Experimental Investigation of the Performance of a Transpired Solar Collector Acting as a Solar Wall

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Abstract

It the current energy context it is necessary to implement highly efficient and cost-effective systems in order to reach indoor comfort conditions with minimum energy consumption. This paper aims to analyze the performance of an unglazed transpired solar collector (UTSC), which represents a building envelope element, and to assess the efficiency of two types of external metal cladding: with circular orifices and with lobed orifices. Several experimental campaigns were conducted using different approaches and the results are very interesting: the metal plate with lobed orifices increases the efficiency of the solar collector, providing an enhanced thermal transfer and higher exhaust temperatures. The use of lobed orifices rises the outlet air temperature with 10% more than in the case with circular orifices by enhancing the heat transfer between the metal plate and the air flow due to the more complex dynamic of the lobed flows near the metal absorber. The rise in temperature in case of using lobed orifices is 22.9°C and the metal plate temperature is 64.5°C. An experimental study regarding the implementation on phase changing materials (PCM) in transpired solar collectors was also conducted.

Keywords: Transpired solar collector, TSC, solar wall, energy efficiency, lobed orifices, circular orifices, PIV, phase changing materials, PCM

1. Introduction

Nowadays, the buildings sector is responsible for over one-third of the total energy consumption and CO_2 emissions, being the largest energy consuming sector in the world (IEA, 2013), while the requirements regarding energy use reduction and the CO_2 emissions are more and more strict (EU, 2015).

After the COP21 conference all the members of the UN agreed to limit the global warming even to 1.5°C above preindustrial level in next eighty years (Gütschow et al., 2015) and furthermore all the European Union states must reduce the CO_2 emissions with 20% until 2020 and 40% until 2030, and must reduce the primary energy consumption with 27% until 2030 (EU, 2014). Therefore, in order to reach these goals it is necessary to implement highly efficient systems and solutions by using renewable energy sources to obtain the indoor comfort parameters with minimum energy consumption.

One of the most promising strategies that could be used in this purpose is the use of the solar air collectors which can represent a cost-effective solution (Dymond and Kutscher, 1997, Gill et al., 2012). There are many types of solar collectors used in order to pre-heat the air (Shukla et al., 2012). Thermal solar walls can be classified in several types and categories (Hami et al., 2012) but the two main categories are: glazed solar collectors (GSC, e.g. Trombe walls) and unglazed transpired solar collectors (UTSC – usually used as façade elements). Transpired solar collector are more efficient than plane solar collectors (Belusko et al., 2008) and the efficiency can be even higher with 50% (Chan et al., 2014). According to the literature transpired solar

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collectors have lower investment costs and also lower operation costs, being an excellent cost-benefit, energy-efficient system (Nkwetta and Haghighat, 2014, Wang et al., 2017).

The UTSC usually presents a perforated metal plate which, together with the building wall, creates a cavity for the air flow. The metal plate is heated by the solar radiation and the energy is yielded to the air which is extracted from the top of the wall and afterwards, it is introduced in the building. The operating principle of the unglazed transpired solar collector which acts as a solar wall for the building envelope is highlighted in figure 1.

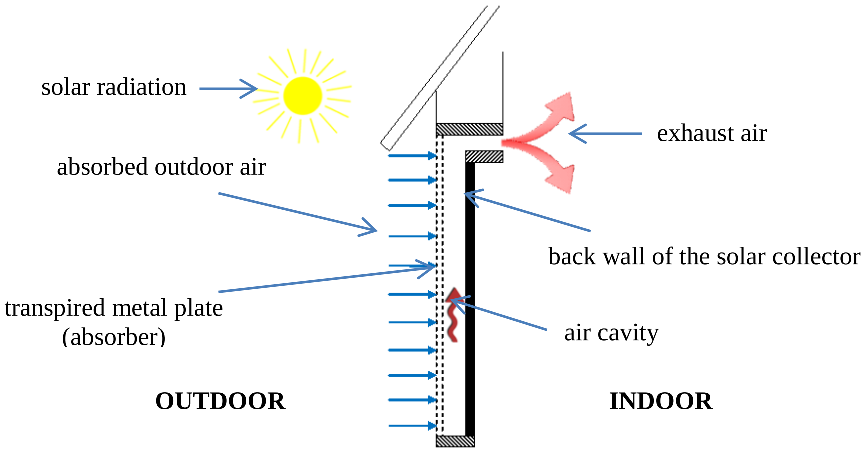

Fig. 1: The operating principle of an unglazed transpired solar collector acting as a solar wall

