DEPENDENCE OF TEMPERATURE VARIATION ON THE SHAPE FACTOR OF A SOLAR PARABOLIC TROUGH CONCENTRATOR (PTC)

BY

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DECLARATION

This work as a whole is my original production and has not been submitted for MSC degree or any other academic qualification in any university or institution of higher learning.

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DEDICATION

This work is dedicated to my dear loving wife Idah and children Levi, Marion and Billy.

ABSTRACT

Solar radiation energy incident on a collector can be converted into electricity using PV cells or thermal energy by means of solar thermal collectors. Solar radiation intensity is sometimes lower than required for suitable applications, hence needs to be concentrated. Solar radiation concentration can be done by mirrors or lenses to obtain higher temperatures and thermal energy required for appropriate applications such as heating, drying, cooking and other industrial applications. This technique is known as concentrated solar power (CSP). To achieve this it is necessary to use devices such as compound parabolic concentrators (CPC) and parabolic trough concentrators (PTC). There is always a variation in solar radiation concentration along the concentrator axis producing temperature variation as a function of both aperture width and distance from the focal point, maximum concentration (temperature) being at the focal point. A lot of research has been done on the types of concentrators, but no information has been given on how the shape factor (curvature) affects temperature distributions within a PTC. The main objective of the study was therefore to determine how the shape factor affects temperature distribution within a solar parabolic trough concentrator. Other objectives were: to investigate the relationship between the parabolic equation coefficient, shape factor and focal length within a given range of parabolic equation coefficient, and also to determine the focal line temperature of a solar PTC from a given range of solar intensity. The shape factor was obtained by dividing the vertical distance from the collector axis to the reflecting surface by axial distance from the base of the collector. Thus different shape factors were determined for various aperture sizes. The temperature variation was determined by measuring steady state temperature of 1 cm^2 black aluminium plates placed at various points along the concentrator axis based on the shape factor. Corresponding temperature measurements at various points of the plates were simultaneously obtained by using thermocouples attached to multi channel data logger. Ambient temperatures were also recorded. Solar radiation falling on the concentrator was also measured using a solarimeter. From the experimental results it was found out that shape factors of 20 and 4 produced average focal point temperatures of 75^oC and 45^oC respectively at an average solar radiation intensity of 620 W/m^2 and average ambient temperature of 26.5^oC. This implies that the focal point temperature of a PTC depends on both the shape factor and ambient temperature, which is also affected by solar radiation intensity. Higher temperatures can be achieved if heat losses are minimized and sun tracking system installed for the solar concentrator. The research findings are useful in determining the focal line temperature of a solar PTC based on average ambient temperature, solar radiation intensity and the shape factor. This enables the PTC users at different locations to make appropriate choice of PTC design suitable for various temperature applications.

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LIST OF SYMBOLS AND ABBREVIATIONS

a, b : Angles defining of the focal space in spherical coordinate system

A : Area of aperture.

$\mathbf{A_{abr}}$: Area of absorber

BIPV : Building integrated photovoltaic

C : Concentration ratio of the concentrating collector.

D : Diameter of a tubular absorber.

DTIRC : Dielectric Totally Internally Reflecting Concentrator

E : Irradiance at a point in the focal plane

D : Aperture width of the concentrator, m.

$\mathbf{E_{A\text{-}R}}$: The fraction of radiation emitted from the surface of the aperture that reaches the absorber, either directly or via reflection at the reflector.

$\mathbf{E_{R\text{-}A}}$: The fraction of the radiation emitted from the surface of the absorber that reaches the aperture either directly or via reflection at the reflector.

E : Angle in interior of beam

F : The focal length

F : Focus of parabola

$\mathbf{G_b}$: The solar beam irradiance.

$\mathbf{g_D}$: The fraction of the diffuse insolation exploitable by a concentrating collector.

H : Height of the concentrator, m.

$\mathbf{H_d}$: The daily total diffuse insolation on a horizontal surface.

$\mathbf{H_h}$: The daily total hemispherical insolation on a horizontal surface.

$\mathbf{I_B}$: Direct component of direct insolation, W/m^2.

I_D : Diffuse component of the total insolation, W/m^2.

I_{eff} : Effective part of the total insolation for a PTC collector.

I_{tot} : Total hemispherical insolation on the collector's aperture plane, W/m^2.

I_u : Insolation absorbed by the absorber in a PTC collector, W/m^2.

$I_\emptyset$: Normalized angular intensity of the diffuse insolation.

k_{norm} : Factor used to normalize the values of the Gaussian part of the hybrid Gaussian distribution of the diffuse insolation in the interval $-\frac{\pi}{2} < \partial < \frac{\pi}{2}$

L_R : The reflected radiance distribution law

n : Number of reflections.

n_o : Long term average optical efficiency

PV : Photovoltaic

QDC : Quantum Dot Concentrator

R : Collector heat removal factor.

R_d : A factor for converting total insolation on a horizontal surface to diffuse insolation on a tilted surface.

R_t : The factor for converting total insolation on a horizontal surface to direct insolation on a tilted surface.

Greek symbols

A	:	absorptance of the absorber.
β_B	:	Correction coefficient for direct insolation reaching the absorber.
β_D	:	Correction coefficient for diffuse insolation reaching the absorber.
Γ	:	The fraction of the direct rays incident on the aperture that are intercepted by the absorber of a PTC collector.
η_{opt}	:	Optical efficiency of a PTC collector.
Θ_c	:	Acceptance half angle, degrees.
Θ_m	:	Mean tolerance angle, degrees.
ρ	:	Reflectance of the reflector.
ρ_o:	:	Isotropic background of the hybrid Gaussian distribution of diffuse insolation.
s	:	the shape factor of a PTC collector.
Φ	:	the utilizability factor.
φ_r	:	the rim angle of the paraboloidal dish.
φ_s	:	the shading angle because of receptor size.
σ	:	Stephan-Boltzmann constant.
∂	:	Standard deviation of Gaussian distribution (subscript indicates the particular case considered),rad.
$\emptyset$	:	Angle of incidence at the aperture plane, degrees.
E	:	Half angle of solar disc
β, Θ	:	Angle defining a point in the concentrator in spherical coordinates

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CHAPTER ONE: INTRODUCTION

1.1 Background Information

Concentration of solar radiation increases radiation flux intensity which in turn increases solar energy incident on a given surface. The maximum concentration of solar radiation incident on the collector occurs when most of the reflected beam converges at the focal point of the concentrator. Thus the greatest thermal energy can be tapped at the focal point of the concentrator; however some concentration of solar radiation also occurs along the axis of the collector which causes varying irradiance or thermal energy distribution. Hence both low and high heat generation can be effectively tapped from the solar radiation concentrators which can be used in domestic and industrial applications such as drying, distillation, dehydration, cooking, burning refuse as well as thermo chemical processes such as decarbonizing, calcination (1000^0C), metallurgical and mineralurgical processes (1500 – 3000^0C), (Sammouda et al 1999).

The concentrated solar energy from a parabolic collector depends on its aperture size, (Amara et al 2011). It has also been established that different types of concentrator shapes have different degree of solar energy concentration and the resulting temperature at their focal points. Hence the choice for a specific concentrator depends on the degree of solar energy concentration and hence the temperature to be achieved. For instance, a parabolic trough concentrator with tracking system can produce a maximum temperature of 538^oC when solar energy concentration is 100 while a parabolic dish concentrator can produce temperatures above 2638^oC when solar energy concentration exceeds 1000, (Kaplan, 1985).

A parabola is the locus of points that moves equal distance from a fixed line and a fixed point.
As shown in figure 16, the fixed line is called the directrix and the fixed point is the focus F. The directrix is described as a line that defines a curve from which a point on conic has a constant

ratio to that from the focus. The line perpendicular to the directrix and passing through the focus F is called the axis of the parabola. The parabola intersects its axis at a point V which is called the vertex, and is exactly midway between the focus and the directrix.

