THERMAL PERFORMANCES PREDICTION OF SOLAR DISH STIRLING SYSTEM

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ABSTRACT

The thermodynamic conversion of solar energy into electricity is a major energy stake. The current systems are primarily based on technology known as "Solar Dish Stirling"", which uses Stirling engines placed at the focal plan of a paraboloïdal concentrator. The Stirling engine presents an excellent theoretical output equivalent to the output of Carnot one. It is with external combustion, less pollutant and silencer. The present study is dedicated to predict the thermal performances of Stirling engine associated with a paraboloïdal concentrator and a receiver of cavity type. We developed a thermodynamic modelling of the kinematics Stirling engine based on the dynamic model that take into account the thermal losses. An optical study of the paraboloïdal concentrator based on Stine model, as well as a thermal analysis of the receiver was made. The calculation programme worked out under MATLAB to solve the equation set makes it possible to calculate the performances of all types of the Solar Dish Stirling System following kinematics used, the types of regenerators, the exchangers, receiver, Dish dimension as well as the various working liquids used.
Key words: Stirling engines, solar energy, dish Stirling, concentrator parabolic.

RESUME

La conversion thermodynamique de l'énergie solaire en électricité est un enjeu énergétique majeur. Les systèmes actuels sont essentiellement basés sur la technologie dite " Solar Dish Stirling", qui utilise des moteurs Stirling placés au foyer d'un concentrateur paraboloïdal. Le moteur Stirling présente un excellent rendement théorique équivalent au rendement de Carnot. Il est à combustion externe, silencieux et moins polluant. La présente étude a pour objet la prédiction des performances thermiques d'un moteur Stirling associé à un concentrateur paraboloïdal et un récepteur de type cavité. Nous avons développé une modélisation thermodynamique du moteur Stirling cinématique basée sur le modèle dynamique qui prend en compte les pertes thermiques dont le moteur Stirling est le siège. Une étude optique du concentrateur paraboloïdal basée sur le modèle de Stine, ainsi qu'une analyse thermique du récepteur ont été faites. Le programme de calcul élaboré sous MATLAB pour résoudre le système d'équations permet de calculer les performances de tous types des systèmes Dish Stirling suivant la cinématique utilisée, les types de régénérateurs, les échangeurs, le récepteur, les dimensions du concentrateur ainsi que les différents fluides de travail utilisés.
Mots Clefs : Moteur Stirling, énergie solaire, Dish Stirling, concentrateur parabolique.

NOMENCLATURE

A	Area	(m^2)	**Subscripts and Superscripts**	
C_p	Pressure constant heat capacity	($J.kg^{-1}.K^{-1}$)	a	Ambient
C_v	Volume constant heat capacity	($J.kg^{-1}.K^{-1}$)	ap	Receiver aperture
$\overline{C}$	Concentration Ratio		C	Compression space

d	Diameter	(m)	CAV	Cavity
F	Focal length	(m)	CK	Interface (C and K)
freq	Engine operating frequency	(Hz)	E	Expansion space
Gr	Grashof number		H	Heater
I	Beam radiation incident	(W/m^2)	K	Cooler
$\dot{m}$	Flow rate	(Kg/s)	KR	Interface (K and R)
Nu	Nusselt number		proj	Concentrator project area
P	Pressure	(Pa)	R	Regenerator
$\dot{Q}$	Power	(W)	R_1,R_2,R_3	Regenerator subdivisions
R	Ideal gas constant	(J.kg^{-1}.K^{-1})	SE	Stirling engine
T	Temperature	(K)	SW	Swept volume
V	Volume	(m^3)		

Greek symbol

α	Receiver absorptance	ρ	Mirror reflectance
Γ	Specific intercept factor	σ	Boltzmann's constant
ε	Emissivity of a surface	τ	Transmittance
η	Efficiency	ψ	Concentrator rim angle
θ	Sun elevation angle	ϕ	Engine Rotation angle