The solar radiation, ambient (outdoor) temperature, air flow, orifices geometry, pitch, collector geometry, solar absorber material are very important parameters which defines the efficiency of a solar collector (Zhang et al., 2016). Also in order to assess the impact of a transpired solar collector it is important to determine the rise in temperature (ΔT, difference between the outlet air temperature and ambient air temperature), the efficiency of the solar collector (η) and the efficiency of heat transfer or heat exchange effectiveness (η_t) (Van Decker et al., 2001, Leon and Kumar, 2007).

According to Wang et al. (2017) these parameters can be calculated with the following formula, where: c_{air} is specific heat capacity of air (J kg^{-1} K^{-1}), $\dot{m}_{air}$ is air mass flow rate (kg s^{-1}), $T_{air,out}$ is outlet air temperature (°C), T_a is the ambient air temperature (°C), G_s is the incident solar radiation on the collector (W m^{-2}), A_s is collector area (m^2) and T_p is the average absorber plate temperature (°C):

$$\eta = \frac{c_{air}\dot{m}_{air}(T_{air,out} - T_a)}{G_s A_s} \qquad \text{(eq. 1)}$$

$$\Delta T = T_{air,out} - T_a \qquad \text{(eq. 2)}$$

$$\eta_t = \frac{T_{air,out} - T_a}{T_p - T_a} \qquad \text{(eq. 3)}$$

A very interesting study found in the literature emphasize that if the orifices diameter and the pitch have lower values, the heat transfer efficiency is enhanced (Leon and Kumar, 2007). An experimental study (Wang et al., 2017) shows that a transpired solar collector could reach a rise in temperature up to 31.16°C and an efficiency up to 74.93% depending on the input conditions (tests were made for solar radiation from 400 W m^{-2} to 1000 W m^{-2} and air flow between 80 (m^3 h^{-1}) and 200 (m^3 h^{-1})).

According the literature a UTSC could reach a rise in temperature between 6°C and 35°C, and an efficiency between 19% and 75% (Konttinen et al., 2005, Leon and Kumar, 2007, Cordeau and Barrington, 2011, Li, 2013, Perisoglou and Dixon, 2015, Wang et al., 2017). Even if there are many studies regarding the performance of the transpired solar collectors, very few authors focused their attention on the geometry of the orifices even if, according to the studies, 28% of the heat is transferred to the air in the orifice (Van Decker et al., 2001). Usually the metal plate orifices have circular shape. However, the lobed geometries studied before by researchers could improve the heat transfer because of the complex dynamics of the flows and streamwise vortices induced (Nastase et al., 2008, Nastase and Meslem, 2010).

The main objective of the present paper is to assess the impact of the geometry of orifices on the thermal efficiency of an UTSC in to cases (circular orifices plate and lobed orifices plate) and to determine new ways to improve the efficiency of the transpired solar collector.

2. Experimental setup and methodology

In order to achieve the objective presented above a physical model was built and tested. The graphical representation is emphasized in figure 2 and the physical experimental stand is pointed in figure 3 and figure 4.

The unglazed transpired solar collector proposed consists of a rectangular box with the following dimensions: 116x70x23 cm (figure 2). In addition to the UTSC built, the following materials and equipment were used for the experimental study (see figure 2, 3 and 4):

- Fan with variable flow (1)
- Interchangeable metal plates (2a – with circular orifices and 2b – with lobed orifices)
- Six halogen lamps (3) in order to simulate solar radiation (800 Wm^{-2}).

