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Development of a solar cavity receiver with a short-term storage system

Ambra Giovannelli*, Muhammad Anser Bashir

Department of Engineering, Roma Tre University, Via della Vasca Navale 79, Rome 00146, Italy

Abstract

The technological progress carried out in the development of high-temperature materials has led to the design of new concentrated solar power plants, like Dish-Micro Gas Turbines (Dish-MGTs). This study proposes a novel cavity receiver for small-scale Dish-MGT plants with a phase-change material storage system integrated inside the receiver container. Such a storage system provides a proper thermal inertia to the component, to level the effects of short-term solar radiation fluctuations which can reduce plant performance and, in the worst cases, damage seriously the MGT. In the paper, results related to CFD steady-state and transient (charge and discharge storage phases) analyses are presented and discussed.

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Keywords: Micro Gas Turbine; PCM storage system; Solar Receiver

1. Introduction

Small-Scale Solar Power Plants can represent an interesting alternative to traditional power production systems for the development of off-grid areas located in regions with a high DNI [1]. Several technologies based on the solar source utilization like Photovoltaic Panels (PVs), Dish-Stirling engines and solar Organic Rankine Cycle systems have been developed or are under development. Each of them has its own peculiar advantages and drawbacks [2].

Recently, the availability on the market of new high-temperature materials has made possible the development of

* Corresponding author. Tel.: +39-0657333424; fax: +39-065593732.
E-mail address: ambra.giovannelli@uniroma3.it

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new Concentrated Solar Power systems as Micro Gas Turbines (MGTs) coupled with solar mini-towers or dishes [3,4]. In Fig. 1 a scheme of a Dish-MGT plant in shown. The main components are a solar radiation concentrator, a high-temperature solar receiver and a recuperated MGT connected with an electric generator. Techno-economic analyses reported in [5-7] show that Dish-MGT systems could outperform Dish-Stirling engines from an economic point of view. Moreover, if equipped with a thermal energy storage, the Dish-MGT system could compete with PVs, cheaper than any other alternative solar plant if a storage system is not taken into consideration.

The most challenging component of a Dish-MGT plant is the solar receiver. In a no-hybridized configuration (without a supplementary combustion chamber), the receiver has to heat up the air coming from the recuperator from about 600 to 800-850 °C at least. Several receivers, most of them based on a cavity concept, have been designed and some prototypes developed [3, 8, 9]. Many technological concerns like material degradation, thermal stress, creep-fatigue potential damage, have been already taken into consideration. Notwithstanding, another relevant aspect has to be highlighted: solar radiation natural fluctuations cause a variability in the impinging solar radiation over the receiver surface. If the receiver has not the proper thermal inertia, a fast variation of the air flow outlet temperature occurs. Such a phenomenon leads to a remarkable system performance drop and, in the worst cases, it could dramatically cause a MGT structural damage. To reduce solar radiation fluctuation effects, the integration of a short-term storage system in a cavity receiver is proposed in the present paper. In particular, a high temperature Phase-Change Material (PCM) storage system has been taken into consideration due to its compactness and its constant-temperature storage feature.

2. The solar receiver: geometry and heat transfer model

For application in Dish-MGT plants, a tubular solar cavity receiver integrated with PCM for a short-term thermal energy storage is proposed. The integrated PCM system stores the thermal energy to reduce air flow outlet temperature fluctuations caused by sudden variations in the solar radiation flux. The receiver consists of a cylindrical container with twelve U-tubes housed inside the structure and submerged in the PCM material. The concentrated solar radiation impinges on the receiver front surface, heating the PCM inside the volume. The PCM is an intermediate medium which can store sensible and latent heat and transfers part of the heat to the compressed air which comes from the recuperator and flows inside the U-tubes. On the basis of previous analyses carried out by the Authors [10 and 11], the receiver front surface has been shaped with a conical cavity. Such a geometry increases the receiver radiation absorption capacity, reducing the hot wall temperature and, consequently, the re-radiation effect.

