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# High-Temperature Cavity Receiver Integrated with a Short-Term Storage System for Solar MGTs: Heat Transfer Enhancement

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## Abstract

Dish-Micro Gas Turbines (MGTs) can be promising systems for power production at small-scale by concentrated solar radiation. Several high-temperature solar receivers have been already designed for such plants, however, nowadays, none of them can assure the proper thermal inertia to level the effects of solar radiation fluctuations on engine performance and safety. In this paper, a solar receiver integrated with a short-term storage system based on high-temperature Phase-Change Materials (PCMs), is proposed. On the basis of a previous preliminary component design and analysis, the receiver geometry has been modified to improve storage capability and heat transfer to the working fluid, reducing temperatures on the irradiated surface making them compatible with material properties and reducing also temperature gradients inside the PCM.

Six different geometries, varying length, opening and shape of a front cavity have been analyzed by means of CFD methods. All the configurations have shown a satisfactory behavior in terms of working fluid outlet temperature, storage capabilities and maximum temperatures reached on the surface and inside the receiver. In particular, among them, three geometries can be considered the most promising ones.

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*Keywords:* High-Temperature Solar Receiver, PCM Storage System, Micro Gas Turbine

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## 1. Introduction

Small-Scale Solar Power plants can play a relevant role for the development of mini and micro-grids in remote areas with high DNI. Furthermore, they represent an interesting option for power production in off-grid regions [1]. Many efforts have been spent to develop Photovoltaic Panels (PVs), Dish-Stirling engines and Solar Organic Rankine Cycle systems. Each of them presents advantages and drawbacks as reported in [2]. In particular, Dish-Stirling engines show higher efficiencies than any other technology but, some key limitations like applied working fluids (helium or hydrogen), high internal pressures, component reliability and maintenance, prevented their spread. The replacing of the Stirling engine with a Micro Gast Turbine (MGT) could solve some of the abovementioned issues [3, 4]. As reported in Figure 1, the solar radiation, concentrated by a parabolic dish, impinges on a high-temperature receiver. Such a component replaces the combustion chamber of a conventional recuperated MGT for power production. 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 also compete with PVs.

The most critical component of a Dish-MGT system is the solar receiver. Without hybridization (a supplementary combustion chamber), the receiver has to heat the air coming from the recuperator up to 850-950 °C. Several receivers have been designed for this purpose starting from concepts applied to solar tower power plants at larger scale [8,9] or applied to small dish-Stirling engines [10-12].

Receivers can be divided in two main groups:

- Volumetric receivers: the working fluid is heated directly by the concentrated solar radiation. The receiver internal volume is separated from the external environment by a quartz window. The working fluid flows inside the component volume and, usually, the heat transfer is enhanced by a medium like a honeycomb or a porous structure [9, 11, 13];
- Tube receivers: the component is shaped as shell and tube exchangers or its casing shows a cavity. In both cases the working fluid is heated indirectly by receiver walls [14-17].

Even if many technological concerns have been already taken into consideration to provide high performance at design conditions, it has to be highlighted that solar radiation short-term variability causes fast fluctuations of the impinging radiation over the receiver surface. Therefore, if the receiver does not have the proper thermal inertia, MGT performance could drop drastically and the engine could be seriously damaged.

To avoid such effects, in this paper the design of a solar receiver integrated with a short-term storage system is proposed. In particular, a high-temperature PCM storage system has been taken into consideration based on its compactness and its constant-temperature thermal storage features.

## 2. Solar receiver geometry

The proposed receiver for Dish-MGT systems is a compact device in which a high-temperature PCM is contained to level instantaneous solar flux fluctuations.

A preliminary simple configuration was designed by Authors in the past [18]. In Figure 2 a component scheme is shown: it consists of a cylindrical container in which some U-tubes submerged in the PCM are housed. The concentrated solar radiation impinges on the receiver front surface, heating the PCM inside the volume. The PCM is an intermediate medium which stores thermal heat. Part of the heat is transferred to the working fluid (in MGT system compressed and pre-heated air coming from the recuperator) which flows inside the U-tubes.

