POLYMER FLAT PLATE SOLAR COLLECTOER: A REVIEW

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Abstract: A brief description on polymer flat plat solar collector manufacturing, design, and applications are given in this work. The main obstacles that face these collectors' type, and how can be processed are also discussed. It is found that polymer low thermal conductivity, and degradation are the most essential difficulties in this industry and increase heat transfer area and additives are the best common solutions. While stabilizers can be added to increase polymer lifetime.
Keywords: Solar Energy, Polymer Flat Plate Collector, Stabilizers, Polymer Lifetime.

1. Introduction

Due to the risk of exhaustibility of the traditional fossil fuels such as petroleum, coal, and natural gas and due to their harmful environmental effects, renewable energy has become the most important energy sources recently. Sun is relatively an everlasting energy source so, solar energy is one of these promising sources [1]. Renewables Global Status Report 2021 declared that at least an addition of 57 large solar heating systems were recorded through 2020 which of at least 350 KW_{th} each. The capacity addition was 93 MW_{th} and the total large collector number reached 471 systems at least which equaled to 1.8 GW_{th} by the end of 2020 as shown in Fig. (1) below.

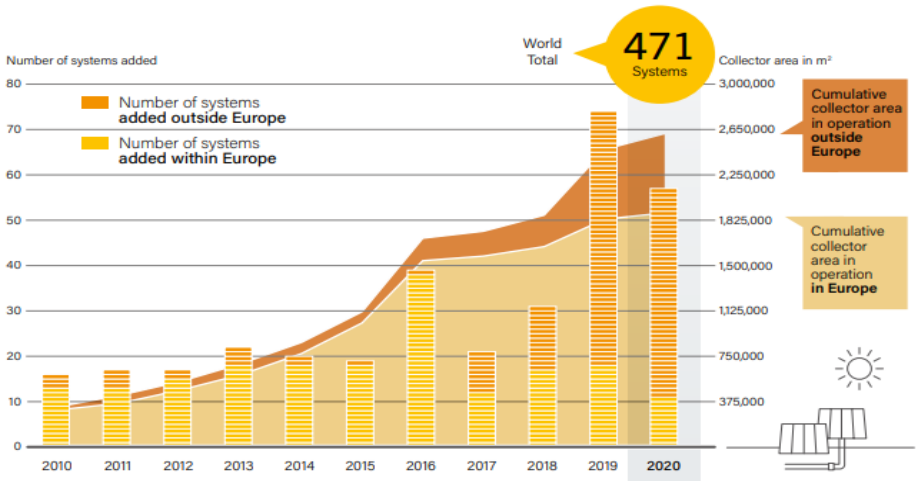


Fig.(1): Global Annual additions and total area in operation of solar district heating through 2010-2020. [2]

Flat plate solar collectors (FPSC) are one of the most common ways to convert solar radiation into useful thermal energy used in residential heating demands. Traditional flat plate solar collectors (TFPSC) require expensive manufacture methods due to different mixture of materials must be used in the multiple device components [3]. Copper and Aluminium are widely used as an absorber material for their very high conductivity values, while glass is usually used in the main collector part (collector cover) because of its high solar radiation transitivity [4]. A considerable increase in copper and aluminium prices expected recently as shown in Fig. (2) and Fig. (3). Also, the glass makes the collector arrangement heavy and hard to handle. So, it's essential to find a lower cost material and to develop a new design in order to reduce the system costs [5]. Polymer flat plate solar collectors (PFPSC) are one of the means to overcome the high cost of (TFPSC). The raw material of most polymer is oil, so polymer materials price depends on oil price. Polymer properties influenced by the complexity of polymer itself as given by Fig. (4).

