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ScienceDirect

Energy Procedia 91 (2016) 346 – 355

Energy Procedia

SHC 2015, International Conference on Solar Heating and Cooling for Buildings and Industry

Comparative analysis of overheating prevention and stagnation handling measures for photovoltaic-thermal (PV-T) systems

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Abstract

The stagnation temperatures experienced by glazed photovoltaic-thermal (PV-T) collectors pose a threat to their performance and longevity, in part due to the limited temperature stability of ethylene vinyl acetate (EVA) encapsulants. In order to identify suitable solutions for application in residential solar domestic hot water (SDHW) PV-T systems, a comparative analysis of known overheating prevention and stagnation handling measures was conducted and dynamic simulations were used to support the analysis. While no measure was found to comply with all desirable goals including reliability, implementation and operation costs, integral venting mechanisms were identified as the most promising among the control systems reviewed. Moreover, active collector heat dumping and automatic collector shading led to minimal electrical efficiency increases and decreases, respectively, while purging tank water when the collector overheats was found to be ineffective due to delays in the start of circulation.

Peer-review by the scientific conference committee of SHC 2015 under responsibility of PSE AG

*Keywords:*stagnation; reliability; photovoltaic; thermal; hybrid; control

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1. Introduction

Photovoltaic-thermal (PV-T) collectors can convert solar energy into heat and electricity simultaneously at rates superior to those of side-by-side conventional PV modules and non-hybrid thermal collectors of equal sizes and matching combined area [1]. Despite this, the potential of PV-T technology can only be fully realized by overcoming

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Peer-review by the scientific conference committee of SHC 2015 under responsibility of PSE AG
doi:10.1016/j.egypro.2016.06.282

the challenges it faces today and which hinder its success in the market. Regarding the technical challenges facing PV-T technology today, arguably the most visible concerns its reliability issues at high collector temperatures, namely during stagnation, which mostly stem from the limited temperature stability of common PV encapsulants particularly those based on ethylene vinyl acetate (EVA). The current effort deals primarily with control strategies to solve or mitigate the problem caused by the stagnation of PV-T systems in the grid-connected solar domestic hot water (DHW) market - which is believed to be the main market for PV-T technology [2].

2. Literature review

Stagnation, however infrequent, is a possible occurrence in forced circulation solar thermal systems and can be caused by low thermal demand (fully charged thermal storage tank), power outages (no electricity available to run the pumps) and other problems leading to a no-flow condition (plugged pipes, leaks, broken pumps, etc). In these situations, the collector temperatures only depend on the idle heat losses and the insolation. Consequently, stagnation temperatures can reach 220-350ºC for evacuated tube collectors, 170-210ºC for flat-plate collectors with selective absorbers and 115-150ºC for flat-plate collectors with non-selective absorbers [3-7]. The occurrence of such high collector temperatures can cause the accelerated ageing of temperature sensitive system components and their eventual failure, safety hazards for humans, uncomfortable acoustic emissions due to condensation pressure shocks, enhanced vulnerability to hot spots resulting from manufacturing imperfections and the vaporisation of common heat carrier fluids and potential release from the loop via safety valves [4,6,8-9]. Moreover, the exposure of glycol-based heat carrier fluids to high temperatures leads to their darkening, a low pH (<7) and consequent acceleration of corrosion, the formation of progressively insoluble deposits and the potential plugging of pipes [10].

The occurrence of stagnation in PV-T systems carries the same risks as in non-hybrid systems although mitigated by the comparatively lower thermal performance of PV-T collectors which is at best comparable to that of non-selective collectors [5,11]. As such, single cover flat-plate PV-T collectors can reach temperatures as high as 145ºC while unglazed versions have been reported to reach at least 75ºC but are generally not considered to have stagnation related problems [12-13]. At the same time, the PV laminates used in PV-T collectors are generally manufactured to the same specifications as regular terrestrial PV modules, which are only certified to operate safely up to 85ºC according to the IEC 61215 standard [5,12,14]. Solar cells can withstand temperatures up to 220ºC but EVA encapsulants lose their mechanical properties at 130-140ºC and can delaminate as a result. At these temperatures EVA can also become brown or yellow under ultra-violet (UV) radiation [3,5,12,15]. Moreover, high temperatures lower the electrical efficiency and can also damage cell connections by thermal strain and corrosion, causing them to become brittle - despite the fact that the melting point of the solder used in most PV cell connections is around 250ºC [2]. High collector temperatures can also overheat the bypass diodes of each PV-T collector and possibly destroy them, rendering the collector's PV array susceptible to hot spots by shading [2]. Therefore, the continued exposure of PV-T collectors to temperatures above 85ºC can result in performance degradation or even premature module failure due to reduced optical transmission to the cells, overheated bypass diodes, broken electrical connections and module delamination. Unless solved, these problems contribute to a reduced lifetime of PV-T collectors compared to PV modules and ultimately compromise their commercial appeal.

