

# **Exergetic Analysis and Optimisation of a Parabolic Dish Collector for Low Power Application**

Lloyd C. Ngo  
University of Pretoria

Centre for Renewable and Sustainable Energy Studies

## **Abstract**

The purpose of this study is to carry out an optimisation and exergetic analysis of a concentrating type (parabolic dish) solar collector to evaluate the actual exergy available from such a system. We have applied the exergy analysis to optimise a parabolic dish solar collector and made detailed parametric analysis taking into consideration the exergetic content of incident solar radiation. The exergy efficiency is derived as the objective function to be optimised subject to constraints and the optimisation toolbox is used to extract the optimum points. By performing exergy analysis, we are able to draw a map of how the exergy destruction and loss is distributed over the parabolic dish collector. The method of exergy analysis (availability analysis) used in this study is well suited for furthering the goal of more effective solar energy use, for it enables the cause and true magnitude of the waste and loss to be determined. Such information can be used in the thermodynamic optimisation of efficient solar power systems and for increasing the efficiency of the existing ones

*Keywords:* Solar power systems; exergy analysis; parabolic dish concentrator; optimisation; radiation

## 1.0 Introduction

The World today has become more and more dependent on fossil fuels such as oil, coal and natural gas. These resources are finite, having been created by natural processes over millions of years. The burning of fossil fuels to produce energy results in emissions of 'greenhouse gases' such as carbon dioxide (CO<sub>2</sub>), sulphur dioxide (SO<sub>2</sub>) and nitrogen oxides (NO<sub>x</sub>). These gases trap solar radiation in the earth's atmosphere and cause undesirable changes to the climate.

The conversion of solar energy into electricity is receiving more and more attention in recent years. Sunlight is the world's largest energy source and the amount that can be readily accessed with existing technology greatly exceeds the world's primary energy consumption. Furthermore, sunlight is free, clean, renewable and technically exploitable in most part of the inhabited earth [1].

Parabolic dish collectors are one of the concentrated solar thermal collectors used for energy conversion and power generation. The parabolic dish collector used in this study consists of a parabolic dish collector and a modified cavity receiver operating in tracking mode.

To avoid confusion of the terminology, the word collector will be applied to the total system, including the receiver and the concentrator. The receiver is the element of the system where the radiation is absorbed and converted to some other energy form; it includes the absorber, its associated covers, and insulation. The concentrator, or optical system, is the part of the collector that directs radiation on to the receiver. The aperture of the concentrator is the opening through which the solar radiation enters the concentrator [2].

The linkages between energy and exergy, exergy and the environment, energy and sustainable development, and energy policy making and exergy is available in literature as presented by Dincer [3].

Nomenclature		Greek symbols	
$A_a$	Concentrator aperture area (m <sup>2</sup> )	$\eta_o$	Optical efficiency
$A_r$	Receiver aperture area (m <sup>2</sup> )	$\rho$	Air density/dish reflectance
$C$	Concentration ratio	$\eta_P$	Petela's efficiency
$C_p$	Specific heat capacity (J/Kg.K)	$\eta_c$	Collector efficiency
$d$	Receiver aperture diameter (m)	$\eta_E$	Exergy efficiency
$D$	Modified cavity diameter (m)	$\lambda$	Factor of un-shading
$\dot{E}$	Exergy rate (W)	$\theta$	Angle of incidence
$F_R$	Heat removal factor	$\tau$	Transmittance
$F'$	Collector efficiency factor	$\alpha$	Absorptance
$I_b$	Direct normal insolation (W/ m <sup>2</sup> )	<i>Subscripts</i>	
$\dot{m}$	Mass flow rate (Kg/s)	opt	Optical
$\Delta P$	Pressure drop (Pascal)	in	in
$Q_l$	Collector ambient heat loss (W)	out	out
$Q_s$	Net solar heat transfer (W)	des	destroyed
$\dot{Q}_u$	Useful energy rate (W)	ab	absorption
$R$	Parabolic dish radius (m)	a	ambient
$S$	Radiation falling on receiver (W/ m <sup>2</sup> )	th	thermal,
$T_{in}$	Temperature in (K)	l	loss
$T_{out}$	Temperature out (K)	cond	conduction
$T_r$	Receiver temperature (K)		

$T_s$ the sun	Apparent black body temperature of	
$U_L$ (W/m <sup>2</sup> K)	Overall heat transfer coefficient	

Hapbasli summarised the following key points to highlight the importance of the exergy and its essential utilization in numerous ways: (a) it is a primary tool in best addressing the impact of energy resource utilization on the environment. (b) It is an effective method using the conservation of mass and conservation of energy principles together with the second law of thermodynamics for the design and analysis of energy systems. (c) It is a suitable technique for furthering the goal of more efficient energy–resource use, for it enables the locations, types, and true magnitudes of wastes and losses to be determined. (d) It is an efficient technique revealing whether or not and by how much it is possible to design more efficient energy systems by reducing the inefficiencies in existing systems. (e) It is a key component in obtaining a sustainable development [1].