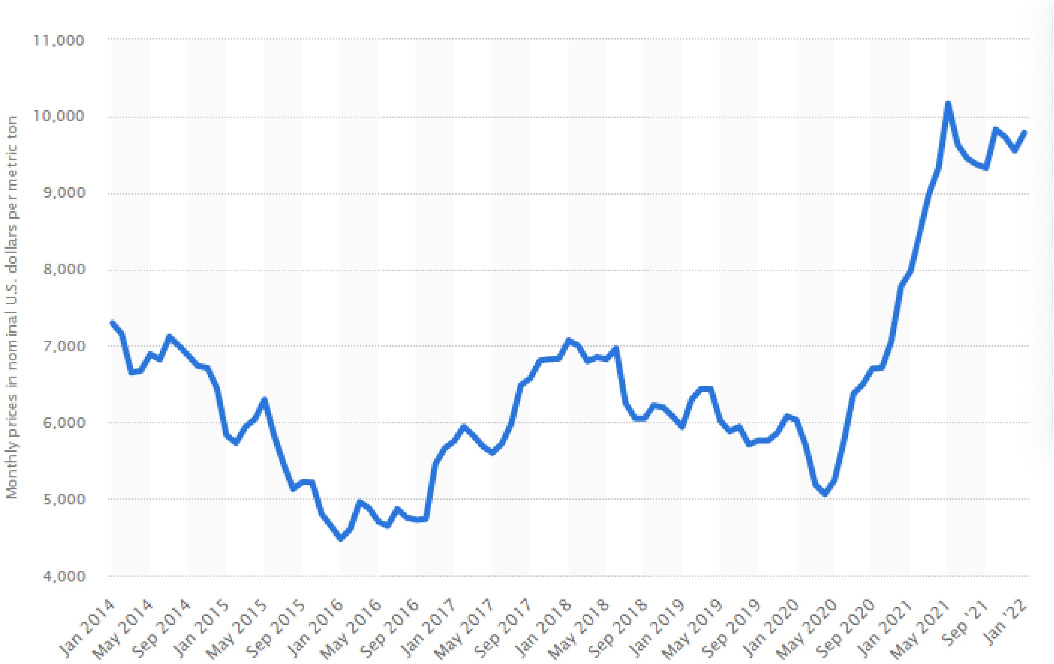
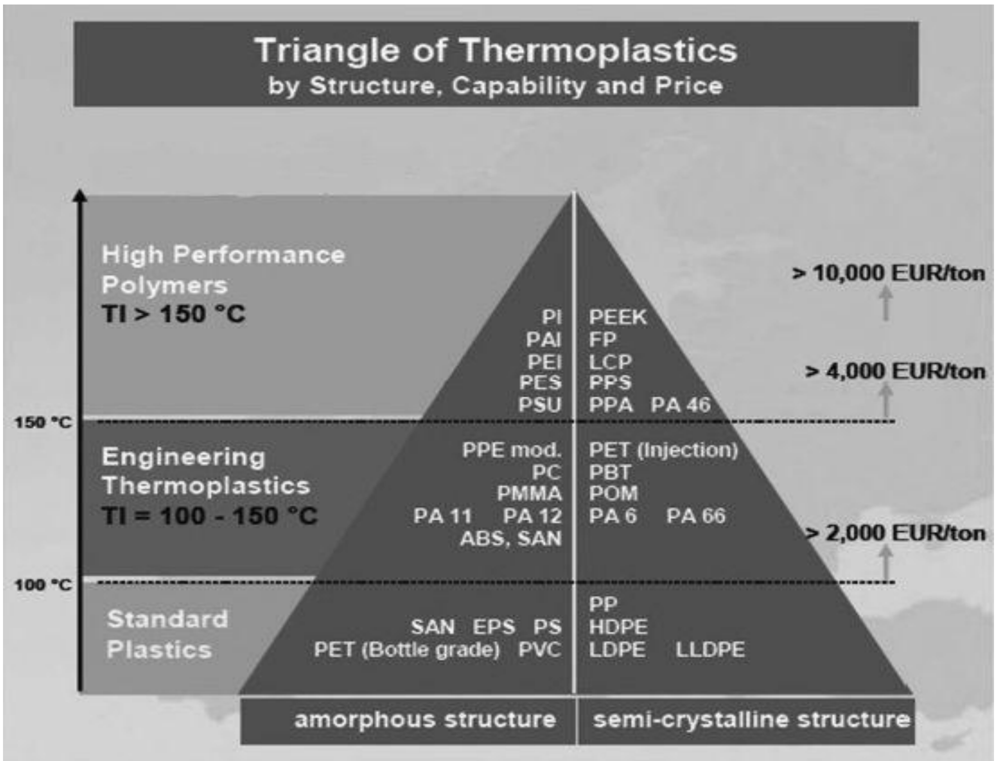


Fig.(2): The increase in copper prices recently[6].

