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EXPERIMENTAL AND NUMERICAL INVESTIGATION OF A SOLAR DISH COLLECTOR WITH SPIRAL ABSORBER

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Abstract: The objective of this work is to investigate experimentally and numerically a solar dish collector and to examine the impact of possible improvements in its performance. The examined solar dish collector has a spiral absorber and it is lightweight, fact that makes the system to have low cost and to be sustainable. The experimental results are compared with the results of a developed numerical model written in EES (Engineering Equation Solver) and validation between the results is observed. The validated numerical model is used for further investigation of the solar collector for operation with Therminol VP1. In the first part of the investigation, the impact of flow rate on the thermal and the exergetic performance is examined, and finally 200 l/h was found as the best solution. The next part is the optical investigation of the collector and greater optical efficiencies are tested. It is found that optical performance of 75% leads to maximum exergetic efficiency of 22.49%, three times greater than 7.49% which corresponds to the present situation of 35% optical efficiency. In the last part of this study, the selective absorber is compared to the non-selective of the real system and it is found that the use of the first is vital for achieving high operating temperature levels. The results of this study can be used as guidelines for the future improvement of the present facility.
Keywords: Solar dish collector, thermal analysis, exergy analysis, parametric analysis

INTRODUCTION

Solar energy utilization is vital for facing the present environmental problems and the fossil fuel depletion [1-3]. The use of concentrating collectors is one of the most promising ways for producing, heating, cooling, electricity and other useful products with a clean and cheap way [4-6]. Solar dish concentrators gain more and more attention the last years and a lot of research has been focused on them. Reddy et al. [7] investigated a modified cavity receiver of a solar dish collector with a numerical model for the natural convection heat losses of the receiver. This configuration includes a tube wound in a hemispherical geometry which is covered with insulation to reduce the thermal losses. Daabo et al. [8] examined three receiver geometries: cylindrical, conical and spherical.

In every case, a helical tube was used in order to utilize the solar energy. According to their results, the conical shape is the best choice among the examined cases. Przenzak et al. [9] examined a solar dish collector with a two optical elements and a curved radiation absorber. This system was designed for operation in high temperature levels and there was a special design for achieving this goal. More specifically, a parametric analysis has been applied in order the optimum receiver location and the most suitable mass flow rate to be determined.

In this study, the spiral absorber is examined in a lightweight receiver which is manufactured by 11 reflecting petals. The basic idea is to create a low cost solar collector which can operate in medium high temperature levels, ideal for polygeneration systems. In literature, there are also preliminary studies about the design of this system [10-12]. In this study, his system is examined experimentally and also a thermal model is developed in order to examine the collector parametrically. The objective of this paper is to show how this configuration can be improved in the future in order to be commercialized.

METHODS

The examined setup

In this section, the examined experimental set up is described. The solar dish collector is given in figure 1. The first innovation of this design is the spiral absorber which leads to a relative uniform heat flux distribution. The next innovations are the low cost and the lightweight structure of this collector. The main characteristics of the collector are given in the flow chart of figure 2 and in Refs [10-12].

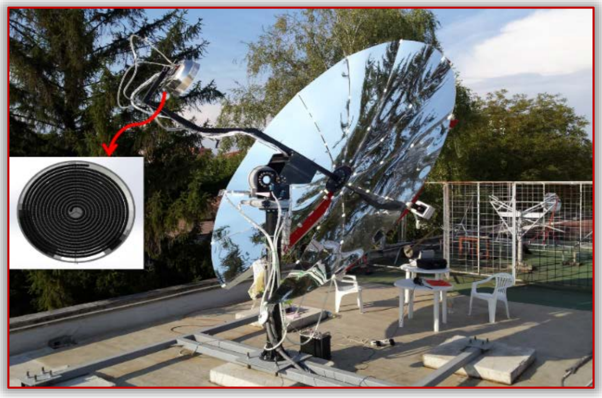

Figure 1. The examined solar dish collector

The numerical model

The developed numerical model is based on the energy balance on the spiral receiver and it is developed in EES (Engineering Equation Solver) by F-Chart [13]. This model has been also used and validated in other literature studies [14-15] and it is presented in figure 2 with the suitable modifications. Also it is essential to state that some useful references have been used for the utilized equations [15-19].

