SOLAR COLLECTOR ABSORBERS IN HIGH-PERFORMANCE POLYMERIC MATERIALS

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Abstract

The aim was to find and explore a material belonging to the class of high-temperature performance polymers, which is robust to sustain temperatures in a glazed solar collector during stagnation. The chosen material is a polyphenylene sulfide (PPS) - based blend from Chevron Phillips Chemicals adapted to the particular requirements related to the application as a solar collector absorber. If the solar collector is designed for a maximum stagnation temperature of the absorber of approximately 160 °C, the material will sustain this temperature for nearly 2000 hours. This thermal dose corresponds to approximately 20 years service life of a collector in south of Europe. Other factors than temperature can influence the material properties. The temperature variations during real operation can also cause effects different from those that are revealed in the present experiments. Still it is fair to conclude that the results indicate PPS as a promising candidate as an absorber material.

1.   A polymeric solar collector

Polymeric materials offer new opportunities as solar collector material related to processing, shaping, transport and installation. Presently the polymer materials are introduced in collector insulation and framing, but it is evident that substituting the conventional materials like glass in the transparent cover, or metals in the absorbers, represent more severe obstacles. One exception is the uncovered swimming pool collectors, where plastics already have a dominant market share [1].

Various studies [2, 3] have revealed that the main limitation when using polymer materials in collector absorbers is the durability, in particular due to the high temperature that may occur inside the collector when circulation of heat carrier is switched off. Other physical factors are also important, like the UV-radiation, thermal stress due to temperature variation during processing and operation and chemicals in the environment.
Solar collectors are expected to be integrated parts of buildings. Consequently the service life should be comparable with conventional building materials, or the exchange of collector parts with failures should be very easy and not represent severe costs.

In spite of these demands and worries, our aim has for a long time been to make feasible solar collectors with transparent cover basically in polymer materials. Figure 1 shows the collectors concept, based on a twin wall cover sheet in polycarbonate with UV absorbing coating, a twin wall absorber sheet in appropriate material and designed as a modular facade or roofing plaster using the insulation and structure elements in the building as the base.

The heat carrier flows upwards in all but one of the parallel channels of the absorber sheet, while the last one is used for return flow. Connections between the collector modules and the pipes for supply and return of the heat carrier are below the collector provided by the integrated manifolds on each absorber.
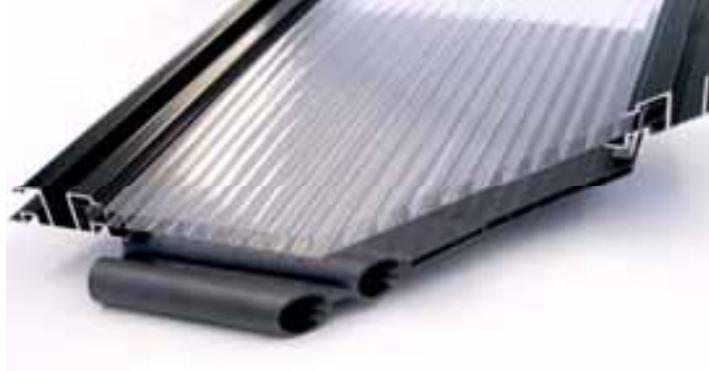
Figure 1   A model of the solar collector with absorber and cover sheet made in polymer materials (manufactured by Aventa AS)
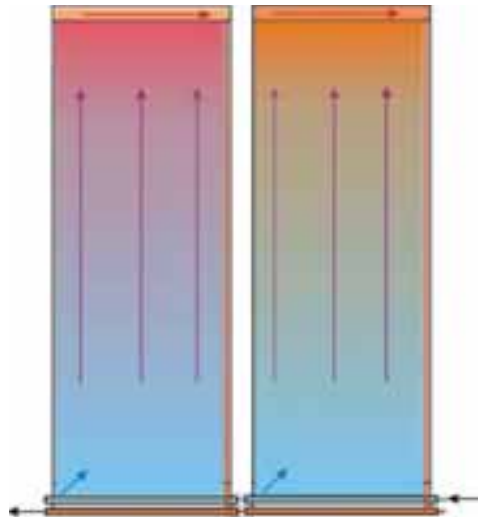

Figure 2   The circulation of heat carrier through the absorber. The collector modules are mounted in parallel by means of connectors between the manifold pipes.