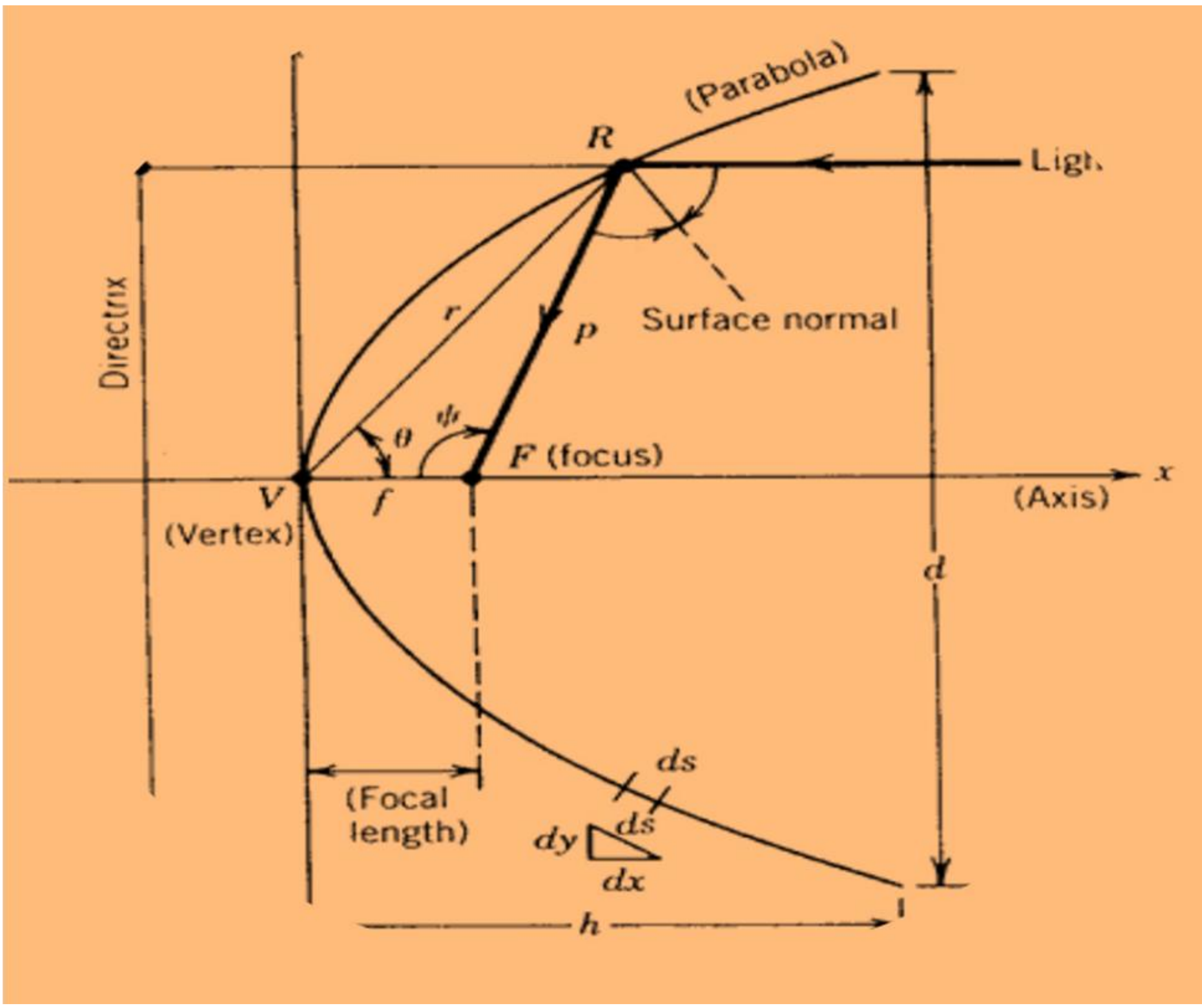

Figure 1: Parabola intersections.

If the origin is taken at the vertex V and the x-axis along the axis of the parabola, the equation of the parabola is:

$$y^2 = 4fx, \tag{1.1}$$

where f, the focal length, is the distance from the vertex to the focus. When the coordinates of the origin is shifted to point F as is often done in optical studies, with the vertex to the left of the origin, the equation of a parabola becomes:

$$y^2 = 4f(x + f), \qquad (1.2)$$

The height h of the parabola is given by the expression:

$$h = \frac{d^2}{16f}, \qquad (1.3)$$

In polar coordinates, using the usual definition of r as the distance from the origin and θ the angle between the x-axis and r, we have for a parabola with its vertex at the origin and symmetrical about the x-axis

$$\frac{\sin\theta^2}{\cos\theta} = \frac{4f}{r}, \qquad (1.4)$$

Usually, in solar studies, it is more useful to define the parabolic curve with the origin at F and in terms of the angle (ψ) in polar coordinates with the origin at F. The angle ψ is measured from the line VF and the parabolic radius p, is the distance from the focus F to the curve. Shifting the origin to the focus F, we have

$$p = \frac{2f}{1+\cos\psi}, \qquad (1.5)$$

The general expressions given so far for the parabola define a curve infinite in extent. Solar concentrators use a truncated portion of this curve. The extent of this truncation is usually defined in terms of the rim angle (ψ) or f/d which represents the ratio of the focal length (f) to diameter of dish (d). The scale (size) of the curve is then specified in terms of a linear dimension such as the aperture diameter d or the focal length f. This is readily apparent in figure 2 which shows various finite parabola having a common focus and the same aperture diameter.

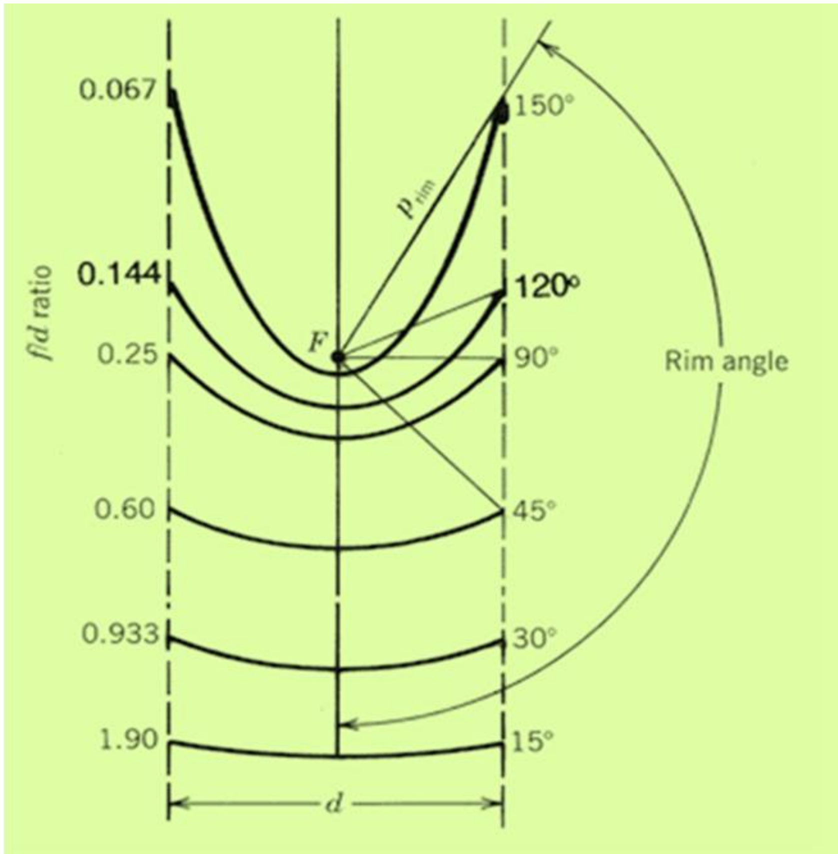

Figure 2: Segments of a parabola having a common focus F and the same aperture diameter

The arc lengths s of a parabola may be found from equation (1.6) by integrating a differential segment of this curve in the limits x = h and y = d/2 as shown in figure1. The result is given by:

$$s = \left[\frac{d}{2}\sqrt{\frac{4h^2\_1}{d}}\right] + 2fIn\left[\frac{4h}{d}\sqrt{\left(\frac{4h}{d}\right)^2 + 1}\right], \qquad (1.6)$$

where d is the distance across the aperture (opening) of the parabola as shown in figure 1 and h is the distance from the vertex to the aperture, (Fareed et al,2012).

The cross sectional area of the space enclosed between a parabola and a line across its aperture and normal to the axis is given by:

$$A_x = \frac{2}{3}dh, \qquad (1.7)$$

This area should not be confused with the reflecting surface area of a parabolic trough or dish or their aperture areas, (Stine and Harrigan, 1985).

The other equation of a parabola centred at the origin used to design the PTC in this research is in the form:

$$y = ax^2, \qquad (1.8)$$

where ‘a’ is a number referred to as a parabolic equation coefficient. It determines the aperture width of the parabola, such that the parabola widens as the value of ‘a’ becomes smaller. The value of the parabolic equation coefficient also affects the focal length of a PTC as will be noted in Chapter Four of this text.

The maximum temperature obtained from a PTC depends on factors such as intensity of incident radiations and the aperture width of the concentrator. The size of the aperture width of the PTC is determined by design parameters such as the coefficient of the parabolic equation, such that the smaller the coefficient the wider the aperture width and vice versa. The wider the aperture width, the longer the focal length. The sharpness or quality of the focal point of parabolic concentrators is greatly affected by spherical aberration, which depends on the rim angle, (Fareed et al, 2012).

Thus another design parameter affecting the performance of a PTC is the rim angle, which is an angle between the focal line and aperture width or rim of the PTC as shown in figure 3.

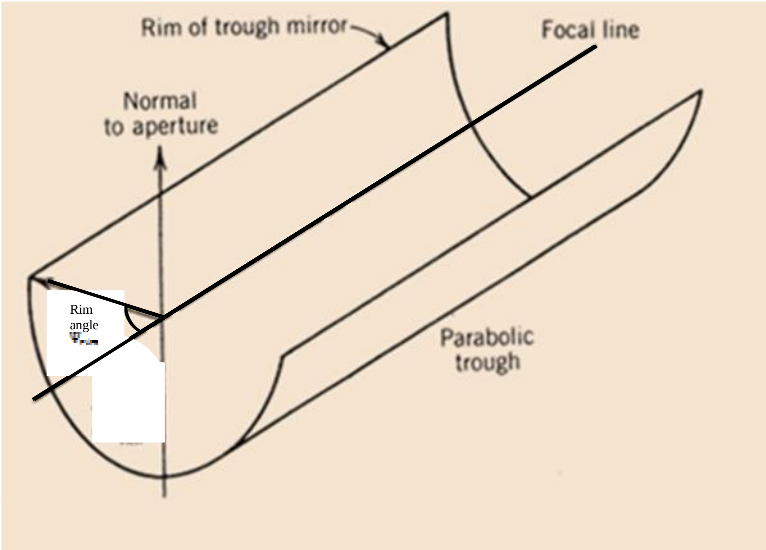

Figure 3: Diagram showing rim angle of a PTC

Apart from the sharpness or quality of focus, the rim angle also affects the magnitude of focal length of the parabolic concentrator as illustrated in figure 4 below.

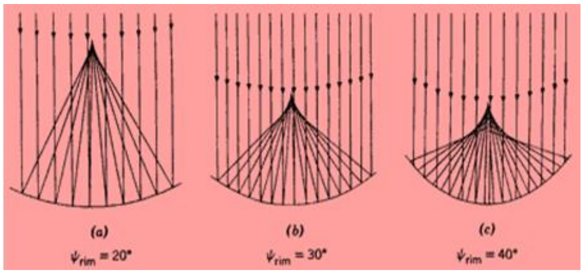

Figure 4: Effect of rim angle on focusing of parallel rays by parabolic concentrator.

A PTC with a small rim has a large aperture width, and a blurred focus, (Duncan, 1977). However, a PTC which has a large rim angle has a sharp focus. Thus a PTC with a small rim angle is more affected by spherical aberration than that with large rim angle. The value of the rim angle also depends on the parabolic equation coefficient as it increases with increase in parabolic equation coefficient. A parabola is part of an ellipse, thus particular range of values of rim angle and parabolic equation coefficient maintains the ellipsoidal shape of the parabolic concentrator which enables it to converge both paraxial and marginal rays to a sharp focus. Thus the focal line temperature of a solar PTC is affected by the value of parabolic equation coefficient and solar radiation intensity within a given range It is important to investigate the relationship between the curvature of the parabolic concentrator (shape factor) within a given range of parabolic equation coefficient and focal line temperature.