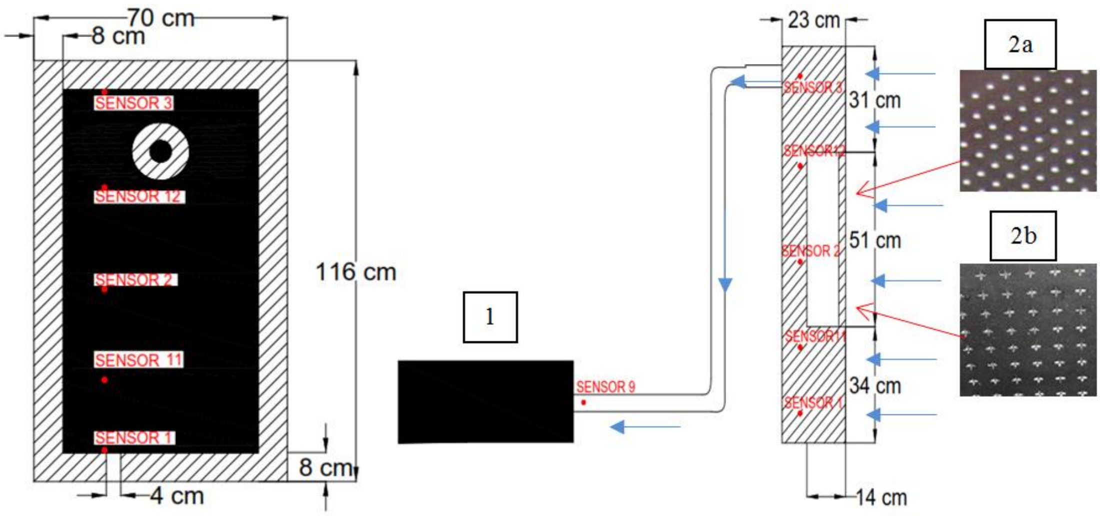

Fig. 2: Graphical representation of the UTSC (front and side view, dimensions, location of the temperature sensors)

The cavity formed between the metal plate and the back wall has 20 cm width and the wall is insulated with 5 cm of extruded polystyrene. The solar radiation is simulated by six halogen lamps placed on a stand 50 cm from the solar wall which generates 800 W m^{-2} (figure 4). Furthermore, the heat is embodied in the metal plate which acts as a solar absorber and then it is ceded to the air that passes through the orifices (circular or lobed). The heated air is extracted from the upper part of the UTSC through a 15cm hole using a fan with variable flow which forces the ambient air to pass through the transpired metal plate.

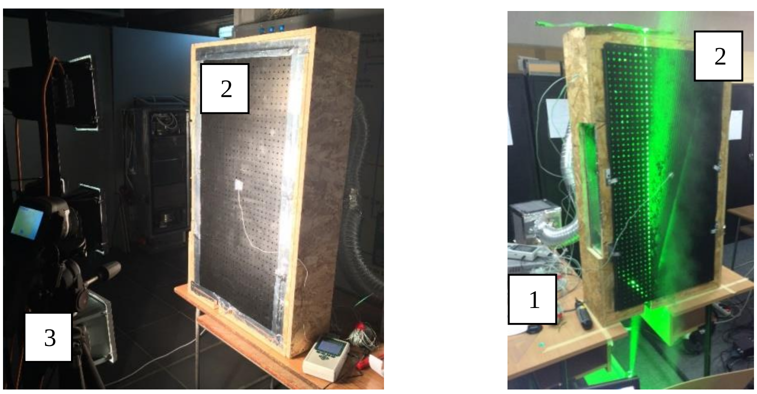

Fig. 3: Experimental setup of the UTSC during the measurements (temperature and velocity)

In order to measure the gradient of temperature within the UTSC, five sensors were placed inside the box in different places at 25 cm distance from each other (1, 11, 2, 12 and 3).

Other three sensors were used in order to assess the impact of the UTSC on the rise in temperature between ambient air extracted and the air exhausted:

- Thermocouple placed on the metal plate (sensor 4, T_p)
- Thermocouple located in ambient (sensor 14, T_a)
- Thermocouple placed on the exhaust/outlet duct (sensor 9, $T_{air,out}$).