An exergy analysis (or second law analysis) has proven to be a powerful tool in the simulation of thermodynamic analyses of energy systems. It has been widely used in the design, simulation and performance evaluation of energy systems [1]. By performing exergy accounting, we are able to draw a map of how the destruction of exergy is distributed over the engineering system of interest. In this way we are able to pinpoint the components and mechanisms (processes) that destroy exergy the most. This is a real advantage in the search for improving efficiency, because it can indicate the possibilities of thermodynamic improvement of the process under consideration [1] and consequently inform us from the start how to allocate engineering effort and resources.

The method of exergy analysis (availability analysis) presented in this paper is well suited for furthering the goal of more effective solar energy use, for it enables the cause and true magnitude of the waste and loss to be determined [1]. Such information can be used in the thermodynamic optimisation of efficient solar power systems and for increasing the efficiency of the existing ones [4]

In those cases where a solar collector is used to drive an energy conversion device, such as an engine, it is the exergy collection capability rather than energy collection capability that is the true measure of the potential of the collector to perform the desired function [5].

The calculation of the exergetic content of the incident solar radiation is very important when evaluating the performance of solar energy system by means of exergy analysis [6]. However, its calculation is a problem of unquestionable interest, since exergy represents the maximum quantity of work that can be produced in some given environment (usually the terrestrial environment, considered as an infinite heat source or sink) [7]. Over a period of more than 20 years, many papers including various approaches to this calculation have been published. Among these, the first one called by Petela the maximum efficiency ratio (or exergy-to-energy ratio for radiation) for determining an exergy of thermal emission at temperature T [1]. Discussion on radiation exergy formulae proposed by several researchers is available [6, 8].

In the literature, there exist a number of papers concerning exergetic analysis of solar thermal collectors with few focusing on concentrating solar collectors. For instance, Kahrobaian et al. [5] presented a new method of optimisation on linear parabolic solar collectors using exergy analysis. Tyagi et al. [9] presented an exergy analysis and parametric study of concentrating type solar collector. Kalogirou [10] analysed an imaging concentrating collector model using the second law analysis. Hepbasli [1] presented a brief exergetic analysis of solar energy systems in his key review on exergetic analysis and assessment of renewable energy resources for sustainable future. Farahat et al. [11] presented an exergetic optimisation of flat plate solar collectors to determine the optimal performance and design parameters. Gupta et al. [20] evaluated the exergetic performance for the maximum exergy delivery in flat plate solar air heaters. Kar [12] investigated the efficiency and optimum operation of flat plate solar collectors in terms of exergy delivery. Kalgirou [13] employed exergy analysis to derive a general equation for the exergy efficiency of flat plate collectors and optimised its design and operation.

The results from these studies cannot be sufficiently be used as design guide for parabolic solar collector using a modified cavity receiver.

In this paper we have applied the exergy analysis on parabolic dish solar collector with a modified cavity receiver taking into consideration the exergetic content of incident solar radiation. By applying a derived expression for exergy efficiency, exergy destruction and losses were generated and the optimum design and operating conditions were investigated. The diameter of the cavity receiver was also optimised to enable a significant fraction of reflected radiation from the concentrator to be transmitted onto the receiver.

## **1.2 objectives**

The purpose of this study is to carry out an optimisation and exergetic analysis of a concentrating type (parabolic dish) solar collector to evaluate the actual exergy available from such a system. We have applied the exergy analysis to optimise a parabolic dish solar collector and made detailed parametric analysis taking into consideration the exergetic content of incident solar radiation.

## **2.0 Proposed system mathematical model and description**

The collector system consists of a parabolic dish collector operating in tracking mode as shown in fig.1. The modified cavity receiver suggested by Reddy and Sendhil Kumar [14] is considered in the analysis. The receiver is made of copper tubing. The copper tubes are wound spirally to get the respective shape of receiver. The outer surface of the cavity receiver is completely covered with opaque insulation.