1. INTRODUCTION

Electricity produced from concentrating solar power has become more economic and its influence in the electricity market is expected to significantly increase in the near future. This technology incorporates three different designs: the parabolic trough, the power tower and Dish Stirling System (DSS). DSS are anticipated to surpass parabolic troughs by producing power at more economical rates and higher efficiencies. They have the potential to become one of the least expensive sources of renewable energy [1]. These systems are characterized by high efficiency, modularity, autonomous operation, and an inherent hybrid capability. Of all solar technologies, DSS have demonstrated the highest solar-to-electric conversion efficiency (29.4%) and annual efficiency (25%). On the other hand these systems have reached an important reliability degree and their cost has considerably decreased during the lasts years [2]. Because the DSS are modular; each system is a self-contained power generator, they can be assembled into plants ranging in size from a kilowatts to ten megawatts. They are well suited for centralized and decentralized power production. DSS was presented as one of the oldest solar technologies. In 1870, the Stirling engine was adapted by Ericson to operate with solar energy [3]. Since the 1970s, several DSS ranging in size from 5 kW_e to 25 kW_e were developed, installed and tested in different regions of the world (USA, Spain, Germany, Italy, Australia…). Nowadays Stirling Energy Systems Company introduced a matured DSS of 25 kWe and its first attempt of commercialization to build 1750 MWe solar plant using this technology in California. It would be the world's largest solar facility.
The contribution of this paper consists in predicting the thermal performances of DSS. A global model associating three individual components models is proposed. The first model is dedicated to a thermodynamic modeling of kinematic Stirling engine. The second one consists on optical modeling of parabolic concentrator. Thermal model of cavity receiver is also presented.

2. DISH STIRLING ENGINE DESCRIPTION

The DSS consists of four components; the parabolic Dish, the thermal receiver, the Stirling engine and electrical generator. The sunlight are reflected and concentrated by the dish parabolic into the receiver. The receiver is designed to transfer the absorbed solar energy to the working fluid (air,H_e, or H_2). The Stirling engine then converts the absorbed thermal energy to mechanical power by expanding the gas in a piston cylinder. The linear motion is converted to a rotary motion to turn a generator to produce electricity.

3. GLOBAL SYSTEM MATHEMATICAL MODEL

The simulation of Dish Stirling System is performed in MATLAB and based on its global thermal model in which the system is divided into five components, each of them representing a stage of the conversion cascade as shown in figure 1[4].