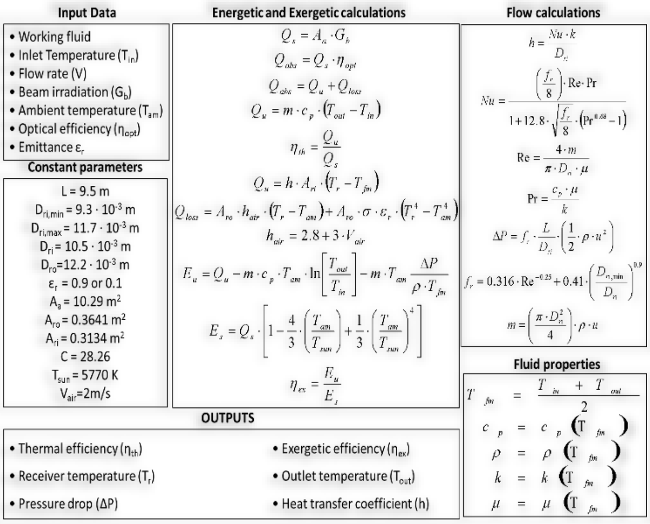

Figure 2. The flow chart of the developed numerical model

Followed methodology

The first part of this study (subsection 3.1) is the validation of the developed thermal model. Experimental results are used in order this model to be tested. For these tests, water has been used as working fluid with volumetric flow rate of 200 l/h. The experiments have performed the time period of August-September 2016, in the solar laboratory of the Faculty of Mechanical Engineering in the University of Nis (latitude 43°19' and longitude 21°54'). Moreover, it is essentially to state that for the real experimental setup, the optical efficiency has been estimated to 35%, after experimental tests. The reason for this low value is the low quality reflectance and manufacturing errors in the paraboloid shape of the concentrator. In the parametric studies, different parameters of the examined solar collector are investigated. In all these studies (subsections 3.2, 3.3 and 3.4) the working fluid is Therminol VP1 [20] because this is the best candidate for operation in higher temperature levels. In section 3.2, the flow rate is investigated, in section 3.3 the optical efficiency and in section 3.4 the receiver emittance. The emittance of the real collector is about 0.9 because the absorber is non-selective, while the case of selective absorber with emittance equal to 0.1 is examined numerically.

3. RESULTS

Model validation

In this subsection, the experimental results are used for validation of the developed model. Figure 1 illustrates the thermal efficiency and it is obvious that the experimental and the numerical results are close to each other, with mean deviation close to 5%. Thus, the developed numerical model is validated. Also it is essential to state that the thermal efficiency of the real collector operating with water (in low temperature levels) is close to 34%; low value which has to be increased for making this collector a competitive technology.

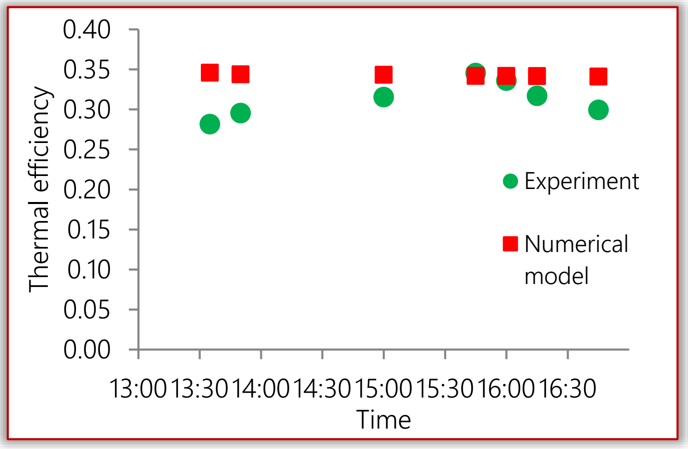

Figure 3. Thermal efficiency comparison between experimental and numerical results

Flow rate investigation

In this subsection, thermal oil is used and six different flow rates are examined. Figure 4 show that higher flow rate leads to higher thermal efficiency. After 200 l/h, all the curves tend to one, so this flow rate is selected as the optimum one. Figure 5 depicts the exergetic performance of the collector for the same examined cases. In low temperature levels, the lower mass flow rate is the best candidate, while in higher temperature levels, higher mass flow rates have to be used. Generally, the maximum exergetic efficiency is observed in the region between 145 °C to 165 °C and it is about 0.075; a low value which is explained by the low optical efficiency.