The present collector is not designed for the absolute maximum efficiency; more emphasis has been on feasibility on the collectors as a building module with full capacity as a barrier for impacts and weather exposures. The design is carefully adapted to the stagnation temperature that the polymer materials can stand. Nevertheless, to total system design, characterized by using unpressurized pure water as heat carrier, automatic drain back after each operational sequence, direct coupling without heat exchangers to the heat store, and, in the case of solar combi systems, combination with low temperature heat distribution like under floor- or wall heating, result in a high system efficiency.

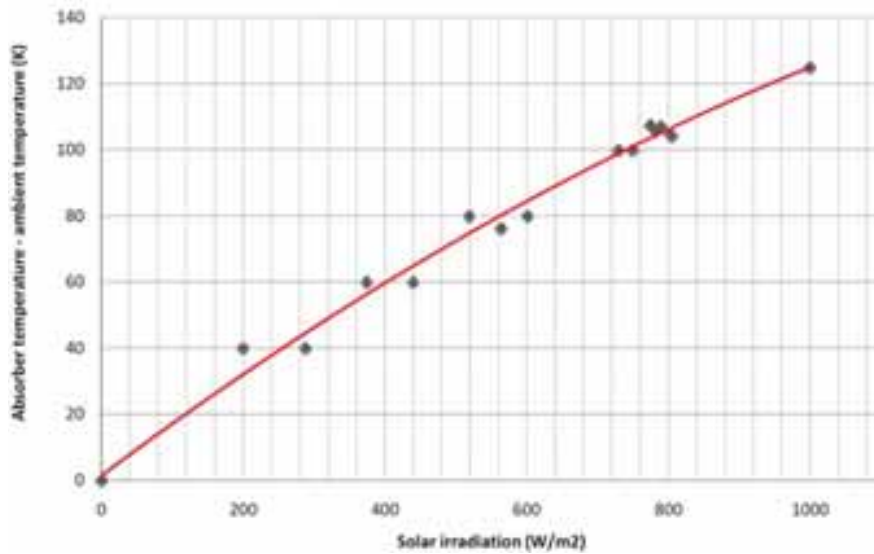Measurements of the stagnation temperature obtained with the present concept are shown in Figure 3.

Figure 3   Absorber temperatures during stagnation (no circulation of heat carrier) as a function of solar irradiation. The temperature in ^{0}C is obtained by adding the ambient temperature.

As seen from Figure 3 the temperature of the absorber will reach values approx. 120 K above the ambient temperature. This situation occurs for maximum irradiation when heat is not removed by the circulation system (stagnation conditions). Assuming ambient temperatures up to 40^{0}C, the absorber must be able to withstand temperatures up to 160^{0}C. This is a substantially higher temperature than the so called commoditive plastics can resist, and also higher than the common engineering thermoplastics are supposed to sustain. The absorber in the collector shown in Figure 1 is made of a high performance PPS material provided by Chevron Phillips Chemicals.

2.   Theoretical considerations

The approach is described in detail in ref [4].

The degradation of the polymeric material is supposed to be caused by sequential breaking of chemical bounds leading to a decrease in the molecular mass and a reduction in the physical properties, especially the ductility of the material. This is a statistical process with a reaction rate given by the Arrhenius function

$$\chi(T) = A \exp(-E_a/kT) \tag{1}$$

where E_a is the activation energy, k is the Boltzmann's constant, T is the absolute temperature and A is a scaling coefficient.

We introduce the thermal dose exposed to the material by the function $D = \chi(T) t$, where t is the time the material has been at the temperature T. Notice that D is a continuous function of the variables t and T. After a certain exposition, the material has gained a critical thermal dose

$$D_{crit} = \chi(T) t_{crit} \tag{2}$$

This critical value corresponds to a loss of ductility where the absorber sheet is not able to withstand the stress and forces acting on it due to hydraulic pressure or other mechanical forces. The critical value can be determined from experimental tests of the absorber sheet.

