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An efficient parabolic dish engine based on Rankine cycle

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Abstract. In this research work, a case study carried out to evaluate the technical viability of a parabolic dish based concentrator to convert solar energy into electric power by means of a high performance Rankine cycle operating with, ethane, ammonia or water. The comparison of such cycles in terms of thermal efficiency and net developed work is the aim of the proposed research. The achieved results show that Stirling engine efficiency is so far lower than that of the Rankine cycle under the same operating temperatures since typical temperatures range from 650 °C to 800 °C resulting in Stirling engine conversion efficiencies of around 30 % to 40 %, while the proposed Rankine cycles can surpass such mark.

Key words

Concentrated solar power, Parabolic dish, Volumetric receiver, Thermal efficiency, Working fluid.

1. Introduction

Solar energy concentration is an interesting option to increase the energy density of the solar radiation resulting in the possibility to use absorbers with small surfaces. Since the objective is to convert the solar energy into useful work, the theory suggests that it can be done more efficiently the higher the temperature is.

The aim of this work is to capture solar radiation and convert it into electric power via solar thermal energy. The capture of solar radiation and conversion of it into solar thermal energy involves the use of solar receivers. In order to improve these solar receivers, some studies have been carried out using computer models and experimental data [1], [2], [3]. A lot of research has been carried out on designing new receivers or improving the performance of existing ones [4; 5], and on understanding factors that affect their performance [6]; [7]. One important group of mentioned receivers is the volumetric solar receivers.

Volumetric receivers are generally used in central receiver solar power plants and have also been used for chemical applications [2] where the applied heat transfer fluid (HTF) is usually air or any other suitable gas such as helium or hydrogen. Several studies have been carried out on volumetric solar receivers that use air as a HTF [2]; [8;] [9]. In order to increase the heat transfer surfaces and consequently the transfer efficiency, the use of wire mesh, ceramic absorbers and other porous materials in these receivers has been applied with the aim of increase their efficiency [3]; [9]; [10]; [11]; [12]; [13], [14].

The reviewed references don't indicate a large use of volumetric receivers applied on indirect solar heat exchangers that have a separate solar collector followed by a power unit or thermal energy storage system [15], [16], [17]. Moreover, these receivers have mainly been used with air as a HTF and metal foams as the porous media. Furthermore, most of the studies on metal foams have focussed on their pressure drop and flow characteristics. Among the studies that have focused on the thermal conductivity of these metals foams, very few have dealt with their characteristics under concentrated solar radiation (CSR) and using a liquid as the HTF. In this study, heat transfer gas is used as the HTF and a wire mesh is used to improve the effective thermal conductivity and the flow of the gas in the proposed receiver. The wire mesh was chosen as the candidate for investigation because it is cheap and readily available.

2. Parabolic dish based receiver

Parabolic Dish Concentrator (PDC) systems convert the thermal energy in solar radiation to mechanical energy and then to electrical power. Dish/engine systems use a

mirror array to reflect and concentrate incoming direct normal solar radiation to a receiver, in order to achieve the temperatures required to convert solar thermal energy into work. Such conversion process requires that the dish track the sun in two axes. The concentrated solar radiation is absorbed by the receiver and transferred to a thermo-electric engine.
Dish/engine systems are characterized by high efficiency, modularity, autonomous operation, and an inherent capability to operate on either solar energy or a fossil fuel, or both. Among all concentrated solar energy technologies, parabolic dish based systems have demonstrated the highest efficiency approaching 30%, while showing the potential to become one of the least expensive sources of solar thermal energy. The success of parabolic dish concentrators is due to its modularity which allows them to be deployed individually for remote applications, or grouped together for small-grid distribution.

A variety of thermodynamic cycles and working fluids have been considered for PDC systems, including Rankine cycles, using water or an organic working fluid; Brayton cycles, both open and closed cycles; and Stirling cycles. More sophisticated thermodynamic cycles and variations on the above cycles have also been implemented such as combined cycles. In figure 1 it is depicted the layout of a PDC coupled to a thermal cycle.
So far, the heat engines that are generally favoured use the Stirling and open Brayton (gas turbine) cycles. Fossil fuel based heat can also be supplied by a supplemental gas burner to allow operation during cloudy weather and at night or simply to increase the temperature input of the thermal engine. Electrical power output in the current dish/engine prototypes approaches 25 kW for dish/Stirling systems and about 30 kW for the Brayton systems under consideration. Demonstrations of smaller dish/Stirling systems (5 to 10 kW) have also been successfully implemented.