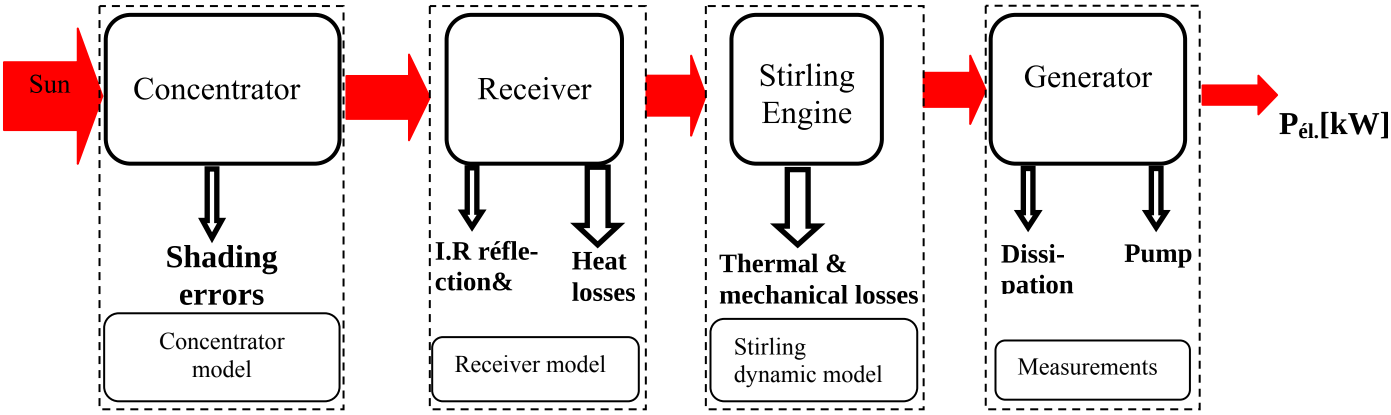

Figure 1. Schematic of Dish Stirling System solved in MATLAB

3.1 **Stirling engine dynamic model**

In the Stirling engine dynamic model developed we consider four types of thermal losses; the thermal lost due to the shuttle effect in the displacer, the lost due to internal conduction through the three exchangers, lost due to external conduction in the regenerator and the pumping losses. Concerning the mechanical frictions we consider only the energy dissipation by pressure drops in heat exchangers. The Stirling engine is divided into 5 control volumes serially connected; in addition the regenerator is divided into three subdivisions, as shown in Figure 2 [5]. The engine consists respectively of a compression space C, a cooler K, a regenerator R, a heater H and an expansion space E. Notice from figure 2 that the temperature in the compression and expansion spaces vary over the cycle in accordance with the adiabatic compression and expansion occurring in the working spaces. In this model the fluid temperature in the wall heat exchangers is taken as uniform and constant. In the regenerator a constant linear fluid temperature profile is assumed. The variable volume expansion and compression spaces depend on the kinematics used.
The instantaneous pressure of the engine is:

$$P = M.R\left(\frac{V_C}{T_C}+\frac{V_K}{T_K}+\frac{V_R}{T_R}+\frac{V_H}{T_H}+\frac{V_E}{T_E}\right)^{-1} \quad (1)$$

The energy equation is written for each control volume to calculate the energy transferred in each element of Stirling engine, for example:

$$d\dot{Q}_K = [V_K.C_v.\frac{dp}{R} - C_p.\left(T_{CK}.\dot{m}_{CK} - T_K.\dot{m}_{KR}\right)].freq \quad (2)$$

The work done in the compression (and expansion) cells is:

$$\delta W_C = -P.\left(\frac{V_{SWC}}{2}.\sin(\varphi)\right) \quad (3)$$

We define the indicated efficiency by:

$$\eta_{SE} = \frac{W}{Q_H} \quad (4)$$

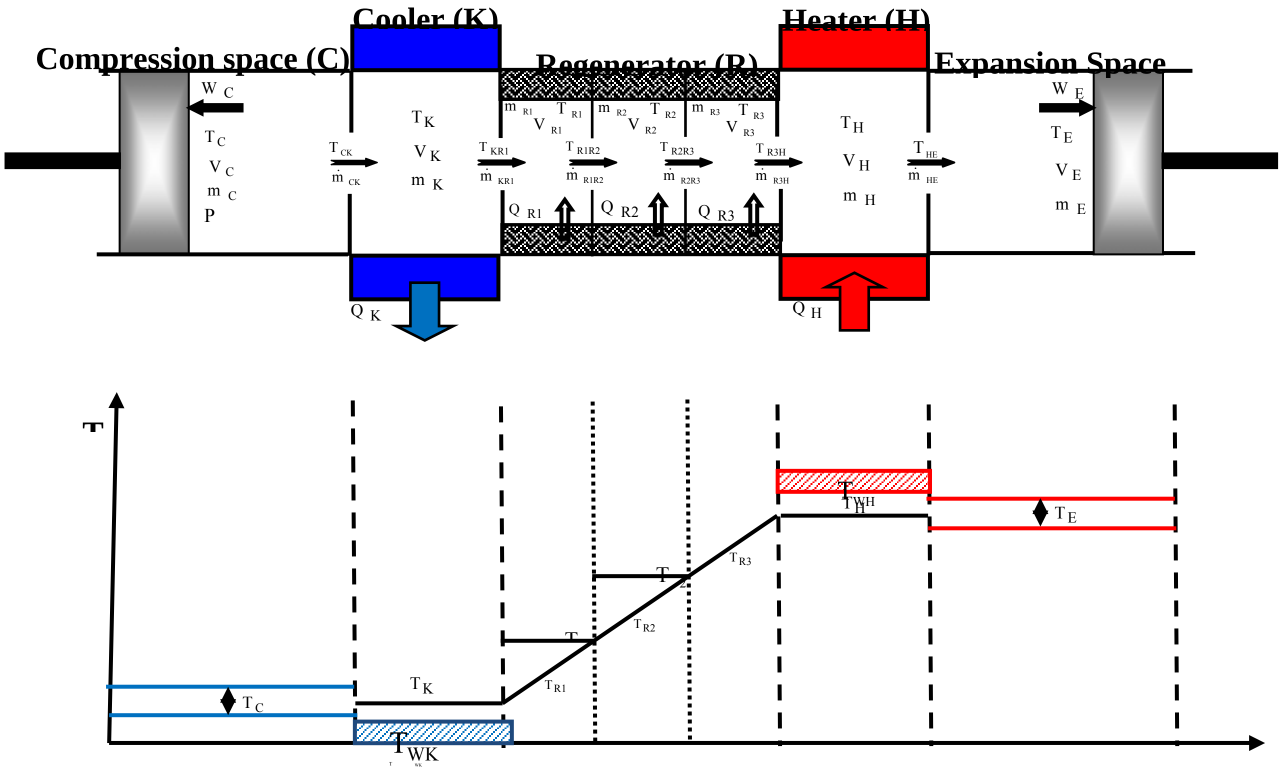

Figure 2. Stirling engine configuration and temperature distribution

3.2 Concentrator model

This model predicts the solar power intercepted by the receiver. It is calculated by:

$$\dot{Q}_{in-receiver} = I.A_{Proj}.\rho.\alpha.\tau..\delta_{int} \quad (5)$$

The intercept factor δ_{int} is done as:

$$\delta_{int} = \frac{8\pi.F^2}{A_{proj}}.\int_0^{\psi_{rim}} \frac{\Gamma.\sin(\psi)}{(1+\cos(\psi))^2}\, d\psi \quad (6)$$

The optical efficiency is:

$$\eta_{optic} = \Gamma.\alpha.\rho.\tau \quad (7)$$

3.3 Receiver model

The objective of this model is to calculate the energy output by the receiver and provided to Stirling engine heater. The calculations have been made to quantify the receiver thermal losses due to conduction, convection and radiation.

The thermal energy provided to Stirling engine is done by:

$$\dot{Q}_{useful} = \dot{Q}_{in-receiver} - (\dot{Q}_{lost,cond} + \dot{Q}_{lost,conv} + \dot{Q}_{lost,rad}) \quad (8)$$

- Natural convection loss: it is represented by the following equation:

$$\dot{Q}_{lost,conv} = h.A_{ap}.(T_{CAV} - T_a) \quad (9)$$

To determine the natural convection coefficient (h) we use the Nusselt number correlation of Stine:

$$Nu_L = 0.088.Gr_L^{1/3}.\left(\frac{T_{CAV}}{T_a}\right)^{0.18}(\cos\theta)^{2.47}.\left(\frac{d_{ap}}{d_{CAV}}\right)^{\left(1.12-0.98.\frac{d_{ap}}{d_{CAV}}\right)} \quad (10)$$

- Radiation loss: the general losses radiation considered both emitted and reflected radiation from a cylindrical cavity receiver. It is given by:

$$\dot{Q}_{lost,rad} = \sigma.A_{ap}.\varepsilon.\left(T_{CAV}^4 - T_{sky}^4\right) \quad (11)$$

The conduction loss through the receiver housing is minimal and neglected.
The receiver efficiency is done by:

$$\eta_{receiver} = \frac{\dot{Q}_{useful}}{I.A_{proj}} \quad (12)$$

The receiver optimum temperature for maximum efficiency is given by the following equation [6]:

$$T_{optimum}^5 - (0.75.T_K).T_{optimum}^4 - \left(\frac{T_H.I.\overline{C}.\alpha}{4.\varepsilon.\sigma}\right) = 0 \quad (13)$$

The global efficiency of Dish Stirling System is by:

$$\eta_{global} = \eta_{optic}.\eta_{receiver}.\eta_{SE} \quad (14)$$

4. RESULTS AND DISCUSSION

The equation system is resolved by an iterative method developed in MATLAB for specific Stirling engine configurations and global system operating conditions. The technical data of DSS investigated in this study (Stirling Energy System (SES)) are summarized in following table.