The proposed solutions to the problem of stagnation in PV-T collectors have focused on the use of control systems and the use of other encapsulants. The use of active control systems to prevent PV-T collectors from overheating was suggested, in part due to the appeal of increased electrical efficiency during periods of low thermal demand [5][15]. Alternatively, the use of silicone for the encapsulation of PV cells was suggested given its very high temperature resistance (-55ºC up to 200ºC) [15]. In this regard, PV-T prototypes using silicone layers for encapsulation were reported to have eventually delaminated after a year under stagnation, although the problem was reportedly solved using much thinner silicone top coatings [16]. Furthermore, silicone encapsulants are employed in cells designed for use in concentrating PV and concentrating PV-T systems, both of which have to endure higher temperatures and high UV exposures [17]. The cost of silicone was also reported to have decreased over the years, which is relevant considering cost was the main factor for its demise as the main encapsulant for PV applications until the early 1980s [13,15]. Nevertheless, the cost of silicon encapsulants is still around 7 times higher than EVA encapsulants, which have found widespread use due to their cost and history of acceptable durability rather than for possessing the best combination of properties among known encapsulants [18,19]. While the use of encapsulants with enhanced stability is a suitable solution for the problem of stagnation in PV-T systems, its cost relative to that of control systems - whose inclusion in PV-T systems has not been previously evaluated - needs to be determined. In this regard, ample experience exists from the use of control systems for overheating prevention or stagnation handling in non-hybrid solar heating systems designed primarily for space heating or process heat, which can serve as the starting point for the evaluation of control measures suitable for application in PV-T systems [4,6-7].

3. Objectives

The purpose of the present undertaking is to determine which control systems are best suited to solve the problem of stagnation in active solar domestic hot water (SDHW) PV-T systems for the residential sector. While combi- and space heating PV-T systems presumably lead to longer and more severe stagnation events, the focus is on domestic hot water systems since this is considered to be the main market for PV-T technology [2]. Nevertheless, the conclusions from this study may also apply to those particular systems assuming the risks are equivalent.

4. Methodology

The procedure used to accomplish the outlined objectives included an assessment of the risk posed by collector overheating events in SDHW PV-T systems, a survey of the known and potential overheating prevention and stagnation handling measures, and an evaluation of these measures based on how well they perform with regard to the specific limitations of active PV-T systems, as defined by the literature review and the risk assessment step.

The analysis conducted was supported by dynamic simulations of indirect SDHW PV-T systems featuring state-of-the-art glazed PV-T collectors used in several system sizes (2, 4 and 6 collectors per system) and using climate data for Lisbon, Portugal (38º42'N, 9º8'W), Freiburg, Germany (47º59', 7º51'E) and De Bilt, Netherlands (52º7'N, 5º12'E). The objective behind these simulations was to examine the occurrence of stagnation events in distinct PV-T systems under fault-free operation and otherwise (by simulating permanent stagnation as a worst case scenario). Moreover, the performance of state-of-the-art glazed PV-T collectors was reproduced since these collectors tend to lead to the highest collector stagnation temperatures. The influence of local climates was also investigated and the data (ambient temperature, wind speed and irradiance) used to represent each location motivated some changes to the simulations. The simulations using climate data for the Portuguese location assumed a collector slope of 30° with the horizontal plane, water as the heat carrier and the utility water temperature at 15°C whereas the simulations using climate data for Dutch and German locations assumed a slope of 45°, a mixture of propylene glycol (40%) and water (60%) as the heat carrier and the utility water temperature at 10°C. Moreover, the thermophysical properties of each heat carrier and the storage fluid were assumed to be constant and evaluated at 60°C and 1 atm.

