

Spectral-splitting hybrid PV-thermal (PV-T) solar collectors employing semi-transparent solar cells as optical filters

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Abstract

Spectral splitting is a promising design methodology than can significantly improve the performance of hybrid photovoltaic-thermal (PV-T) collectors. However, conventional spectral-splitting PVT (SSPVT) collectors require additional optical components, which significantly increases the complexity and cost of the collector. This study proposes SSPVT collector designs that employ semi-transparent photovoltaic (PV) solar cells, which act as both the electricity generator as well as the spectral-splitting optical filter. In these designs, a part of the solar spectrum is absorbed by the semi-transparent solar cells for electricity generation, while the rest (especially the near-infrared region of the solar spectrum) is transmitted to an absorber where it generates a high-temperature thermal energy output. Three types of emerging semi-transparent solar cells, *i.e.*, cadmium telluride (CdTe), perovskite solar cells (PVSCs) and polymer solar cells (PSCs), are selected for investigation in this context. A comprehensive two-dimensional model of such SSPVT collectors is developed and used to investigate their electrical and thermal performance. The results show that the proposed designs are effective at thermally decoupling the PV cells from the solar thermal absorber, thereby promoting a higher electrical efficiency and enabling the simultaneously generation of low-temperature thermal energy ($< 60\text{ }^{\circ}\text{C}$), along with high-temperature thermal energy ($100\text{--}200\text{ }^{\circ}\text{C}$) under one sun. For example, a PVSC-based SSPVT collector is shown to be capable of simultaneously generating: electricity with an efficiency of 13.8%, high-temperature heat ($150\text{ }^{\circ}\text{C}$) with a thermal efficiency of 21.1%, and low-temperature heat ($50\text{ }^{\circ}\text{C}$) with a thermal efficiency of 22.5%. The relative performance between the CdTe-, PVSC- and PSC-based collectors depend on the relative value of the high-temperature thermal energy to that of electricity. It is concluded that semi-transparent solar cells are of great promise in this application, and can give rise to next-generation, high-performance solar collectors.

Keywords: photovoltaics, photovoltaic-thermal, semi-transparent solar cells, solar energy, combined heat and power, perovskite

1. Introduction

Solar energy is able to satisfy both thermal-energy and electrical requirements of end-users through solar thermal [1] and photovoltaic (PV) [2] technologies, respectively. PV technology has attracted considerable interest as it can directly convert solar energy to valuable electricity in reliable and simple systems. Global PV capacity has reached 627 GW in 2019 [3], continuing to rapidly grow and estimated to reach 8000 GW in 2050 [4]. Commercial PV panels are only able to convert 10-25% of the absorbed solar energy into electricity [5], with the rest of the absorbed solar energy ($> 70\%$) being dissipated as waste heat [6]. Hybrid photovoltaics-thermal (PVT) collectors are capable of harvesting this heat, generating useful thermal energy and electricity for the same aperture area [7]. The most common PVT collector type is the flat-plate design. A thermal absorber is usually designed to be tightly attached to the PV cells for better heat transfer and a higher thermal efficiency [8]. The thermal performance of PVT collectors can be further improved by additional glazing layers, vacuum gaps [9], and phase change materials (PCM) [10]. Excellent review articles by Chow [11], Zhang et al. [12] and Li et al. [13] summarise the performance of PVT collectors with different types of thermal absorber structures, working fluids and solar concentrators. Sheet-and-tube designs remain the most common thermal absorbers among commercial PVT collectors [7]. The overall solar utilisation efficiencies of PVT collectors are significantly higher than those of standalone PV panels [14]. However, the PV cells in conventional PVT collectors face overheating problems when pursuing a higher-temperature thermal output from the thermal absorber, leading to a compromised PV electrical efficiency and lifetime. The output temperatures of conventional PVT collectors thus are usually limited to 60-80 °C [11], which can be used for domestic heating [7] and generating electricity via thermoelectric generators [15].

Spectral splitting methodology [16] can significantly improve the performance of PVT collectors by spectrally separating the incident solar spectrum, with only a part of the spectrum sent to the PV cells for the generation of electricity [17]. The rest of the spectrum, which is unusable by the PV cells, is directed to a separate thermal absorber where it is converted to a high-temperature thermal energy output [18]. Therefore, in spectral-splitting PVT (SSPVT) collectors, the PV cells are thermally decoupled from the thermal absorber, generating high-temperature heat without compromising the electrical efficiency [19].

Current spectral-splitting SSPVT collectors typically employ selectively-reflective [20] or selectively-absorptive [21] optical filters to split the solar spectrum. The selectively-reflective optical filter is typically composed of nanofilm stacks [22], *e.g.*, $\text{TiO}_2/\text{SiO}_2$ [23] and SiNx/SiO_2 [24] nanofilm layers. The thicknesses, materials and numbers of the nanofilm layers need to be carefully designed to achieve a desired optical performance [25]. The selectively-reflective filter is able to split the solar spectrum into two parts at desired wavelength bounds, which are then separately directed to the PV cells and thermal absorber [26]. The SSPVT collector with a selectively-reflective filter usually has a more complicated structure than conventional PVT collectors [27]. The selectively-absorptive optical filter can be either liquid [28] or solid, which is able to selectively absorb a part of the solar spectrum which is not electrically usable to the PV cells to generate thermal energy [29]. Some common liquids (*e.g.*, water [30]) are good selectively-absorptive optical filters capable of absorbing a part of the solar spectrum (especially the infrared (IR) region). The optical performance of these liquids can be further improved by suspending nanoparticles [31] (*e.g.*, Ag [32], Ag/SiO_2 [33], Au [34], Au/SiO_2 [35], ZnO [36]). Some solid films are also able to selectively absorb a part of the solar spectrum, such as semiconductor-doped glass [37].

A SSPVT collector with either a selectively-reflective or -absorptive optical filter is able to generate high-temperature heat while allowing the PV cells to operate at relatively low temperatures [38]. However, the current selectively-reflective and -absorptive filters for SSPVT collectors both are still facing crucial challenges even after decades of development since the 1970s [39]. There remains a gap in optical characteristics between the current optical filters and ideal optical filters [17]. The undesired optical loss of the optical filter causes a significant efficiency reduction of the PV cells [40]. Furthermore, challenges for the current optical filters remain also in terms of stability and cost [17].

Semi-transparent PV (SPV) cells have attracted significant interest, especially in building-integrated PV (BIPV) applications [41], as they can selectively absorb only a part of the solar spectrum while transmits the rest [42]. Therefore, SPV cells can be employed in SSPVT collectors, acting as both electricity generators and spectral-splitting optical filters, owing to their excellent optical performance. In this way, the additional optical filters required in conventional SSPVT collectors can be eliminated. Amorphous Si (a-Si), Cadmium telluride (CdTe), Gallium arsenide (GaAs), polymer solar cells (PSC) and perovskite solar cells (PVSC) are most common types of SPV cells available in the literature [43]. The transmittances and electrical efficiencies strongly depend on the material and structure of the SPV cells [41]. Thus, the performance of the SSPVT collector can be optimised by carefully selecting the SPV cells. In the experiments performed by Widyolar *et al.* [44], a double-junction InGaP/GaAs SPV cell was used as a spectral-splitting optical filter in a concentrating SSPVT collector. The solar cell was able to reflect 80-90% infrared photons with wavelengths > 875 nm to a thermal absorber, which generated 600 °C high-temperature heat under a solar concentration ratio of 50. More recently, Codd *et al.* [45] employed III–V triple-junction GaAs SPV cells as the optical filter for a concentrating SSPVT collector. The SPV cell had an average transmittance of 70% in the wavelength range longer than 873 nm. The high-temperature heat output reached 200 °C while the solar cell average temperature was less than 110 °C. High-performance active cooling structures are required to remove the tremendous heat generated in SPV cells especially under a condition with a high solar concentration ratio according to the experimental results by Islam *et al.* [46] and Ji *et al.* [47]. To further improve the optical performance of SPV cells for SSPVT collectors, Liang and Wang [48] proposed a method of constructing biomimetic nanophotonic structures to regulate the photon capture for semi-transparent a-Si cells. Their simulation results show that the power conversion efficiency was effectively improved by 32%, and the transmitted infrared solar radiation ($\lambda > 1100$ nm) was increased by 27% with the aid of the nanophotonic structures. Other types of nanophotonic structures, such as nanopillar and nanohole arrays, were investigated by Xu *et al.* [49]. SPV cells were also investigated to be integrated with thermoelectric modules by Zhang and Xuan [50], or integrated with desalination modules by Xu *et al.* [51]. However, the investigation of SPV-based SSPVT collectors is still at an early stage. The performance of SSPVT collectors with emerging SPV cells (*e.g.*, thin-film CdTe, PVSC and PSC) is still unclear. Limited research has been conducted on the detailed evaluation of the performance of such SSPVT collectors.

Here, SPV-based SSPVT collectors with a compact flat-plate structure are designed, operating under one sun without additional solar concentrators. Three typical SPV cells (*i.e.*, CdTe, PVSC and PSC) are considered for the first time in order to investigate the influence of the SPV material. The SPV-based SSPVT collectors are able to co-generate electricity, low-temperature heat (< 60 °C) and high-temperature heat (100-200 °C) from the same area, and are thus capable of meeting the diverse multi-vector energy demands of domestic or industrial users. In this study, a comprehensive two-dimensional model of the SPV-based SSPVT collector is developed and used to investigate the spectral, energy, temperature distributions through the collectors. The electrical, thermal and total effective efficiencies are then calculated and presented in the form of performance maps. The performance of the

SPV-based SSPVT collectors finally is compared to those of conventional solar technologies in order to understand and quantify the possible benefits of this technology relative to existing options.

2. Modelling method

2.1. Design of SPV-based SSPVT collector

A detailed structure of the SPV-based SSPVT collector is shown in Fig. 1. The SPV cells, which act as both electricity generators and the spectral-splitting optical filter, are placed on the top layer of the collector. The SPV cells selectively absorb a part of the solar spectrum for electricity generation, while the rest of the solar spectrum transmits through the SPV cells to a solar thermal (ST) absorber. Although the SPV cells selectively absorb only a part of the solar spectrum that can be converted to electricity, they still inevitably generate considerable heat. Therefore, a transparent top cooling channel is designed to cool the SPV cells. The ST absorber, coated with a low-emissivity coating, absorbs the solar spectrum transmitted through the SPV cells and produces high-temperature thermal energy. A thermal insulation layer is packed to the back of the SSPVT collector to reduce heat loss.

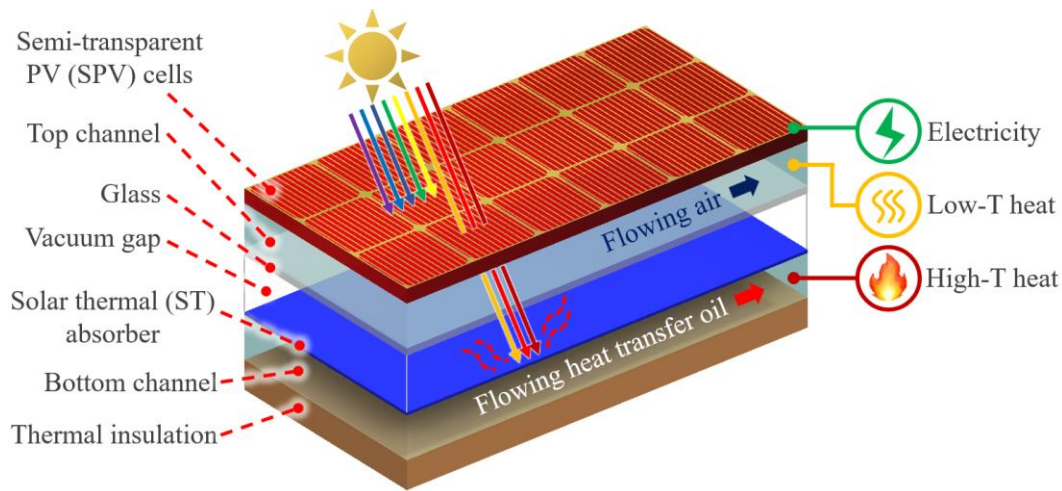


Figure 1. Schematic of a SSPVT collector employing SPV cells as the optical filter.