Table 1. Technical data of DSS investigated

Parabolic concentrator	Projected area	87.7 m^2
	Reflectivity	0.91
Receiver	Aperture diameter	0.2 m
	Receiver temperature	720°C
	Working pressure	20 Mpa
Stirling engine	Type	Kockums 4-95 SES
	Size	4 cylinders 380 cc
Global Dish-Stirling System performances	Electrical output at 1000 W/m^2	25 kW_e
	Peak net efficiency	29.4%
	Annual output	54,500 kWhrs at 7.1 kWhr/m2/day

Figure 3 illustrates a linear relationship between the Dish Stirling System power output and the beam irradiation incident. The power output is lower in the morning due to its thermal inertia.

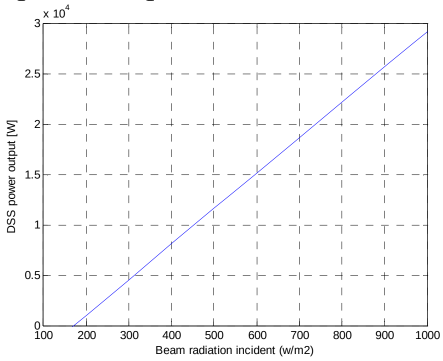

Figure3. Dish Stirling System power output

Figure 4 shows the significant thermal losses in the receiver. The three modes of heat lost are proportional to the internal receiver temperature. Radiation losses are considerable for the systems functioning at high temperatures and become less for that functioning at temperatures slightly above the ambient temperature; on the other hand the conduction losses are neglected

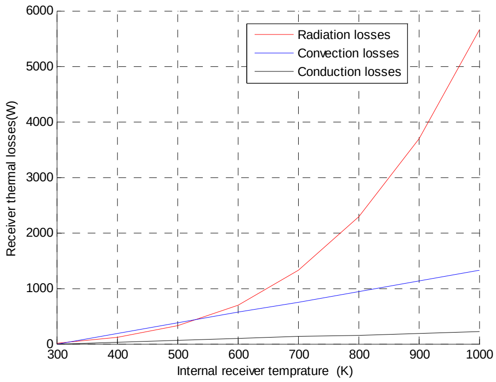

Figure 4. Heat losses in the receiver

The evolution of Stirling engine, receiver and global system efficiency as a function of receiver internal temperature are shown in figure 5. It can be seen a contrary relationship between the global efficiency and the receiver optimum temperature, that indicates that each DSS should be have an optimum temperature in its receiver. At this temperature the systems have the maximum efficiency.

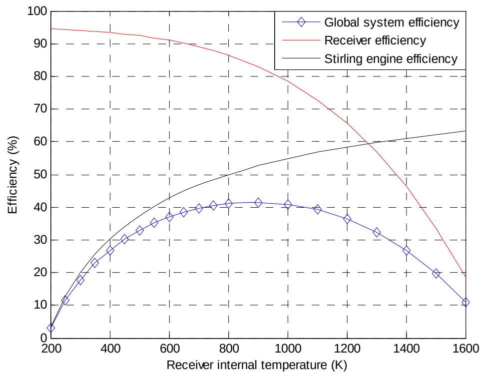

Figure 5. Efficiency versus the receiver internal temperature

5. CONCLUSION

In order to predict the performances of the Dish Stirling System, a global model is proposed. Three separate components models were created for the parabolic concentrator, receiver and Stirling engine. The model is capable to predicting the system performance if there are changes in the Stirling engine type, receiver type, sun elevation angle , concentrator reflectivity, heater temperature, the receiver aperture diameter or the meteorological conditions.

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