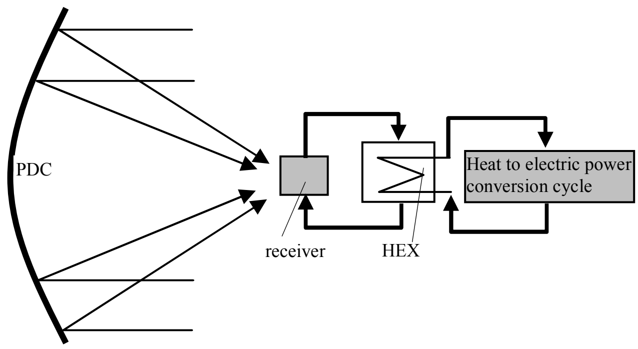

Fig 1. The layout of a PDC coupled to a thermal cycle

A. Solar radiation to heat based power conversion

The device that is used in high temperature solar concentrators for the conversion of concentrated solar radiation to heat is a receiver. It is designed to absorb the concentrated solar radiation and to transfer as much energy as possible to a HTF. Inherent unavoidable heat losses exists from the fact that the absorbing surface cannot be completely black, that it emits thermal radiation to the environment, because it has an elevated temperature, and that convection as well as conduction occur. Assuming that the receiver is affected by inherent heat losses (irreversibilities) the useful heat collected by the receiver can be estimated as

$$Q_U = \dot{m} \cdot C_P \cdot (To - Ti) \quad (1)$$

where

$\dot{m}$ is the fluid mass flow rate
Cp is the fluid specific heat capacity
To is the fluid output temperature from the receiver
Ti is the fluid input temperature to the receiver

The incident solar energy on the PDC is defined as

$$Qs = A_{Ap} \cdot C \cdot E_S \quad (2)$$

where

A_{Ap} is the PDC normal area
E_S is the direct solar radiation density sometimes assumed as 800 W/m^2, although a normal radiation density (a sun) is considered as 1000 W/m^2.

The thermal efficiency ηth of the solar energy to heat power conversion composed by the PDC and receiver is defined by the ratio of the useful heat at the heat exchanger 7 to the incoming solar radiation on the PDC.

$$\eta_{th} = \frac{Q_U}{Q_S} = \frac{\dot{m} \cdot C_P \cdot (To - Ti)}{A_{Ap} \cdot C \cdot E_S} \quad (3)$$

The real scenario efficiency depends strongly on the receiver structure in such a way that a lot of concentrating process variables is involved. Considering achieved experience with regard to the solar to heat conversion process it must be taken into account that
• higher fluid temperatures yields lower efficiencies of the PDC-receiver convertor.
• higher concentration ratios lead to higher efficiencies.
•convection and conduction losses are of minor importance at high concentration ratios.

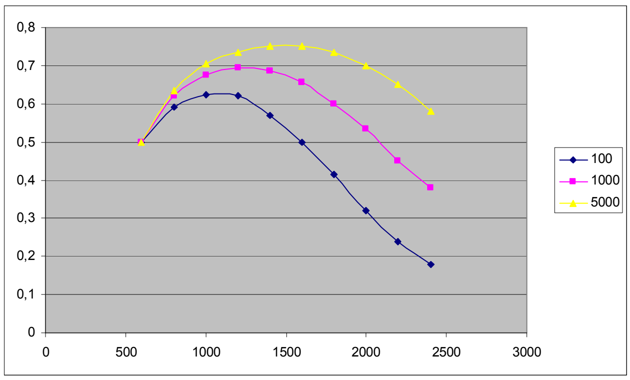

Fig. 2. The ideal total efficiency of a receiver corresponding to a high temperature solar concentrating system.

Nevertheless, for any thermodynamic cycle according Carnot, the thermal efficiency depends on the difference between high and low temperatures (high temperature at heat source and low temperature at heat sink). Since the objective is to achieve the highest technically possible overall efficiency, a compromise between both efficiencies must exist.

In figure 2 it is shown the total efficiency of a high temperature solar concentrating system for the generation of mechanical work as the function of the upper receiver temperature for different concentration ratios and a selective characteristic of the absorber, [18]. According this figure, the total efficiency of a generic volumetric receiver depends on a number of variables different of that mentioned. As consequence, the optimal efficiency deals with such variables more than with the top and down temperatures of the receiver.