Solar concentrator is a device that allows the collection of sunlight from a large area and focusing it on a smaller receiver or exit. A conceptual representation of a solar concentrator has always been used in harnessing the power from the sun to generate electricity. The material used to fabricate the concentrator varies depending on the usage. For solar thermal, most of the concentrators are made from mirrors while for building integrated photovoltaic (BIPV) system, the concentrator is either made of glass or transparent plastic. These materials are far cheaper than the PV material. The cost per unit area of a solar concentrator is therefore much cheaper than the cost per unit area of a PV material. By introducing this concentrator, not only the same amount of energy could be collected from the sun, the total cost of the solar cell could also be reduced. Arizona Public Service has concluded that the most cost effective PV for commercial application in the future will be dominated by high concentration collector incorporated by high-efficiency cell, (Chin, 2009).

Solar radiation can be directly converted into electricity by means of PV cells or thermal energy by means of solar thermal collectors. The temperature level achieved when converting solar radiation into thermal energy depends on the type of system used for conversion. While the flat plate solar collectors are suitable to produce hot water or air up to 80^{o}C, japproximately higher temperature can be achieved when using evacuated tube collectors (125^{o}C), PTC collectors (400^{o}C, central receiver systems (1000^{o}C) or dish concentrators (>2000^{0}C), (Zarza, 2002).

In the analysis of concentrators it is important to distinguish between imaging and non imaging systems. In imaging designs such as burning glass, telescopes, microscopes and parabolic shaped mirrors, all rays leaving a point from an object and entering into the aperture will be imaged on one single point in an exit aperture independently on their way through the optical system. This results into image formation. Non imaging systems such as CPC only require that all rays entering the aperture entrance leave the exit aperture elsewhere. Thus in a PTC which is one of the imaging systems inherent optical errors do not allow it to achieve the maximum theoretical concentration ratio, which is a ratio of outgoing energy density from the absorber to the incoming energy density passing through concentrator aperture. This shows an inverse ratio of the areas of collector opening and the absorber. An ideal 3D parabola can only reach one fourth of the theoretical limit, (Robert, 2005).

The efficiency of the solar PTC and other concentrator types depends on the concentrator location and the sun concentration. This can be noted from the numerous projects regarding the implementation of the solar concentrators shown in tables 1 and 2.

Table 1: Parabolic trough solar concentrator projects adapted from Muhammad et al, 2008.

Name	Location	Output (kW)	Sun concentration	Efficiency (%)
BP Solar and the Polytechnical University of Madrid	Tenerife, Canary Island, USA	480	38	13.0
Australian National University	Spring Valley, Australia	n/a	30	15.0

Table 2: Some projects related to solar concentrators, (Swanson 2000)

Name	Location	Concentrator type	Output (kW)	Sun concentration	Efficiency (%)
AMONIX and Arizona Public Service	Arizona, USA	fresnel lens	300	250	24.0
PETAL	Sede Boqer, Israel	Parabolic Dishes	154	400	16.5
Entech Inc	Ft. Davis, Texas, USA	fresnel lenses	100	20	15.0
Fraunhofer-Institute for Solar Energy Systems	Freiburgh, Germany	Parabolic trough and CPC3	n/a	214	77.5
Photovoltaics International, LLC	Sacramento California, USA	fresnel lens	30	10	12.7
Solar Research Corporation, Pty. Ltd.	Australia	parabolic dish	0.2	239	22.0
SolFocus	Ben Gurien University, Israel	paraboloid and hyperboloid	0.25	500	81
SunPower Corporation	USA	Fresnel lens	n/a	250-400	27

But from the output power indicated in the tables 1 and 2 above it is not clear which size of the concentrators were used. For instance, the focal line temperature of a PTC depends on the amount of incident radiation being allowed to enter the concentrator as determined by the aperture width. This probably explains why different researchers obtain different efficiency values for the same concentrators.

There are many parabolic collector designs being used such as; parabolic trough concentrator (PTC), compound parabolic concentrator (CPC) and parabolic dish, which compares well with a spiral concentrator (Taha et al, 1987). It has been established that the temperatures achieved by low concentration ratio, PTC collectors are comparable with those from CPC collectors. (Prapas, 1987). However there is no expression that can be used to determine the temperature at any given point from the concentrator.

The major advantage of a solar concentrator is its ability to increase the intensity of solar irradiance, thus increasing the efficiency of the thermal energy system. A PTC can be made easily using cheap materials such as plywood, wooden frame and aluminium foil as a reflecting surface. The solar concentrators can also be used independently without PV cell for certain applications such as drying and heating purposes. However, a PTC requires a mechanical sun tracking system for its effective utilization, (Terao et al, 2000). When the concentrator is used with a PV, the latter needs to cool down to ensure optimum PV performance, (Omubo-Pepple, 2009). However, it is important to know the effect of factors such as concentration area, aperture width or shape factor on efficiency of a PTC in terms of focal line temperature in relation to incident solar radiation intensity and ambient temperature for a given weather conditions.

1.2 Statement of the Problem

Solar radiation incident on the earth's surface is not sufficient to produce high temperatures that are often required for some applications such as cooking, distillation and other thermo chemical processes. Concentration of solar radiations can therefore produce the required high temperature. Therefore there is need to know how such an appropriate temperature required can be predicted from a given solar concentrator such as a PTC. However there is inadequate information on how the design parameters of a PTC such as parabolic equation coefficient and the shape factor as a function of aperture width can be used to predict the focal line temperature of a PTC at a given ambient temperature. It is for this reason that this study intends to determine the variation of temperature with the shape factor of the concentrator and predict the maximum temperature that can be obtained from a PTC at a given ambient temperature.

1.3 Justification of the Study

Use of parabolic solar concentrator increases solar radiation intensity which can produce high temperature. A design factor such as parabolic equation coefficient is known to affect the aperture width and shape factor (extent of curvature) of a PTC. It is very important to also know how such a factor can be used to precisely predict the focal line temperature of a PTC for suitable thermal applications. There is significant variation of concentrated solar radiation intensity with the distance from the concentrator as well as the aperture width. Solar concentrators should therefore be carefully designed to meet desired temperature demand for different applications.

Over reliance on conventional forms of energy such as electricity for heating is costly. Use of wood for such purposes also has negative environmental impact such as desertification and global warming. Thus use of renewable energies such as solar energy has environmental conservation advantages.

1.4 Significance of the Study

The research findings are useful in determining the focal line temperature of a solar PTC based on average ambient temperature, solar radiation intensity and the shape factor. This enables the PTC users at different locations to make appropriate choice of PTC design suitable for various domestic and industrial temperature applications.

1.5 Objectives of the Study

The main objective of the study was:

To determine how the shape factor affects temperature distribution along a solar parabolic trough concentrator axis.

Other objectives were:

1. To investigate the relationship between the parabolic equation coefficient ‘a’ defined by the parabolic equation; $y = ax^2$, shape factor, and focal length within a given range of parabolic equation coefficient ‘a’.
2. To determine the focal line temperature of a solar PTC from a given range of solar radiation intensity and ambient temperature.

In this study the following assumptions are made:

1. The reflector surface is specular with constant reflectance, irrespective of incidence angle
2. The contour of the reflector surface is free from imperfections

3. The direct component of the insolation I_B consists of perfectly collimated rays (i.e. the Sun assumed to be a point source on the axis of the concentrator located at an infinite distance).
4. Changing wind speed, convective and radiative heat losses were neglected.

1.6 Limitations of the Study

Accuracy of the experimental results may be affected by factors such as changing weather conditions like wind speed, humidity, tilt angle and rotation of the concentrator to track the sun as it moves across the sky. Other errors can also occur as a result of imperfections of the optic system since the reflecting surface was not very smooth.

CHAPTER TWO: LITERATURE REVIEW

2.1 Solar Concentrator Designs

There has been a lot of developments involving the designs of the solar concentrators. Some of the identified designs which have shown significant contribution to the solar technology are:

- Parabolic Concentrator
- Hyperboloid Concentrator
- Fresnel Lens Concentrator
- Compound Parabolic Concentrator (CPC)
- Dielectric Totally Internally Reflecting Concentrator (DTIRC)
- Flat High Concentration Devices
- Quantum Dot Concentrator (QDC)

2.1.1 Parabolic Concentrator

The two dimensional design of a parabolic concentrator is just a parabola. It is widely used as a reflecting solar concentrator. A distinct property that it has is that it can focus all the parallel rays from the sun to a single focal point, *F* as shown in figure 5.

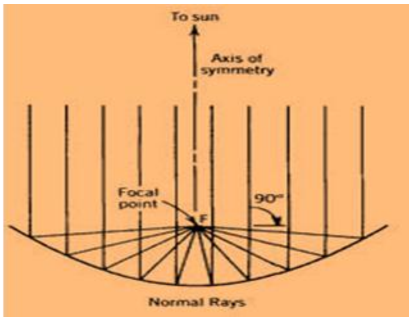

Figure 5: Focusing parallel rays by a parabolic concentrator.

It is not necessary to use the whole part of the parabola curve to construct the concentrator. Most parabolic concentrators employ only a truncated portion of the parabola. There are different designs of parabolic concentrators. For instance, one can be obtained by rotating the two dimensional design along the x-axis to produce a parabolic dish, and another way is by having a parabolic trough. Both designs are used mostly in concentrating solar power system in big solar power plants. For example, The EUCLIDES-THERMIE Plant in Tenerife, Canary Island employs the parabolic trough concentrators in the 480kW concentrator project (Sala et al 1998). Although a PTC can achieve high concentration of incident solar radiation, it requires larger field of view to maximize the solar energy collection. To obtain maximum efficiency, it needs a good tracking system, which is quite expensive. That is why this type of concentrator is not preferred in a small residential house, (Muhammad et al 2008).