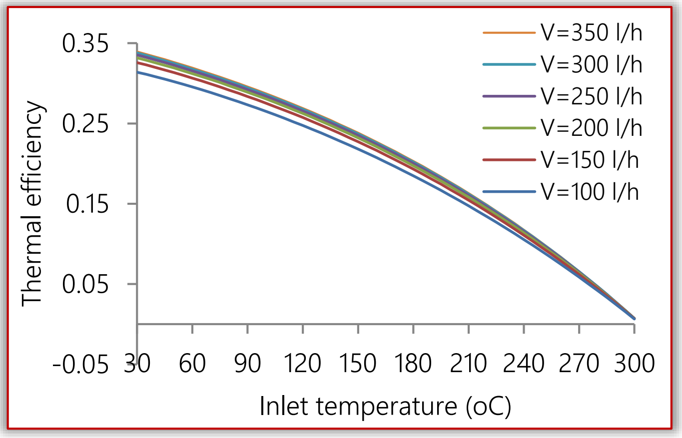

Figure 4. Thermal efficiency for various flow rates

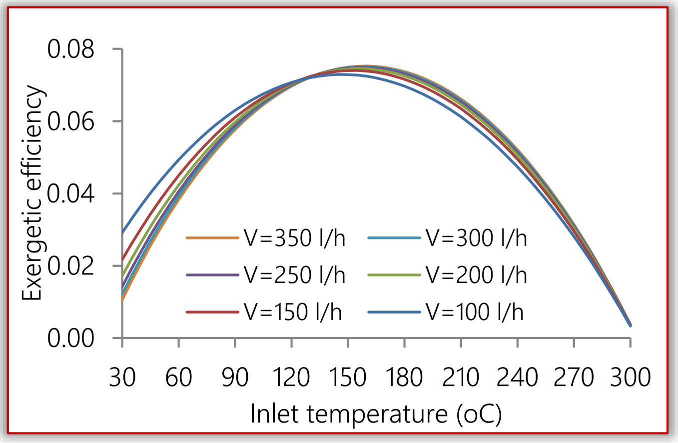

Figure 5. Exergetic efficiency for various flow rates

Optical efficiency investigation

The optical efficiency of the present collector is about 35%. This low value can be increased by using higher quality reflector and improving the shape of the reflector. In this section, the thermal and the exergetic efficiency are examined parametrically with the optical efficiency for thermal oil flow rate equal to 200 l/h. Figure 6 exhibits the thermal efficiency and it is obvious that all the curves seem to be parallel. The interesting result is that higher optical leads to higher thermal efficiency and to higher stagnation temperature. This temperature is the one which leads to zero thermal performance. This results is important for the determining the temperature operating range of the collector in every case.

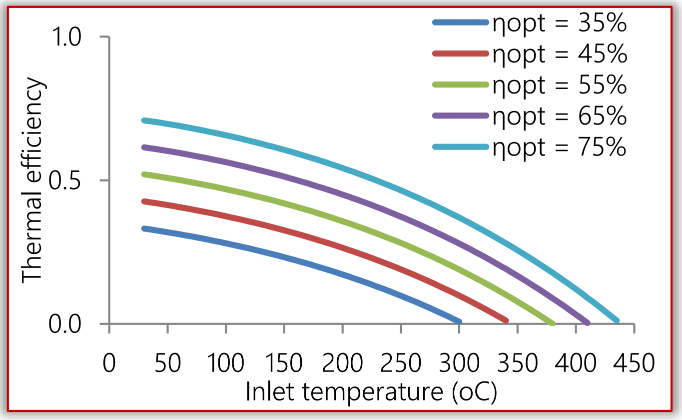

Figure 6. Thermal efficiency for various optical efficiencies

Figure 7 depicts the exergetic efficiency for the similar cases. Higher optical efficiency leads to higher exergetic performance. Moreover, higher optical efficiency leads to the exergetic efficiency to be maximized in greater temperature level. This is an interesting result which indicates that the exergetic performance of the collector is associated with the optical performance of it. For 75% optical efficiency, the maximum exergetic efficiency is 22.49% and it is observed at 210°C inlet temperature. For the optical efficiencies of 65%, 55%, 45% and 35%, the respective maximum exergetic performances are 18.41%, 14.52%, 10.85% and 7.46%, while the respective inlet temperature levels for exergetic maximization are 200°C, 190°C, 175°C and 155°C.

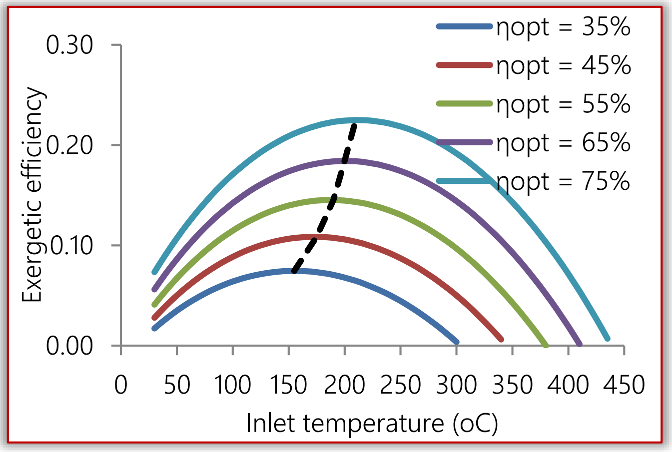

Figure 7. Exergetic efficiency for various optical efficiencies

Emittance investigation

In the last subsection, the impact of emittance on the collector performance is investigated by using 35% optical efficiency and 200 l/h thermal oil flow rate.