Preliminary steady-state numerical analyses carried out with simplified models on a single module of the abovementioned receiver configuration highlighted a good thermal capacity showing that the basic concept can be of interest. Nevertheless, temperatures detected on the receiver front surface and in the PCM close to it, exceed materials maximum allowable upper limits. Furthermore, the storage effectiveness at design conditions is quite low, being the estimated PCM liquid fraction about 60% and being temperature gradients relevant inside the PCM volume [18]. Consequently, to solve such issues, the receiver geometry has been modified. In the present work, the receiver casing has a frontal cavity to improve the heat transfer process by enlarging the irradiated receiver surface without increasing re-radiation effects. Tubes inside the structure are re-arranged consequently. In Figure 3a a sketch of the new receiver configuration is drawn.

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 high melting temperature (946°C), low corrosive properties, small change in volume, high heat of fusion (757 kJ/kg), good thermal conductivity [19, 20]. Such a configuration has been analyzed by means of 3D CFD methods in steady-state nominal conditions varying the most important geometric parameters (cavity length, opening and shape) in order to select the most proper receiver configuration. Results are reported in next chapters.

## Numerical Model

To investigate the effect of cavity geometry on solar receiver effectiveness, 3D simulations were performed for six different cavity dimensions (Table 1) using the commercial CFD code ANSYS FLUENT 18.0.

A geometry for the whole receiver (Figure 3b) and the outer domain have been taken into consideration. The computational domain consists of three fluid domains and two solid ones: an inner receiver domain for the PCM material, the U-tubes fluid domain for the MGT compressed air, an external domain (ambient air) four times longer and three times larger than the receiver structure, the ceramic (SSiC) receiver container and a solid domain for the U-tubes. Figures 3 and 4 show such domains.

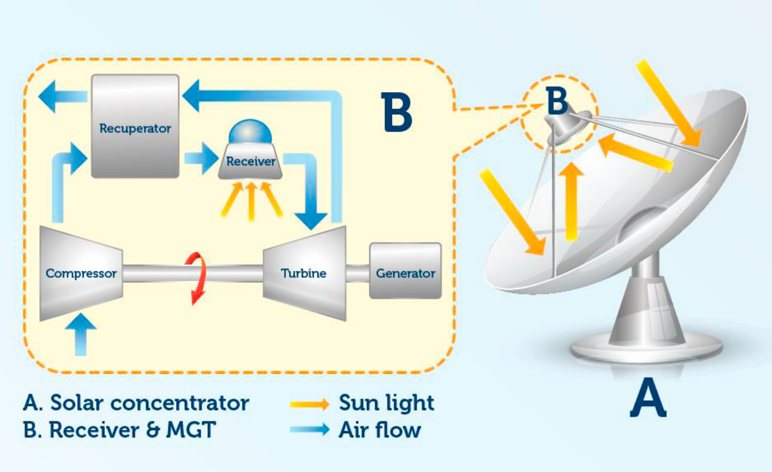

Fig. 1. Scheme of a Dish-MGT concentrating solar power plant [4]

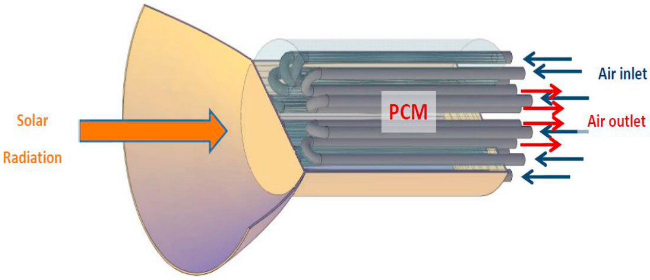

Fig. 2. Solar Receiver: preliminary geometry [18]