A significant number of parabolic troughs have been designed, built, and tested, primarily with private funds. Many types are available on the market. Troughs differ in their reflective materials, structural materials, receiver concepts, etc. The attainable temperature reaches about 540^oC (1000^oF). The designs vary with intended temperature application, since surface error, tracking error, and receiver losses assume considerable importance for a high temperature design. PTCs may be attractive because of their relative simplicity. Because their surface curvature is singular, not compound as for parabolic dishes, parabolic troughs are more easily fabricated. A second-surface reflective plastic with adhesive backing can be easily placed on the curved substrate. A simple pipe or tube will serve adequately as the receiver although various simple techniques, such as a glass vacuum jacket around the receiver tube, will enhance performance. Single-axis tracking is less complex than two-axis tracking. The parabolic trough in figure 6, is an example of line focus solar concentrator.

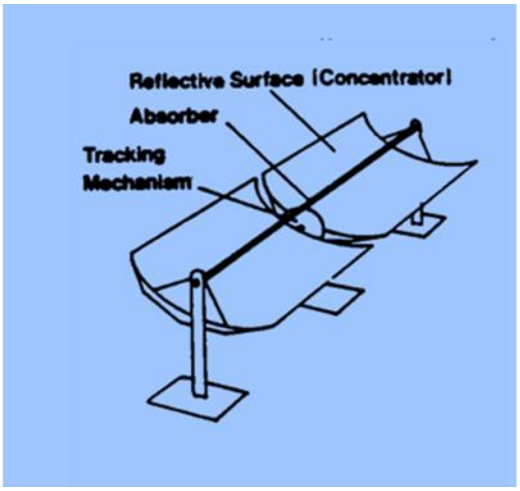

Figure 6: Layout of parabolic trough solar concentrator

The incident direct radiation is reflected from the trough to the focal line along the length of the trough. To maximize energy collection the trough is designed to track the sun. The trough may be oriented with the focal line running east-west, north-south, or north-south with simultaneous tilt toward the sun (polar mount), (Kaplan 1985).

The thermal energy collected by a parabolic trough concentrator is determined by the total number of collector elements, which are characterized by reflecting parabolic section (the concentrator), collecting and continuously concentrating the direct solar radiation by means of a sun tracking control system to a linear receiver located at the focus of the parabola. A circulating fluid flowing inside a linear receiver can be used to transport the absorbed heat, (Salomoni et al, 2009). However, the temperature of the fluid flowing inside the receiver depends on the aperture width of the PTC, such that as the concentrator widens more radiation enters the PTC to be concentrated. Thus it is important to investigate to what extent the shape factor as a function of aperture width affects the focal line temperature of a PTC.

In modular solar power plants, mirror concentration systems (MCSs) are required to ensure highly uniform irradiance distribution at solar concentration of 500-5000 and over. This concentration is achieved by using paraboloidal surfaces, but the irradiance distribution behavior is characterized by strongly pronounced nonuniformity, (Zakhidor, 1989).

2.1.2 Hyperboloid Concentrator

The general design of a hyperboloid concentrator is shown in figure 7. It consists of two hyperbolic sections, AB and A'B'. The hyperboloid concentrator can be produced by rotating the two -dimensional hyperbolic design along its symmetrical axis. The diameters of the entrance and exit aperture are labeled as d1 and d2 respectively. If the inside wall of the hyperbolic profile is considered as a mirror, the sun rays entering the concentrator from AA' will be reflected and focused to the exit aperture BB'. The advantage of this concentrator is that it is very compact, since only truncated version of the concentrator needs to be used. Because of this factor, it is mainly used as a secondary concentrator. An example of application of this concentrator has been developed by SolFocus, with the intention of reducing the cost of solar electricity. The design with Cassegranian-like architecture managed to produce 250W peak in a single Generation 1 solar panel, (Horne et al, 2006). However, in most applications, hyperboloid concentrator requires the usage of lenses at the entrance diameter AA' in order for the concentrator to work effectively, (Welford and Winton, 1989).

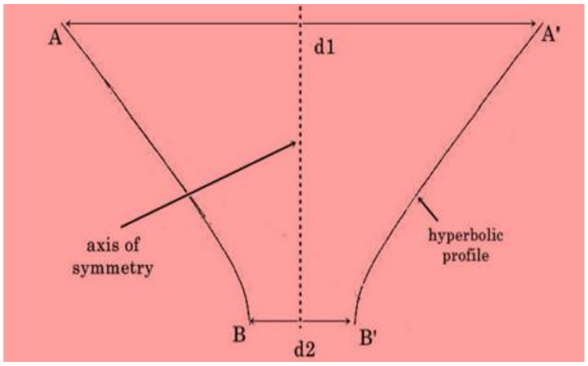

Figure 7: Hyperboloid Concentrator.

2.1.3 Fresnel Concentrator

Fresnel lens function is similar to the conventional lens, by refracting the rays and focusing them at one focal point. It generally has two sections; a flat upper surface and a back surface that employs canted facets. The facet is an approximation of the curvature of a lens (see figure 8). A good linear Fresnel lens could employ around 100 facets per millimeter, (Muhammad et al, 2008).

There are two ways to use this concentrator; a point focus Fresnel lens or a line focus Fresnel lens. An application of this concentrator can be seen in the Sacramento Municipal Utility District, where the Fresnel lenses are used in the 30kW utility grid-connected plant, (Sala et al, 2000).

The advantage of a Fresnel lens over a conventional lens is that it is thinner and requires less material to fabricate, (Kaplan, 1985). It also has the capability to separate the direct and diffuse light, making it suitable to control the illumination and temperature of an interior building, (Tripanagnostopoulos et al, 2007). One of the sources of error of this concentrator results from the sharpness of the facet, an error in the manufacturing process which may create a rounder shape at the edges of the facets. This causes the rays to be improperly focused at the receiver, (Muhammad et al, 2008).

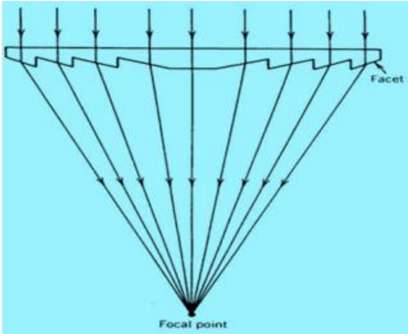

Figure 8: Fresnel Lenses

2.1.4 Compound Parabolic Concentrator (CPC)

The geometry of a two dimensional CPC is shown in figure 9(a). It consists of two segments of parabolas, AC and BD. A CPC can be divided into three parts; a planar entrance aperture, a totally internally reflecting side profile and an exit aperture. The entrance aperture of this CPC is of length CD. The CPC will have an acceptance angle of 2θ and will concentrate all the solar radiation at the exit aperture AB, as shown in figure 9(b).

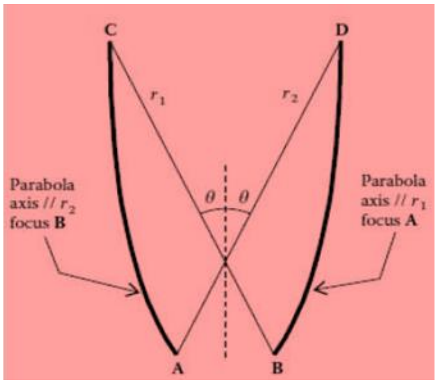

Figure 9(a): Compound Parabolic Concentrator: Geometry of a CPC,

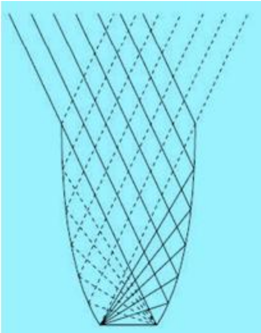

Figure 9(b): Trajectories of the edge rays inside the CPC, (Chaves 2008).

The total length of a CPC depends both on the exit aperture and the acceptance angle of the concentrator. By reducing the acceptance angle, the size of the concentrator will increase. The CPC can either be used as a three dimensional rotational symmetry concentrator or as a two-dimensional CPC design. The latter design is normally employed as a reflector in a solar power plant, (Welford and Winston, 1989).

The two-dimensional CPC achieves maximum irradiance concentration; half width angular spread of the output rays is 90^o, uniformly maintained across the entire exit aperture. The three-dimensional CPC achieved by rotating the two-dimensional CPC about the symmetry axis is not ideal but has losses of just a few percent, (Andrew, 2010).

CPC collector exploits a greater part of available diffuse insolation compared with a PTC although this diminishes as the concentration ratio increases. However a CPC collector is more superior to a PTC because of its larger acceptance angle, which is the angular range over which radiation is accepted without moving all or part of the collector, (Prapas et al,1987).

The main advantage of using a CPC is that it can offer a higher geometrical concentration gain with a narrow field of view, (Ramirez-Iniguez, 2008). The disadvantage of the CPC is the same as parabolic trough concentrator; it requires a good tracking system to maximize the collection of sun radiation.

2.1.5 Dielectric Totally Internally Reflecting Concentrator (DTIRC)

This class of optical element has the capability to achieve very high concentration. There are two ways to produce the DTIRC; maximum concentration method and phase conserving method. Although both methods will create almost identical structure, the first technique offers slightly higher concentration and therefore more suitable for solar application, (Ning et al 1987).

DTIRC consists of three parts; a curved front surface, a totally internally reflecting side profile and an exit aperture (see figure 10). When the rays hit the front curved surface, they are refracted and directed to the side profile. Upon hitting the sidewall, they will be totally internally reflected to the exit aperture. The front aperture can be a hemisphere, but different designs such as parabola and eclipse have been developed recently, (Ramirez-Iniguez and Green, 2005).

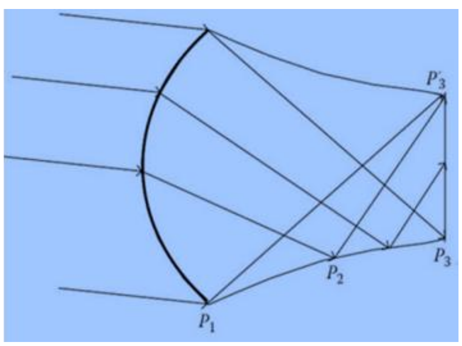

Figure 10: Dielectrically totally internally reflecting concentrator (DTIRC).

