Numerical modeling and simulation comparisons of a cost efficient novel CPVT Solar Collector

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Abstract

In this work, the simulation of a Concentrated PhotoVoltaic Thermal (CPVT) solar collector system has been done by means of Finite Volume Method. The system consists of a parabolic collector, which concentrates solar irradiance onto solar cells, which are refrigerated attaching them to a pipe which contains water. At the same time, water is warmed up. Numerical results were validated with experimental data obtained within the current eranet project for the Economic Cogeneration by Efficiently Concentrated SUNlight (ECOSUN). The idea of this project is to study how to take advantage of the residual heat produced by photovoltaic elements. The CPVT model is oriented to optimize the design for solar cooling applications. Finally, a 1D model is introduced to reduce the computational cost of the simulation for obtaining key parameters.

Keywords: parabolic collector, solar energy, solar power, solar cell, FVM, CPVT.

1. Introduction

Thermal engineering and other fields of physics are combined in order to study solar cell technology. Experiments are very useful tool to understand the behaviour of any system, but on the other hand, they can be very expensive and difficult to perform. In solar cell systems, thermal and solid components are often combined with fluids in order to refrigerate them. Physics of these systems are well understood: they combine Navier-Stokes equations with energy conservation equation (and sometimes radiation equations). Despite of the fact that we know the equations, they do not have an analytical solution for the general case. One powerful tool that allows us to obtain numerical results of a solar cell system and help us in the optimizing process is Computational Fluid Dynamics (CFD) (Guadamund, et al.). Discretising properly the equations and using computational resources, we can simulate these systems and obtain information of them. Once we have our model implemented, it is important to use experimental data to assess that our model is correct, and then we can use it to simulate the system under different conditions, such as different inlet conditions, different geometrical configurations or different materials, avoiding the necessity of repeating the experiments, which is in general expensive.

ECOSun project has as main aim the cost reduction of electricity and heat co-generation via a Concentrated Photovoltaic/Thermal (CPV-T) system by applying low-cost materials and advanced industrial manufacturing methods. In the CPV-T system, the solar radiation is captured in parabolic through concentrator based on a novel support structure fabricated by injection moulding and focused on a Co-Generation Absorber Module (CAM), where special c-SiPV-cells are operated under concentration. The purpose of this project is focused on concentrated photovoltaic thermal collector (CPVT), which concentrates solar irradiance onto a row of photovoltaic solar cells (Sharaf and Orhan). At the same time, these solar cells must be refrigerated in order to work optimally. This could be done, for instance, attaching these solar cells to a pipe which contains some fluid (water in our case). One of the subtasks of the project has been to simulate properly the whole CPVT system, comparing our results against the results obtained experimentally. Different configurations of inflow water will be taken into account, using a closed system with a glass envelope and low-pressure air. The whole CPVT system can be attached to absorption machines in order to take advantage of the residual heat (Castro et al., 2021).

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Selection and/or peer review under responsibility of Scientific Committee
doi:10.18086/eurosun.2022.12.04 Available at http://proceedings.ises.org

2. CPVT solar cell system

Fig. 1: CPVT solar collector experimental configuration (Felsberger, et. al. 2020)

Figure 1 show the experimental configuration of the experiment carried out by Felsberger, et. al. 2020, and Figure 2 and Figure 3 show the structure of the CPVT solar cell system we want to simulate. From a numerical point of view, it consists of three parts: solid regions, fluid domains and coupling interfaces.