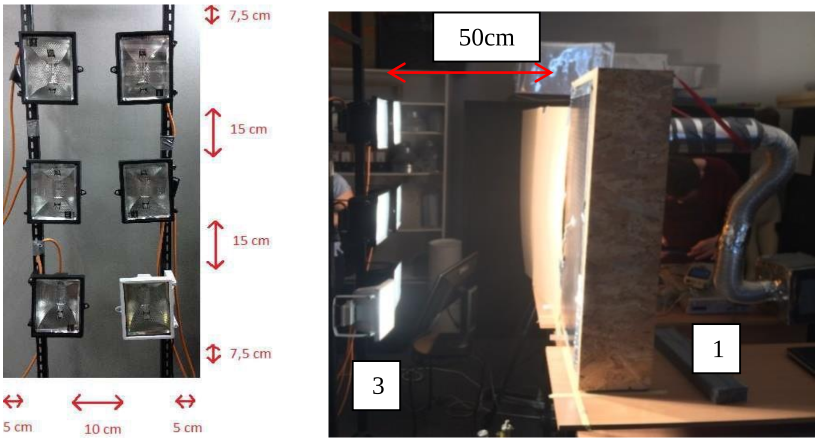

Fig. 4: Positioning of the halogen lamps in the experimental setup

All the data was collected using a very precise data logger. We also used the PIV measuring technique (Particle Image Velocimetry) in order to evaluate the velocity induced by the circular and lobed orifices (figure 3) and to determine the impact of the lobed geometry on the air flow, air mixing and efficiency of the solar collector.

3. Results and interpretations

Following the experimental campaigns conducted we have obtained interesting results. The measurements were made at different air flows and the most representative results are highlighted bellow for 29 (m^3 h^{-1}). Because the ambient temperature has a constant value, we waited for the other values to stabilize (metal plate temperature and exhaust temperature) and we collected the data which is presented below.

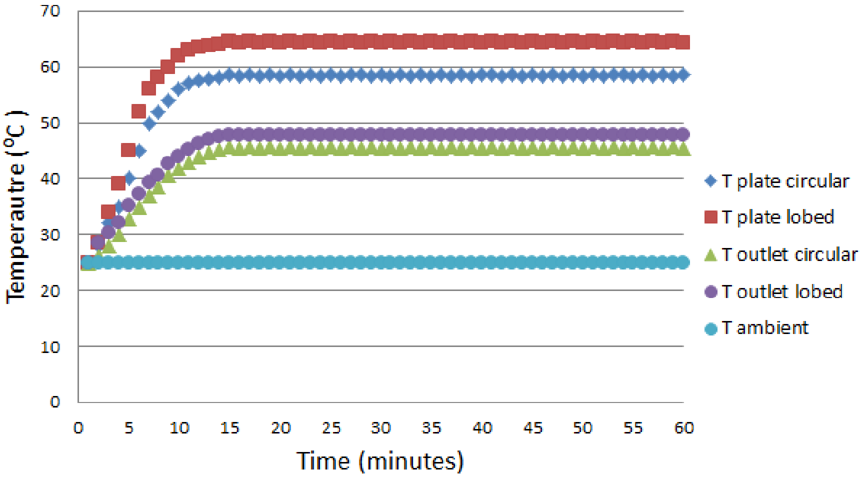

Fig. 6: Temperature variation inside the experimental setup for 29 (m^3 h^{-1})

As it can be observed in figure 6, the metal plate temperature stabilizes after almost 9 minutes of functioning at approximately 58.5°C in case of the metal absorber with circular orifices and at almost 64.5°C in case of the metal plate with lobed orifices. Furthermore, the outlet air temperature stabilizes after 14 minutes of functioning at approximately 45.7°C in case of the metal absorber with circular orifices and at almost 47.9°C in case of the metal plate with lobed orifices.

The measurements conducted analyze the behavior of the unglazed transpired solar collector studied from two points of view: thermal and dynamic.

3.1. Thermal analysis

In figure 6 it is emphasized the variation of exhaust air temperature and also, the temperature on the metal plate, in both cases (metal plate with circular orifices and metal plate with lobed orifices). It can be observed that at the same ambient temperature (25°C), the temperature on the metal plate is 58.5°C in the case of using circular orifices and 64.5°C in case of using lobed shaped orifices. In this case, the temperature on the metal plate is higher with 6°C (which means almost 9.2% more) when using the plate with lobed orifices which clearly means that the geometry improves the heat exchange and the efficiency of the solar collector.