In this design, the top channel harvests (*i.e.*, removes) the heat generated in the SPV cells and produces a low-temperature ($< 60\text{ }^{\circ}\text{C}$) thermal-energy output, which can be used, *e.g.*, for spacing heating. A vacuum gap is placed between the top and bottom channels to suppress heat transfer between these two layers. The ST absorber is thermally decoupled from the SPV cells by the vacuum and a low-emissivity coating, thus the fluid in the bottom channel is heated to a higher temperature without overheating the cells. Of note is that the working fluid in the top channel should be transparent to the solar spectrum, so that the spectrum can pass through the top channel to the ST absorber. The working fluid in the bottom channel should have a high boiling point to avoid unnecessary phase change. Therefore, air is selected as the heat transfer fluid in the top channel, which can be used for direct spacing heating or solar drying, *etc.* A commercial heat transfer oil (*Therminol VP-1*) is selected as the heat transfer fluid in the bottom channel to generate high-temperature heat, which can be used for a wide range of domestic or industrial applications, such as solar cooling, sterilisation, food processing and power generation, *etc.* The length and width of the SSPVT collector are both 1 m. The thicknesses of the top channel, vacuum gap, and bottom channel are taken as 10 mm.

2.2. Characteristics of selected SPV cells

In this study, three typical SPV cells are selected, *i.e.*, CdTe from Ref. [52], PVSC from Ref. [53] and PSC from Ref. [54]. The external quantum efficiencies (*EQE*s) of these SPV cells are shown in Fig. 2(a). All of these SPV cells are only electrically sensitive to a part of the solar spectrum, *i.e.*, in the wavelength range of 300-900 nm. CdTe is more effective in the wavelength range of 500-800 nm, whereas PVSC is more effective within 400-700 nm. The *EQE* of PSC is significantly lower than those of CdTe and PVSC. The transmittance of these SPV cells is shown in Fig. 2(b). All these three SPV cells exhibit significantly high transmittance in the near-infrared wavelength range ($\lambda > 780$ nm), and most (~70-80%) of the near-infrared spectrum can pass through CdTe, PVSC and PSC. PVSC can only transmit a limited fraction of the visible spectrum ($400 \text{ nm} < \lambda < 780 \text{ nm}$), whereas CdTe nearly blocks all the visible spectrum. Around 40-50% visible spectrum can pass through PSCs, which thus visibly looks more transparent than CdTe and PVSCs. These three SPV cells are employed as spectral-splitting optical filters in the SPV-based SSPVT collectors.

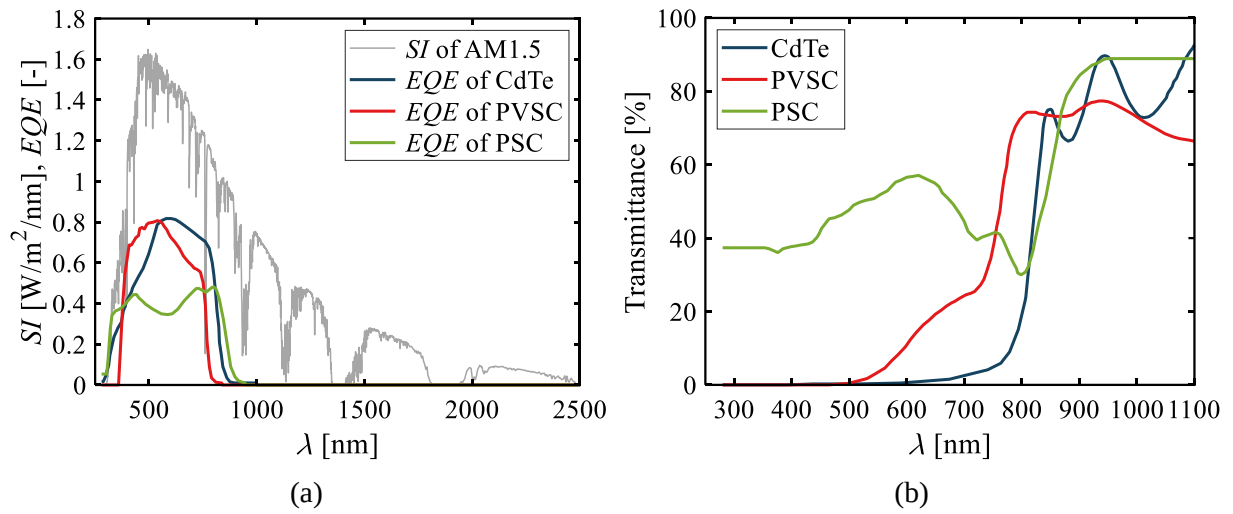


Figure 2. (a) External quantum efficiency (*EQE*), and (b) transmittance of CdTe [52], PVSCs [53] and PSCs [54].

2.3. Model of SPV-based SSPVT collectors

A two-dimensional (2-D) numerical model based on the finite volume method (FVM) is developed for modelling the SPV-based SSPVT collectors, as illustrated in Fig. 3. The incident solar spectrum G_{in} is partly absorbed by the SPV cells, generating electricity and low-temperature heat. A part of spectrum G_{ST} passes through the top channel and then is absorbed by the ST absorber for generating high-temperature heat. The model includes a set of combined conjugate heat transfer, optical and PV sub-models.

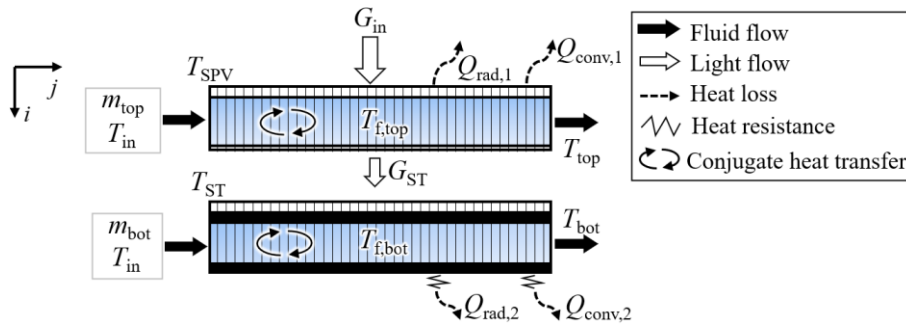


Figure 3. Graphical representation of SPV-based SSPVT collector numerical model.

2.3.1. Heat transfer sub-model

The SPV-based SSPVT collector consists of solid zones (*i.e.*, SPV cells, glass layer and ST absorber) and fluid zones that are filled by the selected heat transfer fluid. Steady-state heat conduction equation and fluid flow energy equation are applied to these zones:

$$k_s \left(\frac{\partial^2 T_s}{\partial x^2} + \frac{\partial^2 T_s}{\partial y^2} \right) + Q_s = 0 \quad (1)$$

$$k_f \left(\frac{\partial^2 T_f}{\partial x^2} + \frac{\partial^2 T_f}{\partial y^2} \right) - \frac{\partial(\rho c_p u T_f)}{\partial x} + Q_f = 0 \quad (2)$$

where k_s and k_f are the thermal conductivity coefficients of the solid and fluid materials, ρ , c_p and u are density, specific heat capacity and velocity of the fluid. The terms Q_s and Q_f of Eqs. (1) and (2) are the energy source terms (unit: W/m²) of solid and fluid elements, which are internally linked with other sub-models. The variable T_s represents the temperature of solid zones, such as SPV cells (T_{SPV}) and ST absorber (T_{ST}) shown in Fig. 3, while T_f represents the temperature of fluid zones, such as the top channel ($T_{f,top}$) and bottom channel ($T_{f,bot}$) shown in Fig. 3. The thermal conductivity coefficients and specific heat capacities of the fluids, and the thermal conductivity coefficients of the solid materials are assumed to be constant in the model.

The interfaces between the heat transfer fluid and walls are described by boundary conditions:

$$-k \frac{\partial T}{\partial y} \big|_{\text{interface}} = h_c \Delta T \quad (3)$$

where h_c and ΔT are the heat transfer coefficient and temperature difference between the solid and fluid zones. The heat convection coefficients are given in Refs. [7] and [21].

The boundary condition on the outer walls of the SPV-based SSPVT collector is given by:

$$-k \frac{\partial T}{\partial y} \big|_{\text{wall}} = h_w (T_w - T_a) + \varepsilon \sigma (T_w^4 - T_{\text{sky}}^4) \quad (4)$$

where T_w and T_a are the temperatures of the outer wall and ambient, ε and σ are the emissivity and Stefan-Boltzmann constant. The heat convection coefficient h_w is related to the wind speed u_w through $h_w = 4.5 + 2.9u_w$ ($u_w < 5$ m/s) as per Ref. [7]. The equivalent sky temperature for radiation is $T_{\text{sky}} = 0.0522T_a^{1.5}$ [7]. The ambient temperature and wind speed in this study are set to be $T_a = 300$ K and $u_w = 1$ m/s. The radiative and convective heat losses Q_{rad} and Q_{conv} shown in Fig.3 are calculated by Eq. (4).

2.3.2. Optical sub-model

An optical sub-model is used to calculate solar energy allocations and spectral distribution through the SPV-based SSPVT collector. The solar energy absorbed a certain layer, i , is calculated from:

$$Q_{\text{abs},i} = \int_0^\infty G_i(\lambda) \alpha_i(\lambda) d\lambda \quad (5)$$

where $\alpha_i(\lambda)$ is the absorptivity of the material of layer i , $G_i(\lambda)$ is the spectral distribution of the incident light onto layer i . The spectral distribution transmitted through layer i is given by:

$$G_{i+1}(\lambda) = G_i(\lambda) \tau_i(\lambda) \quad (6)$$

where $\tau_i(\lambda)$ is the transmittance of the material of layer i , and $G_{i+1}(\lambda)$ is the spectrum that passes through layer i . The absorbed energies Q_{abs} in each layer are transferred to the heat transfer sub-model as the source terms. Of note is that the heat generated in the SPV layer is not only related to its

absorbed energy $Q_{\text{abs,PV}}$, but also related to the electrical characteristics of the SPV cells, which will be introduced in the SPV sub-model (Section 2.3.3 below).

2.3.3. PV sub-model

The SPV cells directly absorb the solar spectrum (AM1.5) to generate electricity as shown in Fig. 1. The electrical efficiency of the SPV cells at the operating temperature T_{SPV} can be described as:

$$\eta_{\text{el}} = \eta_{\text{el},0} [1 + \beta (T_{\text{SPV}} - T_{\text{ref}})] \quad (7)$$

where $\eta_{\text{el},0}$ is the electrical efficiency at $T_{\text{ref}} = 25^\circ\text{C}$ (8.6% for CdTe cells [52], 14.2% for PVSC [53] and 5.5% for PSC [54]), β is the temperature coefficient of the SPV cells (-0.25%/K for CdTe, -0.17%/K for PVSC, and -0.30%/K for PSC).

The heat generated in the SPV cells $Q_{\text{h,PV}}$ is calculated from:

$$Q_{\text{h,PV}} = Q_{\text{abs,PV}} - \eta_{\text{el}} \cdot I_{\text{AM1.5}} \quad (8)$$

where $Q_{\text{abs,PV}}$ is the solar energy absorbed by the SPV cells based on Eq. (5), and $I_{\text{AM1.5}}$ is the solar irradiance (1000 W/m^2). The heat $Q_{\text{h,PV}}$ is then transferred to the heat transfer model as the source term. The parameters used in this study are listed in Table 1.

Table 1. Geometric, thermal and optical parameters for the SPV-based SSPVT collector model.