The geometrical concentration gain of a DTIRC depends on both acceptance angle and also the front arc angle. The geometrical concentration gain of a DTIRC is inversely proportional to the acceptance angle. Also, the front arc angle only gives very minimal effect on the geometrical gain.

The advantage of DTIRC over CPC is that it offers higher geometrical concentration gain and it is conveniently smaller in size. The disadvantage of a DTIRC is that it cannot efficiently transfer all of the solar energy that it collects into a lower refractive index medium. For instance, not all the sun rays are transmitted to the cell area when used in PV application.

The DTIRC is available either as a three- dimensional rotational symmetry concentrator or as a two- dimensional optical extrusion, although the three dimensional design is more favourable. One of the examples is in the NASA flight demonstration program, where a DTIRC is used as the secondary concentrator for the solar thermal application in space, (Piszczor and Macosko, 2000).

2.1.6 Flat High Concentration Devices

These are nonimaging type of concentrator with large acceptance angle and concentration. Since 1995, there are five available designs; RR, XX, XR, RX and RXI, (Muhammad et al 2008). In this design, ‘R’ represents refraction, ‘X’ denotes reflection and ‘I’ means total internal reflection. Basically, an XR concentrator means that the rays in this concentrator will first experience a reflection followed by refraction, before reaching the receiver, (Minano et al,1995).

Figure 9 shows a typical diagram of an RXI concentrator. It is devised using the Simultaneous Multiple Surface, also known as the Minano-Benitez design method. An RXI concentrator has three sections; an upper surface with a mirror at the centre, a lower surface made from mirror, and a receiver. Using an RXI with rotational symmetry and the dielectric of refractive index of 1.5, a concentrator with an acceptance angle of $+2.70^{o}$ could achieve a concentration factor of 1000x, (Minano et al, 1994) .

These concentrators have two major benefits; they are very compact and offer very high concentration. However, there are some disadvantages of this design. When used in PV application, the cell’s position, may make it difficult to create electrical connection and heat sinking. The receiver dimension must be designed to be as minimal as possible to reduce shadowing effect, (Terao et al, 2000).

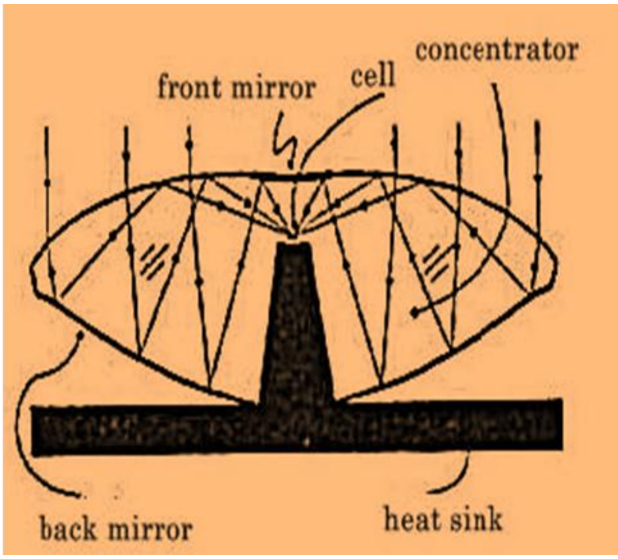

Figure 11: Flat high concentrator device - RXI Concentrator

2.1.7 Quantum Dot Concentrator (QDC)

Quantum dot concentrator, (QDC) is a plane device that consists of three parts; a transparent sheet of glass or plastic doped with quantum dots (QDs), reflective mirrors mounted on the three edges and back surface, and an exit where a receiver such as PV cell is attached, (Gallagher et al,2007).

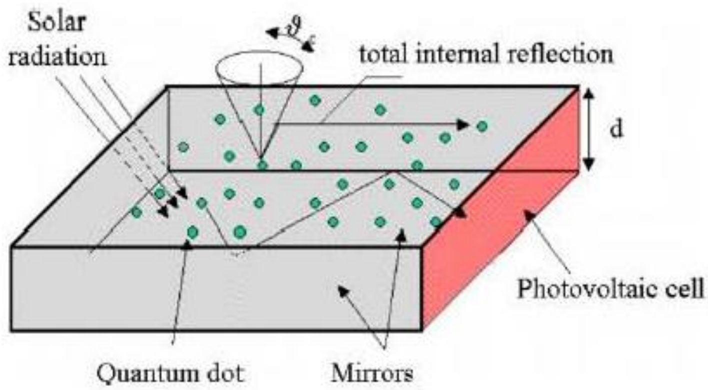

Figure 12: Principal of Quantum Dot Concentrator (QDC)

When the sun radiation hits the surface of a QDC, a part of the radiation will be refracted by the fluorescent material and absorbed by the QDs. Photons are then reemitted in all direction and are guided to the absorber via total internal reflection. The total geometrical concentration will be the ratio of the large surface area of glass to the area of the absorber.

QDC major advantage is that it does not require any tracking as other conventional concentrator. It can also make full use of both direct and diffuse solar radiation , (Chatten et al,2004).

However, the main drawback of the QDC is that the development of QDC is restricted to high requirements on the luminescent dyes; i.e. high quantum efficiency, suitable absorption spectra and redshifts, and stability under illumination, (Goetzberger et al, 1985). The concentrators can also be categorized according to their optical principles as shown in Table 3, (Kaplan, 1985).

Table 3: Types of Solar Concentrators

Type	**Description**
Reflector	Upon hitting the concentrator, the sun rays will be reflected to the absober. Example: *Parabolic Trough, Parabolic Dish, CPC Trough,*
Hyperboloid refractor concentrator	Upon hitting the concentrator, the sun rays will be refracted to the absorber. Example: *Fresnel Lens Concentrator*
Hybrid	Upon hitting the concentrator, the sun rays can experience both reflection and refraction before hitting the receiver. Example: *DTIRC, Flat High Concentration Devices*
Luminescent	The photons will experience total internal reflection and guided to the absorber. Example: *QDC*

2.2 Previous Work Done on Parabolic Concentrators

Important characteristics of a solar concentrator are concentration, acceptance angle, sensitivity to mirror and alignment errors, size of reflector area, and average number of reflections, (Rabl, 1976). The concentration ratio is used to describe the amount of light energy concentration achieved by a given collector. Two different definitions of concentration ratio are in general use, that is, optical concentration ratio and geometrical concentration ratio. The Optical Concentration Ratio (CR_O) can be calculated using equation:

$$CR_O = \frac{1}{A_a}\int \frac{I_r\, dA_r}{I_o}, \qquad (2.2.1)$$

where, I_r represent insolation over the receiver area A_r and I_o the insolation incident on the collector aperture. The Geometric Concentration Ratio can be defined as the area of the collector aperture A_a divided by the surface area of the receiver A_r and can be calculated by equation:

$$CR_g = \frac{A_a}{A_r}, \qquad (2.2.2)$$

where A_a is the area of collector and A_r is the area of the receiver. Optical concentration ratio relates directly to lens or reflector quality, (Fareed et al, 2012).

The maximum possible geometrical concentration ratio for a given acceptance half angle θ_c is

$$C = \frac{1}{\sin\theta_c} \quad \text{for 2- dimensional PTC,} \qquad (2.2.3a)$$

$$C = \frac{1}{\sin^2\theta_c} \quad \text{for 3 -dimensional PTC,} \qquad (2.2.3b)$$

This is stated in terms of *f* number and is expressed as

$$f = \frac{focal\ length}{aperture\ diameter}, \qquad (2.2.4)$$

Thus no optical system can have *f* number less than ½, (Rabl, 1976).

The rate of energy delivered to the absorber can be expressed as

$$I_{U,B} = I_B \alpha \frac{D}{W} + I_B \rho \alpha \frac{W-D}{W}, \qquad (2.2.5a)$$

where the first and second terms of the right hand side of equation (2.2.5a) correspond to the direct insolation reaching the absorber directly and indirectly respectively $I_{U,B} < I_{B,}$ as actual values for ρ,α are less than unity. Equation (2.2.5a) can be rewritten as

$$I_{U,B} = (\rho\alpha)\beta_B I_B. \qquad (2.2.5b)$$

where, $\beta_B = 1 + \frac{D}{W}\left(\frac{1}{\rho} - 1\right)$, . (2.2.6)

β_B is a correction coefficient for the direct insulation reaching the absorber and is not attenuated by reflective losses. β_B would take a value of unity for ρ=1; in practice ρ<1, so β_B>1, (Prapas, et al,1987).

If E_{R-A} and $E_{A\text{-}R}$ represent the exchange factor for radiation exchange between absorber and aperture then the following equation applies:

$$\pi D E_{R-A} = W g E_{A-R}, \qquad (2.2.7)$$

For a compound parabolic concentrator the exchange factor E_{R_-A} is unity as any ray emitted from the absorber will either directly or after more reflections reach the aperture, (Winston, 1976).

It the implies that;

$$E_{A-R} = \frac{I}{C}, \qquad (2.2.8)$$

E_{A-R} in equation (2.2.8) also represents the exploitable part of the diffuse radiation of a CPC collector $g_{D,CPC}$ that is

$$g_{D,CPC} = \frac{1}{C}, \qquad (2.2.9)$$

For a PTC collector $E_{A-R}< 1$ as the absorber can 'view' itself on the reflector. Hence the exploitable part of the diffuse radiation of a PTC collector $\beta_{D,PTC}$ is less than given in equation (2.2.9). The diffuse radiation absorbed by the absorber can then be given as

$$I_{U,D} = (\rho\alpha)\beta_D g_{D,PTC} I_D, \tag{2.2.10}$$

where β_D is a correction coefficient accounting for the part of the diffuse radiation that reaches the absorber directly (i.e., is not attenuated by the reflective losses).

The total insolation absorbed by the absorber I_U is obtained by combining equation (2.2.5b) and (2.2.10) as follows;

$$I_U = \rho\alpha\gamma I_{eff}\ , \tag{2.2.11}$$

where γ is the intercept factor, (Rabl and Bendt, *1982*).