Fig. (3): Aluminum price per metric ton [6]



Polyimide	PI	Polyamide-imide	PAI	Polyethylenimine	PEI
Polycarbonate silane	PCS	Polysulfone	PSU	Polyether ether ketone	PEEK
Phenol formaldehyde resins	FP	Liquid-crystal polymer	LCP	Polyphenylene sulfide	PPS
Polyphthalamide	PPA	Polyamide 46	PA 46	Polyphenyl ether	PPE
Polycarbonate	PC	Poly(methyl methacrylate)	PMMA	Acrylonitrile butadiene styrene	ABS
Styrene acrylonitrile resin	SAN	Polyethylene terephthalate	PET	Polybutylene terephthalate	PBT
Polyoxymethylene	POM	Expanded Polystyrene	EPS	Polystyrene	PS
Polypropylene	PP	High density polyethylene	HDPE	Low density polyethylene	LDPE
Linear low density polyethylene	LLDPE	polyphenylene ether polystyrene bend	PPE PS	Polyethylene Naphthalate	PEN

Fig.(4): Thermoplastic polymers prices and Properties [8]

2. Main Components of Traditional Flat Plate Solar Collector (TFPSC):

Simply it is an arrangement used for residential water heating by converting the solar radiation (irradiance) into thermal useful energy without any heat concentration process. It is used for intermediate or low temperature demand of approximately 80℃ [9]. As given in Fig. (5) TFPSC consists of an insulated metal or wooden box with a glass cover and a black colored absorber plate which heats due to the exposure to the solar radiation[10]. Liquid in metal pipes (risers) that attached to absorber plate carried heat out of the collector by passing through the working fluid (usually water) to cool the plate and produce accumulatively the required heat demand [11]. An air gap of 2-10 cm is found between the glass cover and the absorber plate to reduce heat loss by convection [12]. The incident solar radiation (short wave solar radiation) was transmitted by the glass cover while it is opaque to the long wave of radiation that is remitted by the absorber plate (Green house phenomena) [10]. To reduce the thermal losses an insulation layer is placed at the back of absorber plate.

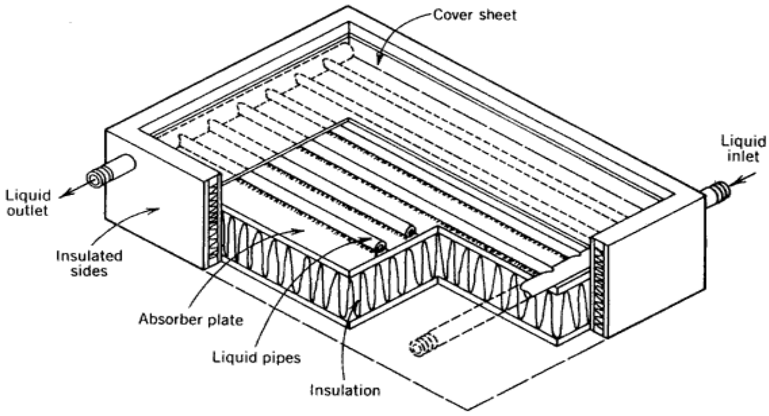


Fig.(5) Flat Plate Solar Collector **FPSC** [4]

3.Polymer Flat Plate Solar Collectors PFPSC

To achieve cost reduction demand and ensure mass fabrication in FPSC production the absorber and the collector cover are manufactured from polymer as shown by Fig. (6).

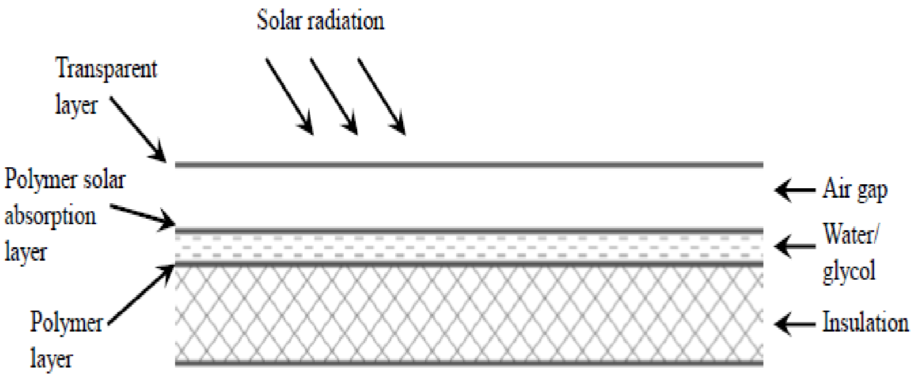


Fig. (6): Section of PFPSC [20]