Layer	Parameter/variable	Value	Unit	Refs.
SPV solar cells	τ_{SPV}	Transmittance	Fig. 2(b)	-
	γ_{SPV}	Reflectivity	0.07	-
	ε_{PV}	Emissivity	0.90	-
Top channel fluid (air)	τ_{top}	Transmittance	1.00	-
	δ_{top}	Thickness	0.01	m
Glass layer (low-iron glass)	τ_{g}	Transmittance	0.95	-
	α_{g}	Absorptivity	0.01	-
	ε_{g}	Emissivity	0.90	-
	k_{g}	Thermal conductivity	1.80	W/m·K
	δ_{g}	Thickness	0.003	m
Solar thermal absorber	α_{ST}	Absorptivity	0.93	-
	ε_{ST}	Emissivity	0.07	-
	δ_{ST}	Thickness	0.003	m
	k_{ST}	Thermal conductivity	401	W/m·K
Bottom channel fluid (Therminol VP-1)	δ_{bot}	Thickness	0.01	m
Thermal insulation	k_{ins}	Thermal conductivity	0.04	W/m·K
	δ_{ins}	Thickness	0.03	m

The temperature distribution throughout the collector is the main output of the numerical model, based on which the thermal efficiencies of the top and bottom channels are calculated from:

$$\eta_{\text{th-top}} = \frac{m_{\text{top}} c_{\text{p,top}} (T_{\text{top}} - T_{\text{in}})}{A \cdot I_{\text{AM1.5}}} \quad (9)$$

$$\eta_{th-bot} = \frac{m_{bot} c_{p,top} (T_{bot} - T_{in})}{A \cdot I_{AM1.5}} \quad (10)$$

where m_{top} and m_{bot} are the mass flow rates of the heat transfer fluid through the top and bottom channels, and T_{top} and T_{bot} are the output temperatures of the top and bottom channels. The inlet temperature of the top and bottom channels both are $T_{in} = 300$ K.

The reduced temperatures of the top and bottom channels are defined as:

$$TR_{top} = \frac{T_{m,top} - T_a}{I_{AM1.5}} \quad (11)$$

$$TR_{bot} = \frac{T_{m,bot} - T_a}{I_{AM1.5}} \quad (12)$$

where $T_{m,top}$ and $T_{m,bot}$ are the average temperatures of the top and bottom channels. The output temperature of the top and bottom channels (*i.e.*, T_{top} and T_{bot}) can be changed by adjusting either the mass flow rates or inlet temperature.

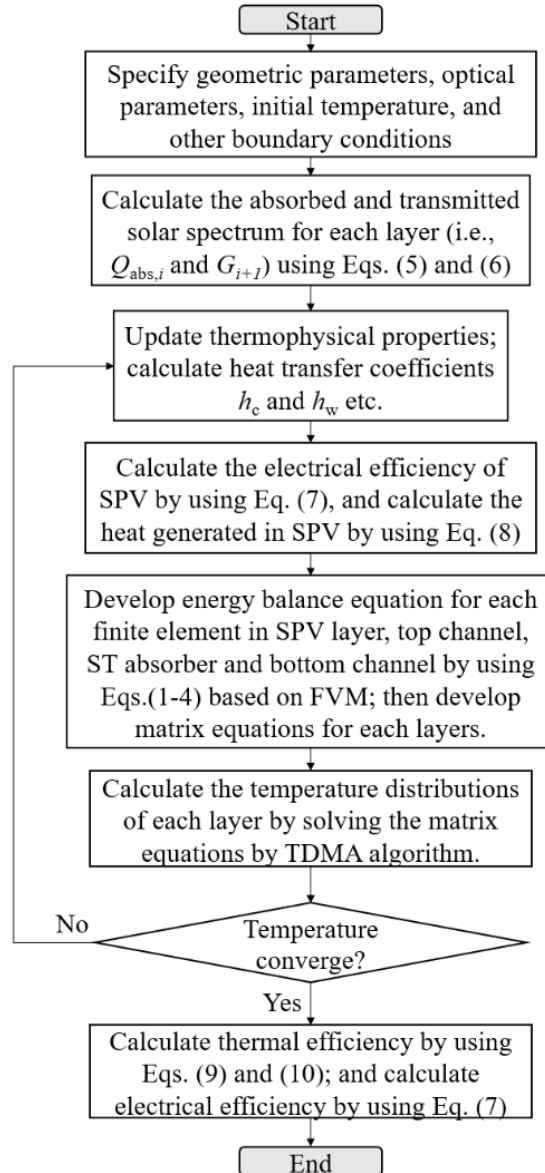


Figure 4. Flowchart of the numerical simulation.

To solve these equations numerically, the whole physical region is divided into a set of finite rectangular elements as shown in Fig. 3. The FVM is then used to discretize the partial differential equations for each finite element, and generate a system of algebraic equations, which is solved by numerical iteration to compute the temperature for each element. More details regarding the FVM for solar collectors are introduced by Guarracino et al. [55]. Figure 4 shows the flowchart of the procedure for the numerical simulation. The convergence criteria for the temperature is defined as that the relative errors between two successive iterations are less than 10^{-5} .

2.4. Model validation

The SPV-based SSPVT collector consists of two parts, *i.e.*, the upper part (the SPV cells) for spectral splitting and the lower part (the ST absorber) for high-temperature heat generation. As no experimental data are available for the specific SPV-based SSPVT design as proposed in the study, the models for the upper and lower parts are validated separately. Figure 5 shows the average transmittance of different types of SPV cells in the wavelength range of 400-650 nm, which are calculated using the above optical model. The spectral-splitting performance of different SPV cells predicted by the model agrees well with the experimental results from Chen et al. [54].

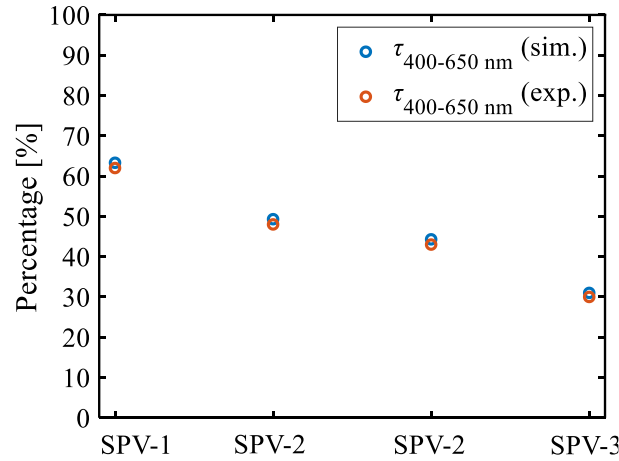


Figure 5. Average transmittance of different types of SPV solar cells in the wavelength range of 400-650 nm, validated against the experimental results from Chen et al. [54].

Thermal efficiency is a crucial performance indicator. The manufacturers' data of the thermal efficiency from a commercial flat-plate ST collector (*HEWALEX* [58]) is selected here to provide further validation of the model, for which all geometric parameters, working fluids, mass flow rates and solar irradiance of this model are set to be the same as those provided by the manufacturer [58]. The thermal performance of the ST collector predicted by the model agrees well with the manufacturer's data, as shown in Fig. 6, suggesting that the model is capable of accurately simulating the thermal performance. In addition to thermal efficiency, electrical efficiency is another crucial performance indicator. This study employs the PV sub-model (*i.e.*, Eqs. (7) and (8)) having been widely utilised and validated by other researchers (Herrando et al. [7], Wang et al. [8], Hu et al. [9] and Huang et al. [29] etc.).

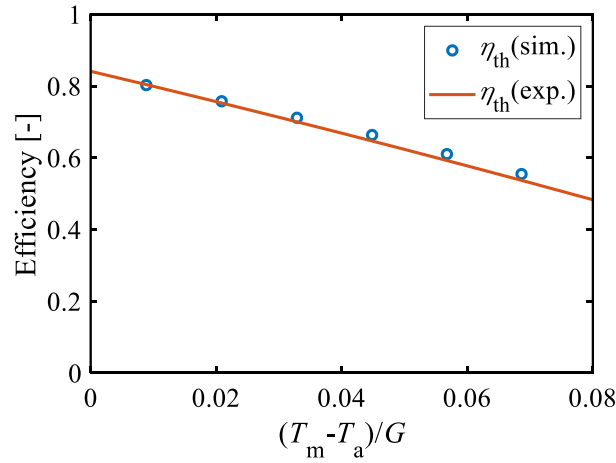
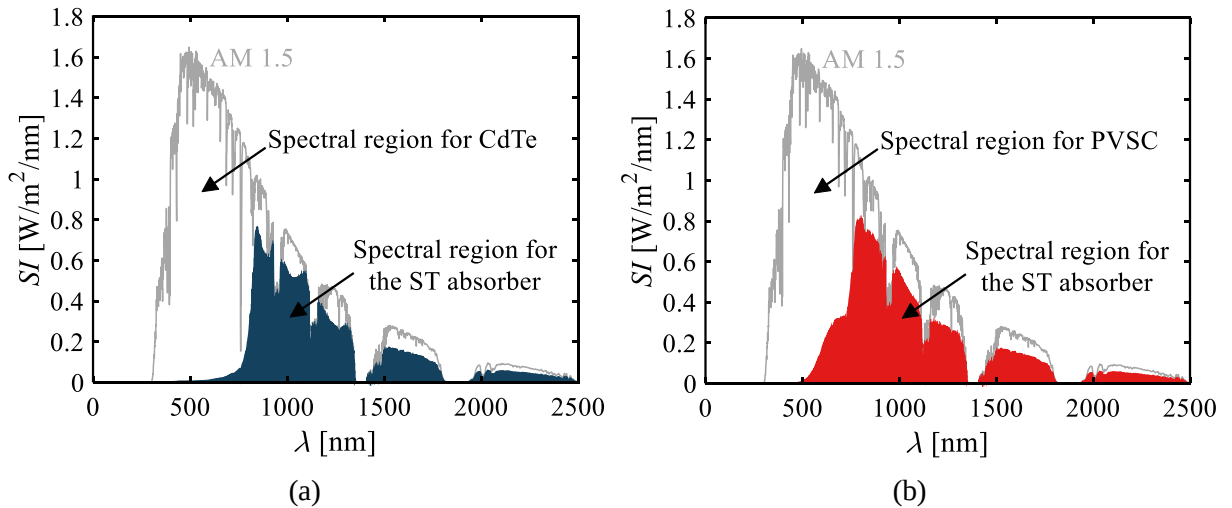


Figure 6. Thermal efficiency of a flat-plate solar-thermal collector as a function of its reduced temperature, validated against the data from the manufacturer (*HEWALEX* [58]).

3. Results and discussion

3.1. Spectral distribution and solar energy allocation

The SPV cells in this study act as both PV electricity generators and spectral splitting optical filters. The spectral distributions of the original AM1.5 incident light and the filtered light to the ST absorbers in the CdTe-, PVSC- and PSC-based SSPVT collectors are shown in Figs. 7(a), (b) and (c), respectively. The SPV cells directly receive the original solar spectrum and produce electricity with their designed electrical efficiencies. The white areas in Fig. 7 (a), (b) and (c) are the spectral regions of the SPV cells, including the solar spectrum absorbed and reflected by the SPV cells. The spectrum that reaches ST absorber strongly depends on the optical characteristics of the SPV cells. The CdTe absorbs most of the ultraviolet (UV) and visible spectrum ($\lambda < 780$ nm), and transmits most of the rest spectrum ($\lambda > 780$ nm), as shown in Fig. 7(a). A small part of the visible spectrum ($400 \text{ nm} < \lambda < 780 \text{ nm}$) can pass through the PVSC and be directed to the ST absorber, as shown in Fig. 7(b). The PSC has the highest transmittance among these three SPV cells. A significant part of UV, visible and IR spectrum passes through the PSC and is directed to the ST absorber, as shown in Fig. 7(c). The spectral distributions through the CdTe-, PVSC- and PSC-based SSPVT collectors are appreciably different, suggesting that the selectin of the SPV cell material has a strong impact on both the electrical and thermal performance of the overall collector.