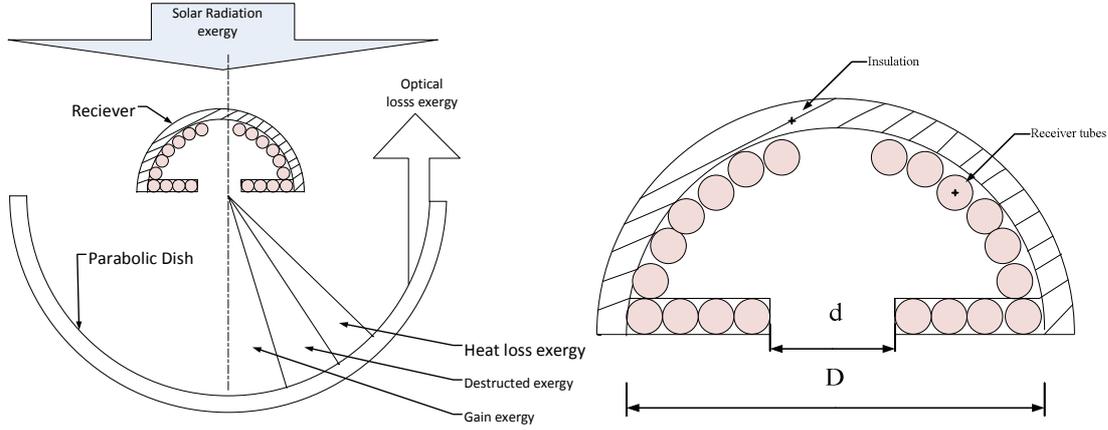


Fig. 1. Schematic of a Parabolic Dish concentrating collector with modified cavity model

## 2.1 Thermal Analysis

The exergy analysis of solar collectors is parametrically dependent on the thermal analysis. Hence, the thermal analysis is carried out first.

The collector thermal efficiency is defined as the ratio of the useful energy delivered to the energy incident on the concentrator aperture and is given as:

$$\eta_c = Q_u / Q_s \quad (1)$$

The dish concentrator has an aperture area  $A_a$  and receives solar radiation at the rate  $Q_s$  from the sun. The net solar heat transferred  $Q_s$  is proportional to  $A_a$ , and the incident solar radiation per unit of concentrator area  $I_b$ , which varies with geographical position on the earth, the orientation of the dish concentrator, meteorological conditions and the time of day.

In this analysis,  $I_b$  is assumed to be constant and the system is in steady state, i.e.

$$Q_s = I_b A_a \quad (2)$$

Under steady state conditions, the useful heat delivered by a solar collector system is equal to the energy absorbed by the heat transfer fluid, which is determined by the radiant solar energy falling on the receiver minus the direct or indirect heat losses from the receiver to the surroundings. That is,

$$Q_u = Q_r - Q_l \quad (3)$$

The radiation falling on the receiver  $Q_r$  is a function of the optical efficiency  $\eta_0$ , which is defined as the ratio of the energy falling on the receiver to the energy incident on the concentrator's aperture.

The collector thermal efficiency can be written as [15]:

$$\eta_c = \frac{Q_u}{Q_s} = \eta_0 - \frac{Q_l}{Q_s} \quad (4)$$

where  $Q_l$  is the total heat loss rate of the receiver. In order to determine the thermal efficiency of the collector, the optical efficiency  $\eta_0$  and the total heat loss rate of the receiver  $Q_l$  should be obtained.

$$Q_l = Q_s - Q_u \quad (5)$$

$$Q_l = U_L A_r (T_r - T_a) \quad (6)$$

Where  $U_L$  is the overall heat transfer coefficient based on  $A_r$ . The overall heat loss coefficient  $U_L$  arises from the contribution of radiative, conductive and convective heat losses from the receiver.

The useful heat gain can also be defined on the basis of fluid difference temperatures as:

$$Q_u = \dot{m} c_p (T_{out} - T_{in}) \quad (7)$$

The Hottel–Whillier equation for the actual useful heat gain ( $Q_u$ ) of a concentrating solar collector system is given as:

$$Q_u = F_R A_a \left[ S - \frac{A_r}{A_a} U_L (T_{in} - T_a) \right] \quad (8)$$

where  $C$  is the concentration ratio,  $S$  is the absorbed flux ( $\eta_0 \times I_b$ ),  $F_R$  is the heat removal factor of the collector and  $T_a$  is the ambient temperature. The heat removal factor accounts for the temperature gradients in the receiver and allow for the use of inlet fluid temperatures in the energy balance equations [1]. This is convenient when analysing solar energy systems, since the inlet temperature is usually known.

The heat removal factor ( $F_R$ ) is defined as:

$$F_R = \frac{\dot{m} c_p}{A_r U_L} \left[ 1 - e^{-\left( \frac{A_r U_L F'}{\dot{m} c_p} \right)} \right] \quad (9)$$

From eqs. 8 and 9 the actual useful heat gain is given as:

$$Q_u = \frac{\dot{m} c_p A_a}{A_r U_L} \left( S - \frac{A_r}{A_a} U_L (T_{in} - T_a) \right) \left( 1 - e^{-\left( \frac{A_r U_L F'}{\dot{m} c_p} \right)} \right) \quad (10)$$