3.1 Types of Most Common polymer in PFPSC

The most significant properties in polymer materials used as glazing's are the high transmittance of solar spectrum and the ability to resist long term UV exposure and withstand weathering circumstances [13]. Generally, the form of glazing are thin film, multichannel construction, and rigid sheet. The most common polymer materials used in PFPSC are [14]:

Polycarbonate: In spite of having very good optical properties, it is suitable only for air collectors and glazing. Exposure to hot water has negative effect on the physical and chemical properties which reduce absorber age [15][16] .It has good impact strength and optical properties but yellows and changes to brittle due to exposure to ultraviolet (UV) radiation[17].Generally yellowing is the most common failure causes in polymer glazing materials ,therefore a protective suitable material must be added to work as a ultraviolet radiation stabilizer[18] .

Polyamide: is used successfully for glazed solar collectors, but a mechanism should be added to protect against internal overheating [17].

Polyphenylene Ether Polystyrene Blend and Polyethylene: It is considered that polyphenylene ether polystyrene blend and Polyethylene are good materials to be used in thermal solar application especially in case of low stagnation temperature [17].

Polyethylene terephthalate: It has good mechanical and optical properties with low cost. On the other hand it has poor UV resistance in spite of addition of UV blocker and also the safe continuous temperature is less than 90℃ [13].

Polypropylene Naphthalate: It is more expensive than the above type, but it has better mechanical and thermal properties. As well as it has better UV stability but the optical properties doubtful in case of UV exposure [18]

Polyvinyl chloride: It is also called by vinyl in which chlorine makes up more than 50% by weight. It represents the third common polymer materials after Polyethylene and Polyphenylene. Approximately forty million tons per year produces [19].

Acrylic or Perspex: It has poor mechanical properties, but it is UV resistant and more sensitive to the development of temperature in collector glazing's [18]. A summary of the properties of each of the following materials are given in table (1).

Fluoropolymers: The most promising class of polymers, usually use as film thin for collector glazing in spite of their high price, they have excellent UV resistance and stability and sufficient tear resistance [18] **[**13] like:

Ethylene-tetrafluoroethylene ETFE or Tefzel .

Ethylene and chlorotrifluoro-ethylene (ECTFE) or Halar.

Polytetrafluoroethylene (PTFE) or Teflon**.**

Poly(vinylidene fluoride) Kynar

Table(1) properties of some polymers.

Polymer	**Transitivity**	**UV Resistance**	**Max. Temperature (℃)**	**Impact strength J/m**	**Thermal conductivity W/m.k**
Polycarbonate	0.8-0.9	Good	130	641- 691	0.2
Polyamide	0.9	Poor	160-200	28(Izod)	0.25
Polyethylene (high density)	0.92	Poor	130-133	27-160	0.44
Polypropylene	0.7-0.8	Poor	90-120	27-107	0.11
Polyvinyl chloride	0.77-0.92	Poor	75-100	21-160	0.19
Acrylic or (PMMA)	0.92	Good	70-200	16-22	0.187-0.2

On the other hand absorber materials must have high thermal resistance for a long time and, good as well as fixed mechanical properties during work but the major requirements in absorber material is high thermal conductivity. Polymer has a conductivity in range of 0.1 to 0.5 W/m.K[20]. This obstacle can overcome by increasing absorber area. But addition of carbon black which is extremely fine carbon powder to polymer used in **PFPSC** can enhance the conductivity to 3 to 5 times while in case of using expensive type of carbon fiber the enhancement can be reached to 1000 times as shown in Table (2) below.

Table (2) the thermal conductivity of some polymer additives [21].

Filler	**Conductivity (W/m.K)**	**Filler (metal)**	**Conductivity (W/m.K)**
Carbon Black	6-174	Copper	483
Graphite	100-400	Aluminum	204

CNT	2000-6000	Gold	345

The quantity of filler added to polymer must be high enough to make a significant change in thermal conductivity values but at the same time, the large amount of additives or fillers may change the polymer mechanical properties [22]. Due to the high value of conductivity of CNT as given in table (1) and because of a good CNT aspect ratio, so good results can be achieved for a little amount of addition of CNT. Table (3) given by [23] below shows tested samples of polycarbonate with different addition of CNT. It can observed as the addition percent increases a noticeable deterioration can be observed, until polycarbonate converted with 4% NCT to relatively brittle.