It accounts for the optical losses occurring in a real PTC due to optical errors and I_{eff} represent the effective insolation at the concentrator's aperture given by

$$I_{eff} = \beta_B I_B + \beta_D g_{D,PTC} I_D\ , \tag{2.2.12}$$

The capture of the diffuse radiation by the absorber with respect to the angle of incidence is shown in figure 13 for two concentration ratios. It can be seen that at incidence angle near normal, most of the diffuse insolation reaches the absorber after reflection. However, at incidence angles greater than critical angle that depends on concentration ratio, the diffuse insolation can only reach the absorber directly.

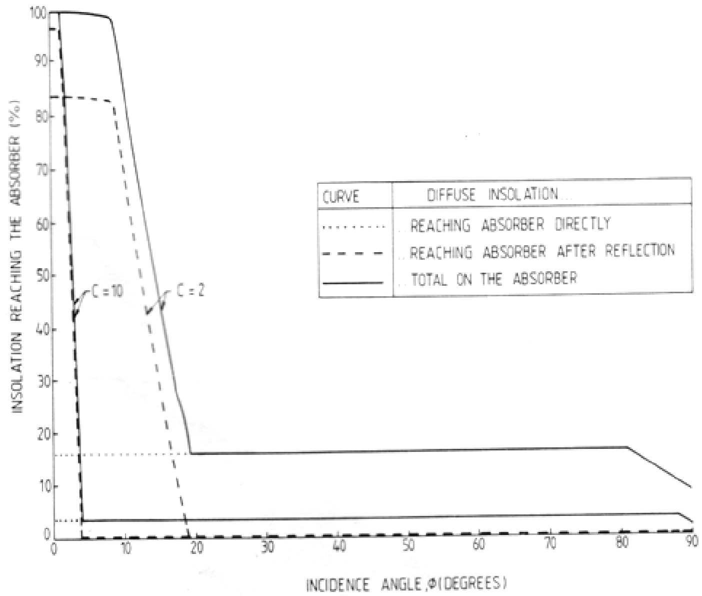

Figure 13: Exploitation of the diffuse component of insolation incident on the aperture of a PTC collector, (Prapas et al, 1987).

Thus, the curves shown in figure 13 can quantitatively show the contribution of the diffuse insolation to the collected solar energy and can therefore be used to determine the correction coefficient β_D indicated in equation 2.2.10. The variation of β_D with the concentration is shown in figure 14 for three assumed values for the reflectance of the reflector. Also shown in figure 14 is the correction coefficient β_B, calculated from equation 2.2.6.

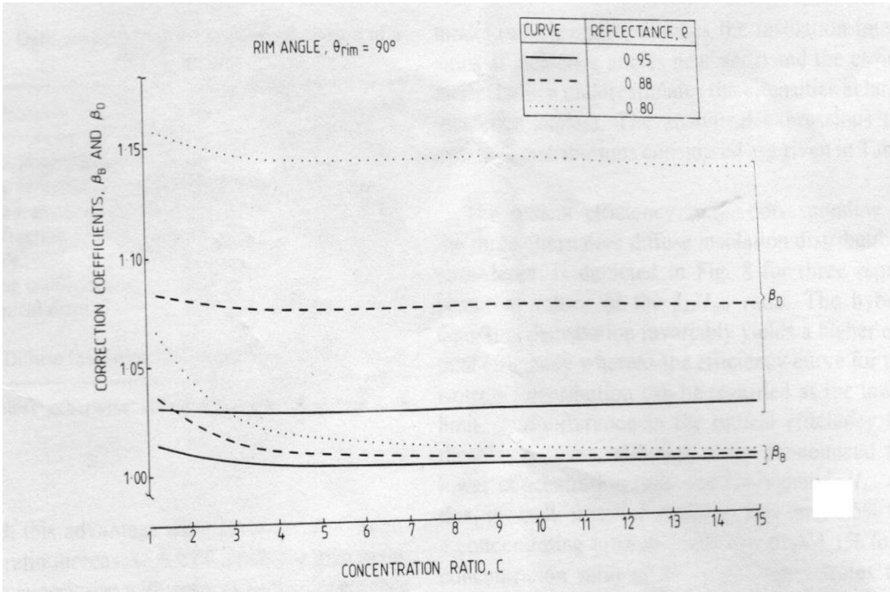

Figure14: Correction coefficients β_B and β_D for the three values of reflector reflectance. (Prapas et al, 1987)

The long term average daily total irradiation incident on the collector, within its acceptance angle is determined by

$$H_C = \left(R_t - R_d \frac{H_d}{H_h}\right) H_h \,, \qquad (2.2.13)$$

where, R_t is the factor for converting total insolation on a horizontal surface to direct insolation on a tilted surface. R_d is a factor for converting total insolation on a horizontal surface to diffuse insolation on a tilted surface. H_d is the daily total diffuse insolation on a horizontal surface and H_h is the daily total hemispherical insolation on a horizontal surface.

The long term average daily energy delivered by the collector per unit area is given by;

$$Q_d = n_o \phi H_c R, \qquad (2.2.14)$$

where, n_o is long term average optical efficiency, ϕ is the utilizability factor and R is collector heat removal factor, (Canada and Ruiz, 1988).

The energy rate Q_p hitting a flat receiver of a paraboloidal concentrator is given by;

$$Q_p = \pi f^2 (sin^2 \varphi_r - sin^2 \varphi_s) \rho_m G_b, \qquad (2.2.15)$$

where f is the focal length, ρ_m is the reflectance of the surface, φ_r is the rim angle of the paraboloidal dish φ_s is the shading angle because of absorber size and G_b is the solar beam irradiance, (Jaramilio, 2002).

If both source and absorber are black bodies at temperatures T_s and T_{abs} respectively then the source emits an amount of radiation

$$Q_s = 4\pi r^2 \sigma T_s^4, \qquad (2.2.16)$$

The fraction of radiation from the source reaching the aperture can be obtained using the relation

$$F_{s\to A} = \frac{A}{4\pi R^2}, \qquad (2.2.17)$$

Solar collectors which may require little or no tracking must have a fairly large acceptance angle. This enables them to collect a significant amount of diffuse radiation. The fraction of totally diffuse radiation accepted can be calculated by considering the radiation balance between the absorber and aperture. The net radiation transfer between absorber and aperture is:

$$Q_{A\to abs} - Q_{abs\to A} = A_A E_{A\to abs} \sigma T_A^4 - A_{abs} E_{abs\to A} \sigma T_{abs}^4, \qquad (2.2.18)$$

In perfect concentrator optics, no radiation is lost between aperture and absorber, therefore, heat radiated from the source to absorber is

$$Q_{s\to abs} = Q_s F_{s\to A} = \frac{Ar^2 \sigma T_s^4}{R^2}, \qquad (2.2.19)$$

The absorber in turn radiates an amount

$$Q_{abs} = A_{abs} \sigma T_{abs}^4, \qquad (2.2.20)$$

where subscripts A and abs in equations 2.2.16 up to 2.2.20 refer to aperture and absorber respectively,(Rabl, 1976).

The performance of a PTC solar energy collector is affected by skyward angular distributions of diffuse insolation, which are in a cross-sectioned plane of the collector. They include; isotropic, cosine and hybrid Gaussian. The isotropic model underestimates the insolation intensities at incident angles near zero, cosine model underestimates intensities at large incident angles and hybrid Gaussian distribution combines an isotropic background with a circumsolar Gaussian part. This distribution is more realistic for a tracking system than both isotropic and cosine distributions.

The shapes of the three distributions above are shown in figure 13 using the expressions in table 4 below.

Table 4.Data used for evaluating the performance of a PTC collector

Distribution	**Normalized angular intensity,** $I_{D,\emptyset}$
Isotropic	$I_{D,\emptyset}=1$
Cosine	$I_{D,\emptyset}=\frac{\pi}{2}\cos\emptyset$
Hybrid Gaussian	$I_{D,\emptyset} = \rho_O + k_{norm}(1-\rho_o)\frac{\pi}{\partial\sqrt{2\pi}}\exp(-\emptyset^2/2\partial^2)$, For values: $\rho_o = 0.8$, $\partial = 7.5 \times 10^{-3}$ rad, k_{norm}=1.

where:

I_D is the diffuse component of the total insolation, $I_{\emptyset}$ represents normalized angular intensity of the diffuse insolation and k_{norm} factor is used to normalize the values of the Gaussian part of the hybrid Gaussian distribution of the diffuse insolation in the interval $-\frac{\pi}{2} < \partial < \frac{\pi}{2}$ ρ_o and isotropic background of the hybrid Gaussian distribution of diffuse insolation.

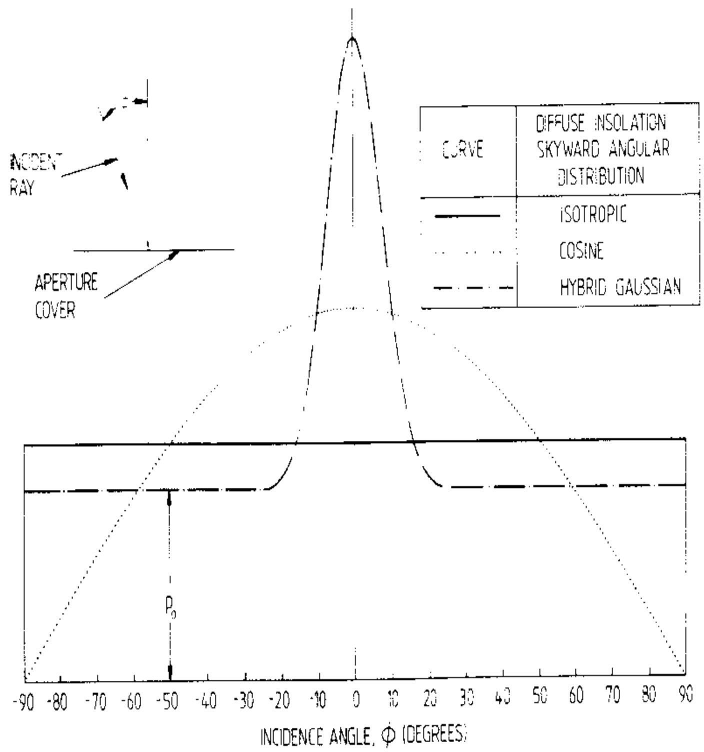

Figure 15: Alternative skyward angular distributions of the diffuse component of insolation, (Prapas et al. 1987).