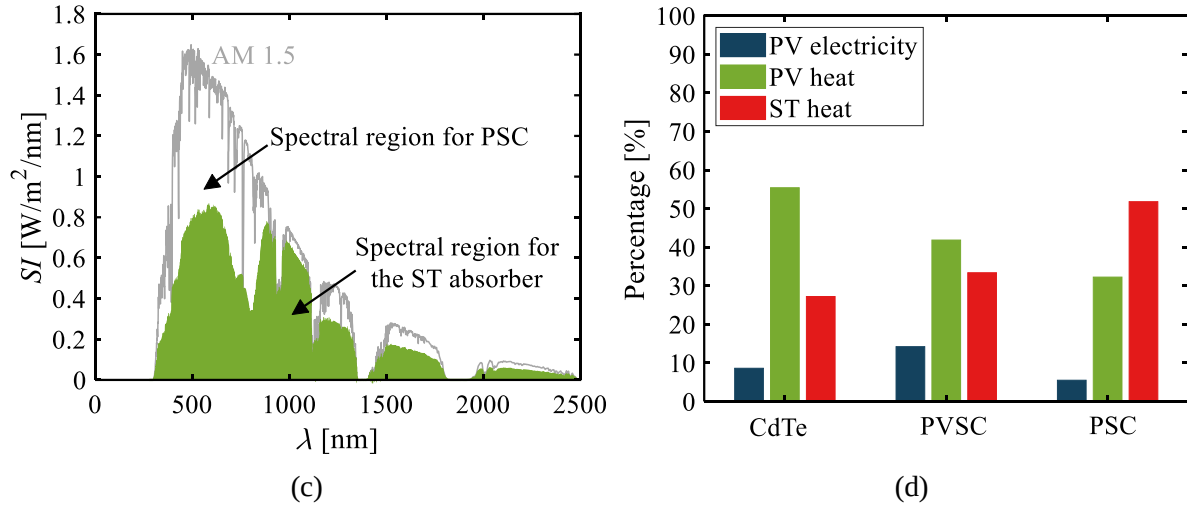


Figure 7. Spectral distributions through the: (a) CdTe-SSPVT, (b) PVSC-SSPVT, and (c) PSC-SSPVT collectors. (d) Solar energy allocations within the same three types of SSPVT collectors.

The solar energy allocations through the CdTe-, PVSC- and PSC-based SSPVT collectors are illustrated in Fig. 7(d). The PV efficiencies of CdTe, PVSC and PSC are taken from the test results in Refs. [52-54], which depend on materials and fabrication technologies. The heat generated in the SPV cells and the solar heat generated in the ST absorber can be calculated by the optical sub-model.

As shown in Fig. 7 (d), 64.0% of the incident solar energy is absorbed by the CdTe but only 8.6% is converted to electricity in the CdTe-based SSPVT collector. Although the semi-transparent CdTe only selectively absorbs the electrically usable spectrum, considerable undesirable heat (accounting for 55.4% of the total incident solar energy) is still unavoidably generated in the solar cell. Thus, the top cooling channel is essential for the CdTe-based SSPVT collector design. 27.2% of the total incident solar energy is finally absorbed by the ST absorber in the CdTe-based SSPVT collector, which can be used for generating high-temperature heat.

In the PVSC-based SSPVT collector, 14.2%, 41.8% and 33.3% of the incident solar energy is respectively converted to electricity, heat in the solar cells and heat in the ST absorber. The PVSC has a higher electrical efficiency than the CdTe and transmits considerable solar energy to the ST absorber for high-temperature heat generation. Among the three SPV solar cells, PSC has the highest visible light transmittance, thus the lowest electrical efficiency (5.5%), but the most amount of solar energy absorbed by the ST absorber (51.8%). Considerable fractions (55.4%, 41.8% and 32.2%) of the solar energy is converted to heat in CdTe, PVSC and PSC, suggesting that it is essential to design the top cooling channel to remove and recover the heat generated in the SPV cells. SPV cells have shown the capability of spectrally separating the solar spectrum for high-performance combined electricity and heat generation in SSPVT applications.

3.2. Temperature distributions

The top channel is designed to cool the SPV cells and to produce low-temperature (< 60 °C) hot air, while the bottom channel, filled with *Therminol VP-1* heat transfer oil (HTO), is designed to generate high-temperature (100-200 °C) heat. In order to achieve the desired temperatures described above, the flow rates in both channels are carefully selected and identified via the enumeration algorithm provided in the paper. The mass flow rates through the top and bottom channels are set here to: $m_{top} = 0.01$ kg/s and $m_{bot} = 0.001$ kg/s, respectively. Figure 8 shows temperature distributions through the CdTe-, PVSC- and PSC-based SSPVT collectors. The bottom channel generates higher-temperature

heat ($> 100\text{ }^{\circ}\text{C}$), while the SPV cells operate at a lower temperature ($< 60\text{ }^{\circ}\text{C}$) owing to the effective cooling of the top channel, as illustrated in Fig. 8.

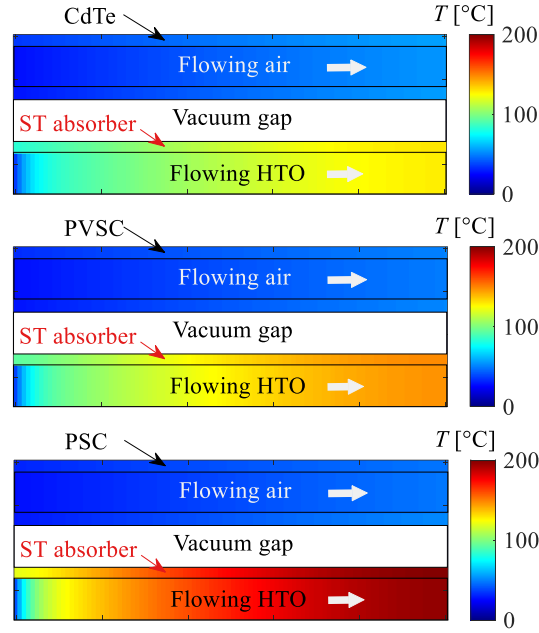


Figure 8. Temperature distributions through CdTe-, PVSC- and PSC-based SSPVT collectors ($m_{\text{top}} = 0.01\text{ kg/s}$, $m_{\text{bot}} = 0.001\text{ kg/s}$).

The temperature distributions through the SPV-based SSPVT collectors clearly show that the SPV cells are thermally decoupled from the high-temperature ST absorbers (*i.e.*, bottom channels) as expected. The vacuum gap and low-emissivity ST absorber are effectively at suppressing both the radiative and convective heat exchange between the top and bottom channels, resulting in an effective thermal-decoupling effect. The bottom channel is well thermally insulated by the vacuum gap, the low-emissivity coating and the back insulation layer, thereby significantly reducing heat loss to the ambient. The outlet temperature of the bottom channel of the PSC-based SSPVT collector can reach high values, up to $\sim 200\text{ }^{\circ}\text{C}$, while the average temperature of the PSC is only $\sim 45\text{ }^{\circ}\text{C}$. The output temperature of the bottom channel strongly depends on the type of SPV cells utilised in the SSPVT collector.

Figure 9(a) shows detailed temperature distribution curves over the length of the top channel, bottom channel and solar cells of the CdTe-based SSPVT collector for different flow rates. The mass flow rate in the top channel m_{top} is kept constant at 0.01 kg/s , while three different mass flow rates in the bottom channel (*i.e.*, $m_{\text{tobot}} = 0.0005, 0.001$ and 0.002 kg/s) are considered in the simulation. The air is heated from $27\text{ }^{\circ}\text{C}$ to $56\text{ }^{\circ}\text{C}$ by the top channel and the average temperature of CdTe is around $48\text{ }^{\circ}\text{C}$. The output temperature of the bottom channel significantly increases from $93\text{ }^{\circ}\text{C}$ to $160\text{ }^{\circ}\text{C}$ as the mass flow rate m_{bot} decreases from 0.002 kg/s to 0.0005 kg/s . The temperature distributions in the bottom channel are significantly non-linearly with the position when $m_{\text{bot}} = 0.0005\text{ kg/s}$, which suggests that a 2-D simulation is necessary for the accurate modelling of such collectors at a small mass flow rate. The high-temperature bottom channel temperature has a very slight influence on CdTe temperature due to the thermal-decoupling effect. The temperature distributions through the PVSC-based SSPVT collector for different mass flow rates are shown in Fig. 9(b). The output temperature of the bottom channel increases from $106\text{ }^{\circ}\text{C}$ to $181\text{ }^{\circ}\text{C}$ as m_{bot} decreases from 0.002 kg/s to 0.0005 kg/s . The ST absorber of the PVSC-based SSPVT collector absorbs 33.3% of the incident solar energy, which is higher than 27.2% of the CdTe-based SSPVT collector. Thus, the bottom channel of the

PVSC-based SSPVT collector produces higher temperature heat than the CdTe-based SSPVT collector at the same mass flow rate. The average temperature of PVSC is around 42 °C.

Figure 9(c) shows the temperature distributions through the PSC-based SSPVT collector. The heat transfer oil in the bottom channel is heated from 27 °C to 240 °C when $m_{\text{bot}} = 0.0005$ kg/s, while the average temperature of the PSC is considerably lower, at only 43 °C. The temperature distributions in the bottom channels are significantly non-linear with the position when $m_{\text{bot}} = 0.0005$ kg/s, which means the bottom channel nearly reaches its thermal limit. The bottom channel of the PSC-SSPVT collector generates 240 °C high-temperature heat, which is 80 °C higher than the heat generated by the CdTe-based SSPVT collector at the same mass flow rate of $m_{\text{bot}} = 0.0005$ kg/s, because the ST absorber of the PSC-SSPVT collector absorbs significantly more solar energy (51.8% vs. 27.2%). The simulation results show that all the CdTe-, PVSC- and PSC-based SSPVT collectors can produce significantly higher-temperature heat (100-200 °C) than the conventional PVT collectors (< 80 °C), while the solar cells are kept at a lower temperature.