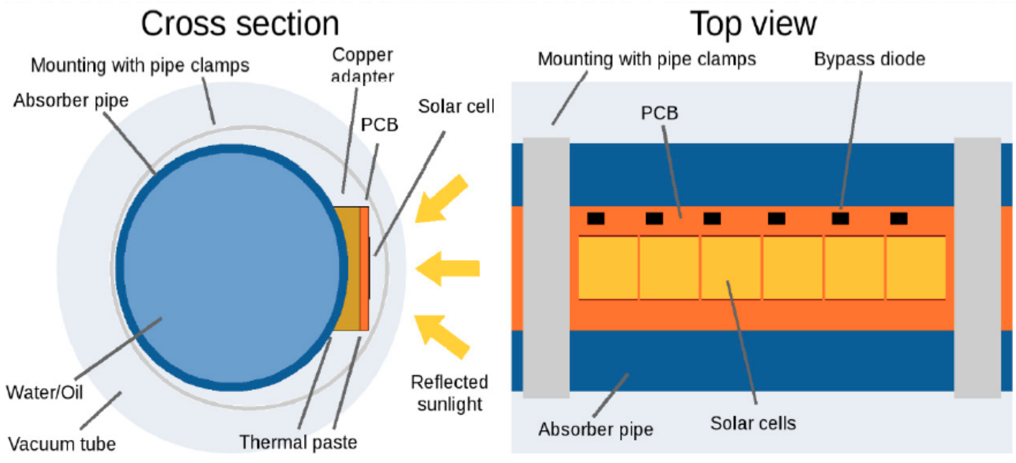

Fig. 2: Side scheme of the CPVT solar collector experimental configuration (collector not included) (Felsberger, et. al. 2020)

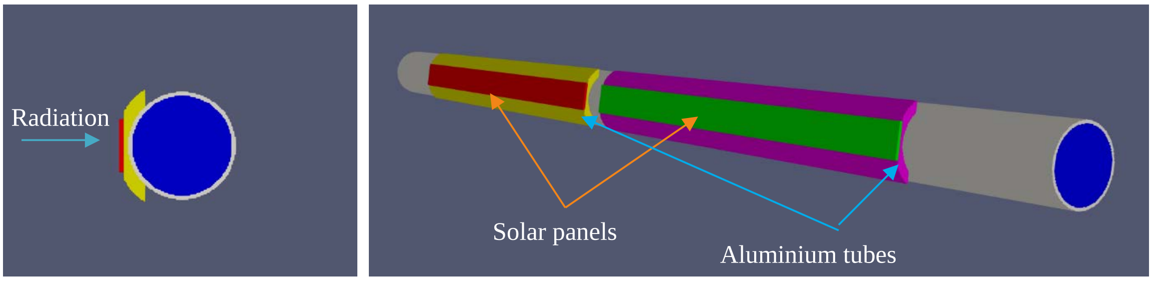

Fig. 3: CPVT cross section configuration (left); CPVT configuration front of parabolic collector (collector not included)

Figure 2 also shows the important parts of the system: i) an absorber pipe; ii) a printed circuit board (PCB) which have the solar cells attached; and iii) a piece which connects the PCB with the pipe iv) and an envelope glass to isolate the system. Finally, a parabolic solar collector is used to concentrate solar power onto the solar cells, as shown in Figure 1.

3. 3D Numerical model and validation

The equations we need to solve for each region are:

- Solid elements: energy equation conservation, (note that for this case, the velocities are equal to 0).

$$\frac{\partial T}{\partial t} + \boldsymbol{u} \cdot \nabla \mathrm{T} = \frac{k}{\rho c_p} \nabla^2 \boldsymbol{T} + \frac{J}{\rho c_p}, \qquad \text{(eq. 1)}$$

where T is the temperature, **u** is the velocity (**u**=0 for solid elements), k is the thermal conductivity, ρ is the density, c_p is the heat capacity and J is the source term.

- Fluid elements: (Eq.1) + Incompressible Navier-Stokes equations with buoyancy term (Boussinesq approximation):

$$\nabla \cdot \boldsymbol{u} = 0, \qquad \text{(eq. 2)}$$

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\mathbf{u} = -\frac{1}{\rho}\nabla(p - \rho \boldsymbol{g} \cdot \boldsymbol{z}) + \nu \nabla^2 \boldsymbol{u} - \boldsymbol{g}\beta(T - T_0), \qquad \text{(eq. 3)}$$

where **u** is the velocity, p is the pressure, ρ is the density, ν is the kinematic viscosity, **g** is the gravity constant, β is the thermal expansion coefficient, and T is the temperature. Buoyancy term is needed to take into account natural convection with the exterior air. Forced convection appears between the flow inside the pipe and the pipe, so this term is not really relevant there.

- Coupling interfaces (solid-solid and fluid-solid):
  - Heat flux exiting one domain enters the other: $Q_1 = -Q_2$.
  - Same temperature at the interface: $T_1 = T_2$.