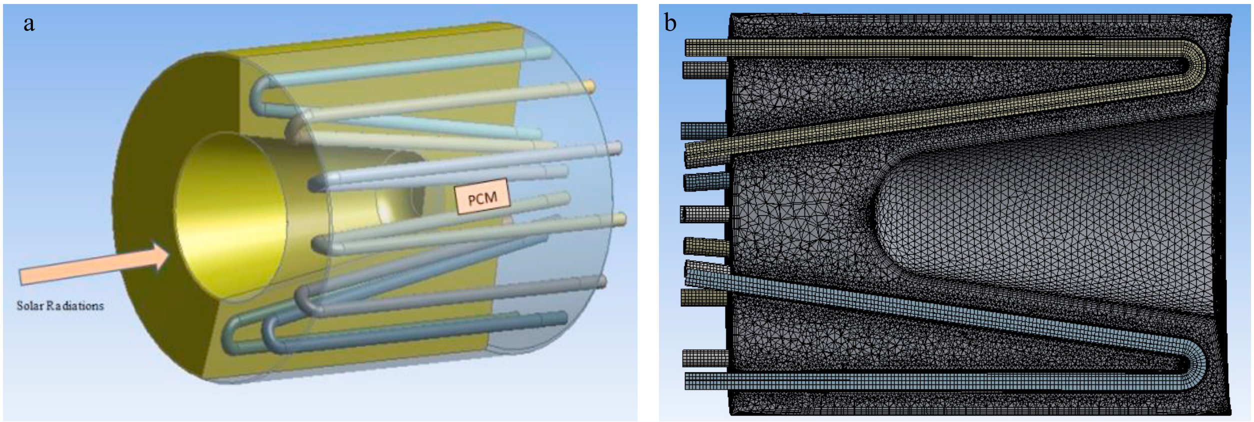

Fig. 3. (a) Receiver geometry; (b) Receiver typical mesh structure

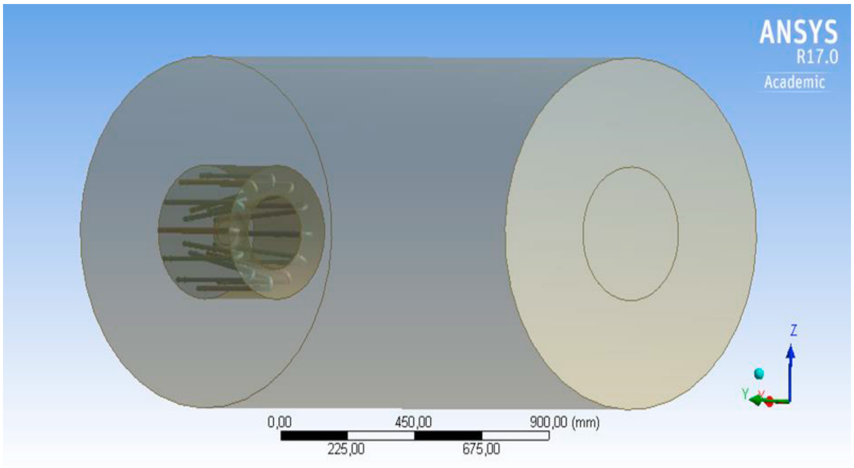

Fig. 4. Computational domain of CFD analyses

Table 1. Main cavity dimensions

| Cavity configurations | Cavity length L (mm) | Cavity diameter D (mm) |
|---|---|---|
| G1 | 250 | 180 |
| G2 | 300 | 180 |
| G3 | 350 | 180 |
| G4 | 250 | 210 |
| G5 | 300 | 210 |
| G6 | 350 | 210 |

The external domain has been considered to set up a proper heat transfer model. Such model takes into consideration a concentrated solar flux (500 kW/m2) applied on a focal spot located in the boundary surface in front of the receiver absorber surface (Figure 4). The receiver heat transfer model takes into consideration the impinging radiation absorbed by the device front surface, re-radiation, convection and reflection loss effects related to the absorber surface. The receiver outer wall has been considered well-insulated.

According to a preliminary analysis of a 5 kWe Dish-MGT system [21], the air inlet mass flow rate, temperature and pressure are 0.01 kg/s, 590 °C and 200 kPa, respectively. Air has been considered as a perfect gas while the PCM as a eutectic alloy.

To establish appropriate mesh size for an accurate solution, a preliminary study was conducted on a smaller geometry given by a receiver sector with two U-tubes, on the basis of the radial symmetry of the receiver. Hexa cells were assigned to the working fluid domain and tetra cells were used in the PCM domain in the cylinder and outer far field boundary. The final grid resolution has about 1.6 106 nodes and about 6 106 cells. α-Silicon Carbide (SSiC) was selected as cavity wall material having a thickness of 5 mm. A ray-tracing model has been applied to simulate the concentrated solar radiation. The k-ε turbulence model with standard wall function, the "solidification and melting" model for the PCM and gravity effects have been taken into consideration. The convergence criterion of the residuals has been maintained at 10-4 (10-6 for energy).