In order to eliminate the scaling coefficient, we introduce the function

$$t_{crit} = t_0 \; \chi(T_0) / \chi(T) \tag{3}$$

where t_0 is the critical time associated with a constant temperature T_0. Hence, knowing the associated quantities t_o and $\chi(T_0)$, the critical time or service life of an absorber can be predicted from Eq. (3) if we know the temperature function $T(t)$ that the collector will be exposed to.

A common test procedure for plastic materials is to study the force at break with different standard tools. If the samples have been exposed to different thermal loads, this technique enables to establish a functional dependency between the material, or product properties and temperature and confinement time. The standard tests are performed with standardized material samples. In the present study, where we investigate a finite product, the instrument has to be chosen in a somewhat different way.

When a sample is exposed to a high temperature, the force that causes a break will decrease when time at elevated temperature increases. This is illustrated in Figure 4, which shows the force causing the break versus the confinement time for two temperature cases T_1 and T_2
$(T_2 > T_1)$. The shape of these curves can be expressed by the formula [5]

$$dF(T,t)/dt = - \chi(T) \, F^n \tag{4}$$

where the exponent n is a parameter. Good fits to the F-curves are normally obtained with values of n between 1 and 2. The quantity F_{crit} shown in Figure 4 represents the minimum force or load the solar absorber should resist in order to sustaining the impacts caused by the hydraulic pressure and other mechanical impacts during normal operation.
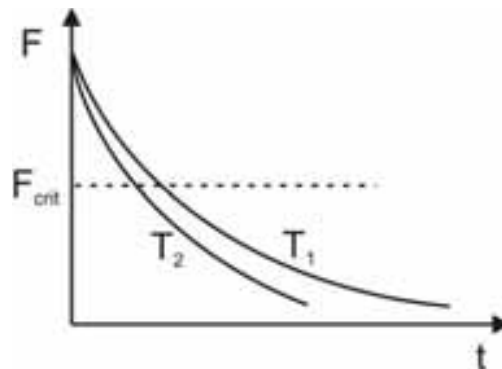

Figure 4   The quantity F as a function of time for two temperatures T_1 and T_2. The critical value F_{crit} is determined from the requirements to mechanical stress and hydraulic   pressure experienced by the collector

3.   The experiments

The tests described in this paper are all done on the end product. It means that the eventual structural changes caused by the processing (extrusion) are also present in the samples. A special technique has been chosen, based on comparative studies of the type of stress and impacts appearing under typical operation as a solar collector.

Figure 5 (left) shows a part of an extruded absorber sheet in the material PPS during an indentation test [3], which allows exploring the ductility of the sheet. The triangular brass indenter is pushed toward the sheet, and the applied force and the vertical position of the indenter is recorded. By performing such tests with different samples, which have been exposed to high temperatures over a period of time, the impact on the material structure due to thermal doses can be determined. The indentation depth represents the bending of the surface of the sheet, and the compressive load is the force that has been applied on the indenter. If the material becomes brittle, a crack will occur at a certain compressive load resulting in a sudden decrease of the load. We define a failure by the presence of a crack in the indentation curves at compression loads in the range between 300 and 500 N.

Sheets were exposed to constant temperatures of 150 °C, 160 °C, 175 °C and 200 °C respectively. The results are summarized in Table 1 and in Figure 5 (right).
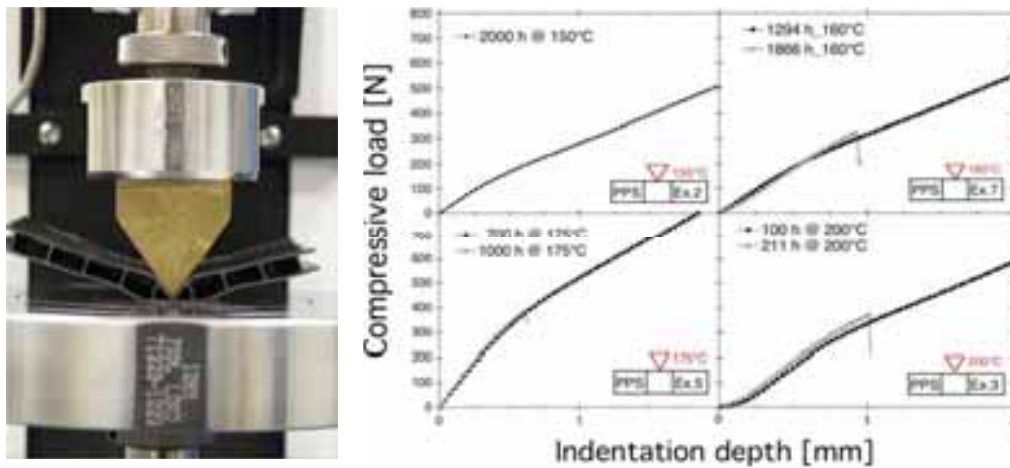