For the proper PCM choice, many factors have been considered: melting temperature, heat of fusion, volumetric heat storage, liquid/solid void volume, thermal conductivity, compatibility with other materials. Finally, the eutectic metallic alloy Si-Mg (56/44wt%) was selected on the basis of its high melting temperature (946 °C), low corrosive properties, small change in volume, high heat of fusion (757 kJ/kg), good thermal conductivity [12, 13]. Fig. 2 shows the detailed structure of the solar receiver and the most relevant dimensions and PCM properties.

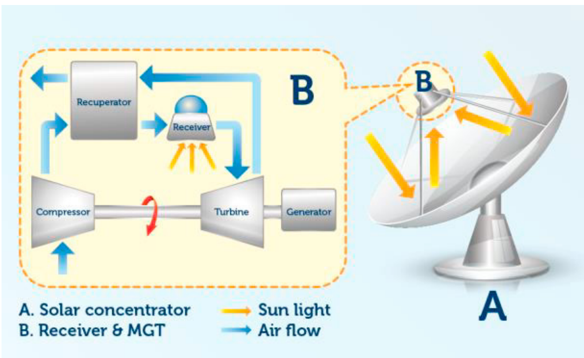
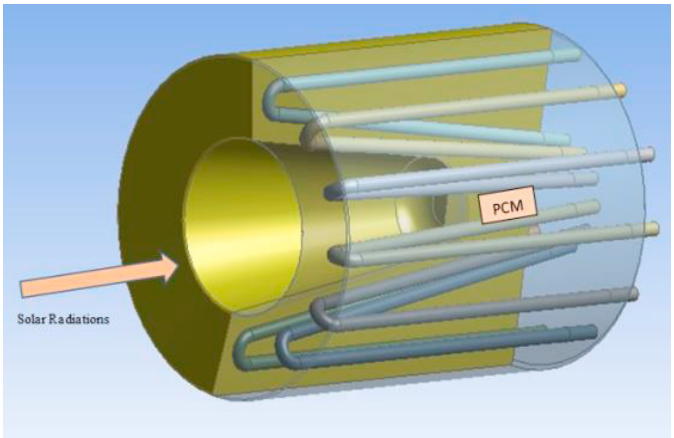


Fig. 1. Scheme of a Dish-MGT concentrating solar power plant [4]



Receiver Dimensions	
Cylinder diameter	380 mm
Cylinder length	440 mm
Cavity aperture diameter	180 mm
Cavity length	300 mm
Tube diameter	15 mm
U-Tube length	826 mm
No. of tubes	12
PCM (Mg56-Si44) Properties	
Density	1900 kg/m^3
Specific heat	632 J/kgK
Thermal conductivity	70 W/mK
Melting temperature	1219 K
PCM volume	41 Liters

Fig. 2. Receiver geometry: scheme and details

2.1. Heat transfer model

The receiver heat transfer model takes into consideration the device front (including cavity) and lateral surfaces, the PCM material and the compressed air flow inside the tubes. In Fig. 3 a sketch is given. Part of the impinging radiation Q_{solar} is absorbed by the front surface, while another part is lost by convection Q_{conv} and reflection Q_{ref}. Due to the high temperatures reached over the front surface, the most relevant losses are connected with the re-radiation phenomenon ($Q_{re\text{-}rad}$) and, secondary, with Q_{conv}. Most of the absorbed power is transmitted to the PCM (Q_{PCM}) and just a small amount is absorbed by the ceramic receiver container. The PCM heats the compressed air (Q_{AIR}) and a small amount of heat is rejected through the lateral surface of the receiver container (Q_{loss}).

In the analyses reported in the following chapter, Q_{loss}, Q_{ref} and the heat absorbed by the material of the U-tubes (a superalloy) have been considered negligible.