## 2.2 Optical and Geometrical analysis.

The optical efficiency  $\eta_0$  depends on the optical properties of the materials involved (e.g. the reflectance of dish and the optical properties of the receiver etc.), the geometry of the collector, and the various imperfections arising from the construction

of the collector [15]. The following equation form can be used to perform an approximated optical efficiency analysis,

$$\eta_0 = \lambda \rho \tau \alpha \gamma \cos(\theta) \quad (11)$$

where  $\lambda$  is the factor of un-shading,  $\rho$  is dish reflectance,  $\tau \alpha$  is transmittance–absorptance product,  $\gamma$  is the intercept factor of receiver, which is defined as the ratio of the energy intercepted by the receiver to the energy reflected by the focusing device, i.e. parabola dish,  $\theta$  is angle of incidence. As the solar parabolic dish concentrator maintains its optical axis always pointing directly towards the sun to reflect the beam, which means the incidence angle of solar beam into the dish is zero degree, and the cosine loss equals to zero. The Eq. (11) can be written as [15]:

$$\eta_0 = \lambda \rho \tau \alpha \gamma \quad (12)$$

In this study, in order to evaluate the thermal performance of the parabolic dish collector system, the optical efficiency has been approximately estimated [15] as value of 0.85.

The concentration ratio  $C$  is the ratio of the effective area of the concentrator aperture to the area of the receiver and is given as:

$$C = \frac{A_a}{A_r} \quad (13)$$

The aperture area of parabolic dish concentrator is defined by

$$A_a = \pi R^2 \quad (14)$$

Where  $R$  is the radius of the parabolic dish concentrator. The receiver aperture area of the modified cavity receiver is given as:

$$A_r = \frac{\pi}{4} d^2 \quad (15)$$

The modified cavity receiver diameter as function of the receiver aperture  $d$ , for minimum heat loss is given as [16, 19]:

$$D = \sqrt{3}d \quad (16)$$

The essential feature of a receiver is to absorb the maximum amount of reflected solar energy and transfer it to the working fluid as heat, with minimum losses. Generally, a conventional receiver is used to accomplish this purpose. For a focal solar dish concentrator, the size of the focal image is normally higher than the theoretical design. This is mainly due to reflector surface being imperfect and contour of the concentrator deviating from the ideal geometric shape. Thus the increase in the aperture to accommodate the larger focal image leads to the requirement of a large aperture to reduce spillage, and consequently a high convective heat loss through the receiver. So, the normal conventional/cavity receivers tend to be inadequate for focal solar dish [17] and as such a modified cavity receiver has been used in this analysis.

The aperture of the modified receiver must be designed to be large enough to enable a significant fraction of reflected radiation from the concentrator to be transmitted onto the receiver. Increasing the aperture size will increase the amount of solar radiation intercepted by the receiver, but also increase the losses due to convection and radiation out of the receiver aperture. Convection and radiation decrease the effective radiative energy absorbed in the receiver.

### 2.3 Exergy Analysis

Application of exergy analysis to solar parabolic concentrators helps designers to achieve an optimum design and gives direction to decrease exergy losses. Exergy concept is one of the two ways to the second law analysis, and entropy generation from irreversibilities is the other method. However, both techniques fundamentally give identical results. Use of the exergy concept is preferred because it yields directly the system work attainable for ideal processes [18]. Decreasing exergy destructed during thermodynamic processes can be achieved by the view point of maximizing exergy efficiency.

By applying exergy balance on a solar collector (shown in Fig. 1), exergy efficiency can be derived and the shares of irreversible factors are defined as well. Exergy balance can be generally be expressed as [5]:

$$\sum \dot{E}_{in} - \sum \dot{E}_{out} - \sum \dot{E}_{loss} - \sum \dot{E}_{change} - \sum \dot{E}_{des} = 0 \quad (17)$$

In general, exergy can be exchanged in two ways in parabolic solar collectors: the first, by fluid flow and the second by heat transfer through the absorbed solar radiation. Therefore, the inlet exergy rate includes the inlet exergy rate with fluid flow and the absorbed solar radiation exergy rate. The exergy accompanying an incompressible fluid flow is given as [5]:

$$\dot{E}_{in,f} = \dot{m}c_p \left( T_{in} - T_a - T_a \ln \frac{T_{in}}{T_a} \right) + \frac{\dot{m}\Delta P}{\rho} \quad (18)$$

where  $T_{in}$  is inlet fluid temperature and  $\Delta P$  is pressure difference between the fluid and ambient pressure.

Using Petela's approach of defining the exergy of solar radiation, the exact exergy solar radiation for a typical collector with concentrator area of  $A_a$  is defined as:

$$\dot{E}_{in,r} = I_b A_a \eta_p \quad (19)$$

$\eta_p$  is Petela's efficiency of converting radiation energy (i.e.  $I_b A_a$ ) into work given as [8]:

$$\eta_p = 1 - \frac{4T_a}{3T_s} + \frac{1}{3} \left( \frac{T_a}{T_s} \right)^4 \quad (20)$$

where  $T_s$  is the apparent black body temperature of the sun, which is about 6000 K.