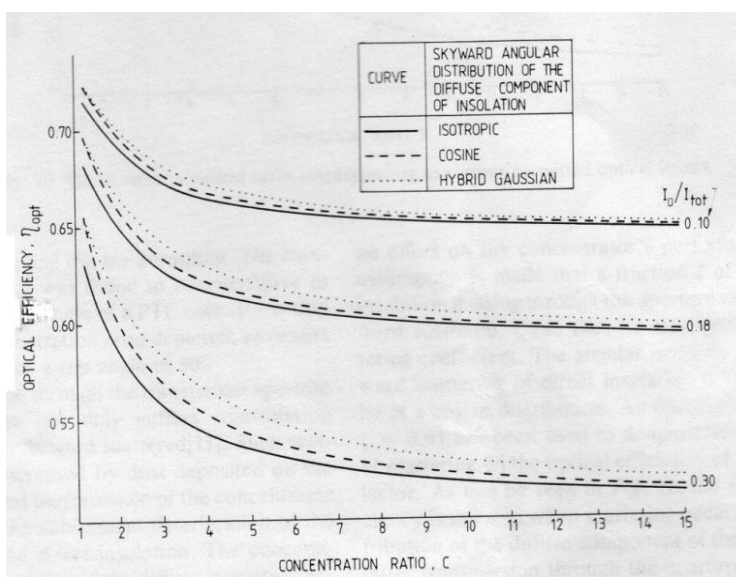

Figure 16: The effect of skyward distribution of the diffuse insolation and the optical efficiency of a PTC collector . (Prapas et al.1987).

The theoretical analysis of radiation flux density distribution in a focal plane of a parabolic concentrator is done with the following hypothesis:

(i) The reflecting surface of the concentrator is perfectly parabolic.

(ii) The solar radiation from the sun fall within the focal plane after reflections.

(iii) Incident solar radiations are parallel to the contractor axis.

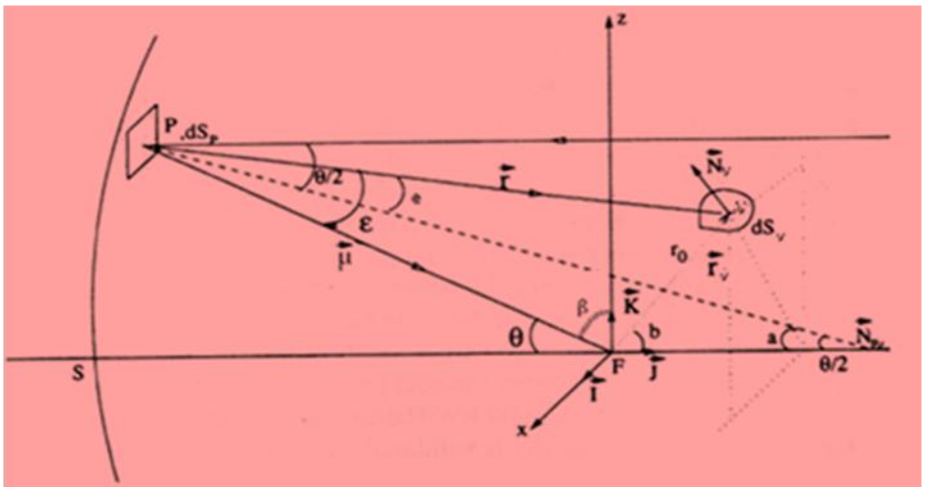

Figure 17: Path of incident parallel solar rays as reflected by the PTC.

With reference to figure 17, we consider the reflecting elementary surface dS_p of the concentrator, centred at point P reflecting rays from the sun which are parallel the principal axis towards an absorber V. The elementary surface of the absorber placed at the focal plane is dS_V. The radiant flux towards absorber V per unit steradian in the $\overrightarrow{PV}$ direction is defined as:

$$L_R(\overrightarrow{PV}) = \frac{d^2\emptyset}{dPdV}\cos\vartheta\,(d\omega_p dSV_v) \qquad (2.2.21)$$

where $\emptyset$ is the solar radiation reflected from the concentrator system towards the receiver surface and $d\omega_p$ is the solid angle of the surface element at dS_p as seen from V.

The energy directed towards the focal point, obtained by the interception of ray $\overrightarrow{PV}$ at the receiving plane is determined as follows:

$$\frac{d^2P}{dPdV} = L_R(\overrightarrow{PV})d\omega_p dS_v \frac{\overrightarrow{PV}}{|\overrightarrow{PV}|}\overrightarrow{N_V}, \tag{2.2.22}$$

Relatively to a fixed reference (F,**I,J,K**) centred at theoretical focus F of the concentrator, the concentrated radiation intensity is expressed as follows:

$$\frac{d^2P}{dPdV} = L_R(\overrightarrow{PV})\mu^2 \frac{\sin\theta d\theta d\beta d S_A}{\cos\frac{\theta}{2}r^3}(\vec{N}_P.\vec{r})(\vec{r}.\overrightarrow{N_V}), \tag{2.2.23}$$

where: $\overrightarrow{N_V}$ is the normal for receiver element centred at point V, $\overrightarrow{N_P}$ is the normal for reflected element centred at point P, $\vec{r}$ unit vector in FV direction, and μ is a function that gives the radius of the geometric form of a concentrator, definite in our case as;

$$\mu = \frac{f}{\cos\theta} \quad \text{and} \quad f = |\overrightarrow{SF}|, \tag{2.2.24}$$

Thus, the radiation flux density becomes;

$$\frac{d^2E}{dPdV} = \frac{d^3P}{dS_V} = L_R(\overrightarrow{PV})\mu^2 \frac{\sin\theta d\theta d\beta}{\cos\frac{\theta}{2}r^3}(\vec{N}_P.\vec{r})(\vec{r}.\overrightarrow{N_V}), \tag{2.2.25}$$

By substituting r, N_P and N_V with their components, following the coordinate system and integrating the resulting equation with respect to θ and β. The radiation flux densities in three directions can be expressed as $E(V_x)$, $E(V_y)$, $E(V_z)$. Hence the irradiance at a point V can be calculated as;

$$E(V) = [E^2(V_x) + E^2(V_y) + E^2(V_z)]^{1\backslash 2}, \tag{2.2.26}$$

where:

$$E(V_x) = \iint L_R(P,V)G\left|\frac{r_o}{\mu}\sin b \sin a - \sin\theta \sin\beta\right| d\theta d\beta$$

$$E(V_y) = \iint L_R(P,V)G\left|\frac{r_o}{\mu}\cos b + \cos\theta\right| d\theta d\beta$$

$$E(V_z) = \iint L_R(P,V)G\left[\frac{r_o}{\mu}\sin b\cos a - \sin\theta\cos\beta\right]d\theta d\beta$$

where $G = G(r, r\_o, a, b, \beta, \theta)$

$$G = \frac{\mu^4}{r^4}\sin\theta\left[1 - \frac{r_o}{\mu}\tan\frac{\theta}{2}\sin b\cos(a-\beta) + \frac{r_o}{\mu}\cos b\right], \qquad (2.2.27)$$

The apparent diameter of the sun $(2\varepsilon, o)$ can be calculated from the condition:

$0 \leq \tan\varepsilon \leq \tan\varepsilon_o$, where ε is the angle between vectors $\overrightarrow{PF}$ and $\overrightarrow{PV}$ given as;

$$\text{Cos}\,\varepsilon = \frac{\overrightarrow{PF}.\overrightarrow{PV}}{|\overrightarrow{PF}|.|\overrightarrow{PV}|} \qquad (2.2.28)$$

The radiation energy captured by a surface V is calculated as follows:

$$P = \iint E(V)dS_v \qquad (2.2.29)$$

where $dS_{v,}$ is the centre of surface element obtained by diving the receiving surface V and the double integral represents the surface integral, (Gupta, 1993)

However the above condition does not agree with theoretical and experimental results, (Sammouda et al, 1999).

Error in mirror surface or alignment is determined by an angle Δ, defined as one sided average deviation from the perfect value. A ray undergoing n reflections may deviate from the correct direction by 2nΔ. If no radiation is to miss the target, the nominal half acceptance angle θ_c must be increased by this amount, with a corresponding loss of concentration. Effect of mirror errors depends on the relative magnitude of Δ and the angular width of the source. In practice mirror error is neglected since they are random hence leading to cancellation, (Rabl, 1976).

Despite the fact that a lot of work has been done on parabolic solar concentrators as cited in the literature review no information has been given on how the shape factor (extent of curvature) affects temperature distribution within a solar PTC. There is also no information on how to determine focal line temperature of a solar PTC at a given solar radiation intensity. It is therefore on this basis that this study is intended to find out.

CHAPTER THREE: METHODOLOGY

3.1 Experimental Procedure

Five solar PTCs were designed by making the framework of parabolic troughs using thin steel metal rods. The parabolic shapes were obtained using an equation: $y = ax^2$, as expressed in equation 1.8, where 'a' was in the range, $0.0125 \leq a \leq 0.0625$. The chosen range of 'a' was to ensure that the focal lengths of the PTCs were sufficiently long but within the PTC to allow temperature measurements to be done at several points both below and above the focal point of each PTC.

A thin flexible sheet of dimensions 2m by 1m with aluminium foil as a reflecting surface was attached on each parabolic trough frame made of steel rod. The parabolic arc length was maintained at 2m while the PTC length kept at 1m throughout the experiment. The focal lengths, f, of such PTCs were obtained from the expression:

$$f = \frac{1}{4a} \qquad (3.1)$$

When the PTCs had been made, the aperture width and the corresponding depth of each solar PTC was measured and half the aperture width determined. The shape factor of the PTC, s, was obtained from the equation:

$$s = \frac{d}{2h} \qquad (3.2)$$

where, d, is the aperture width or opening, and h is the axial distance from the base of the collector (height of the PTC) as shown in the figure 18 below. Thus each PTC had a different shape factor.