3. CFD analyses of the receiver

Simulations have been carried out using the commercial CFD code ANSYS FLUENT 17.2. The computational domain consists of two solid domains, one for steel tubes and another one for the ceramic container. Furthermore, three fluid domains have been created: one for the air flow inside tubes, one for the PCM into the receiver and the

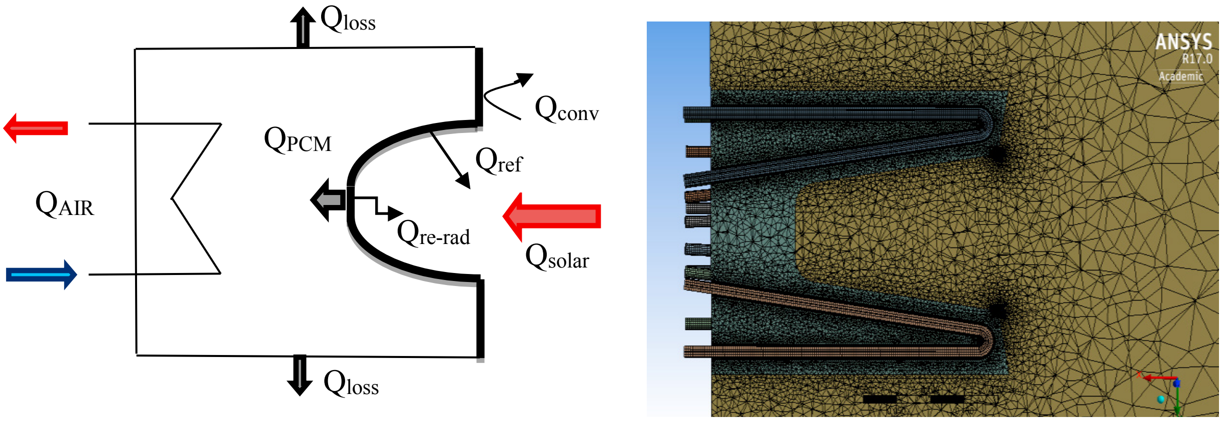


Fig. 3. Receiver heat transfer scheme (left), detail of the mesh (right)

last one for the outer domain. The external domain is four times longer and about three times larger than the receiver structure. In order to establish the appropriate mesh size for an accurate solution, a preliminary study have been conducted on a smaller geometry given by a receiver sector with two U-tubes, on the basis of the radial symmetry of the receiver. Hexahedral cells were assigned to the working fluid (compressed and pre-heated air) domain and tetrahedral cells were applied to the PCM domain. The Spalart-Allmaras one equation turbulence model was selected and for the modelling of the phase-change process the "Solidification and Melting" model was taken into consideration. The convergence criterion of the residuals was 10^{-4} (10^{-6} for energy).

According to a preliminary analysis of a 5 kWe Dish-MGT system [14], air mass flow rate for each U-tube, inlet temperature and pressure were assumed 0.008 kg/s, 590 °C and 200 kPa, respectively. Air has been considered as a perfect gas while the PCM as a eutectic alloy.

3.1. Steady state analysis

For steady state evaluation, a uniform solar radiation of 500 kW/m^2 concentrated in a spot with the same diameter of the receiver front face has been modelled. A complete geometry for the whole receiver and the outer domain have been taken into consideration. According to preliminary mesh-independence study, a grid of about 5.4×10^6 cells was arranged. Results related to temperature and liquid fraction are reported in Fig. 4. It can be noticed that PCM has a 72% of liquid fraction. The average hot wall temperature is about 1160 °C which is compatible with the maximum service temperatures of ceramic materials. The air flow outlet temperature is about 820 °C, higher than the minimum allowable MGT service temperature.