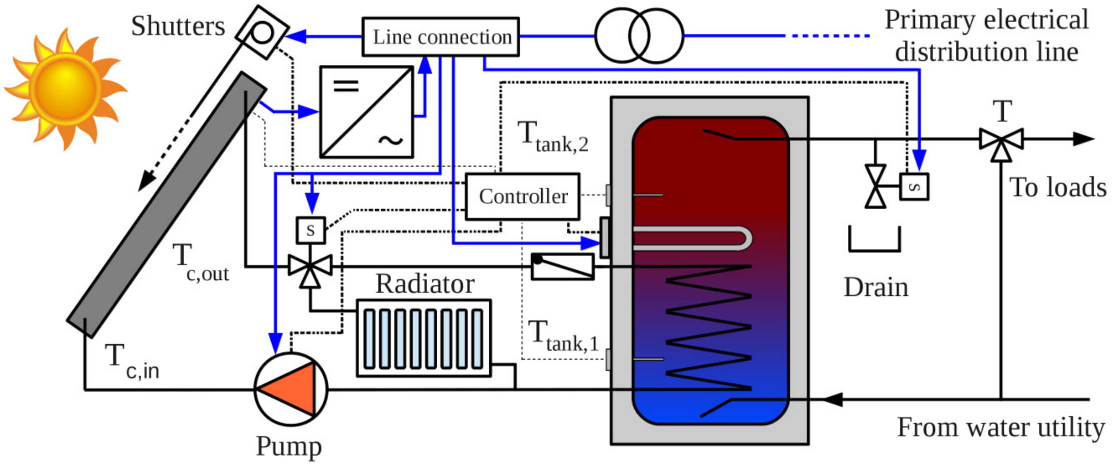

Fig. 1 – System diagram for the active indirect solar water heating PV-T system reproduced in the simulations conducted.

4.1. Simulation models

The simulations relied on several submodels to compose a SDHW system model according to the diagram featured in Fig. 1. The models are well known except the PV-T collector model which is discussed at greater length in this section. Nevertheless, some of the key models used include a tank model (based on TRNSYS type 60), an insulated pipe segment model (based on TRNSYS type 709) and a radiator model (based on TRNSYS type 162).

The model used to reproduce the performance of PV-T collectors is based on the equation for the quasi-dynamic test method featured in the EN 12975-2:2006 standard but adapted to PV-T collectors according to (1) [20,21]. The electrical power (2) was calculated assuming maximum power point (MPP) operation and a linear efficiency variation with the mean cell temperature ($T_{pv,m}$) [5]. In turn, $T_{pv,m}$ was estimated in open-loop - since the collector heat capacity is concentrated on the fluid node - and under the assumption that the concept of collector efficiency factor (F′) – implicit in the construction of the original equation – can be extended to transient situations including stagnation. Specifically, $T_{pv,m}$ was estimated by equaling (1) and (3) and solving for $T_{pv,m}$ although assuming c_5 is zero and using a previously determined – using the correct c_5 - solution ($T_{f,m}$) for (1). On the other hand, the long wave radiative heat losses and the wind dependence of the zero loss efficiency were assumed to be negligible. Therefore, the model requires the estimation of F′, the coefficients obtained through performance tests according to the EN 12975-2:2006 standard for open-circuit mode, in addition to details about the PV array and the glass cover.

$$\frac{\dot{Q}}{A} = \eta_0 G - \frac{F' P_{pv}(T_{pv,m} = T_{f,m})}{A} - (c_1 + c_3 u)(T_{f,m} - T_a) - c_2 (T_{f,m} - T_a)^2 - c_5 \frac{dT_{f,m}}{dt} \tag{1}$$

$$\frac{P_{pv}(T_{pv,m})}{A} = \tau_{cover} \rho_{pv} \eta_{e,r} G \left[1 + \beta_{pv} \left(T_{pv,m} - T_{STC} \right) \right] \tag{2}$$

$$\frac{\dot{Q}}{A} = \frac{1}{F'} [\eta_0 G - (c_1 + c_3 u)(T_{pv,m} - T_a) - c_2 (T_{pv,m} - T_a)^2] - \frac{P_{pv}(T_{pv,m})}{A} \tag{3}$$

4.2. Parameter values and input data

The aforementioned model was used to reproduce the performance of the PV-T collector reported to have the highest measured optical and thermal efficiencies among glazed PV-T collectors according to the EN 12975-2:2006 standard [5]. However, its performance and stagnation temperatures were determined via the static test method and the high temperature resistance test using an indoor solar simulator, which must comply with a wind speed (u) parallel to the collector plane of 3±1 m/s and under 1 m/s, respectively. Consequently, the stagnation temperatures calculated using the published parameter values are about 20ºC lower than the measured temperatures presented in the same publication for the same collector[1]. Therefore, the parameter values published (η_0, c_1* and c_2) should not be used for different wind conditions than those used in the original tests or unacceptable errors will result.