Table (3) Tensile and impact tests results for Polycarbonate with 0%,2%, and 4% CNT given by [23]

Additive ratio by mass	**Tensile Test measurement**			**Impact test measurement**		
	Stress (MPa)	**Strain %**	**E(MPa)**	**Force (N)**	**Peak Energy(J)**	**Total Energy(J)**
Pure Polycarbonate	73	197	424	1832	44.6	54.7
Polycarbonate+2% CNT	74	195	504	766	5.7	7.2
Polycarbonate+4% CNT	24	11	289	442	0.46	4.4

4. Durability of Polymeric Materials Used in PFPSC

One of the most important tasks in the designing of PFPSC is prediction of the lifetime of the used polymeric materials [24]. Long-term thermos oxidative degradation is a major issue for polymers under all environmental conditions. As mentioned above polymers are subjected to high temperatures level with several adjacent fluids for a long time and exposed to UV oxidation, so usually stabilized with antioxidant to avoid degradation through application stages [25][26]. In order to evaluate thermo-oxidative degradation and to guess polymeric materials lifetime, several studies were achieved (as shown below in literature review**).** One of the most common methods is to correlate mechanical properties and degradation chemistry. If rich oxygen environment combined with polymer high temperature exposure a suitable way can be obtained to accelerate polymer degradation. Infrared spectroscopy is proper to monitor chemical changes (evaluation of carbonyl index) [27] or molecular weight analysis by size exclusion chromatography [17]. These tests are correlated by traditional mechanical tests like tensile and /or impact tests to estimate polymer lifetime [28].

5. Literature Review

The polymer flat plate solar collector was studied from many points of view, some research concerned with the performance of the collector itself and the factors affecting the optimum design. Other studies investigate the suitable polymer material and additives to enhance conductivity, polymer lifetime, and many other research points. A brief description of previous studies is summarized below:

5.1 Recent Research on PFPSC performance

A great attention was taken to produce a low-cost flat plat solar collector since 1970. But recently Afzanizam et.al 2014[29] investigated theoretically the efficiency of PFPSC in case of variations of many parameters such as collector thickness, the thermal conductivity to plate thickness and top heat loss coefficient. It was concluded the efficiency decreased as the collector thickness increased, but it was increased as the value of the ratio of absorber plate conductivity to plate thickness increased. It was found also that the convenient plate thickness was (1.5 to 2.5) mm for their own design. Ehrenwirth et.al 2017[30] produced a novel approach known as Twin-Sheet-Thermoforming (TST) to manufactured acrylonitrile butadiene styrene absorber and to produce an economical novel PFPSC. Their designed prototype was tested and approved according to EN ISO 9806 (2013). The results were compared with the available data from commercial PFPSC models and literatures. It was proved that their prototype tested model recoded higher thermal efficiency if it compared with market PFPSC and similar to efficiency of prototypes in literatures published at that period. Selikhov et. al.2018 [31] introduced an experimental study to test a PFPSC absorber made of polyethylene. Correlations obtained to find the relation of efficiency, and heat flux from heat carrier (working fluid), exit working fluid temperature, and heat carrier flow rate. It was deduced that the obtained relations reliable for commercial and industrial applications. Mintsa et. al.2019[32] presented a numerical simulation in order to optimize PFPSC design. Parameter design such as collector length, air gap thickness, mass flaw rate, inlet temperature, incident solar radiation. It was proved that the polymer collector length had no effect on PFPSC Performance, while an optimum performance occurred at a gap thickness of about 10mm. Although the outlet coolant temperature reduced in case of increasing mass flow rate, but the collector efficiency increased. Also, it was concluded that the incident solar radiation had a little effect on PFPSC efficiency. Ullah and Kasi 2019[33] discussed many techniques to improve the performance of FPSC. Heat transfer controlled by using double glazing cover, or by decreasing the pipe diameter and increasing pipe length. It was concluded that these design contributed to improve harvesting of heat and improve heat absorption ability. Dobriyal et a. 2020[34] reviewed studies to improve the heat absorption in FPSC and it had been suggested that nano fluid addition one of the promising ways to capture more heat and improve collector efficiency. Mutizhongo et. al. 2021[35] developed a novel experimental PFPSC by using low cost martials with new design in south Africa . Long black polymer connected in series pipes positioned in grooves covered by steel plate. The water circulated by a small solar panel. Their configuration increased the absorption heat into the circulation water used. The cost was estimated as 0.25R (Rand) per kWh of energy /day. This price vied the cost of grid electrical energy of 2R per kWh.A brief description for factors studied by previous studies are showed in Table (4).