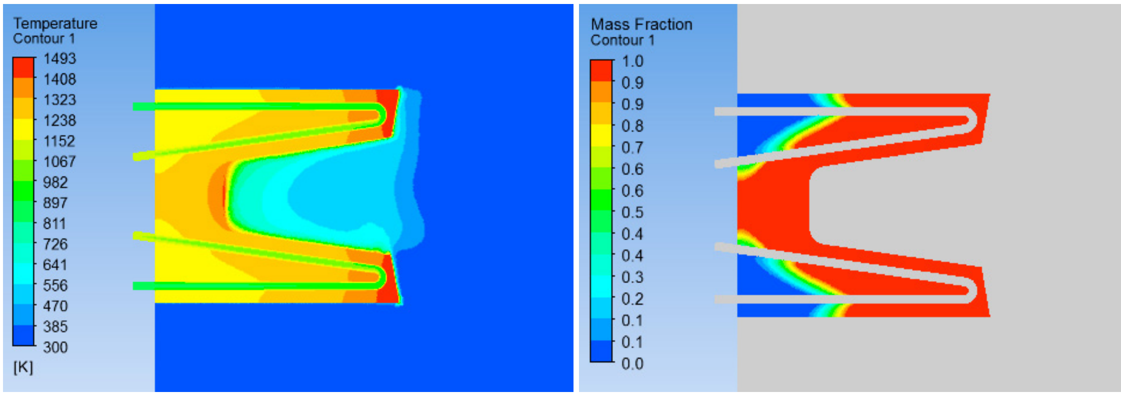


Fig. 4. Temperature (left) and liquid Fraction (right) contours of steady state process

3.2. Transient analysis: charge and discharge process

For transient simulations, a symmetrical model was applied to reduce the mesh size. The 3-D computational domain was reduced to a receiver sector containing two U-tubes. A grid of about 10^6 cells was generated.

At the beginning of the charge phase, the PCM is initialized at ambient temperature (15°C). During the charging process, the PCM absorbs heat from the cavity wall and starts melting. PCM melting gradually increases away from the hot wall (Fig.5 a-b-c) and latent (and sensible) heat is stored in the PCM. Heat is transferred to the WF and its outlet temperature rises gradually up to 800°C as shown in Fig. 6. The charging process requires about 1 hour and, in the end, the PCM is not completely melted (the liquid fraction is about 75%).

Starting from such results, the discharge process was simulated. The concentrated solar flux is set to zero and the heat stored in the PCM begins to be utilized. Initially, sensible heat is transferred to the working fluid, as, locally, the PCM temperature is higher than the melting one. Thereafter, the PCM begins to solidify and heat at constant temperature is extracted until the complete PCM solidification. In Fig. 5 d-e-f the PCM liquid mass fraction is reported after 16, 31 and 46 minutes from the discharge phase beginning.

The average effects of charging and discharging phases on PCM liquid mass fraction, air flow outlet temperature, PCM and receiver front surface temperatures are clearly highlighted in Fig. 6.

At constant air mass flow rate for each tube, inlet temperature and pressure (0.008 kg/s, 590 °C and 200 kPa, respectively), the discharge process requires about 30 minutes. Thereafter, the PCM becomes completely solid.