$$\eta = \eta_0 - c_1^* (\frac{T_{f,m} - T_a}{G}) - c_2 G (\frac{T_{f,m} - T_a}{G})^2 \tag{4}$$

$$c_1^* = c_1 + c_3 u \tag{5}$$

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[1] Interestingly, the ISO 9806:2013 standard provides an additional method for the calculation of the stagnation temperature compared to the EN 12975-2:2006 standard, which adds exactly 20ºC to the stagnation temperature determined by solving the quadratic equation (using the parameter values obtained through performance tests) precisely due to the convective losses caused by the higher wind speeds [21,22].

The parameter values published for open-circuit conditions were used to deduce the linear heat loss coefficient for stagnant wind conditions (c_1) and the wind dependence of the heat loss coefficient (c_3) through equations (4) and (5) [5]. In order to do so, the static test and the high temperature resistance test were assumed to have taken place at wind speeds of exactly 3 m/s and 0 m/s, respectively, while any potential effect on the zero loss efficiency (η_0) and the quadratic heat loss coefficient (c_2) was considered negligible. The parameter values obtained this way enabled the reproduction of the collector's performance for different wind conditions than originally specified in the performance tests. Moreover, the estimated stagnation temperature showed no error for open-circuit operation and an increase of 2.3ºC for MPP operation - which is low relative to the errors without the adjustment [5]. On the other hand, the collector heat capacity (c_5), the collector incidence angle modifier coefficient (b_0) and the diffuse incidence angle modifier (K_d) were assumed to be 20 kJ/m^{2}K, 0.1 and 1, respectively, for simulation purposes.

The parameter values used in the remaining models were reflective of the residential SDHW market segment, readily available technologies and recommended practices. Fluid circulation was set to start and end at temperature differences between the collector and the storage tank of 10 K and 2 K, respectively, while the specific mass flow rate was set to 0.02 Kg/m^{2}s. The storage tank was modeled as four isovolumetric cylindrical vertical nodes featuring the solar heat exchanger in the bottom three nodes and the auxiliary electrical heater in the top node. The auxiliary system was set to continuously keep the top node at its design temperature (60°C) according to a hysteretic control loop (5°C deadband) and, at the same time, partially deliver a daily volume of 200 liters at 45°C according to a load pattern modelled after the ISSO withdrawal schedule used in previous studies [1,23]. On the other hand, the solar heat delivered to the tank was transported across two insulated pipe segment pairs, one of which exposed to the outdoor temperature and the other to a room temperature of 22°C, as was the tank. The radiator model reproduced the performance of a 1 m^2 double-panel stainless steel radiator typically used for space heating but used instead for heat dumping according to different control options. The remaining parameter values are indicated in Table 1.

Table 1 – Parameter values used in the thermal storage tank, insulated pipe segment and radiator system models.

Parameter	Value	Unit	Parameter	Value	Unit
Tank volume	300	L	External pipe length	2	m
Tank height	1.6	m	Internal pipe length	3	m
Tank heat loss coefficient	1	W/m^{2}K	Pipe internal diameter	0.018	m
Tank heat exchanger pipe length	17	m	Pipe thickness	0.001	m
Tank heat exchanger pipe thermal conductivity	400	W/m^{1}K	Pipe insulation thickness	0.02	m
Tank heat exchanger pipe internal diameter	0.025	m	Pipe thermal conductivity	400	W/m^{1}K
Tank heat exchanger pipe external diameter	0.028	m	Pipe insulation thermal conductivity	0.04	W/m^{1}K
Tank wall thickness	0.005	m	Radiator coefficient	1.32	-
Tank wall thermal conductivity	16	W/m^{1}K	Radiator nominal power	1528	W
Tank internal electrical heater power rating	2500	W	Radiator nominal inlet temperature	75	ºC
Tank internal free convection coefficient	0.5	-	Radiator nominal outlet temperature	65	ºC
Tank internal free convection exponent	0.25	-	Radiator nominal ambient temperature	20	ºC
Maximum admissible tank temperature	80	ºC	Radiator dry weight	27	Kg
Maximum collector fluid temperature for circulation	95	ºC	Radiator liquid volume	5.2	L

5. Risk assessment of PV-T collector overheating in SDHW systems

The need for collector protection in PV-T systems depends on how the cell temperatures relate to the two aforementioned thresholds: 85ºC and 130ºC. The worst case scenario for PV-T collectors is during stagnation and open-circuit conditions, which can lead to temperatures in excess of 130ºC but not 150ºC [5, 11-12]. Consequently, it is conceivable for PV-T collector temperatures to exceed both thresholds and jeopardize their functional integrity.