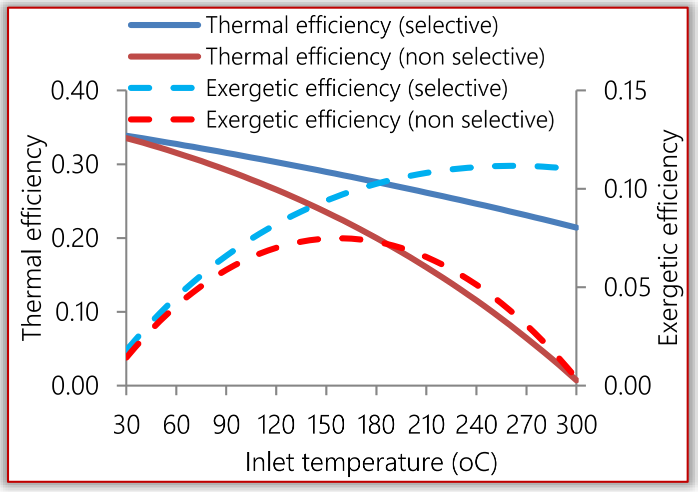

Figure 8. Thermal and exergetic efficiencies for the examined absorbers

Figure 8 show the thermal and the exergetic efficiencies for the non-selective absorber case (emittance equal to 0.9 – real case) and for selective absorber case (emittance 0.1). It is obvious that the performance with selective absorber is higher and the collector can operate in higher temperature levels. It is important to state that the non-selective case presents maximum exergetic efficiency for 155 °C and the selective for 265 °C with 7.49% and 11.17% respectively.

4. CONCLUSIONS

In this paper, a solar dish collector with spiral absorber is examined experimentally and numerically. The developed numerical model is validated with the experimental results for operating with water. Moreover, the developed numerical model with EES is utilized for examining the solar collector in various operating conditions, by changing the inlet temperature levels and the mass flow rates. Moreover, the impacts of the optical efficiency and of the absorber emittance are examined. The most important conclusions are summarized below:

- The present collector has low efficiency (about 34%) and it can operate up to 300 °C.
- The minimum suitable flow rate for thermal oil is 200 l/h for efficient operation.
- Higher optical efficiency makes the system to operate with higher thermal and exergetic efficiency, as well as to increase the maximum temperature close to 400°C.
- The maximum exergetic efficiency of the present system (optical efficiency equal to 35%) is about 7.49% and it is observed for 155°C, while for optical efficiency equal to 75%, the maximum exergetic efficiency is 22.49% for 210°C.
- The influence of the absorber emittance on the results is critical and it can make the collector to perform better and to operate in higher temperatures.

Nomenclature

A	Area, m2	μ	Dynamic viscosity, Pa s
C	Concentration ratio, -	ρ	Density, kg/m^3
c_p	Specific heat capacity, kJ/kg K	σ	Stefan–Boltzmann constant
D	Diameter, mm	**Subscripts and superscripts**	
E	Exergy flow, W	a	aperture
f_r	Friction factor, -	abs	absorbed
G_b	Solar beam radiation, W/m^2	air	ambient air
h	Convection coefficient, W/m^{2}K	am	ambient
k	Thermal conductivity, W/mK	ex	exergetic
L	Tube length, mm	fm	mean fluid
m	Mass flow rate, kg/s	in	inlet
Nu	Mean Nusselt number, -	loss	losses
Pr	Prandtl number, -	opt	optical
Q	Heat flux, W	out	outlet
Re	Reynolds number, -	r	receiver
T	Temperature, K	ri	inner receiver
u	Working fluid velocity, m/s	ri,max	inner receiver max
V	Volumetric flow rate, m^3/s	ri,min	inner receiver min
V_{air}	Ambient air velocity, m/s	ro	outer receiver
Greek symbols		s	solar
ε	Emittance, -	sun	sun
ΔP	Pressure drop, kPa	th	thermal
η	Efficiency, -	u	useful

Note

This paper is based on the paper presented at 13th International Conference on Accomplishments in Mechanical and Industrial Engineering – DEMI 2017, organized by University of Banja Luka, Faculty of Mechanical Engineering, in Banja Luka, BOSNIA & HERZEGOVINA, 26 - 27 May 2017.

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