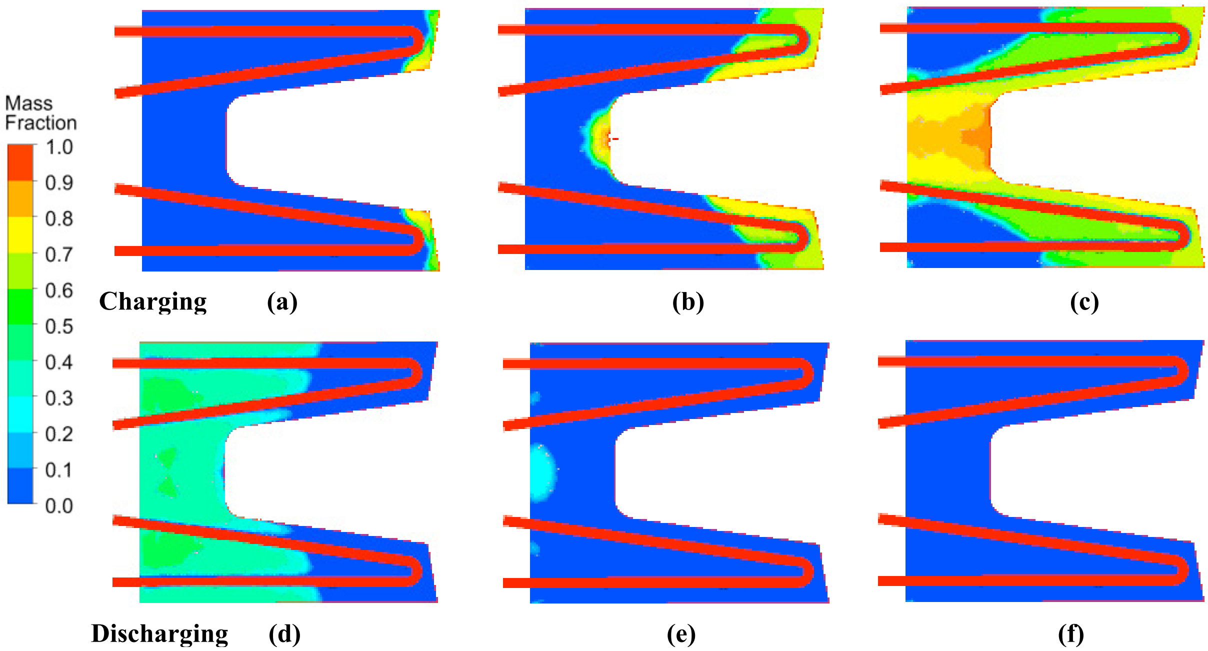


Fig. 5. Liquid fraction of PCM during charging and discharging process. Charging: (a) 13 min. (b) 25 min. (c) 41 min. Discharging: (d) 16 min. (e) 31 min. (f) 46 min

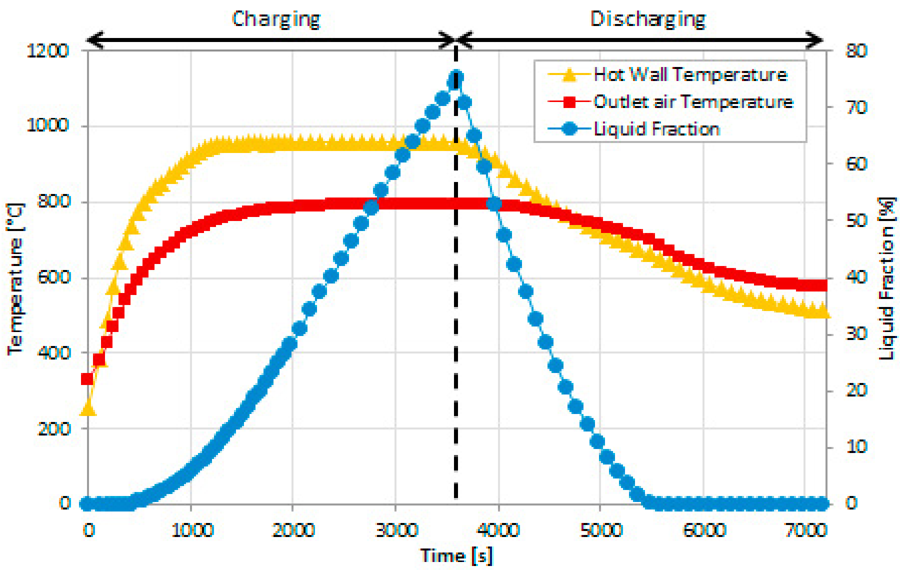


Fig.6. Temperature and liquid fraction during charging and discharging process

4. Conclusions

A novel High-Temperature Cavity Solar Receiver for Dish-MGT plants, equipped with a PCM short-term storage system has been designed.

The component has been analyzed in steady-state (nominal conditions) and transient conditions (charge and discharge storage process), by means of CFD methods. A steady-state analysis at nominal boundary conditions has been carried out, using the complete receiver geometry integrated with an external domain to model the effects of receiver wall re-radiation, absorption and convection. Setting a 500 kW/m^2 solar radiation, a satisfactory behavior has been detected in terms of air flow outlet temperature, PCM liquid fraction and maximum temperatures compatible with selected material.