Convective and radiative terms are taken into account in order to compute the heat flux. The radiation model used is the Finite Volume Discrete Ordinates Method, which solves the RTE (Radiative Transfer Equation):

$$\hat{\boldsymbol{s}} \cdot \nabla I(\boldsymbol{r}, \hat{\boldsymbol{s}}) = \kappa I_b + (\kappa + \sigma_s) I, \qquad \text{(eq. 4)}$$

applying a finite volume method (Colomer, 2006; Wang, 2020). In the previous equation, the intensity radiation field I is solved, which is defined as the energy due to radiation, propagating along a given direction $\hat{\boldsymbol{s}}$, that crosses a unit area normal to $\hat{\boldsymbol{s}}$, per unit area, unit solid angle around $\hat{\boldsymbol{s}}$, unit wavelength and time. The absorption coefficient κ and the scattering coefficient σ_s model the medium behavior.

Finally, the radiation coming from the parabolic collector is assumed as a radiative boundary condition computed as (Zarza, 2015):

$$q = \frac{W_{par}}{W_{pV}} G_b \eta_{opt}, \qquad \text{(eq. 5)}$$

where W_{par} is the aperture width of the parabola, W_{pV} is the height of the solar cells, G_b is the direct solar irradiance and η_{opt} is the optical efficiency of the parabola.

Many codes such as Ansys Fluent or OpenFOAM are able to deal with cases which need to solve the previous equations. OpenFOAM was the code chosen in our case. In particular, we selected the “chtMultiRegionFoam” solver, which can solve transient cases with conjugate heat transfer between solids and fluids. Furthermore, radiation is solved by means of fvDOM method, which is the more precise model that OpenFOAM has integrated.

This model was validated using experimental data coming from EcoSUN experimental test cases under lab tests conditions (Felsberger, et. al. 2020; Buchroithner, et al.). Besides, other experiments have been done within this configuration in order to obtain experimental data (Felsberger, et. al. 2021). Our model was capable of reproduce properly the results of these experiments. The main objective of the model was to obtain the temperature reached by the system in the steady state. Figure 4 shows the validation of the model under lab conditions. The validation of the model is deeply examined in Santos, et.al (2021).

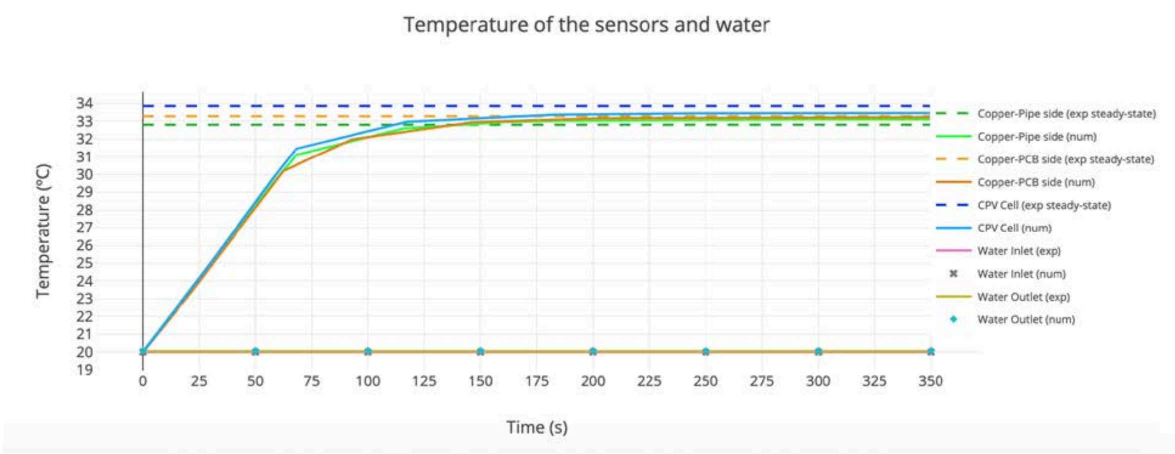

Fig. 4: Temperature obtained at temperature sensors. Water input temperature is 20.0ºC. Slashed lines represent the steady state temperature found in the experiment.