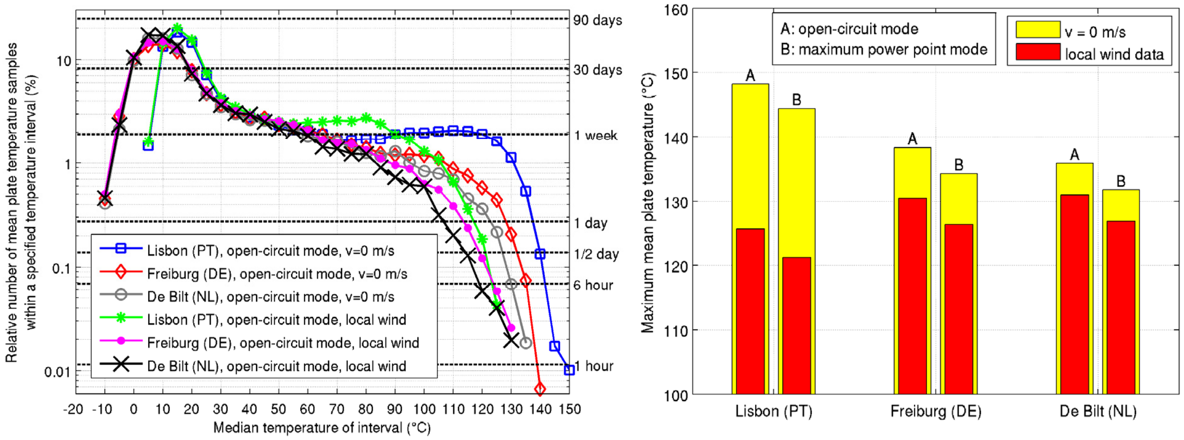

Fig. 2 – Relative annual frequency of PV cell temperatures (left-hand side) and maximum PV cell temperatures (right-hand side) for permanent annual stagnation, calculated using TMY data for the following locations: Lisbon, Portugal; Freiburg, Germany; De Bilt, Netherlands.

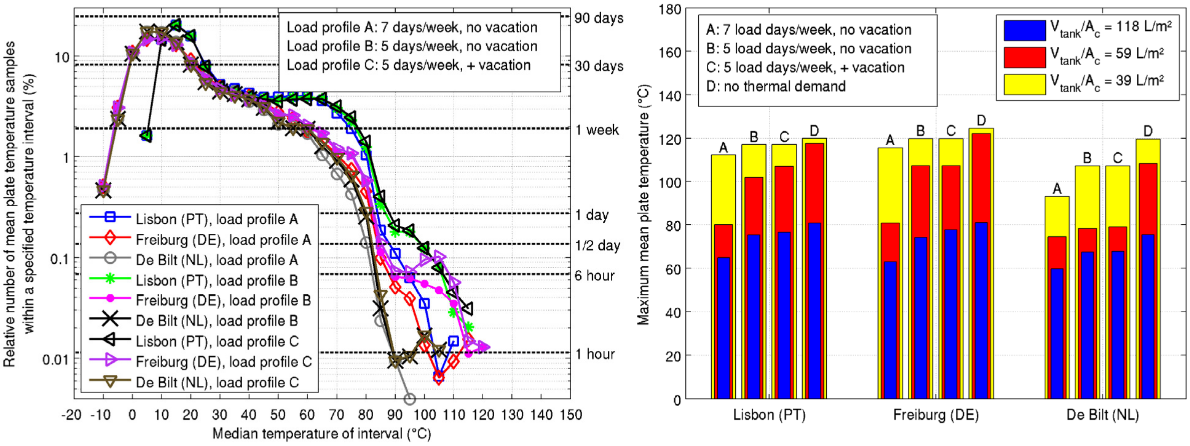

Fig. 3 - Relative annual frequency of PV cell temperatures (left-hand side; for a specific tank volume of 39 L/m^2) and maximum PV cell temperatures (right-hand side) under normal operation, calculated for: Lisbon, Portugal; Freiburg, Germany; De Bilt, Netherlands.