Thereafter, transient analyses have been carried out. Using the radial symmetry, a simplified geometry has been set up taking a sector of the receiver with two U-tubes into account. Thus, some convection and radiation effects on the cavity wall have been neglected reducing significantly computational efforts. A storage charge process of 1 hour and a discharge phase of 50 minutes have been simulated, highlighting a partial use of the storage system potentialities. According to service limitations (e.g. in terms of maximum temperatures and thermal stress) for selected materials, the radiation concentrated on the receiver front face could be increased in order to achieve a complete PCM liquefaction in nominal and charge conditions (enhancing the storage capacity) and increasing the air flow outlet temperature (improving MGT performance).

Acknowledgements

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References

[1] Quoilin, Sylvain, and Orosz, Matthew, (2013) "Rural elettrification through decentralized concentrating solar power: technological and socio-economic aspects", *Journal of Sustainable Development of Energy, Water and Environment Systems* 1(2) (2013): 199-212.
[2] Giovannelli, Ambra. (2015) "State of the Art on Small-Scale Concentrated Solar Power Plants", *Energy Procedia* 82 (2015): 607-614.
[3] Blanco, Manuel, and Santigosa, Lourdes Ramirez, (2017) "Advances in Concentrating solar thermal research and technology", Woodhead Publishing (eds), ISBN 978-0-08-100516-3.
[4] OMSOP EU Project, https://omsop.serverdata.net/Pages/Home.aspx (retrieved April 11th, 2017).
[5] Prosin, T., Pryor, T., Creagh, C., Amsbeck, L., Uhlig, R., (2015) "Solar gas turbine systems with centrifugal particle receivers, for remote power generation", *Energy Procedia* 69 (2015): 1382-1392.
[6] Ragnolo, Giacomo, Aichmayer, Lukas, Wang, Wujun., Strand, Torsten, Laumert, Bjorn, (2015) "Technoeconomic design of a micro gas-turbine for a solar dish system", *Energy Procedia* 69 (2015): 1133-1142.
[7] Semprini, Simone, Sanchez, David, De Pascale, Andrea, (2016) "Performance analysis of a micro gas turbine and solar dish integrated system under different solar-only and hybrid operating conditions" *Solar Energy* 132 (2016) 279-293.
[8] Aichmayer, Lukas, Spelling, James, Laumert, Bjorn, (2015) "Preliminary design and analysis of a novel solar receiver for a micro gas-turbine based solar dish system", *Solar Energy* 114 (2015): 378-396.
[9] Wang, Wujun, Laumert, Bjorn, Xu, Haoxin, Strand, Torsten, (2015) "Conjugate heat transfer analysis of an impinging receiver design for a dish-Brayton system", *Solar Energy* 119 (2015) 298-309.
[10] Giovannelli, Ambra, Bashir, Muhammad Anser, Archilei, Erika Maria, (2017) "High-Temperature solar receiver integrated with a short-term storage system", *AIP Conference Proceedings* 1850 (2017) 050001.
[11] Giovannelli, Ambra, and Bashir, Muhammad Anser (2017) "High-Temperature cavity receiver integrated with a short-term storage system for solar MGTs: heat transfer enhancement", *Energy Procedia* (in press).
[12] Liu, Ming, Saman, Wasim, Bruno, Frank (2012) "Review on storage materials and thermal performance enhancement techniques for high temperature phase change thermal storage systems", *Renewable and Sustainable Energy Reviews* 16 (2012): 2118-2132.
[13] Birchenall, C. Ernest et al. (1981) "Heat storage in alloy transformations – Final Report", Technical report DOE/NASA/3184-2.
[14] Lanchi, Michela, et al. (2015) "Investigation into the coupling of Micro Gas Turbines with CSP technology: OMSoP project", *Energy Procedia* 69 (2015): 1317-1326.