Therefore, the absorbed solar radiation exergy rate at the receiver, considering Petela's theorem, is given by:

$$\dot{E}_{in,Q} = SA_a \eta_p \quad (21)$$

The outlet exergy rate includes only the exergy rate of the outlet fluid flow (11):

$$\dot{E}_{f,out} = \dot{m} c_p \left( T_{out} - T_a - T_a \ln \frac{T_{out}}{T_a} \right) + \frac{\dot{m} \Delta P}{\rho} \quad (22)$$

The gain exergy rate ( $\dot{E}_{gain}$ ) is the exergy that is accumulated by fluid flow through the receiver and is expressed as:

$$\sum \dot{E}_{gain} = \sum \dot{E}_{out,f} - \sum \dot{E}_{in,f} \quad (23)$$

And the exergy efficiency is the ratio of the gain exergy to solar radiation exergy expressed as (5) :

$$\eta_E = \frac{\dot{E}_{gain}}{\dot{E}_{in,r}} \quad (24)$$

or

$$\eta_E = 1 - \left( \sum \dot{E}_{loss} - \sum \dot{E}_{change} - \sum \dot{E}_{des} \right) / \dot{E}_{in,r} \quad (25)$$

Under steady state conditions,  $\sum \dot{E}_{change} = 0$ . In order to show which exergy fractions are major, the exergy efficiency should be expressed in terms of lost and destructed exergy. Exergy loss rate is the amount of exergy that a thermodynamic system loses in processes. In the actual sense, it is the exergy leakage rate out to the surroundings due to optical errors and heat transfer to ambient in a solar receiver which is unwanted and be expressed as:

$$\sum \dot{E}_{loss} = \sum \dot{E}_{l,opt} + \sum \dot{E}_{l,th} \quad (26)$$

Because of the optical properties of the materials involved (e.g. the reflectance of dish and the optical properties of the receiver etc.) not all solar radiation reach the receiver. Therefore, optical efficiency is considered in the expression of the optical exergy rate fraction and is given as:

$$\dot{E}_{l,opt} = (1 - \eta_0) I_b A_a \eta_p \quad (27)$$

The heat leakage from receiver to ambient is defined by equation (6) and its corresponding exergy loss is:

$$\dot{E}_{l,th} = \frac{U_L A_r (T_r - T_a)^2}{T_r} \quad (28)$$

Exergy destruction is caused by irreversibilities in the system and there are two ways of exergy destruction in solar collectors; exergy destroyed due to friction of viscous fluid and exergy destroyed due to heat transfer processes. Since the viscous fluid causes pressure drop between inlet and outlet of the receiver, considering correspondent entropy generation, exergy destroyed due to pressure drop during this process can be stated as [5]:

$$\dot{E}_{des,\Delta P} = T_a \frac{\dot{m}\Delta P}{\rho} \frac{\ln(T_{out}/T_{in})}{T_{out} - T_{in}} \quad (29)$$

Exergy also is destroyed while heat is transferred from hot to cold temperatures. There are two heat transfer processes in the receiver that cause exergy rate destruction; 1) heat transfer caused by the temperature difference between the receiver surface and the sun, which is the heat transfer of the solar energy absorbed by the surface of the receiver. 2) heat transfer conduction from outer receiver surface to fluid flow caused by the temperature difference between the receiver surface and the agent fluid [5, 11]. Therefore, the exergy destruction rate due to heat absorption is defined as [5]:

$$\dot{E}_{des,abs} = \dot{Q}_u T_a \left( \frac{1}{T_r} - \frac{1}{T_s} \right) \quad (30)$$

where  $\dot{Q}_u$  is the useful energy rate added to the fluid flow energy. Considering useful energy rate as  $\eta_0 I_b A_a$ , the exergy destruction due to heat absorption is defined as:

$$\dot{E}_{des,abs} = \eta_0 I_b A_a T_a \left( \frac{1}{T_r} - \frac{1}{T_s} \right) \quad (31)$$

And the exergy destroyed due to heat transfer conduction is given as:

$$\dot{E}_{des,cond} = \dot{m} c_p T_a \left( \ln \left( \frac{T_{out}}{T_{in}} \right) - \frac{(T_{out} - T_{in})}{T_r} \right) \quad (32)$$

Defining a non-dimensional parameter as  $\ddot{E} = \dot{E} / \dot{E}_{in,r}$  and substituting eqs. (27-32) into eq. 25, exergy efficiency can be presented as:

$$\eta_E = 1 - \left[ \underbrace{(1 - \eta_0)}_{\ddot{E}_{i,opt}} + \underbrace{\frac{U_L (T_r - T_a)^2}{I_b C \eta_p T_r}}_{\ddot{E}_{i,th}} + \underbrace{T_a \frac{\dot{m} \Delta P}{I_b A_a \eta_p \rho}}_{\ddot{E}_{des,\Delta P}} \frac{\ln\left(\frac{T_{out}}{T_{in}}\right)}{T_{out} - T_{in}} \right. \\ \left. + \underbrace{\frac{\eta_0 T_a}{\eta_p} \left(\frac{1}{T_r} - \frac{1}{T_s}\right)}_{\ddot{E}_{des,abs}} + \underbrace{\frac{\dot{m} c_p T_a}{I_b A_a \eta_p} \left(\ln\left(\frac{T_{out}}{T_{in}}\right) - \frac{(T_{out} - T_{in})}{T_r}\right)}_{\ddot{E}_{des,cond}} \right] \quad (33)$$

Eq. (33) is the objective function and illustrates which parts of losses or destruction have greater influence on its value.