3. The Rankine cycle based on the parabolic dish concentrator.

There are four processes in the basic RC, each changing the state of the working fluid. These states are identified by numbers in the diagram shown in figure 3.

The ideal RC is inspired by the Carnot cycle. In figure 3 (a) it is depicted in the T-S diagram associated with the physical components shown in figure 3(b).

The thermodynamic efficiency of the cycle is defined as the ratio of net power output to heat input as shown in equation (4).

$$\eta_R = \frac{W_i - W_o}{Q_i} \approx \frac{W_n}{Q_i} = \frac{Q_i - Q_o}{Q_i} \qquad (4)$$

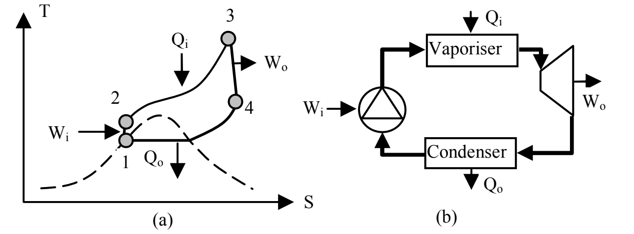

Fig. 3. Basic ultra-supercritical RC: (a) the T-S diagram. (b), the basic plant structure

The general layout of a parabolic dish engine, receiver and power converter composed by RC based thermodynamic cycle is shown in figure 4. According such a figure, the structure of the power convertor is simpler than that of an Stirling engine.

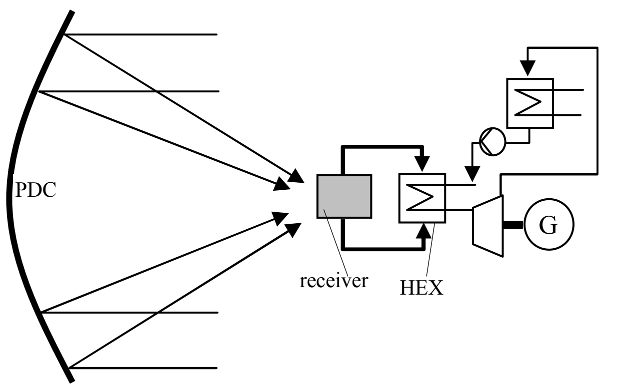

Fig. 4. The PDC coupled to a power generator based on the Rankine cycle.

The Rankine cycle structure with regeneration is shown in figure 5. The selected structure is composed by a double turbine RC equipped with a regenerator which contributes to efficiency enhancement.

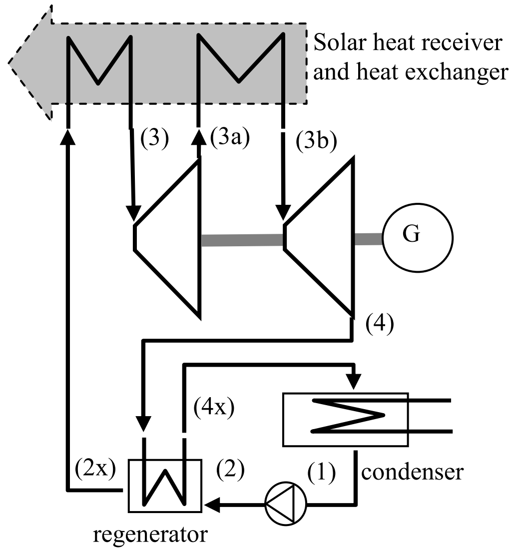

Fig. 5. Structure of a double turbine Rankine cycle

4. The analysis of proposed cycle.

The main results of the proposed thermodynamic cycles for the mentioned working fluids are depicted in table 1, 2 and 3 respectively, where cycle state point parameters for the studied working fluids: ethane, ammonia and water is shown. An isentropic efficiency of 0.9 is being considered for pumps and turbines.