## 3. Shape optimization results and discussion

Cavity shape has a relevant effect on heat transfer mechanisms. For the design of the proper shape, steady state simulations were performed with two different cavity diameters (180 and 210 mm) and three cavity lengths (250, 300 and 350 mm), modifying cavity shape and tubes arrangements, accordingly. Figure 5 shows average temperatures of the whole receiver absorber surface (cavity and side walls of the device front surface) and of the working fluid at the outlet section for the six configurations analysed (Table 1). Figure 6 shows in detail the temperature distribution inside and outside the receiver varying cavity dimensions. Furthermore, the figure shows the PCM liquid fraction at design conditions. Comparing new configurations with the previous one without cavity [18], it can be noticed that, at 500 kW/m$^2$, the cavity increases the working fluid heating reducing considerably temperatures on the receiver front surface and inside the PCM (from 2400 K to maximum 1400 K), making temperatures compatible with material limits. Moreover, the storage system can work with a better effectiveness, improving the energy storage (liquid fraction increases from about 60% to 80-100%). Figure 6 shows also temperature distributions inside and outside the receiver, varying cavity dimensions. Configurations G1 and G2 have a less uniform temperature distribution with a peak at the cavity bottom and in the front corners. Configuration G3, with the smallest opening and the greatest depth, shows the low temperature in the cavity (Figures 5, 6 and 7a) and it is not able to liquefy the PCM completely. It can be observed that there is not a relevant temperature difference on front face walls in the cases taken into account. However, there is a significant temperature difference on the bottom of the cavity for different cavity geometries. High temperatures increase heat losses, especially due to re-radiation, while temperature gradients lead to high material thermal stress.

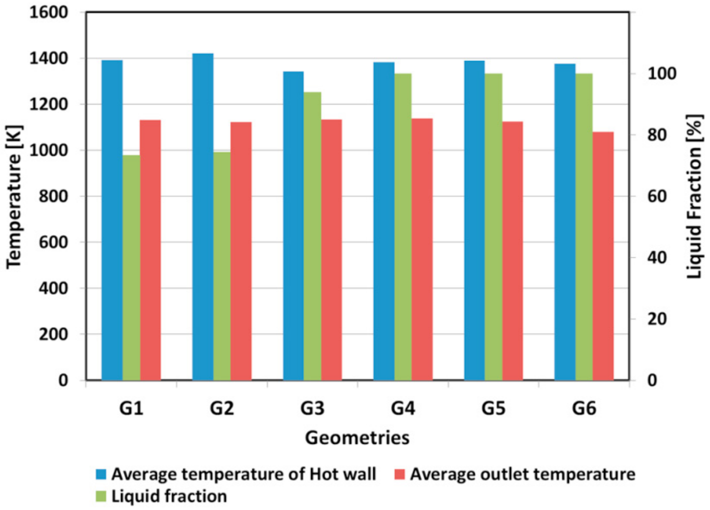

Fig. 5. PCM liquid fraction and average temperatures for the receiver absorber surface and the WF at the outlet section

The highest temperature is always under the allowable working temperature of the S-SiC material. The PCM inside the receiver for G4, G5 and G6 is completely melted while configurations G1 and G2 show a PCM liquid fraction of about 74% and G3 of about 95%. Figure 7a shows in detail the temperature distribution along the cavity length. It can be seen that G1 and G2 show the most temperature gradient on the cavity surface (about 150 °C) and a high temperature at the bottom part of cavity.