### 3.0 Research methodology

The thermal, geometric and exergetic models presented in the previous sections is transposed into MATLAB computation program. In the program some of the geometric parameters and operating conditions can be variables. The optimisation problem is given by (33). The problem considers,  $T_a, T_s, I_b, c_p, \eta_0, F'$  etc., as constants subject to eqs. (1) to (15) modelled in the thermal, optical and geometric analysis. Mass flow is constrained to  $0.001 \leq \dot{m} \leq 0.009$ .  $T_{in}, T_{out}, T_r, U_L, Q_u, \Delta P, F_R$ , are considered to be greater than zero.

The objective function and its constraints are nonlinear and has been maximised numerically with the MATLAB optimisation toolbox. The fmincon and SQP algorithms which calculate the minimum of a nonlinear function with multivariable and constraints are used. fmincon attempts to find a constrained minimum of a scalar function of several variables starting at an initial estimate. SQP methods represent the state of the art in nonlinear programming methods.

The selected environmental and design conditions of the parabolic dish solar collector and constant parameters for the optimisation procedure are shown in table 1. The parabolic dish adopts the dimensions used in [17].

### 4.0 Results and discussion

The resulted design parameters are listed in table 2. which are characteristic of the parabolic dish collector at optimum point.

**Table 1. Environmental and design conditions of the parabolic dish collector**

$T_a$ , ambient temperature	300 K
$T_s$ , sun's temperature	6000 K
$I_s$ , solar intensity	980 W/m <sup>2</sup>
$R$ , parabolic dish diameter	1.02 m
$A_r$ , receiver area	variable
$C$ Concentration ratio	variable
$T_r$ , Receiver temperature	variable
$T_{in}$ , Inlet temperature	variable
$T_{out}$ , Outlet temperature	variable
$\eta_o$ , Optical efficiency	0.85
$c_p$ , specific heat capacity	1005J/Kg.K
$\Delta P$ , pressure drop	variable
$\dot{m}$ , Mass flow rate	variable
$U_L$ , overall heat loss coefficient	variable
$F'$ , collector efficiency factor	0.90

**Table 2. Results at optimum and operating conditions**

$\eta_E$ , Exergetic efficiency	0.24
$A_r$ , receiver area	0.01 m <sup>2</sup>
$d$ , aperture diameter	0.1123 m
$D$ , cavity diameter	0.1945 m
$C$ Concentration ratio	330
$T_r$ , Receiver temperature	550.51 K
$T_{in}$ , Inlet temperature	300 K
$T_{out}$ , Outlet temperature	601.01 K
$\Delta P$ , pressure drop	0.001 Pa
$\dot{m}$ , Mass flow rate	0.009 Kg/s
$U_L$ , overall heat loss coefficient	150 W/ m <sup>2</sup> K
$Q_u$ , useful energy	2.278 kW
$F_R$ , heat removal factor	0.8366

#### 4.1 Effects of receiver temperature and solar intensity

Fig. 2 shows the sensitivity of dimensionless exergy ratios to receiver temperature while other variables are kept at optimum values. The assumed constants as shown in table 1 are used for other parameters such as solar intensity. The exergy efficiency increase with increasing receiver temperature until the optimum temperature is reached and then start to decrease.

The main values of dimensionless exergy losses at this point belong to exergy destructed by absorption heat transfer, exergy loss due to optical and heat leakage loss. Exergy destruction due to absorption is quite large, as compared with other processes. To decrease this destructed quantity, the receiver temperature must be as high as possible. This is one advantage of using concentration-types of solar collectors because they make this exergy destruction smaller due to high temperatures. However, whilst a high receiver temperature decreases the exergy