Table I. – State point values for the RC operating with ethane

Ethane	T(K)	h(kJ/kg)	S(kJ/kg-K)/S'	p(bar)
1	300	359,8	1,4334	45
2	350	464,47	1,4636	400
3	675	1520,8	3,5735	400
3a	604	1339,54	3,607	130
3b	675	1572	3,971	130
4	613,6	1405,68	4,0	45
4x	370	740,4		45
2x	561	1126		400

Table II. – State point values for the RC operating with ammonia

NH3	T(K)	h(kJ/kg)	S(kJ/kg-K)	p(bar)
1	295	445,8	1,823	10
2	305	513,80	1,8456	400
3	700	2462	5,9726	400
3a	490,35	2038,37	6,0745	60
3b	700	2658	7,1255	60
4	521,78	2196,30	7,2256	10
4x	325	1734		10
2x	397,6	948		400

The Table I shows the State point values for the RC operating with ethane.

The Table II shows the State point values for the RC operating with ammonia.

The Table III shows the state point values for the RC operating with water.

Table III. – State point values for the RC operating with water

H2O	T(K)	h(kJ/kg)	S(kJ/kg-K)'	p(bar)
1	320	196,18	0,66285	0,19
2	320,2	199,8	0,6628	40
3	700	3277,5	6,8632	40
3a	445,8	2799,51	6,9856	4,5
3b	700	3329,5	7,9271	4,5
4	369,7	2679,88	8,1329	0,19

The main results of the performed RC analysis with regard to the cycle thermal efficiency for the mentioned working fluids depicted in tables 1, 2 and 3 respectively, are shown in table 4.

Table IV. – Summary of RC thermal efficiencies as function of the cycle top temperatures for the considered working fluids: ethane ammonia and water.

	Ethane	Ammonia	Water
Qi	623,51	2075,53	3607,53
Qo	380,60	1258,20	2480,25
W	242,91	817,33	1127,61
Eff	38,96	39,38	31,16

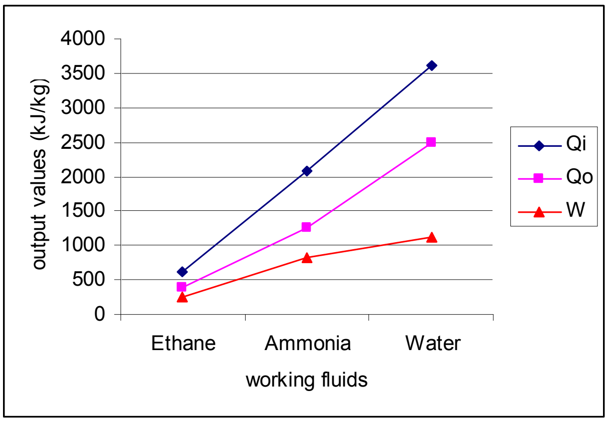

Fig. 6. Specific input heat, output heat and work for the RC

The specific input heat flow rate, output heat flow rate and specific work carried out by the Rakine cycle operating with the mentioned working fluids is shown in figure 6. In figure 7 it is depicted the thermal efficiency of the Rankine cycle for every working fluid. In any case the thermal efficiency is greater than 30%.

5. Conclusions

According the results depicted in table 4, the usefulness of the Rankine cycle operating with solar heat from a parabolic dish has been demonstrated. Cycle regeneration contributes to efficiency enhancement by applying known and well experimented technology.

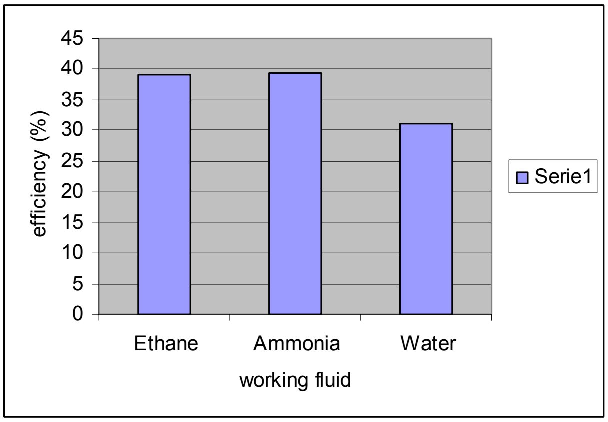

Fig. 7. Thermal efficiency of the for the cited working fluids

While thermal efficiency for a dish/Stirling engine approaches 30%, in the proposed case studies, for ethane and ammonia as working fluids, the efficiency is significantly higher. As consequence of such results, power converters based on RC, could be implemented rendering higher efficiency that than of the Stirling engine.

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