Moreover, it can be noticed from figure 6, that at the same ambient temperature (25°C), the exhaust temperature is with 2.2°C higher when using the plate with lobed orifices (47.9°C unlike 45.7°C), which means 5% more compared to the use of the metal plate with circular orifices. The rise in temperature in the case of the experimental study conducted with the plate with circular orifices is approximately 20.7°C and, in the second case, with the metal absorber with lobed orifices, the rise in temperature is approximately 22.9°C which means an increase of 10%.

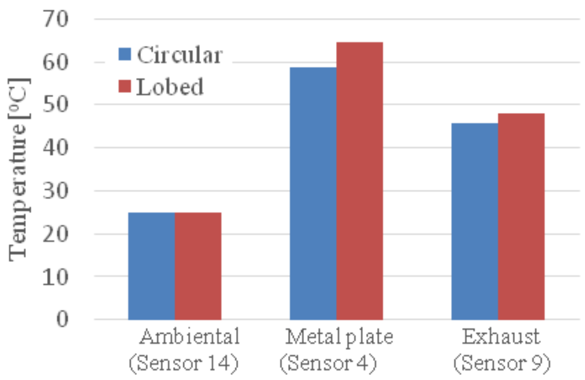

Fig. 6: Metal plate temperature variation and exhaust air variation for 29 (m^3 h^{-1})

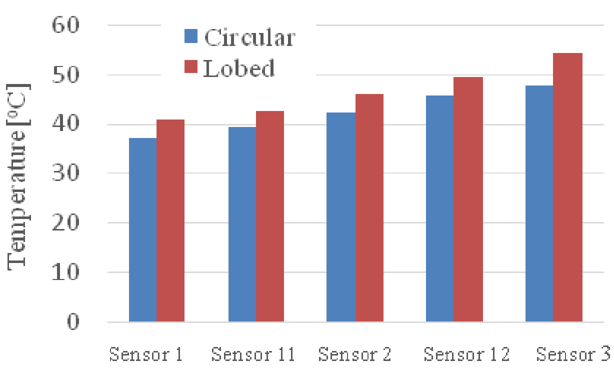

Fig. 7: Temperature measured in several points in the UTSC for 29 (m^3 h^{-1})

In figure 7 it is represented the vertical temperature variation inside the UTSC, also in both cases with circular and lobed orifices. It can be observed that the metal plate with lobed orifices enhances the heat transfer and air reaches a temperature of 54.3ºC at the top of the experimental setup (sensor 3), while in case of the metal plate with circular orifices, the air temperature reaches 47.6ºC, which means an increase in efficiency of 14%. Also, in every point where the sensors are placed, the temperature values are bigger in case of using the lobed orifices. Sensor 1 measures 40.5ºC in case of using lobed orifices unlike 37.5ºC in case of using circular shaped orifices, sensor 11 measures 42.5ºC unlike 39.7ºC, sensor 2 measures 46.2ºC unlike 42.1ºC and sensor 12 measures 49.8ºC unlike 45.6ºC.

3.2. Dynamic analysis

Regarding the dynamical analysis, the plate with lobed orifices presents several advantages. From the results obtained using the PIV methodology, it can be noticed (figure 8) that the metal plate with lobed orifices provides higher velocities (in longitudinal section) and a uniform velocity variation. In case of using the plate with lobed orifices the maximum air flow velocity is 0.6 m s^{-1} and in case of using the plate with circular orifices the maximum air flow speed is 0.3 m s^{-1}. Moreover, the jet length is bigger for plate with lobed orifices (with 3.1 mm), resulting a better air mixing.

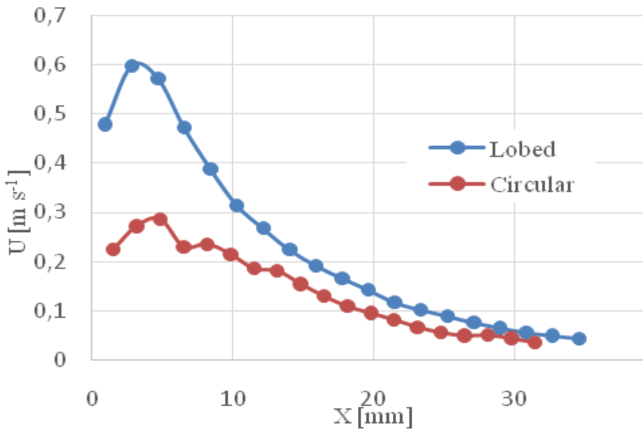

Fig. 8: Air flow velocity profile along the jets axis for airflow of 29 (m^3 h^{-1})