Figures 5, 6 and 7 show an example of the temperature reached by the back part of the PCB in the steady state. All the results have a reliable agreement with the experimental ones (Santos, et. al. 2021).

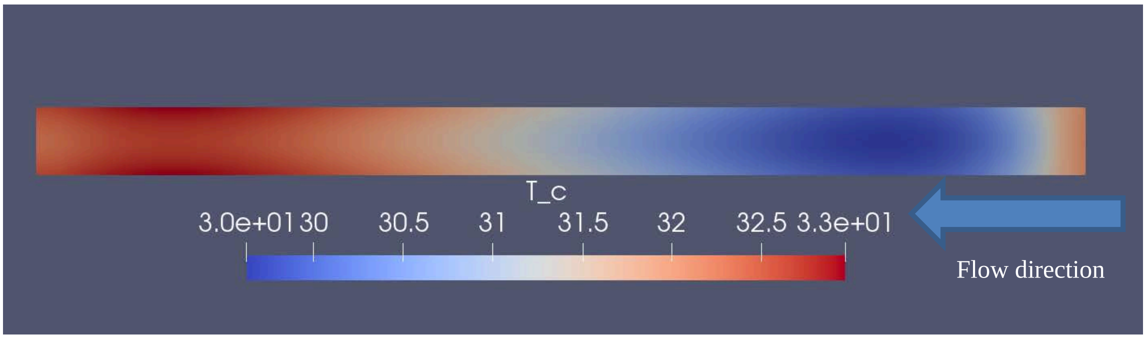

Fig. 5: HTF 17ºC case. (Top) Steady state temperature profile behind the PCB. (Bottom) Temperature of the sensors over time.

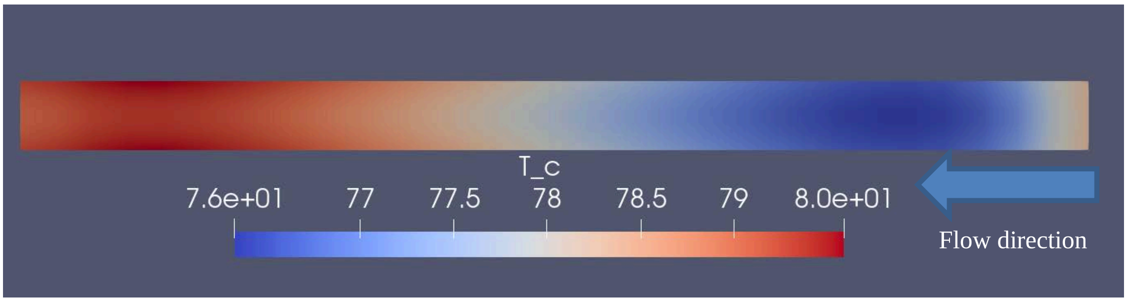

Fig. 6: HTF 65ºC case. (Top) Steady state temperature profile behind the PCB. (Bottom) Temperature of the sensors over time.

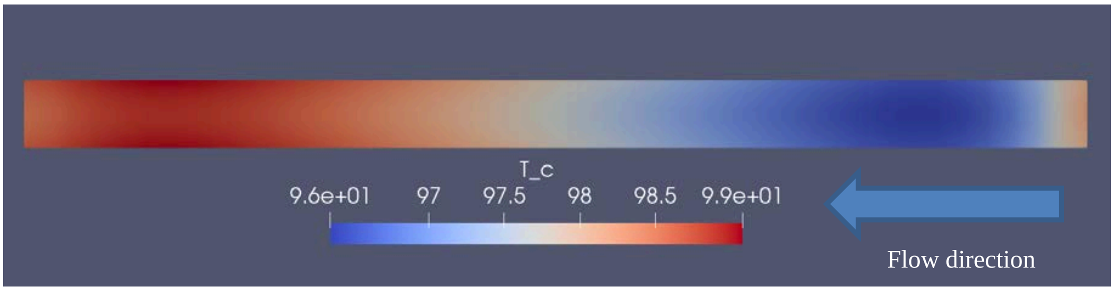

Fig. 7: HTF 90ºC case. (Top) Steady state temperature profile behind the PCB. (Bottom) Temperature of the sensors over time.