Dynamic annual simulations conducted for glazed PV-T collectors under permanent stagnation in different continental European cities confirm this scenario, as shown in Fig. 2. According to the results, stagnation temperatures between 121ºC and 148ºC are possible and overheating events can last between 2.5-18.3% of a year. Furthermore, the results show that stagnation under open-circuit conditions led to maximum temperatures between 3.8ºC and 4.4ºC higher than under MPP operation, which indicates the magnitude of the stagnation temperature increase to be expected if PV generation is interrupted. The simulations also revealed that for local wind conditions the stagnation temperatures are between 4.9 and 23.2 ºC lower than in a worst case scenario in which the wind speed is negligible - and in some cases cell temperatures over 130ºC were not reached. As such, conservative stagnation conditions such as those defined in the standard EN 12975-2:2006 are useful but may not occur at all [21].

Common stagnation events are forced by the pump controller and result from low collector temperatures and low thermal demand. Simulations for SDHW PV-T systems excluding all other causes of stagnation revealed the maximum temperatures reached by the collectors are still within the same range as if under permanent stagnation except for undersized systems, as shown in Fig. 3. On the other hand, the threat posed by high collector temperatures is infrequent and exists only for a short period of time annually. According to simulations conducted, the duration and the number of times the collectors overheat during normal operation was estimated to reach a maximum of 69 hours (0.8% of a year) and 34 cycles per year – for a specific tank volume of 39 L/m^2 and a load profile (C) featuring 5 load days per week and 28 cumulative days of vacations spread into four one week vacations taking place from June to September. Nonetheless, without quantitative data about the effect of overheating on the longevity of PV-T collectors it is prudent to prevent them from overheating by using suitable control systems.

The control systems compatible with such a task fall within the category of overheating prevention – defined in [7] – rather than stagnation handling since the evaporation of the collector loop fluid – which would occur above 85ºC for any of the common heat carrier fluids used in SDHW systems - is not an accepted mode of operation. Furthermore, any measure designed to prevent PV-T collectors from overheating should consider its effect on the electrical efficiency, positive or negative. In conclusion, the control systems indicated for use in PV-T systems should address the problems common among solar water heating systems and those exclusive to PV-T technology.

6. Analysis of overheating prevention and stagnation handling strategies in SDHW PV-T systems

The overheating prevention and stagnation handling control systems which have found use in non-hybrid solar heating systems were evaluated with regard to their potential application in PV-T solar heating systems. A preliminary evaluation of the control systems concerned their conformity with the main protection requirements of PV-T systems, namely collector overheating prevention, because otherwise their use has to be regarded as insufficient or complementary. Such is the case of control systems which isolate the collector from the rest of the system, in particular the draindown, drainback, steamback and heat pipe control systems, since their use still requires collectors to be able to endure stagnation [6]. Another example is the use of high pressures in the solar loop to prevent the heat carrier fluid from boiling, which has a low implementation cost, is suitable for PV-T systems - due to the respective temperature ranges - but does not prevent the collectors from overheating since temperatures close to the heat carrier boiling point (or beyond) at the system pressure are still possible [4].

The collector overheating prevention systems are those that waste heat or reduce the solar radiation reaching the absorber. Among these, defocusing is exclusive to systems requiring solar tracking and is generally integral to them since it is effective and does not require additional parts other than an uninterruptible power supply (UPS). These attributes make it an obvious first choice for concentrating PV-T systems although other measures could complement it. A brief overview of the remaining systems is provided in the next sections, followed by an analysis of their collector overheating prevention capacities and their influence on the performance of PV-T systems.

6.1. Shading

Shading mechanisms consist of covering the collectors to prevent incoming radiation from reaching the absorber. The simplest form of collector shading involves manually placing a completely or mostly opaque surface over the collectors while more complex solutions use motor-actuated shutters integrated into the collector design or otherwise [6]. While cheap, the problem with manually covering the collectors is the required user interaction which needs to precede the stagnation events, may be challenging or dangerous depending on the position of the collectors and may require a partial or complete charge of the tank after extended stagnation periods. While the automated designs overcome some of these problems, they will add to the cost of the system, require power and may not be reliable or suitable for every climate since they are exposed to the elements all year long and are seldom used.