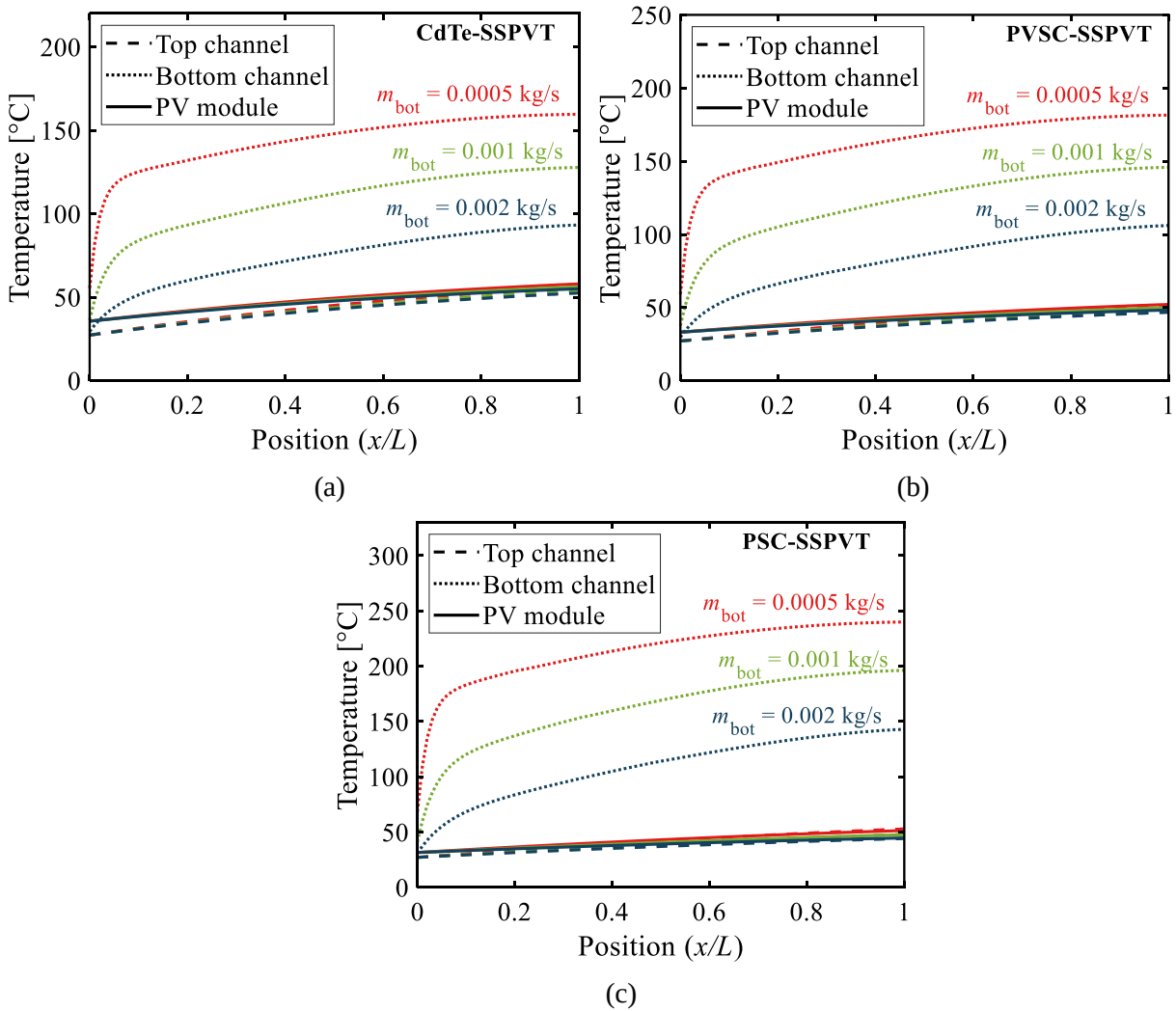


Figure 9. Temperature distributions through the top channel, bottom channel and SPV cell of SSPVT collectors for different mass flow rates. (a) CdTe-SSPVT collector, (b) PVSC-SSPVT collector, and (c) PSC-SSPVT collector ($m_{\text{top}} = 0.01$ kg/s; $m_{\text{bot}} = 0.0005, 0.001$, and 0.002 kg/s). The red, green and blue colour represent for $m_{\text{bot}} = 0.0005, 0.001$ and 0.002 kg/s respectively.

3.3. Thermal and electrical efficiencies

In this section, results relating to the electrical and thermal efficiencies of the CdTe-, PVSC- and PSC-based SSPVT collectors under different operating conditions are discussed, as shown in Figure 10. The mass flow rate in the top channel m_{top} is kept constant at 0.01 kg/s, while the mass flow rate in the bottom channel m_{bot} varies from 0.0005 kg/s to 0.01 kg/s. Figure 10(a) shows the output temperatures and efficiencies of the CdTe-based SSPVT collector for different m_{bot} . The bottom channel outlet temperature T_{bot} increases from 44 °C to 160 °C as m_{bot} decreases from 0.01 kg/s to 0.0005 kg/s. The bottom channel is capable of generating thermal energy with a wide range of temperature, in order to meet various thermal demands. Although the bottom channel temperature varies over a large range, it slightly affects the outlet temperature of the top channel T_{top} , owing to the aforementioned thermal-decoupling effect. The output temperature T_{bot} increases but the thermal efficiency $\eta_{\text{th-bot}}$ decreases as the mass flow rate m_{bot} decreases, as shown in Fig. 10(a). The CdTe cells maintain stable electrical efficiency under different working conditions owing to the effective thermally-decoupling design. The CdTe-based SSPVT collector simultaneously generates high-temperature heat ($T_{\text{bot}} = 150$ °C, $\eta_{\text{th-bot}} = 14.2\%$), low-temperature heat ($T_{\text{top}} = 56$ °C, $\eta_{\text{th,LT}} = 29.1\%$), and electricity ($\eta_{\text{el}} = 8.1\%$). The thermal efficiency $\eta_{\text{th-bot}}$ increases as m_{bot} increases, and is limited to 27.2% (i.e., the ST absorption efficiency).

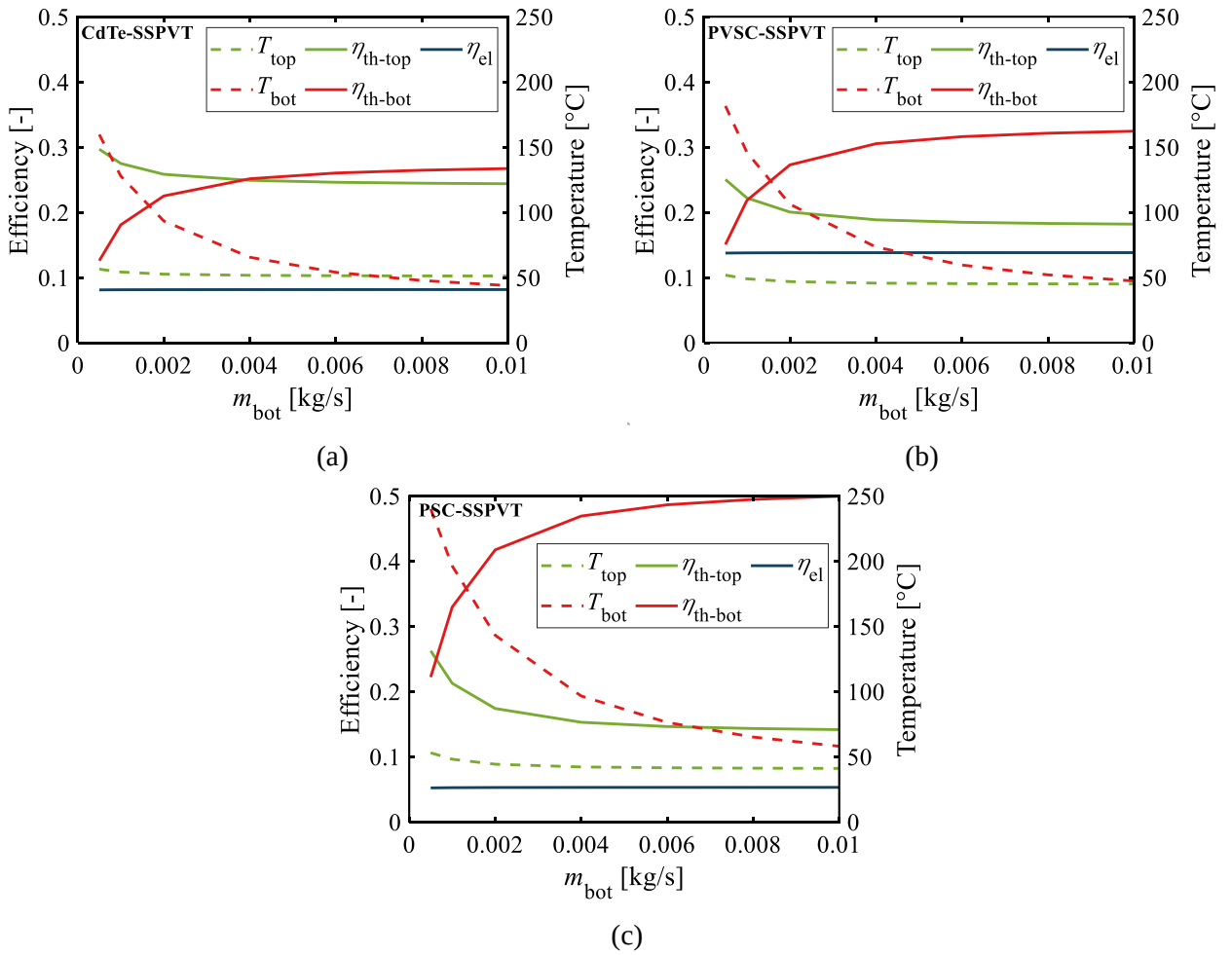


Figure 10. Output temperatures and efficiencies of SSPVT collectors as a function of flow rate in the bottom channel: (a) CdTe-SSPVT, (b) PVSC-SSPVT, and (c) PSC-SSPVT collector ($m_{\text{top}} = 0.01$ kg/s).

Figure 10(b) shows the output temperatures and efficiencies of the PVSC-based SSPVT collector, which has better electrical and thermal performance than the CdTe-based SSPVT collector.

The values of T_{bot} , $\eta_{\text{th-bot}}$, and η_{el} of the PVSC-based SSPVT collector are all higher than those of the CdTe-based SSPVT collector for the same flow rate when comparing Fig. 10(b) with Fig. 10(a). The PVSC-based SSPVT collector simultaneously produces high-temperature heat ($T_{\text{bot}} = 150$ °C, $\eta_{\text{th-bot}} = 21.1\%$), low-temperature heat ($T_{\text{top}} = 50$ °C, $\eta_{\text{th,LT}} = 22.5\%$), and electricity ($\eta_{\text{el}} = 13.8\%$). The thermal efficiency $\eta_{\text{th-bot}}$ is limited to 33.3%. Of interest is that the PSC-based SSPVT collector has significantly better thermal performance than the CdTe- and PVSC-based SSPVT collectors as shown in Fig. 10 (c), due to the significantly higher ST absorption efficiency (51.8%) in the PSC-based SSPVT collector. However, the PSC-based SSPVT collector delivers a relatively low electrical efficiency (only 5.3%). The PSC-based SSPVT collector simultaneously generates high-temperature heat ($T_{\text{bot}} = 150$ °C, $\eta_{\text{th-bot}} = 40.6\%$), low-temperature heat ($T_{\text{top}} = 45$ °C, $\eta_{\text{th-top}} = 17.9\%$), and electricity ($\eta_{\text{el}} = 5.3\%$).

The SPV-based SSPVT collectors produce two thermal-energy outputs by the top and bottom channels. Although the heat transfer between the top and bottom channels has been significantly suppressed by the vacuum gap and low-emissivity coating, there remains unavoidable radiative heat exchange between the top and bottom channels. Therefore, it is necessary to evaluate the electrical and thermal efficiencies of the SPV-based SSPVT collectors by using 2-D performance maps as a function of the reduced temperatures of the top and bottom channels (*i.e.*, TR_{top} and TR_{bot} defined in Eqs. (11) and (12)). Figure 11 shows the performance maps of the CdTe-based SSPVT collector. The 2-D map of the thermal efficiency of the top channel $\eta_{\text{th-top}}$ as a function of the TR_{top} and TR_{bot} is shown in Fig. 11(a). The thermal efficiency $\eta_{\text{th-top}}$ decreases as TR_{top} increases due to the increased heat loss. Interestingly, the value of $\eta_{\text{th-top}}$ increases as TR_{bot} increases owing to the increased radiative heat transfer from the bottom channel to the top channel. The white dash line in Fig. 11 (a) is the limit of the thermal efficiency of the top channel (*i.e.*, $\eta_{\text{th-top}} = 0$), which indicates the limit value of TR_{top} .