The difference between the jets and the flows in both cases can be seen in figure 9, which represents the velocity fields for the airflow of 29 (m^3 h^{-1}). As it can be observed, in case of using the lobed orifices it results a better air mixing and a stabilization of the jet flows inside the cavity determined by streamwise vortices created by this geometry. Moreover, because of the more complex dynamic of the lobed flows near the metal plate (absorber) the heat transfer is enhanced which determines a higher air temperature inside the cavity and a higher outlet air temperature, as it has been presented in the previous chapter.

With all these important results taken into account we can conclude that the lobed geometry provides a better flow profile and enhances the thermal transfer while increasing the efficiency of the unglazed transpired solar collector.

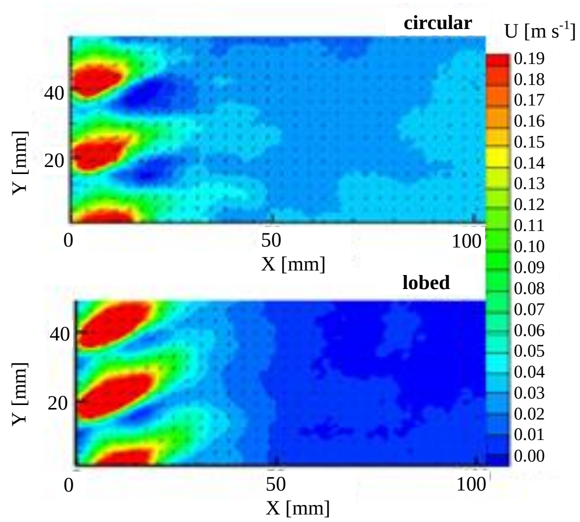

Fig. 9: Velocity fields of the circular and lobed jets extracted from PIV measurements (m^3 h^{-1})

3.3. Further studies and perspectives

According to the literature, the solar air collectors which are using renewable solar energy could be improved by adding thermal storage (Goyal et al., 1998, Khadiran et al., 2016). Thermal inertia can increase the operation time of the unglazed transpired solar collector, could stabilize the outlet air temperature (also increasing the comfort) and could increase its overall efficiency by overcoming the periods when the solar radiation is unstable/variable (during the day or during the night-time).

One of the most effective way to store energy is the use of latent heat storage materials or Phase Changing Materials (PCM) which can store 5 to 14 times more energy than classical materials (Kuznik et al., 2011).

In order to assess the impact of thermal inertia implemented in the solar collector we used the RT-25 phase change material from Rubitherm, an organic material (paraffin) with the following characteristics:

- Melting temperature: 22-26ºC
- Congealing area: 26-22ºC
- Heat storage capacity: 170 kJ kg^{-1}
- Specific heat capacity: 2 kJ kg^{-1} K^{-1}
- Heat conductivity: 0.2 W m^{-1} K^{-1}
- Density: 0.88 kg l^{-1} (solid), 0.76 kg l^{-1} (liquid).

The PCM was macro-encapsulated in four aluminum recipients with the following dimensions: 200x100x10 mm which were placed on the back wall of the UTSC presented in the previous chapters, with the same geometry and with the same conditions. For this experimental study we used the metal plate absorber with lobed orifices and the ambient temperature was 21ºC.

The study was conducted for two hours, respectively 7200 seconds. The test was divided in two equal steps: heating (the lamps are on, simulating solar radiation) and cooling (lamps are off, simulating cloudiness or night-time). As it can be observed in figure 10, the outlet air temperatures are stabilizing very quickly, after approximately 9 minutes. During the heating phase the outlet air temperature is lower in case of using PCM (with approximately 7ºC) which means that the materials store the heat. After the heating phase is over, the outlet air temperature drops also quickly (almost 15 minutes) but for the remaining time, the outlet air temperature is higher with 1.3ºC in case of using phase changing materials in the cavity of UTSC, which means that PCM are slowly releasing the heat stored.