Shading PV-T collectors has the additional consequence of reducing the electrical output during periods which are prone to high yields. According to simulations conducted for PV-T systems with automatic shutters covering the collectors once cell temperatures exceed 85ºC, the performance ratio (PR) and electrical efficiency reductions stemming from its use were minimal and peaked at 0.34% and 0.02%, respectively – assuming a power converter efficiency of 90%. On the other hand, by also covering the collectors during scheduled low demand periods (load profile C) irrespective of cell temperatures, the decreases were much higher and reached 6.2-7.5% and 0.43-0.52%, respectively, although lower decreases can be expected if partially opaque curtains are used – provided they can effectively prevent overheating. On the other hand, if motorised systems are used and fail to cover the cells evenly then hot spots may occur and impair or disable the electrical output of the collectors affected. Consequently, the use of motorised shades is not recommended for PV-T systems unless their long-term reliability is firmly established.

6.2. Night-time tank cooling

Night-time tank cooling refers to the circulation of the heat carrier in the solar loop to waste heat accumulated in the storage tank as a way to prevent stagnation during the following day – although other uses are known. The method does not prevent stagnation directly, is unavailable during the actual stagnation events and for this reason requires yield prediction capabilities and user-supplied advance notices of low demand periods. Furthermore, it requires additional parasitic energy, is not power failure-safe and can be ineffective in - otherwise desirable - well insulated solar loops. The main advantage of night-time tank cooling is its low implementation cost assuming daily energy yields can be reasonably estimated without additional equipment or are simply not necessary. Non-predictive schemes, namely timer-based circulation, are known to have been implemented but were complemented by other measures [7]. Alternatively, a conservative approach relying on cooling the tank until low temperature differences between the collector and the tank are reached could be - hypothetically - effective assuming non-selective flat-plate collectors are used and sized for the Summer months. Although potentially mitigated by the infrequent nature of overheating events in well sized SDHW systems, the operating costs can be relevant since the pump(s) need to run during the day and at night even though the heat collected is wasted. Consequently, the cost effectiveness of night-time tank cooling depends on the ability to cool the tank quickly, the parasitic energy cost and the system size. Nevertheless, the difficulty in generating accurate yield predictions and the level of protection offered mean such a system should not be considered reliable for overheating prevention but could serve as a complementary method.

The use of night-time tank cooling to prevent stagnation in PV-T SDHW systems presents some risks due to its preventive nature and inability to apply corrective measures once normal circulation begins. For these reasons, it should not be regarded as a primary or the sole measure to prevent high temperatures. On the other hand, flat-plate PV-T collectors, namely those without low-emissivity coatings, are well suited for night radiative cooling [23].

6.3. Tank fluid purging

Purging tank fluid can keep the thermal storage tank from being fully charged and in doing so prevent stagnation by keeping the pump running. The method can be implemented inexpensively using a motorised valve to release unmixed tank water to a drain on command, which means it can be used preventively and during actual overheating periods. At the same time, the method wastes hot water, requires parasitic power - and for that reason is not power failure-safe without other energy sources, and depending on the implementation can introduce a delay between fluid purging and circulation. Moreover, its infrequent use as the result of few and far between overheating events could lead to the valve's premature failure due to limestone deposits [7]. In this regard, periodic discharges could contribute to a longer valve lifetime and increase the likelihood of faults being detected in advance.

The ability to prevent PV-T collectors from overheating through the use of tank fluid is hindered by its reliance on electrical power and any residual thermal stress caused by delayed circulation. Simulations showed that tank fluid purging at flow rates equivalent to those of the collector loop and triggered by a fully charged tank (T>80ºC) did not have a fast response time since in the most pertinent cases it failed to prevent temperatures from reaching 95ºC - and potentially fluid boiling, after which temperatures needed to drop for circulation to resume. Despite this, 24-81 Kg of water were purged per hour of overheating which resulted in an energy waste between 10-217 kWh. Consequently, the control system should instead prevent the tank from being fully charged at all times, which is more wasteful but more effective since it enables a faster response time. Nevertheless, the method has clear limitations and shouldn't be regarded as a reliable long-term solution to the problem of PV-T collector overheating.

6.4. Active collector heat dumping

Active collector heat dumping refers to the rejection of heat from the collectors in heat dumps such as finned tubes, radiators, fan-coil units or heat exchangers cooled by utility water [6-7]. The method is reliant on the ability to power the pump(s), valve(s) and fan(s) – if present – and requires stable energy sources for effective protection. Moreover, the implementation of these solutions can increase the system cost by as much as 100$/m² [6]. Consequently, its application may not be justifiable in residential SDHW systems which mostly stagnate during holiday periods or power outages. Nevertheless, active collector heat dumping is relatively simple to implement, effective and reliable at preventing overheating provided the heat dumps are properly sized and power is available.