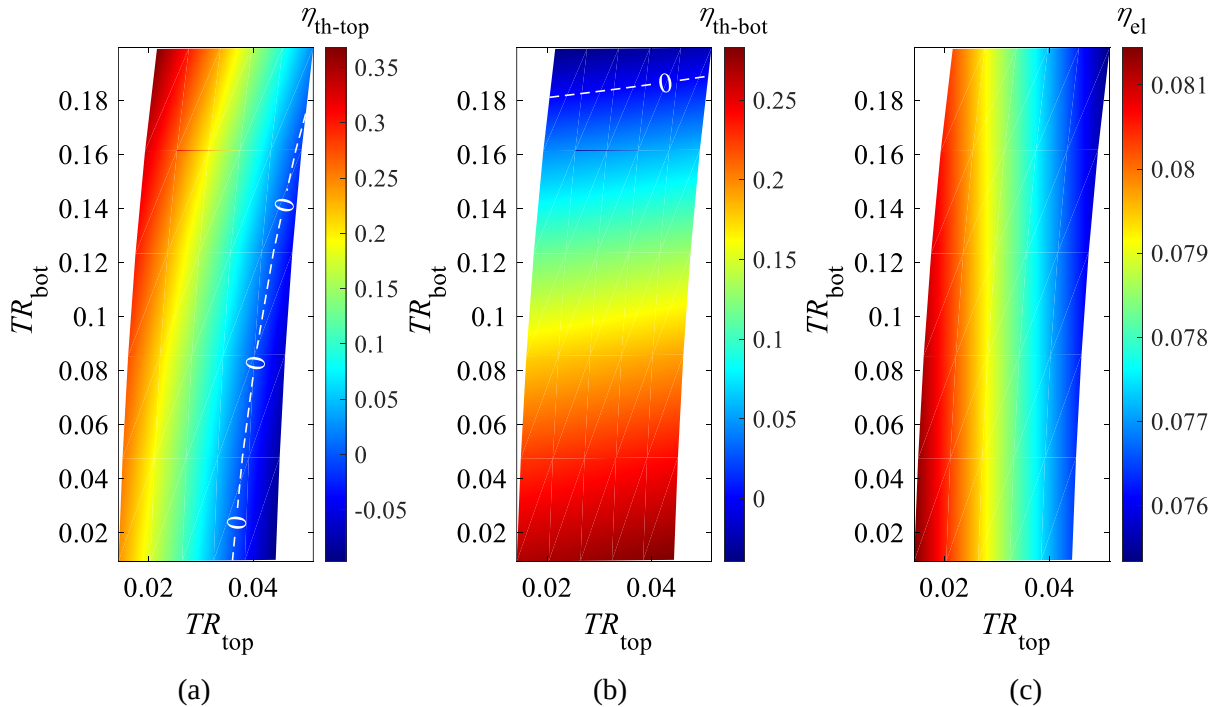


Figure 11. Performance maps of the CdTe-SSPVT collector. (a) Thermal efficiency of the top channel, (b) thermal efficiency of the bottom channel, and (c) electrical efficiency of the solar cells; here $TR_{\text{top}} = (T_{\text{m,top}} - T_{\text{a}})/I_{\text{AM1.5}}$, $TR_{\text{bot}} = (T_{\text{m,bot}} - T_{\text{a}})/I_{\text{AM1.5}}$.

Figure 11(b) shows the thermal efficiency of the bottom channel $\eta_{\text{th-bot}}$ as a function of the TR_{top} and TR_{bot} . Compared to TR_{top} , TR_{bot} has a more significant influence on $\eta_{\text{th-bot}}$. The thermal efficiency

$\eta_{\text{th-bot}}$ decreases as TR_{bot} increases. The white dash line in Fig. 11 (b) is the limit of the thermal efficiency of the bottom channel (*i.e.*, $\eta_{\text{th-bot}} = 0$). The cross point of the white dash lines in Figs. 11(a) and (b), *i.e.*, $TR_{\text{top}} = 0.053$ and $TR_{\text{bot}} = 0.189$, is the limit point of the thermal performance, which suggests that the low-temperature and high-temperature heat outputs are limited to 53 °C and 189 °C higher than the ambient temperature. The limit value of TR_{bot} is significantly higher than that of TR_{top} due to the excellent thermal insulation approaches employed to the bottom channel (*i.e.*, the vacuum gap, low-emissivity coating and back insulation layer). Therefore, the bottom channel is able to produce much higher-temperature heat compared to the top channel. The electrical efficiency of the CdTe-based SSPVT collector as a function of the TR_{top} and TR_{bot} is shown in Fig. 11(c). The electrical efficiency strongly depends on the value of TR_{top} , while TR_{bot} slightly affects the electrical efficiency due to the thermally-decoupled design of this collector type.

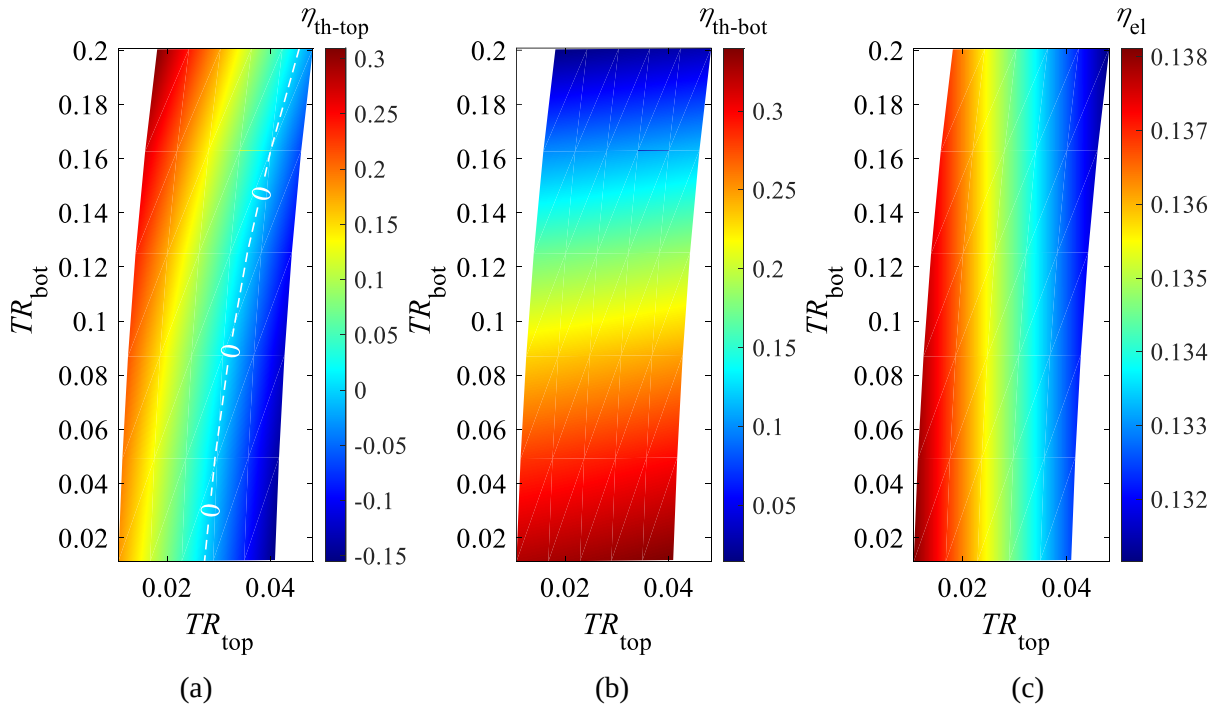


Figure 12. Performance maps of the PVSC-SSPVT collector. (a) Thermal efficiency of the top channel, (b) thermal efficiency of the bottom channel, and (c) electrical efficiency; here $TR_{\text{top}} = (T_{\text{m,top}} - T_{\text{a}})/I_{\text{AM1.5}}$, $TR_{\text{bot}} = (T_{\text{m,bot}} - T_{\text{a}})/I_{\text{AM1.5}}$.

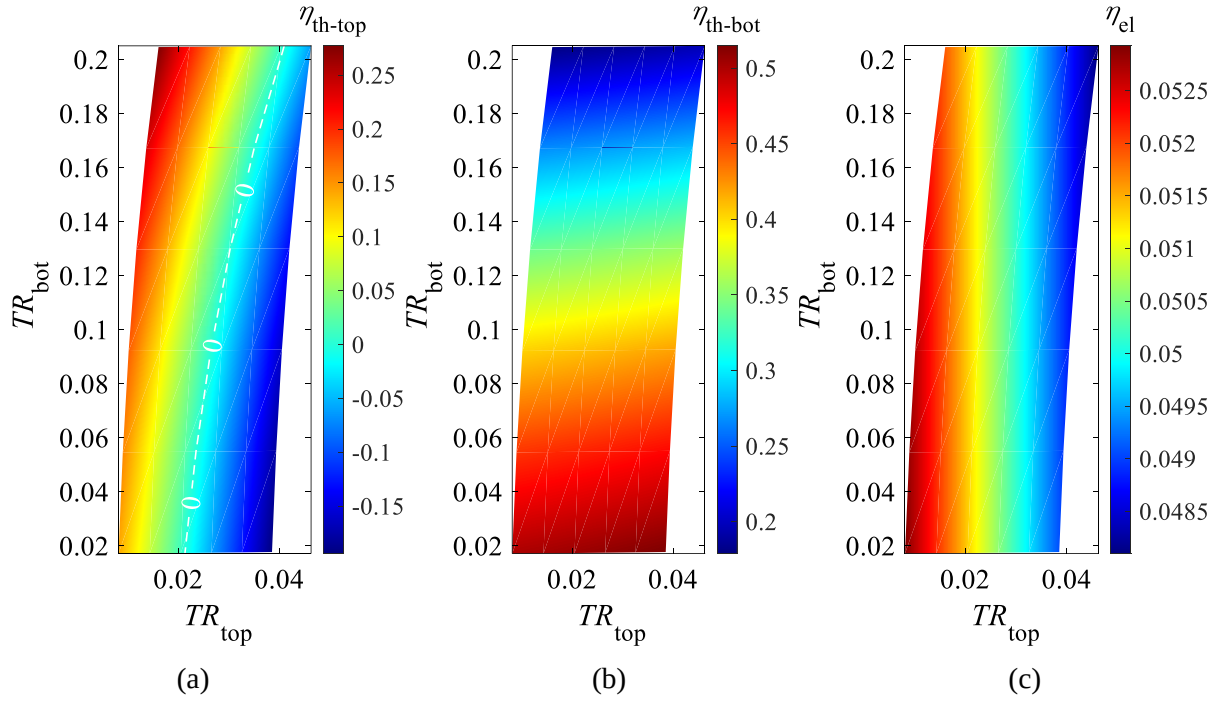


Figure 13. Performance maps of the PSC-SSPVT collector. (a) Thermal efficiency of the top channel, (b) thermal efficiency of the bottom channel, and (c) electrical efficiency; here $TR_{top} = (T_{m,top} - T_a)/I_{AM1.5}$, $TR_{bot} = (T_{m,bot} - T_a)/I_{AM1.5}$.

Figure 12 shows the performance maps of the PVSC-based SSPVT collector. The thermal efficiency η_{th-top} of the PVSC-based SSPVT collector is lower than that of the CdTe-based collector for the same TR_{top} and TR_{bot} . The upper limit of TR_{top} of the PVSC-based SSPVT collector (*i.e.*, the white dash line shown in Fig. 12(a)) is lower than that of the CdTe-based SSPVT collector. However, the thermal efficiency of the bottom channel η_{th-bot} of the PVSC-based SSPVT collector is significantly higher than that of the CdTe-based collector as shown in Fig. 12(b). The value of TR_{bot} can be as high as 0.2, and it still has not yet reached its limit. The performance maps of the PSC-based SSPVT collector are shown in Fig. 13. Among these three types of SSPVT collector, PSC-based SSPVT collector has the highest thermal efficiency, but the lowest electrical efficiency.

Comparing to the conventional PVT collector that has only one low-temperature thermal output, the SPV-based SSPVT collector usually has two thermal outputs, *i.e.*, high- and low-temperature outputs. The 2-D performance maps are able to present the electrical and thermal performance of the SSPVT collector under different working conditions. The SPV cells are effectively thermally-decoupled from the high-temperature thermal absorber. Therefore, the output temperature of the bottom channel can be increased without compromising the SPV electrical efficiency, capable of meeting the requirements of high-temperature applications. The SPV material significantly affects not only the electrical performance but also the thermal performance. Detailed performance maps can assist designers and researchers in selecting appreciate SPV materials, estimating tech-economic performance in specific conditions and applications.