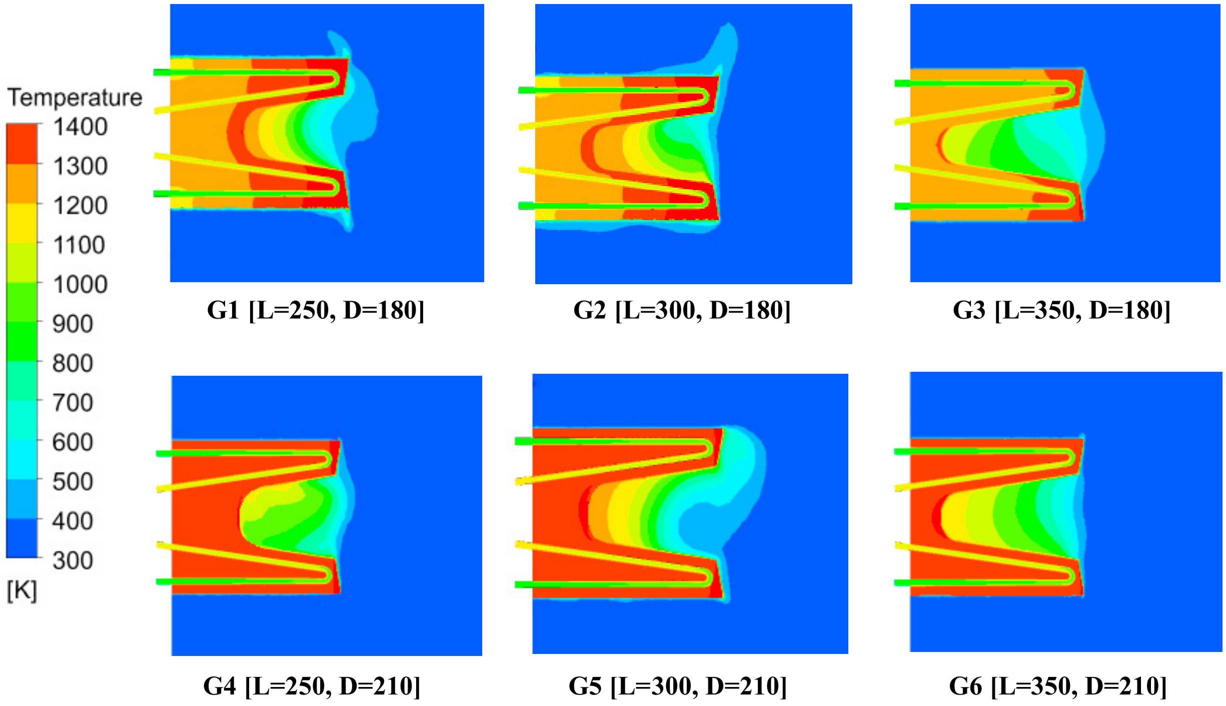

Fig. 6. Temperature distribution inside the solar receiver varying cavity geometries

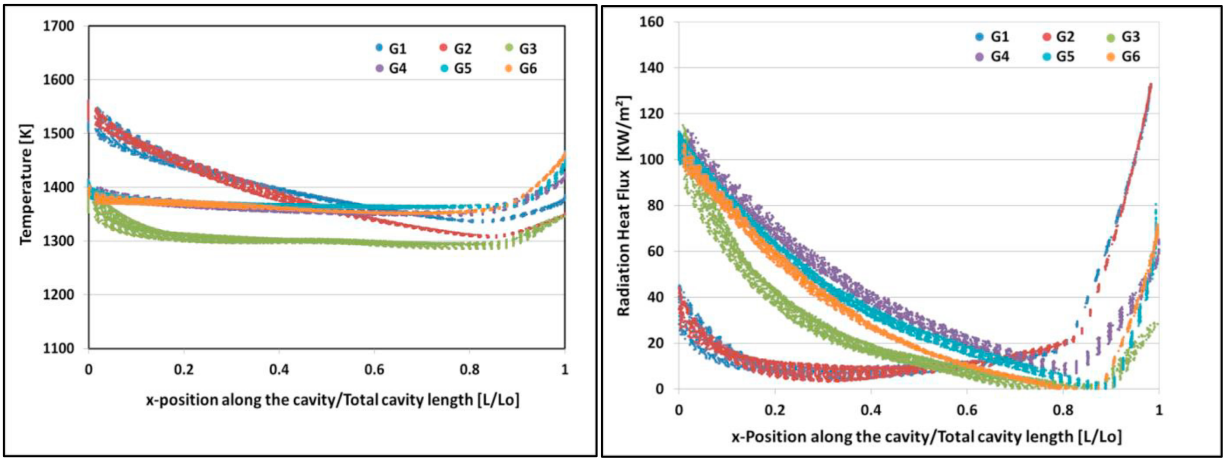

Fig. 7. a) Wall temperatures along cavity length; b) Radiative heat flux along cavity length

As explained above, simulations have been performed fixing a concentrated solar flux of 500 kW/m$^2$. In dish systems, the direction of the concentrated solar rays strictly depends on the concentrator layout and on the focal length. Therefore, a small concentration solid angle should be taken into account. For the present study, simulations do not take into account this parameter and concentrated radiation has been assumed with parallel rays applied on a circular spot having an area equal to the receiver front surface. Under such conditions, the radiative heat flux distribution along the cavity length is dependent from the cavity shape, as shown in Figure 7b. Peak flux on the cylindrical surface decreases toward the bottom in all the configurations.