The short orange region found at the HTF entrance is caused by the heat transfer from the pipe to the PCB, and it was also observed in the experiments. Radiation also warms up the solid pipe, and part of this heat is transferred to the PCB.

4. 1D Numerical model and comparison of models

A transient 1D integration of the continuity, momentum and energy equations was done by means of finite volume method. Once we have the 1D discretization of the equations in the axial direction, they are solved by means of a step-by-step method. Some parameters such as friction factor and heat transfer coefficient are estimated using empirical correlations. In our case, the model was used to solve only the pipe, taking into account the width of the pipe and the flow. For more details of this discretization, see Morales, et. al. (2009).

Such model, due to the nature of a 1D simulation, has the advantage of needing much less computational power in comparison with a 3D simulation. On the other hand, it is only capable of providing information about some key parameters such as pressure drop, local heat transfer coefficient or outlet temperature of the HTF. For instance, it is not capable of providing information about the map temperature of the pipe or the PCB.

Another limitation of this model, which is very important in our analysis, is that it is assuming that heat flux is known as a boundary condition and it is assumed to be entering through all the pipe homogeneously. Clearly, this is not happening in our case, where the radiation enters only from the cells side and it is not arriving homogeneously to the pipe. However, as we will see now, this approximation is capable of reproducing some key aspects of the real experiments.

Tab. 1: Pressure drop, average heat transfer coefficient and outlet temperature obtained for the different test cases using both models.

	Pressure drop 3D model [Pa]	Pressure drop 1D model [Pa]	Heat transfer coed 3D model [W/m2K]	Heat transfer coed 1D model [W/m2K]	Experimental outlet temperature [ºC]	Outlet temperature 3D model [ºC]	Outlet temperature 1D model [ºC]
HTF 17ºC	9	8	703	674	17.48	17.46	17.57
HTF 65ºC	10	7	1259	1221	65.00	65.02	65.02
HTF 90ºC	25	17	2252	2221	88.68	88.67	88.69

As we can see in Table 1, the 1D model is able to obtain proper values for the pressure drop, the heat transfer coefficient and the outlet flow temperature. However, as we can see in Figures 8, 9 and 10, it is not capable of reproducing properly the fluid temperature along the pipe. This is due to the assumption that the heat flux is entering homogeneously the pipe. As the heat flux entering the system is the same in both models, the outlet temperature is very similar, but as it is entering the system homogeneously for the 1D case and in homogeneously for the 3D case, the temperature map is going to differ. From this feature, the 1D model adjusts the wall temperature to fix the flux, so the wall temperature is not going to be correct either.

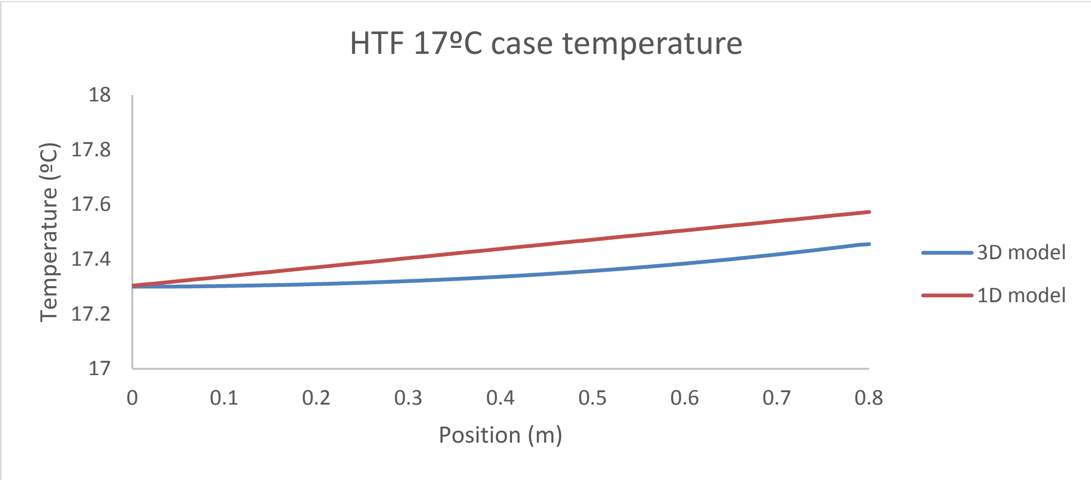

Fig. 8: Outlet temperature of the heat transfer fluid for the 17 ºC HTF case obtained using both models.