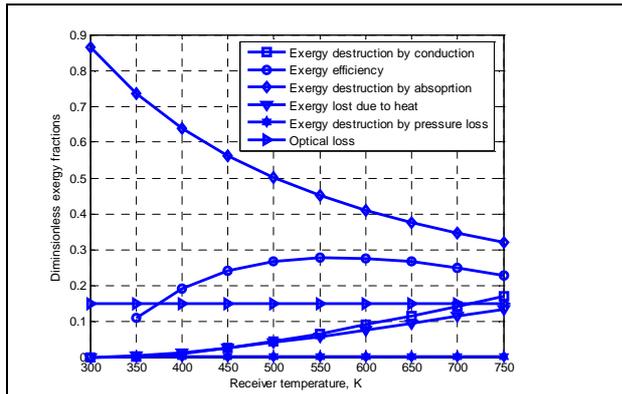


Fig. 2: The variation of dimensionless exergy ratios versus receiver temperature

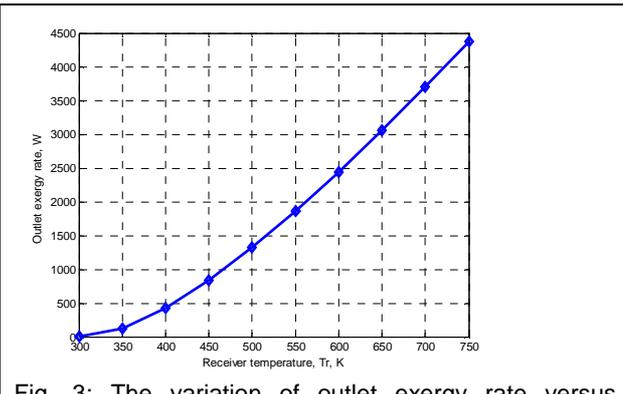


Fig. 3: The variation of outlet exergy rate versus receiver temperature

destruction by absorption, it also increases the dimensionless exergy loss due to heat and exergy destruction by conduction. The exergy loss due to optical loss remains constant with increasing receiver temperature.

The exergy destruction by pressure drop is very small and can be neglected since its contribution is much smaller than other exergy rate destruction.

It can be seen from fig. 3 that the outlet exergy rate increases with increasing receiver temperature.

#### 4.2 Effects of mass flow rate

The main values of dimensionless exergy losses in this case of mass flow rate belong to exergy destroyed by absorption heat transfer and heat leakage loss. Exergy destruction due to absorption increases with increasing mass flow. This destroyed quantity is small at lower mass flow rates. However, at lower mass flow rates the dimensionless exergy loss due to heat is high but decrease with increasing mass flow. The effect of the exergy destruction by conduction is not much and decreases with increasing mass flow. The effect of exergy destruction by pressure drop is very small.

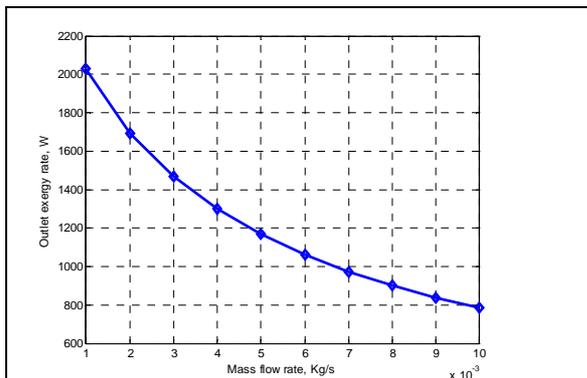


Fig. 4: The variation of outlet exergy rate versus mass flow rate

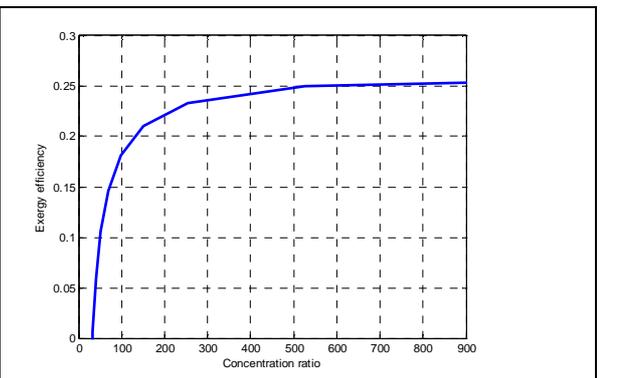


Fig. 5: The variation of exergy efficiency versus concentration ratio

The exergy efficiency increase with increasing mass flow until the optimum is reached and then start to decrease. It is observed from the fig. 4, that the outlet exergy rate is a decreasing function of mass flow rate. The meaning of this effect can be explained in

different ways. For example, as the mass flow rate is increased, the heat transfer time reduces therefore reducing the exergy output.

#### *4.3 Effects of concentration ratio and parabolic dish collector areas*

By keeping variables at optimum and other parameters constant, the value of the exergy efficiency rises with increasing concentration ratio  $C$  as can be seen in fig. 5. By increasing the parabolic dish radius diameter, the exergy efficiency increases until an optimum is reached, beyond which it start to decrease. This also increases the receiver aperture diameter until an optimum is reached since the concentration ratio remains constant at optimum.

### **4.0 Conclusion**

The exergy analysis and optimisation was carried out on the parabolic dish solar collector with a modified cavity receiver taking into consideration the content of incident solar radiation. By applying a derived expression for exergy efficiency, exergy destruction and losses were generated and the optimum design and operating conditions investigated. The diameter of the cavity receiver was also optimised to enable a significant fraction of reflected radiation from the concentrator to be transmitted onto the receiver.