However, G4, G5 and G6 have the highest radiative flux, while in configuration G3 radiative flux gradients are concentrated in the first 20% of the cavity length near the opening. Such results are in good agreement with considerations and results reported in [22] for a solar receiver with a 200 mm diameter cavity matched with a typical dish.

In Figure 8, details of the temperature contours inside the receiver container are reported for a distance of 200 mm from the cavity opening. All the configurations show a good heat transfer in the PCM. Therefore, metallic alloys can be considered suitable materials for thermal storage systems integrated in the device.

## Conclusions

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

The device was analysed in steady-state (design) conditions by means of CFD methods varying the most relevant cavity geometry dimensions (length, opening and shape). In particular, steady-state analyses were carried out on the whole receiver geometry completed with an external domain to model the effects of receiver wall re-radiation, absorption and convection, for six selected configurations. Setting a 500 kW/m2 solar radiation, a satisfactory behaviour has been detected in terms of working fluid outlet temperature (800-850°C), PCM liquid fraction (80-100%) and maximum temperatures (1100-1150°C) compatible with material selected.

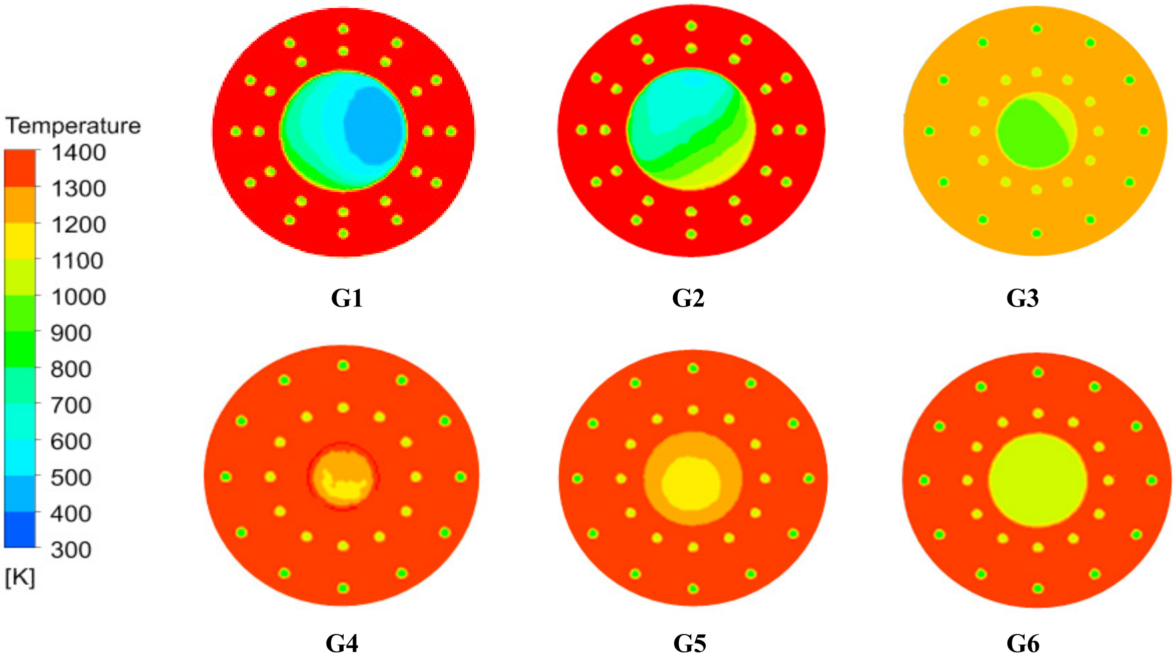

Fig. 8. Temperature Contours of receiver and cavity of all geometries at 200 mm distance from the cavity opening.