The application of active collector heat dumping in PV-T systems has been previously proposed [5,15]. Simulations conducted showed active heat dumping triggered by collector overheating (T>85ºC) while the tank is not being charged proved effective for well sized heat dumps – which required a minimum radiator to collector area ratio of 26.2% at matched flow rates. On the other hand, the PR and electrical efficiency increases were minimal and lower than 0.3% and 0.02%, respectively. Heat dumping can also be used during scheduled low demand periods to boost electrical yields but the maximum PR and electrical efficiency increases obtainable were limited to 1.02% and 0.07%, respectively, according to a best case scenario using up to 6 radiators and in which pump operation was also triggered by generation of electrical power. In conclusion, active collector heat dumping can be effective but is expensive, inelegant and its use for the purpose of augmenting the PV yields does not lead to tangible increases.

6.5. Venting

Venting consists of temporarily increasing the convective heat losses with the aim of preventing high collector temperatures. Examples include the use of shape memory alloys (SMA) to open doors and enable air circulation within flat-plate collectors and the use of heat pipes within high performance flat-plate collectors whose evaporator and condenser are in contact with the absorber and a heat sink, respectively [7,24-26]. While the aforementioned solutions are entirely passive, alternatives requiring the use of fans are also possible but unappealing due to their inability to function without external power. On the other hand, integral venting mechanisms unequivocally leads to increased collector costs and complexity but can avoid expenditures and inelegant designs at the system level [7].

The inclusion of venting in PV-T collector designs, whose technology has struggled to secure its position in the market as it is, would further increase the collector cost and complexity. At the same time, its inclusion could solve the problem of collector overheating if reliable and designed to reflect the stability of the PV encapsulant used – which is yet to be demonstrated via PV-T prototypes. Moreover, venting benefits the electrical efficiency during otherwise high temperature periods and could pay for itself over time via PV revenue and additional longevity. In conclusion, venting is a promising solution but may render collectors too expensive and limit their appeal.

7. Discussion

The determination of the most suitable control systems should prioritise reliable collector overheating prevention. Nevertheless, the aforementioned goal is to a large extent compatible with enhancing the electrical efficiency – the exceptions being defocusing and shading – even though the resulting electrical efficiency gains are not expressive. On the other hand, implementation and operation costs are decisive factors in securing a technology's adoption. While no perfect solutions were found among the reviewed control systems, it is clear venting mechanisms constitute a promising control system for glazed PV-T collectors. The remaining systems require power for fluid circulation (purging, dumping, night cooling) in order to function properly – which in turn demands the use of other energy sources for reliable protection, present serious risks (automatic shading) or at least partially disrupt solar loop operation when used (manual shading). On the other hand, PV-powered pumps, valves and controls can potentiate more reliable control systems since collector overheating correlates well with periods of high solar intensity.

Alternatively, the lamination of PV cells for use in PV-T collectors with silicone encapsulants allows for higher temperatures and can bridge the gap between the level of protection required for hybrid and non-hybrid systems - to the point of making overheating prevention in the former desirable but not necessary. While the cost of silicone encapsulants can reach 21 $\$/m^2$ compared to 3$\$/m^2$ for EVA encapsulants, its use can be cheaper than installing a heat dumping circuit [6,18,27]. Furthermore, the silicone encapsulation process has been described as simple [15]. Thus, the use of silicone encapsulants stands as a viable alternative to some of the control systems reviewed.

8. Conclusions

Several overheating prevention and stagnation handling control systems were evaluated with regard to their potential application in PV-T SDHW systems to avoid the consequences of stagnation. Many of the control systems evaluated require power for pumps or actuators which makes them unreliable under worst case scenarios such as a power outage unless backup power is used. PV-powered pumps, controls and actuators constitute a potential solution to this. Alternatively, the use of venting mechanisms to increase convective losses above predetermined temperatures was found to be a promising way to avoid high PV-T collector temperatures. Finally, cooling PV-T collectors through any of the simulated control systems did not lead to substantial electrical efficiency increases.

Acknowledgements

This study was made possible by a doctoral grant (reference SFRH/BD/76747/2011) issued by the Foundation for Science and Technology (FCT). The authors would like to acknowledge the assistance provided by Dr. Carlos Rodrigues and Dr. Maria João Carvalho and thank the National Laboratory of Energy and Geology (LNEG) and the Faculty of Science and Technology, New University of Lisbon (FCT-UNL) for the institutional support.

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