The parametric study has been made for different receiver temperatures and mass flow rates. The exergy efficiency increase with increasing receiver temperature until the optimum temperature is reached and then start to decrease. The main values of dimensionless exergy losses in this analysis belong to exergy destructed by absorption heat transfer, exergy loss due to optical and heat leakage loss. The dimensionless exergy loss due to heat increase as the receiver temperature increases whereas the dimensionless exergy destruction decreases.

The method of exergy analysis (availability analysis) presented in this paper is well suited for furthering the goal of more effective solar energy use, for it enables the cause and true magnitude of the waste and loss to be determined. Such information can be used in the thermodynamic optimisation of efficient solar power systems and for increasing the efficiency of the existing ones.

### **4.1 Recommendations**

Investigate the exergetic efficiency of parabolic dish collector-heat engine combination. In general, the higher the temperatures provided by the working fluid from the collector, the lower will be the collector efficiency. However, for heat engines, the higher the energy supply temperature, the greater will be the efficiency. This incompatibility in temperature efficiency relationships indicates that any solar collector-heat engine combination will have an optimum operating temperature.

### **Acknowledgements**

This research is funded by the University of Pretoria and National Research Foundation (NRF).

## References

1. HEPBASLI, A., 2008. A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future. *Renewable and Sustainable Energy Reviews*, **12**(3), pp. 593-661.
2. DUFFIE, J. and BECKMAN, W., 2006. *Solar Engineering of Thermal Processes*. 3rd ed edn. New Jersey: John Wiley and Sons.
3. DINCER, I., 2002. The role of exergy in energy policy making. *Energy Policy*, **30**(2), pp. 137-149.
4. BEJAN, A., TSATSARONIS, G. and MORAN, M., 1996. *Thermal Design and Optimisation*. New York: John Wiley and Sons.
5. KAHROBAIAN, A. and MALEKMOHAMMADI, H., 2008. Exergy Optimization Applied to Linear Parabolic Solar Collectors. *Journal of Faculty of Engineering*, **42**(1), pp. 131-144.
6. ZAMFIRESCU, C. and DINCER, I., 2009. How much exergy one can obtain from incident solar radiation. *Journal of Applied Physics*, **105**.
7. BEJAN, A., 1988. *Advanced Engineering Thermodynamics*. New York: John Wiley and Sons.
8. PETELA, R., 2010. Discussion of Radiation Exergy Formulae Proposed by Researchers. *Engineering Thermodynamics of Thermal Radiation*. McGraw-Hill, pp. 247-263.
9. TYAGI, S.K., WANG, S., SINGHAL, M.K., KAUSHIK, S.C. and PARK, S.R., 2007. Exergy analysis and parametric study of concentrating type solar collectors. *International Journal of Thermal Sciences*, **46**(12), pp. 1304-1310.
10. KALOGIROU, S.A., 2004. Solar thermal collectors and applications. *Progress in Energy and Combustion Science*, **30**(3), pp. 231-295.
11. FARAHAT, S., SARHADDI, F. and AJAM, H., 2009. Exergetic optimization of flat plate solar collectors. *Renewable Energy*, **34**(4), pp. 1169-1174.
12. KAR, K., A., 1985. Exergy Efficiency and Optimum Operation of Solar Collectors. *Applied Energy*, **21**, pp. 301-314.
13. KALOGIROU, S., A., 2012. Exergy Analysis and Genetic Algorithms for the Optimisation of Flat Plate Solar Collectors, *The 25th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems 2012*.
14. SENDHIL KUMAR, N. and REDDY, K.S., 2008. Comparison of receivers for solar dish collector system. *Energy Conversion and Management*, **49**(4), pp. 812-819.
15. WU, S., XIAO, L., CAO, Y. and LI, Y., 2010. A parabolic dish/AMTEC solar thermal power system and its performance evaluation. *Applied Energy*, **87**(2), pp. 452-462.
16. LE ROUX, W., GABRIEL., 2011. *Maximum Net Power Output from an Integrated Design of a Small-Scale Open and Direct Solar Thermal Brayton Cycle*, University of Pretoria.
17. KAUSHIKA, N.D. and REDDY, K.S., 2000. Performance of a low cost solar paraboloidal dish steam generating system. *Energy Conversion and Management*, **41**(7), pp. 713-726.
18. SUZUKI, A., 1988. General theory of exergy-balance analysis and application to solar collectors. *Energy*, **13**(2), pp. 153-160.
19. LE ROUX, W.G., BELLO-OCHENDE, T. and MEYER, J.P., 2011. Thermodynamic optimisation of the integrated design of a small-scale solar thermal Brayton cycle. *International Journal of Energy Research*.
20. GUPTA, M.K. and KAUSHIK, S.C., 2008. Exergetic performance evaluation and parametric studies of solar air heater. *Energy*, **33**(11), pp. 1691-1702.