Fig. 5. The instrument used for the indentation tests (left). The relation between indentation depth and compressive load for four different samples of the absorber sheet with corresponding exposure times (right). Notice the sudden drops in the compressive load observed for the samples that were heated to 160 °C, 175 °C and 200 °C respectively.

Table 1.   Exposure times to dry heat at different temperatures, which caused first failure in the indentation test

Temperature (^{0}C)	Confinement time until first failure (hours)
150	> 2000
160	1866
175	1000
200	211

Based on the results in Table 1, the critical exposure time versus temperature can be found from of Eq. 3. The results for the actual absorber sheet in PPS are shown in Figure 6. The quantitative results enable us to determine the molecular activation energy of PPS according to Arrhenius formula. The best fit is obtained with the value $E_a = 0,9 \pm 0,2$ eV
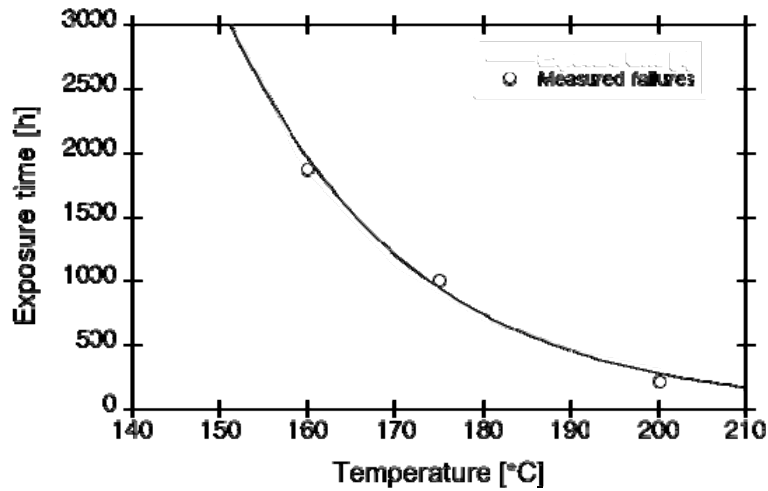
Fig. 6   Measured critical failure points (Table 1) and calculated relation for failure according to Eq. (3).

4.   The service life for a plastics absorber made in PPS

The "acceptance curve" shown in Figure 6 enables an evaluation of service life of the solar collector presented in Section 1 with an absorber made in the actual PPS material. One should emphasize that the thermal impact only has been considered. Other factors that influence the life time can also have significant effects, although previous studies [2, 3] have shown that the thermal load is by far the most critical.

A solar collector oriented toward south with a tilt angle of 30^0 has been evaluated. The latitude is 40^0N. The thermal load has been simulated day by day, based on assumption about the ambient temperature given in Table 2.

Table 2 . The ambient day temperature used in the simulation of the thermal load on the absorber

Month	Ambient temperature (^{0}C)
Jan - Feb	20
March - April	30
May - August	40
Sept - Oct	30
Nov - Dec	20