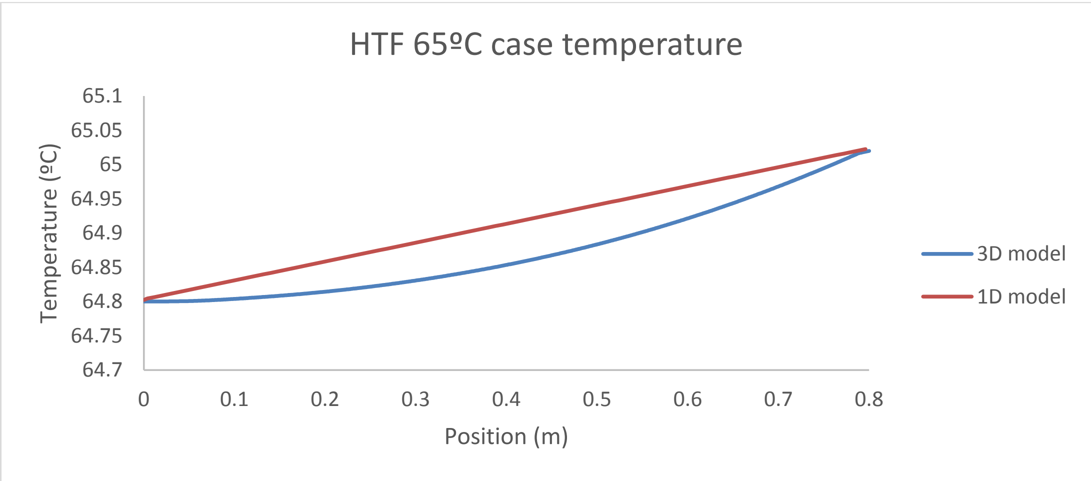

Fig. 9: Outlet temperature of the heat transfer fluid for the 65 ºC HTF case obtained using both models.

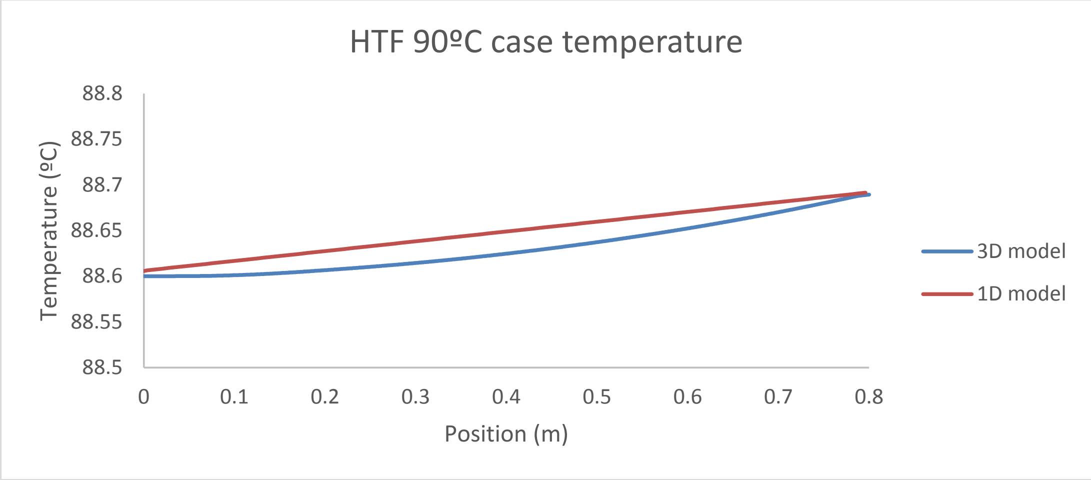

Fig. 10: Outlet temperature of the heat transfer fluid for the 90 °C HTF case obtained using both models.