3.4. Total effective efficiencies of SSPVT collectors

The three outputs of the SPV-based SSPVT collector, *i.e.*, electricity, low-temperature heat and high-temperature heat, have significantly different values. Therefore, it is not that reasonable to directly use the sum of the electrical and thermal efficiencies to compare the performance of the different types of

SSPVT collectors. Here, the total effective efficiency, which considers the value differences of the outputs, is selected as a criterion for comparing the performance of different SSPVT collectors [29]:

$$\eta_{\text{tot}} = \eta_{\text{el}} + w_{\text{LT}} \cdot \eta_{\text{th-top}} + w_{\text{HT}} \cdot \eta_{\text{th-bot}} \quad (13)$$

where w_{LT} and w_{HT} are weight coefficients that reflect the worth of low- and high-temperature heat relative to that of electricity. These weight coefficients can be calculated according to thermodynamic values (*e.g.*, via heat engine conversion efficiencies or second-law arguments), cost values (*e.g.*, via a price ratio of thermal energy to electricity), *etc.* Of note is that the values for w_{HT} and w_{LT} strongly depend on the specific application scenario, *i.e.*, the required temperature of the thermal energy, the demands of the end-users, *etc.*, such that it is necessary to specify an application scenario when comparing the performance of different SSPVT collectors.

Here, an assumed common application scenario is defined, *i.e.*, the required temperatures of the low- and high-temperature thermal energies by an end-user are 50 °C and 120 °C (*i.e.*, $TR_{\text{top}} = 0.023$ and $TR_{\text{bot}} = 0.093$). The high temperature of 120 °C is typically selected here as it can be widely used for sterilisation, chemical processing and power generation, *etc.*, while the 50 °C hot air can be directly used for solar drying and space heating, *etc.* According to the performance maps in Figs. 11-13, the values of η_{el} , $\eta_{\text{th-top}}$ and $\eta_{\text{th-bot}}$ are 8.0%, 20.7% and 16.6% for the CdTe-based SSPVT collector; 13.6%, 10.6% and 22.6% for the PVSC-based SSPVT collector; 5.0%, 3.8% and 40.7% for the PSC-based SSPVT collector. The total effective efficiencies of the CdTe-, PVSC- and PSC-based SSPVT collectors for different values of w_{HT} and w_{LT} are calculated by Eq. (13), which are shown in Fig. 14. High-temperature heat is always more valuable than low-temperature heat, thus w_{HT} is higher than w_{LT} . Therefore, half areas in Figs. 14 (a), (b) and (c) where $w_{\text{HT}} < w_{\text{LT}}$ are blank. The total effective efficiency linearly increases as the values of w_{HT} and w_{LT} increase. The performance of the CdTe-, PVSC- and PSC-based SSPVT collectors under different seniors (*i.e.*, different w_{HT} and w_{LT}) can be compared by comparing Figs. 14 (a), (b) and (c). The total effective efficiency of the PVSC-based SSPVT collector is always higher than that of the CdTe-based SSPVT collector for the same values of w_{HT} and w_{LT} . The total effective efficiency of the PSC-based SSPVT collector is also higher than that of the CdTe-based SSPVT collector for most situations (w_{HT} and $w_{\text{LT}} > 0.1$). Interestingly, the relative performance of the PVSC- and PSC based SSPVT collectors depend on the values of w_{HT} and w_{LT} . The PSC-based SSPVT collector has a higher efficiency than the PVSC-based SSPVT collector only when the values of w_{HT} and w_{LT} locate in the area above the white dash line in Fig. 14(c), and *vice versa*. The PSC-based SSPVT collector has better thermal performance than the PVSC-based SSPVT collector. Therefore, the advantage of the PSC-based SSPVT collector is more significant when the thermal energy has a higher value.

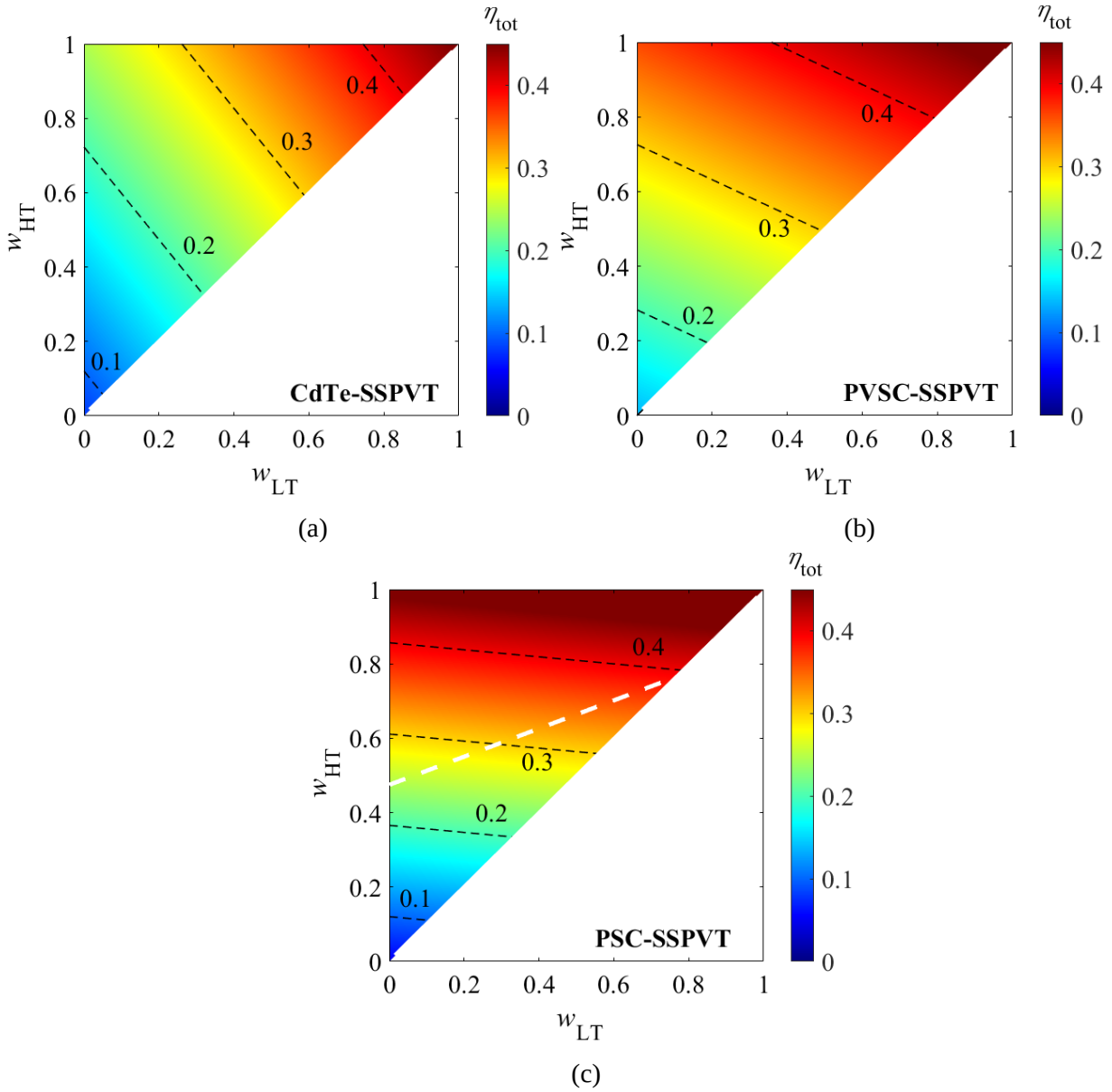


Figure 14. Total effective efficiencies of for: (a) CdTe-, (b) PVSC-, and (c) PSC-based SSPVT collectors ($T_{\text{top}} = 50\text{ }^{\circ}\text{C}$ and $T_{\text{bot}} = 120\text{ }^{\circ}\text{C}$).

3.5. Comparison with other solar conversion technologies

Solar energy can be harvested by PV panels, evacuated tube (ET) solar-thermal collectors, and conventional PVT collectors. Here, the performance of the SPV-SSPVT solar collector is compared with those of PV, ET and PVT collectors. A factor is defined to indicate the relative performance:

$$r_{\text{eff}} = \frac{\eta_{\text{tot}}}{\eta_{\text{PV}}, \eta_{\text{ET}}, \text{ or } \eta_{\text{PVT}}} \quad (14)$$

where η_{tot} is the total effective efficiency of the SPV-based SSPVT collector given by Eq. (13), η_{PV} the electrical efficiency of the standalone PV panel, and η_{ET} is the equivalent efficiency of the ET collector:

$$\eta_{\text{ET}} = w_{\text{HT}} \cdot \eta_{\text{th-ET}} \quad (15)$$

where $\eta_{\text{th-ET}}$ is the thermal efficiency of the ET collector. ET collectors are able to generate valuable high-temperature heat, thus the weight coefficient w_{HT} is used in Eq. (15) to calculate the equivalent efficiency of the ET collector. The total effective efficiency of the PVT collector, η_{PVT} , is defined as:

$$\eta_{\text{PVT}} = \eta_{\text{el-PVT}} + w_{\text{LT}} \cdot \eta_{\text{th-PVT}} \quad (16)$$

where $\eta_{\text{el-PVT}}$ and $\eta_{\text{th-PVT}}$ are the electrical and thermal efficiencies of the PVT collector.

Conventional PVT collectors are usually only able to generate low-temperature heat, thus the weight coefficient w_{LT} is used in Eq. (16) to convert the thermal energy to equivalent electricity. The SSPVT collector has a better performance than PV, ET or PVT collectors when the value of r_{eff} in Eq. (14) is larger than one, and *vice versa*.

In this section, PVSC is selected as the SPV cells for the SSPVT collector, considering that the PVSC-based SSPVT has good performance in both electrical and thermal generations. The same application scenario as the last section is defined, *i.e.*, the required temperatures of the low- and high-temperature thermal energies by an end-user are 50 °C and 120 °C.

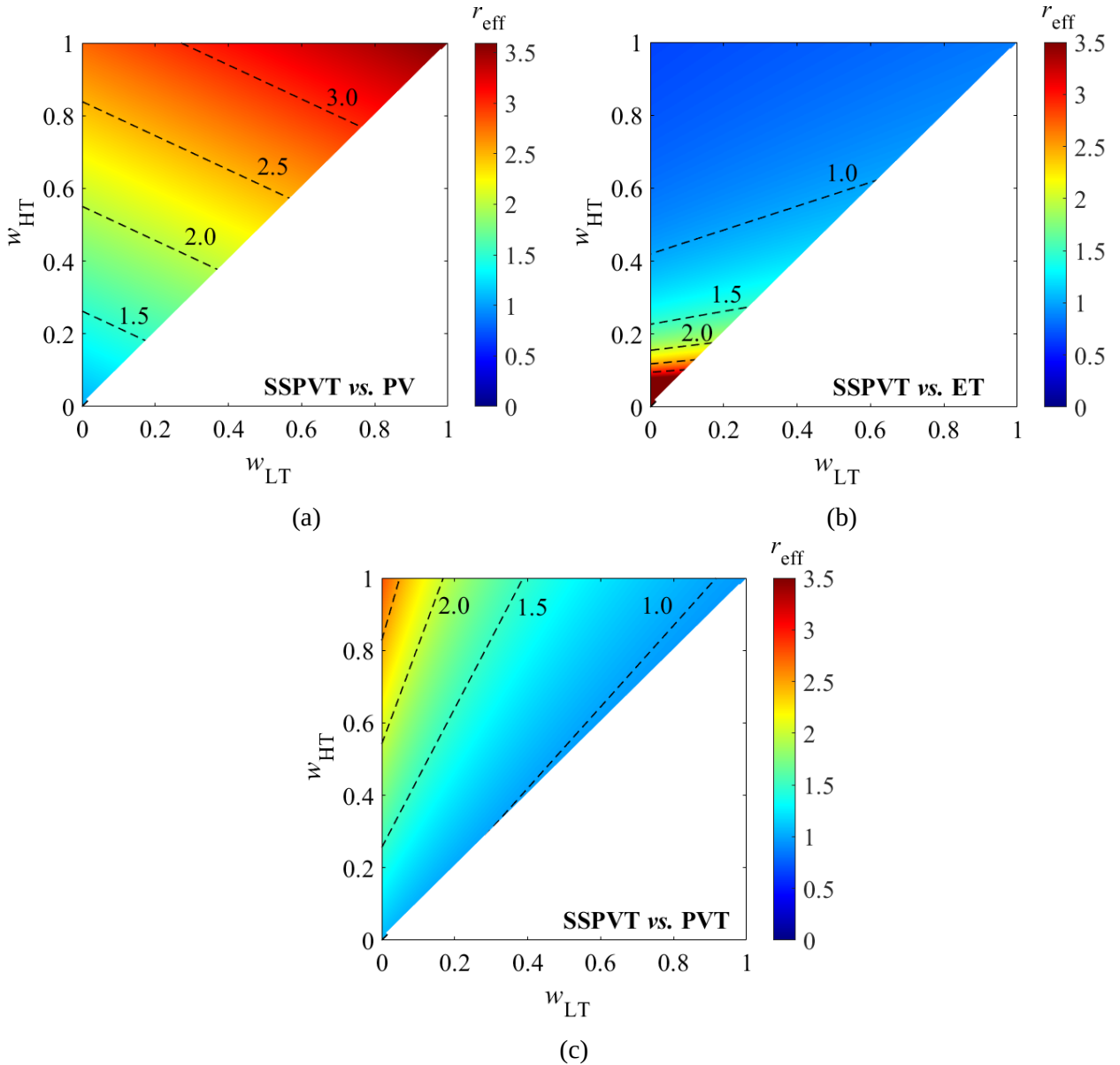


Figure 15. Comparison of total effective efficiency of the PVSC-based SSPVT collector with (a) standalone PV, (b) ET, and (c) PVT solar collectors.