Moreover, the detailed analysis of temperature distributions and radiative heat flux on the cavity lateral and bottom surfaces, the average temperature achieved by the receiver absorber surface and the outlet working fluid and PCM melting behaviour reveal that configuration G3, with a deep and narrow cavity, shows the better behaviour in terms of lowest average temperature on the receiver hot wall, but shows also remarkable temperature gradients near the cavity opening. Furthermore, configurations G5 and G6 present a good behaviour and they will be taken into consideration for future transient analyses (charge and discharge processes) to evaluate device storage capabilities.

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## References

[1] Quoilin, Sylvain, Orosz, Matthew. (2013) “Rural electrification 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, Santigosa, Lourdes Ramirez, (2017) “Advances in Concentrating solar thermal research and technology”, Woodhead Publishing, ISBN 978-0-08-100516-3

[4] OMSOP EU Project, https://omsop.serverdata.net/Pages/Home.aspx (retrieved April 11, 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] Ho, Clifford K., Iverson, Brian. (2014) “Review of high-temperature central receiver designs for concentrating solar power” Renewable and Sustainable Energy Reviews 29 (2014): 835-846.

[9] Kribus, A., Doron, P., Rubin, R., Reuven, R., Taragan, E., Duchan, S., Karni J. (2000) “Performance of the Directly-Irradiated Annular Pressurized Receiver (DIAPR) Operating at 20 Bar and 1,200°C” Journal of Solar Energy Engineering 123(1) (2000): 10-17.

[10] Kongtragool; Bancha, Wongwises; Somchai (2003) “A review of solar-powered Stirling engines and low temperature differential Stirling Engines” Renewable and Sustainable Energy Reviews 7 (2003): 131-154.

[11] Xu, Guoqiang, Wang, Ye, Quan, Yongkai, Li, Haiwang, Gao, Wei (2015) “Design and characteristics of a novel tapered tube bundle receiver for high-temperature solar dish system” Applied Thermal Engineering 91 (2015): 791-799.

[12] Nepveu, Francois, Ferriere, Alain, Bataille, Francoise (2009) “Thermal model of a dish/Stirling systems” Solar Energy 83 (2009): 81-89.

[13] 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.

[14] Wang, Wujun, Laumert, Bjorn, Xu, Haoxin, Strand, Torten (2015) “Conjugate heat transfer analysis of an impinging receiver design for a dish-Brayton system”, Solar Energy 119 (2015): 298-309.

[15] Pozivil, P., Aga, V., Zagoerskiy, A., Steinfeld, A. (2014) “A pressurized air receiver for solar-driven gas turbines” Energy Procedia 49 (2014): 498-503.

[16] Neber, Matthew, Lee, Hohyun. (2012) “Design of a high temperature cavity receiver for residential scale concentrated solar power” Energy 47(1) (2012): 481-487.

[17] Lim, Sehwa, Kang, Yongheack, Lee, Hyunjin, Shin, Seungwon (2014) “Design optimization of a tubular solar receiver with a porous medium” Applied Thermal Energy 62(2) (2014): 566-572.

[18] Giovannelli, Ambra, Bashir, Muhammad Anser, Archilei, Erika Maria. (2017) “High-Temperature solar receiver integrated with a short-term storage system”, AIP Conference Proceedings 1850, 050001 (2017).

[19] 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.

[20] Birchenall, C. Ernest, Guceri, Selcuk I., Farkas, Diana, Labdon, Michael B., Nagaswami, Nikhil, Pregger, Bruce. (1981) “Heat storage in alloy transformations – Final Report”, Technical report DOE/NASA/3184-2.

[21] Lanchi Michela, Montecchi, M., Crescenzi, T., Mele, D., Miliozzi, A., Russo, V., Mazzei., M., Misceo., M., Falchetta, M., Mancini, R. (2015) “Investigation into the coupling of Micro Gas Turbines with CSP technology: OMSoP project”, Energy Procedia 69 (2015): 1317-1326.

[22] Wang, Wujun, Xu, Haoxin, Laumert, Bjorn, Strand, Torsten. (2014) “An inverse design method for a cavity receiver used in solar Dish-Brayton system”, Solar Energy 110 (2014): 745-755.