The acceptance curve in Fig.6 shows that the degradation of the material due to thermal load is negligible during normal operation, when the absorber temperature is typically in the range from 40^0C to 90^0C. The significant thermal load appears when the solar system is out of operation, and the absorber temperature reaches the stagnation value with a balance between absorbed heat and heat loss from the collector to the ambient. We assume that the total load due to stagnation can be represented by three perfect sunny days pr. month, with the extreme ambient temperature (Table 2). The actual absorber temperature during these days is shown in Figure 7.
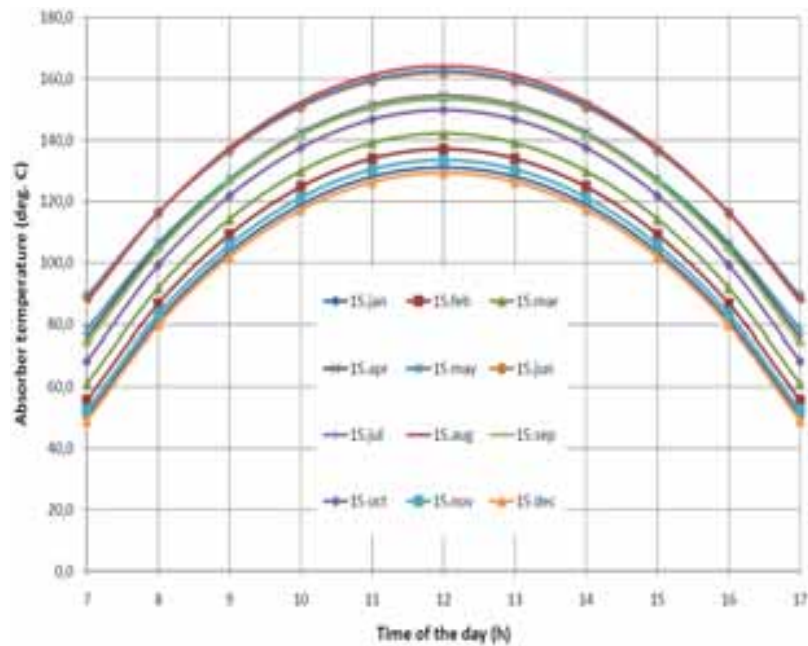
Figure 7.   The stagnation temperature during the day calculated from the simulated irradiation on a
perfect sunny day, and with the ambient temperature given in Table 2.

These continuous temperature functions are folded with the acceptance curve in Figure 6, resulting in a thermal dose pr day. The dose estimate is normalized in such a way that the full acceptance dose is represented by the value 1. The results obtained for one year is shown in Figure 8, where both the monthly load and the accumulated load are presented. The total yearly load, under these conditions, is 0.055. Hence, thermal loads only indicate a service life of 18.2 years.
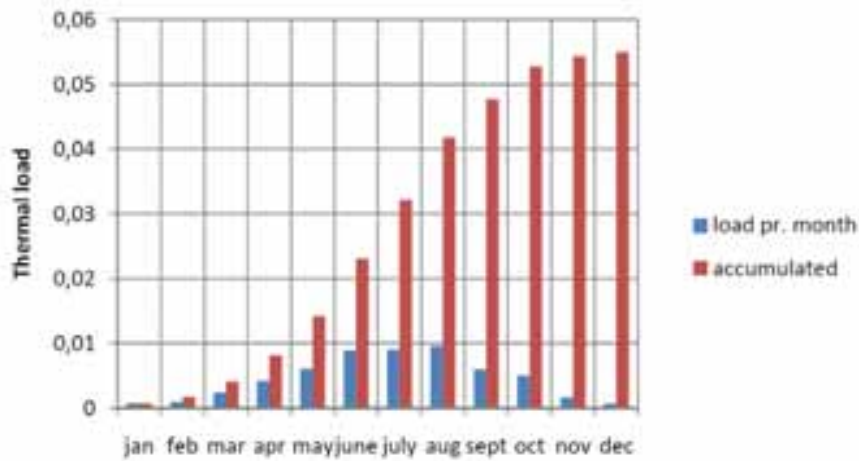

Figure 8.   The thermal load pr. year on an absorber under the conditions described in the text. The total
annual load indicates a service life of more than 18 years.

5.   Conclusions

The present study shows that a material like the PPS provided from Chevron Phillips Chemicals, and extruded into twin wall sheets for circulation of the heat carrier, is able to sustain the absorber temperatures appearing in a glazed solar collector with a moderate collector efficiency (not selective).

The analysis is based on climatic conditions in the south of Europe, and based on reasonable assumptions about the frequency of thermal stagnation the service life is estimated to more than 18 years.

Less demanding climates will of coarse give a much longer service life.

Other factors than temperature can influence the material properties. Further the temperature variations during real operation can cause effects different from those revealed in the present experiments. Still it seems fair to conclude that the results make PPS a promising candidate as an absorber material in a glazed solar collector.

1 References

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