Figure 15(a) shows the value of r_{eff} when comparing the PVSC-SSPVT collector with a standalone PV panel which is comprised of the same PVSC. The operating temperature of the

standalone PV panel is assumed to 50 °C, which is in a reasonable range under a solar irradiance of 1000 W/m² [12]. The value of r_{eff} is always larger than 1 as shown in Fig. 15(a), suggesting that the SSPVT collector always has a better performance than the standalone PV panel. The PV cells in the SSPVT collector is not shaded by any layers (*e.g.*, additional spectral-splitting filters or glazing layers), thus the SSPVT collector still performs better than the PV panel even when the thermal energy is cheap (*i.e.*, small w_{LT} and w_{HT}). Figure 15(b) shows the value of r_{eff} when comparing the SSPVT collector with an ET collector which produces 120 °C high-temperature heat. The thermal efficiency of the ET collector is taken from Ref. [1]. The ET collector has a better performance than the SSPVT collector when $w_{\text{HT}} > 0.6$, but has a worse performance when $w_{\text{HT}} < 0.4$. The ET collector is effective at generating high-temperature heat. Thus, the advantage of the ET collector is more significant when the high-temperature heat is more valuable (*i.e.*, the value of w_{HT} is larger). The SSPVT collector usually performs better than a conventional glazed PVT collector which employs the same PVSC, as shown in Fig. 15(c). The thermal efficiency of the PVT collector is taken from Ref. [7]. The SSPVT collector especially shows its significant advantage over the conventional PVT collector when the high-temperature heat is much more valuable than the low-temperature heat (*i.e.*, w_{HT} is large while w_{LT} is small), as shown in the upper-left corner of Fig. 15(c).

Comparing to other types of SSPVT collectors (*e.g.*, the nanofluid-based SSPVT collector [40]), SPV-based SSPVT collectors do not require additional optical filters, and thus have simpler structures and potentially lower cost. The electrical efficiency of SPV-based SSPVT collectors can be as high as the standalone PV cells (*e.g.*, ~14% for both the PVSC-based SSPVT collector and standalone PVSC in this study). However, a significant decrease of electrical efficiency was observed in the nanofluid-based SSPVT collector due to the optical loss of the nanofluid optical filter (*e.g.*, the electrical efficiency decreases from ~10% to ~5% according to the results in Ref. [40]).

The SPV-based SSPVT collectors investigated in this study, constructed of existing materials instead of assumed ideal materials, have been proved to be effective at harvesting solar energy. Furthermore, compared with PV and ET collectors that can only generate electricity or thermal energy, and the conventional PVT collectors that can only generate electricity and low-temperature thermal energy, SPV-based SSPVT collectors are able to simultaneously produce electricity, low-temperature heat and high-temperature heat. SPV materials are under fast development and thus the performance of SPV-based SSPVT collectors still can be further improved in future.

4. Conclusions

This study investigates a set of compact flat-plate spectral-splitting PVT (SSPVT) solar collector designs employing semi-transparent photovoltaic (SPV) cells as both the spectral-splitting optical filters and for electricity generation. Different types (*i.e.*, materials) of semi-transparent solar cells were selected for investigation, namely CdTe, PVSC and PSC.

It was demonstrated that SPV cells are effective at spectrally separating the solar spectrum, with simulation results showing that 27.2%, 33.3% and 51.8% of the incident solar energy is transmitted through the CdTe, PVSC and PSC cells and then absorbed by the high-temperature solar thermal (ST) absorber. Observations of the temperature distributions through the collectors showed that the SPV cells were effectively thermally decoupled from the high-temperature ST absorber, and that the bottom channel was able to generate high-temperature (100-200 °C) heat, while the SPV cells were maintained at relatively lower working temperature (< 60 °C).

It was found that the performance of SPV-based SSPVT collectors depends strongly on the SPV material, since the optical properties of the cells significantly affect the solar energy allocation. It was shown that a CdTe-based SSPVT collector under one sun can generate simultaneously: high-temperature heat ($T_{\text{bot}} = 150\text{ }^{\circ}\text{C}$, $\eta_{\text{th-bot}} = 19.5\%$), low-temperature heat ($T_{\text{top}} = 56\text{ }^{\circ}\text{C}$, $\eta_{\text{th-top}} = 29.1\%$), and electricity ($\eta_{\text{el}} = 8.1\%$). Similarly, a PVSC-based collector can generate: high-temperature heat ($T_{\text{bot}} = 150\text{ }^{\circ}\text{C}$, $\eta_{\text{th-bot}} = 21.1\%$), low-temperature heat ($T_{\text{top}} = 50\text{ }^{\circ}\text{C}$, $\eta_{\text{th-top}} = 22.5\%$), and electricity ($\eta_{\text{el}} = 13.8\%$). A PSC-based collector can generate: high-temperature heat ($T_{\text{bot}} = 150\text{ }^{\circ}\text{C}$, $\eta_{\text{th-bot}} = 40.6\%$), low-temperature heat ($T_{\text{top}} = 45\text{ }^{\circ}\text{C}$, $\eta_{\text{th-top}} = 17.9\%$), and electricity ($\eta_{\text{el}} = 5.3\%$).

Detailed performance maps for the CdTe-, PVSC- and PSC-based SSPVT collectors were provided. The output temperature of the SSPVT collector was adjusted over a wide range to meet the different temperature requirements/demands of diverse end-users. The maximum reduced temperatures of the top and bottom channels of the CdTe-based SSPVT collector were 0.053 and 0.189, *i.e.*, the low-temperature and high-temperature thermal-energy outputs were $53\text{ }^{\circ}\text{C}$ and $189\text{ }^{\circ}\text{C}$ higher than the ambient temperature. The output temperatures of PVSC- and PSC-based collectors were $> 200\text{ }^{\circ}\text{C}$ higher than the ambient temperature. The bottom channels of these collectors reach such high temperatures owing to the excellent thermal insulation characteristics of the design. Of note is that the thermal efficiency of the collectors decreases at higher operating temperatures.

The total effective efficiency, which considers the value differences of the three outputs (*i.e.*, electricity, high- and low-temperature heat), was selected as a criterion for comparing the performance of different SPV-based SSPVT collectors. Among the three types of SPV-based SSPVT collectors, both PVSC- and PSC-based collectors had better performance than CdTe-based collectors. The relative performance between the PVSC- and PSC-based collectors depended on the relative value of the high-temperature thermal energy to that of electricity (*i.e.*, w_{HT}). PVSC-based collectors had better performance than PSC-based collectors when the value of w_{HT} was lower than the bound given in this study (around 0.5-0.7), and *vice versa*. Considering the fact that the value of heat is usually less than half of that of electricity in most practical applications (*i.e.*, $w_{\text{HT}} < 0.5$), the PVSC-based collector currently is the best one among the three types of SPV-based collectors investigated in this study. But of note is that SPV materials are under fast development and thus the performance of SPV-based SSPVT collectors still can be further improved in future.

Compared to conventional solar technologies, PVSC-based SSPVT collectors always have a better performance than standalone PV panels and conventional PVT collectors. PVSC-based collectors also have a better performance than ET collectors when the value of w_{HT} is below ~ 0.5 .

In summary, SPV cells can act as effective spectral-splitting optical filters in SSPVT collectors. SPV-based SSPVT collectors have simple structures and high reliability because they do not require additional complex optical filters compared to conventional SSPVT collectors. Detailed performance maps and results, based on existing available materials, provide insights of such next-generation solar technologies. SPV-based SSPVT collectors are of great promise in full-spectrum solar energy harvesting and conversion.

Nomenclature

Abbreviations

CdTe	Cadmium telluride solar cell
EQE	External quantum efficiency

ET	Evacuated tube
FVM	Finite volume method
IR	Infrared
PSC	Polymer solar cell
PV	Photovoltaic
PVT	Photovoltaic-thermal
PVSC	Perovskite solar cell
SPV	Semi-transparent photovoltaic
SSPVT	Spectral-splitting photovoltaic-thermal
ST	Solar thermal
UV	Ultraviolet

Symbols

c_p	Specific heat capacity
G_i	Spectral distribution of the incident light onto layer i
G_{in}	Incident solar spectrum for the SPV cells
G_{ST}	Solar spectrum for the solar-thermal absorber
h_c	Heat transfer coefficient
$I_{AM1.5}$	Solar irradiance of AM1.5
k_f	Thermal conductivity of the fluid
k_s	Thermal conductivities of the solid materials
m_{bot}	Mass flow rate of the bottom channel
m_{top}	Mass flow rate of the top channel
$Q_{abs,i}$	Solar energy absorbed by layer i
$Q_{abs,PV}$	Solar energy absorbed by PV
Q_{conv}	Convective heat loss
$Q_{h,PV}$	Heat generated in the SPV cells
Q_f	Energy source term of fluid elements
Q_{rad}	Radiative heat loss
Q_s	Energy source term of solid elements
T_a	Ambient temperature
T_{bot}	Output temperature of the bottom channel
$T_{m,bot}$	Mean temperature of the bottom channel
$T_{m,top}$	Mean temperature of the top channel
T_{ref}	Reference temperature (25 °C)
T_{sky}	Equivalent sky temperature
T_{SPV}	Operating temperature of the SPV cells
T_{ST}	Temperature of the solar-thermal absorber
T_{top}	Output temperature of the top channel
T_w	Outer wall temperature
TR_{bot}	Reduced temperature of the bottom channel
TR_{top}	Reduced temperature of the top channel
u	Velocity of the fluid

u_w	Wind speed
w_{HT}	Weight coefficient for high-temperature heat
w_{LT}	Weight coefficient for low-temperature heat

Greek

α	Absorptivity
β	Temperature coefficient
γ	Reflectivity
δ	Thickness
ε	Emissivity
η_{el}	Electrical efficiency of the SSPVT collector
$\eta_{el,0}$	Electrical efficiency at 25 °C
η_{ET}	Equivalent efficiency of the evacuated-tube solar-thermal collector
η_{PV}	Electrical efficiency of the standalone PV panel
η_{PVT}	Total effective efficiency of the conventional PVT collector
η_{th-ET}	Thermal efficiency of the evacuated-tube solar-thermal collector
η_{th-bot}	Thermal efficiency of the bottom channel
η_{th-top}	Thermal efficiency of the top channel
η_{tot}	Total effective efficiency
ρ	Density
σ	Stefan-Boltzmann constant
τ	Transmittance

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Author contributions

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Conflict of interest

The authors declare that they have no conflicts of interest.

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