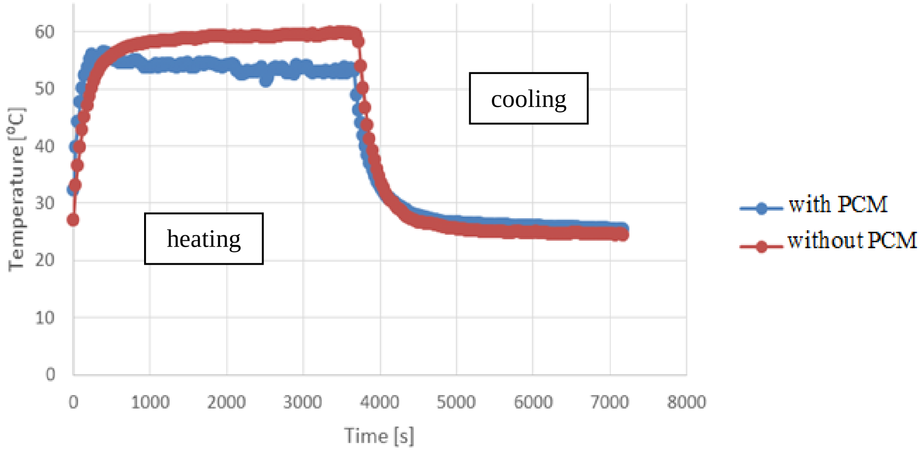

Fig. 10: Outlet air temperature variation in both cases: with and without PCM mounted on the back wall

This phenomenon still needs to be investigated and it opens new perspectives regarding the improvement of transpired solar collector efficiency by storing solar energy. More thermal storage could be added which can enhance the total capacity and a higher phase changing temperature is needed, near to the average temperature inside the cavity.

4. Conclusions

Transpired solar collectors are cost-benefit solutions which can significantly reduce the heating systems consumptions by heating or preheating the fresh air and could contribute to the reduction of CO_2 emissions around the world.

This paper is assessing a transpired solar collector performance by comparing and highlighting the importance of metal plate absorber by means of orifices geometry. Two types of orifices were studied: circular and lobed, and many interesting results were obtained.

After several experimental campaigns conducted we can conclude that:

- In case of using circular orifices the metal plate temperature is stabilized at 58.5ºC, while using lobed orifices the metal plate temperature is approximately 64.5ºC
- In case of using circular orifices the outlet air temperature is stabilized at 45.7°C, while using lobed orifices the outlet air temperature is approximately 47.9°C (5% more)
- The UTSC using metal plate with lobed orifices is more efficient, the temperature at the upper side of the UTSC being higher with 14% (6.7°C)
- The rise in temperature in case of the metal plate with lobed orifices is being higher with 10% (2.2°C)
- The rise in temperature in case of using lobed orifices is 22.9°C (unlike 20.7°C in the case of circular orifices)
- After the dynamic analysis we can observe that in case of using the lobed orifices it results a better air mixing and a stabilization of the jet flows inside the cavity determined by streamwise vortices created by this geometry
- In case of using the metal plate with lobed orifices the maximum air flow velocity is 0.6 m s^{-1} and in case of circular orifices the maximum is 0.3 m s^{-1} resulting a better air mixing (the jet length is also bigger with 3.1 mm)
- Because of the more complex dynamic of the lobed flows near the metal plate (absorber) the heat transfer is enhanced which determines a higher air temperature inside the cavity and a higher outlet air temperature.

We've also conducted studies with thermal inertia materials, such as phase changing materials and the preliminary results are promising. The thermal storage implemented in the transpired solar collector can increase the operation time of the unglazed transpired solar collector and could increase its overall efficiency by lagging the solar energy absorbed during the day-time and using it during the periods when the Sun is not available. During the heating period the PCM are storing the heat and the outlet air temperature is lower than in the case without PCM (with almost 7ºC) and furthermore, in the cooling stage, the heat stored is released slowly, the outlet temperature being higher with almost 1.3ºC.

The implementation of the PMC in UTSC needs to be further investigated. Further studies will be conducted with different types of thermal inertial elements which could improve the effect of the plate with lobed orifices implemented in a UTSC, with different phase change temperatures, different quantities and different orifices geometries.

5. Acknowledgement:

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