the attraction is low-cost components which can be easy to manufacture, or even a complete lightweight collector which is easy to assemble and install. Therefore, given the modern developments in polymer technology, efforts to develop a low-cost, lightweight collector made of polymer materials should continue.

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