Table (4) Factors Studied.

Ref.	Studying Criteria	Factors under Study			
[29]	Theoretical study	Plate thickness	Thermal conductivity to plate thickness	Top heat loss coefficient	
[30]	Theoretical and experimental (Twin-Sheet-Thermoforming)	Absorber made from acrylonitrile butadiene styrene	$\frac{(T_{mean} - T_{amb})}{solar\ intesity}$	Efficiency	
[31]	Experimental	Heat flux from heat carrier	Exit working fluid temperature,	Heat carrier flow rate	
[32]	Theoretical (numerical simulation)	Collector length	Air gap thickness	Mass flaw rate	Inlet temperature and solar intensity
[33]	Experimental	Heating loss	Solar radiations	Double glazing	Pipe length and diameter
[34]	Theoretical review	Nano fluid addition			
[35]	Experimental	Configuration (new design)	Heat absorbed	Cost	

5.2 Recent Research on polymer lifetime

Degradation changes mechanism and various polymer lifetime were described by several authors such as, [15] and [16], [36]. Degradation can be defined as the changes that occur in polymer materials due to chemical or physical transformation [37]. **Beißmann et. al.2013[**38] successfully studied the degradation paths of three commonly antioxidants by using polymers accelerated aging tests. Resistance to discoloration and thermal stability of seven stabilizers were examined by using aging pure stabilizers. Tests rely on high performance liquid chromatography hyphenated with highly sensitive tandem mass spectrometric detection for structural elucidation of degradation products. UV-detection used for subsequent quantification. A similar degradation mechanism with highly colored decomposition products could be given by Irganox 1330, Irganox 3114 and Cyanox 1790 stabilizers. Irganox 1010 stabilizer was less proper for materials proposed for water applications, because the preferred degradation mechanism was hydrolysis in case of Irganox 1010. As a results product with an increased solubility in water were produced. **Grabmann et.al.2016**[38] dealt with the estimation of the lifetime of black painted polypropylene absorber, which temperature profile is simulated by SHW tool (Simulation Software for Thermal Solar Systems) for a maximum working temperature of 105℃. The global polymer aging was experimentally tested in case of hot water or air at a temperature up to 135 ℃ subjected to specimen of black painted polypropylene absorber. Fracture strain test used as an aging indicator and the lifetime was considered by weighting the temperature dependent endurance times with the loading profiles assuming accumulative damages. It was found the lifetime from 20 to 45 years for the polymer under test.**Blázquez 2020[39]**deduced that additives were essential in improving polymeric materials. It was also considered a comprehensive control of structure and changes in these additives through time was required to confirm their polymer performance. Gas chromatography coupled with mass spectrometry, was termed in their work to investigate the behavior of various additive types. For relatively high molecular weight additives such as Irganox 1330 and Irganox 1010 the test had been successfully achieved. Then, the test used for evolution under solar exposure over time for other 11additives and derived substances, which used in a commercial polypropylene sample. Infrared spectroscopy used to test photo oxidation to groups of polymers of high carbonyl in macro chains. Gas chromatography coupled with mass spectrometry was found to be a proper tool to analyze the evolution of commonly used polymer additives under specific degradation conditions, and it was considered to be useful for improving of additives.

6.Conclusions

PFPSC can be a convenient alternative to overcome the high cost of TFPSC with relatively acceptable thermal performance.

Polycarbonate, Polyamide, Polyphenylene ether polystyrene blend, Polyethylene, Polyethylene terephthalate, Fluoropolymers, and Acrylic are used successfully as collector cover while polypropylene are commonly used as absorber.

The low thermal conductivity of polymer can be dramatically enhanced by additives, but the quantity of additions must be optimized to ensure the stability of mechanical properties.

Polymers are subjected to high temperatures level with several adjacent fluids for a long time and exposed to UV oxidation, so usually stabilized with antioxidant to avoid degradation through application stages.

Nano fluid addition is one of the promising ways to capture more heat and improve collector efficiency.

Polymer lifetime can be reached to 40 years in PFPSC applications.

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