5. Conclusions

A whole and detailed 3D numerical model for CPVT systems has been numerical developed, validated and experimentally tested under laboratory and real tests conditions. This model has demonstrated an excellent capability of prediction of the thermal behaviour of the system, and it can also be used as a numerical tool to study different geometries configurations for specific solar cooling application.

On the other hand, the 1D numerical model is useful for performance comparisons, but it is not bale to stablish detailed values of the system. However, it gives good results for outlet temperature, pressure drop and heat transfer coefficients.

6. Acknowledgments

This project has received funding from SOLAR-ERA.NET Cofund 2 joint call undertaking under the European Union’s Horizon 2020 research and innovation programme.

7. References

Buchroithner, A., Gerl, B., Felsberger, R., Wegleiter, H., 2021. Design and operation of a versatile, low-cost, high-flux solar simulator for automated CPV cell and module testing, Solar Energy, Volume 228, Pages 387-404, ISSN 0038-092X. DOI: https://doi.org/10.1016/j.solener.2021.08.068

Castro, J., Rigola, J., Kizildag, D., Oliet, C., 2021. Preliminary assessment of a polygeneration system based on a concentrated photovoltaic thermal (CPVT) solar collector, ISHPC 2021: proceedings, Technische Universität Berlin Campus Charlottenburg, pp. 176-180. DOI: http://dx.doi.org/10.14279/depositonce-12278

Colomer, G., 2006. Numerical methods for radiative heat transfer, PhD thesis, Universitat Politècnica de Catalunya (UPC), Terrassa.

Felsberger, R., Buchroithner, A., Gerl, B., Wegleiter, H., 2020. Conversion and Testing of a Solar Thermal Parabolic Trough Collector for CPV-T Application, Energies, 13, 6142, 1-24. DOI: https://doi.org/10.3390/en13226142

Felsberger, R., Buchroithner, A., Gerl, B., Schweighofer, B., Wegleiter, H., 2021. Design and testing of concentrated photovoltaic arrays for retrofitting of solar thermal parabolic trough collectors, Applied Energy, Volume 300, 117427, ISSN 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2021.117427

Guadamund, E., Chiva, J., Colomer, G., Farnós, J., Al Mers, A., Rigola, J., Perez, C., 2017. Development of a high accurate numerical platform for the thermal and optical optimization of linear Fresnel receivers. *ISES Solar World Congress/IEA SHC Solar Heating and Cooling Conference*, pp. 2000 – 2011. DOI:10.18086/swc.2017.31.04

Morales-Ruíz, S., Rigola, J., Pérez-Segarra, C.D., García-Valladares, O., 2009. Numerical analysis of two-phase flow in condensers and evaporators with special emphasis on single-phase/two-phase transition zones, Applied Thermal Engineering, Volume 29, pp 1032-1042. DOI: https://doi.org/10.1016/j.applthermaleng.2008.05.017

Santos, D., Castro, J., Kizildag, D., Rigola, J., Oliva, A, 2021. Numerical Simulation of a Cost Efficient Novel CPVT Solar Collector. *ISES Solar World Congress*, Virtual conference, October 25-29. DOI:10.18086/swc.2021.22.08

Sharaf, O. Z., Orhan, M. F., 2015. Concentrated photovoltaic thermal (CPVT) solar collector systems: Part I – Fundamentals, design considerations and current technologies. Renewable and Sustainable Energy Reviews. Volume 50, 1500-1565. DOI: https://doi.org/10.1016/j.rser.2015.05.036

Wang, B., 2020. OpenFOAM fvDOM Model discretization notes (URL: https://boyaowang.github.io/boyaowang_OpenFOAM.github.io/2020/09/30/fvdom/). Last access: 08/10/2021.

Zarza, E., 2015. Sesión 13: Diseño de captadores y de campos de captadores cilindroparabólicos, lecture notes, Electricidad Termosolar, Escuela de Organización Industrial, delivered in 2015-2016. URL: (https://www.eoi.es/es/savia/publicaciones/25357/electricidad-termosolar-captadores-cilindroparabolicos-sesion-13-y-14). Last access: 08/10/2021.