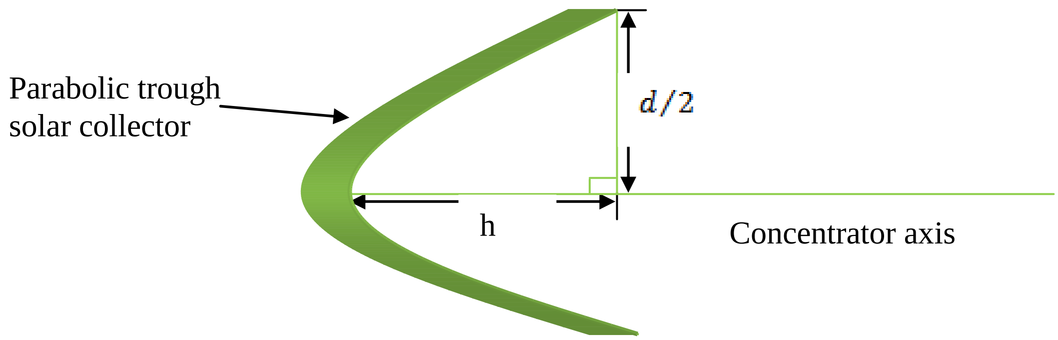

Figure 18: Components of the shape factor of an experimental solar PTC.

A thin rigid rod obtained from an insulator was fixed along each solar PTC axis. Black 1 cm^2 aluminium plates were then fixed at the focal points along the thin rigid rods fixed along the PTC axes. The temperatures of these plates were simultaneously measured by thermocouples attached to a multi- channel dataloger model “Fluke 2286A Data logging system”. Ambient temperature was also simultaneously measured by another thermocouple attached to the same dataloger which was programmed at one minute interval. The incident solar radiation intensity was also measured using a solarimeter of model LSL200. This would enable us to determine the relationship between the focal line temperature, ambient temperature and the shape factor of a solar PTC at a given incident solar radiation intensity.

Once the focal point of each of the solar PTC had been located, nine 1cm^2 black aluminium plates were then fixed on the thin rod placed along each PTC axis at 2cm interval one being at the principal focus and 4 other plates fixed both below and above the focal line of each PTC.

The temperature of these plates along the concentrator axes of the solar PTCs were also measured simultaneously by the multi channel datalogger within the same time interval of one minute. The corresponding incident solar radiation intensity was also measured by the solarimeter within the same period.

This would also enable us to determine the focal line temperature of a particular PTC based on the shape factor and ambient temperature at a given range of incident solar radiation intensity and range of parabolic equation coefficient ‘a’. Once the focal point of each of the solar PTC had been located, nine $1cm^2$ black aluminium plates were then fixed on the thin rod placed along each PTC axis at 1cm interval one being at the principal focus and 4 other plates fixed both below and above the focal line of each PTC. The temperature of these plates along the concentrator axes of the solar PTCs were also measured simultaneously by the multi channel dataloger within the same time interval of one minute. The corresponding incident solar radiation intensity was also measured by the solarimeter within the same period. This would enable us to study how the shape factor affects the temperature variation along the concentrator axis of a solar PTC at a particular range of incident solar radiation intensity.

3.2 Data Analysis

Values of average focal line temperature for a given range of incident solar radiation intensity and the corresponding shape factor of each PTC were plotted in a graph. Interpretation of the graph was used to formulate an equation connecting focal line temperature obtained from a PTC and its shape factor at a given ambient temperature.

From the records of temperature variation with distance from both below and above the focal line of each particular PTC, different sets of curves were drawn on the same graph. Such a graph showed the effect of aperture size or shape factor on the temperature distribution along the axis of a PTC.

A graph showing the variation of the shape factor and parabola coefficient ‘a’ was also drawn using classical Freundish model from Origin 8.1 program. Interpretation of such a graph enabled us to investigate the relationship between the design parameters of the PTC such as the parabola coefficient, shape factor and assess their overall influence on thermal performance of a PTC.

CHAPTER FOUR: RESULTS AND DISCUSSION

The relationship between the design parameters of a PTC such as shape factor, parabolic equation coefficient and focal length, and their influence on solar -thermal energy conversion was investigated. Values of the shape factor of the solar PTCs were determined and plotted against those of parabolic equation coefficient. The experimental results showed that the aperture width of a PTC decreased with the increase in the value of the coefficient 'a' of the equation of the parabola shown in equation 3.1. The variation of the shape factor, s and parabola coefficient 'a' was represented graphically using classical Freundish model from Origin 8.1 program as shown in figure 19 below, for a constant length of a parabolic curve.

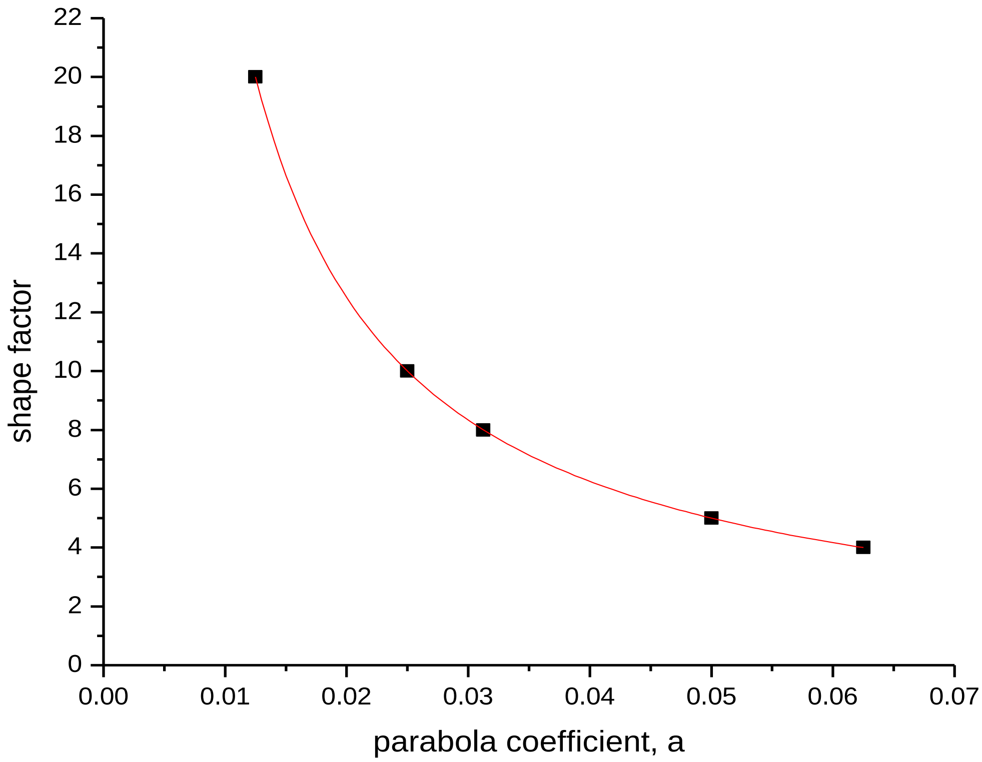

Figure 19: Variation of shape factor,s with the parabola coefficient 'a'

From above graph in figure 19, it can be noted that the shape factor of a parabola varies inversely with the parabola coefficient ‘a’ for a constant arc length of a parabola. Thus the smaller the value of parabolic equation coefficient the wider the PTC designed from such an equation and vice versa.

In order to determine an equation relating shape factor s and parabolic equation coefficient ‘a’ values 1/s, were plotted against values of parabolic equation coefficient for the five solar PTCs designed for the research. The graphical representation of the result was as shown in figure 20.

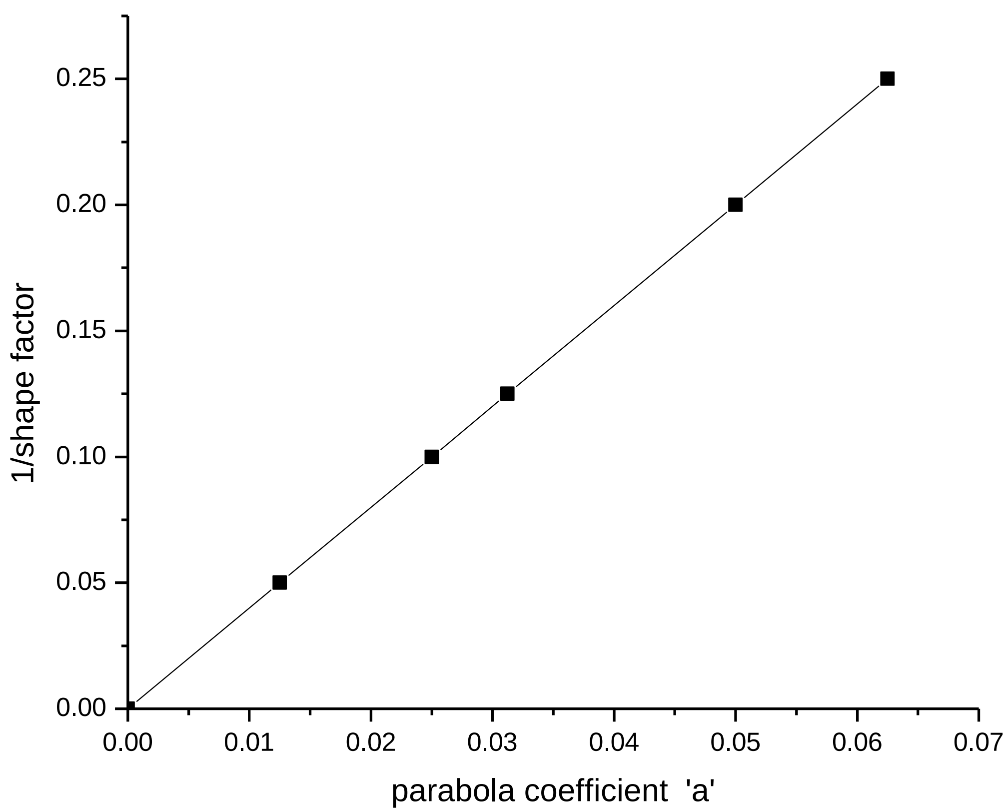

Figure 20: Variation of 1|s with parabola coefficient ‘a’

From the graph in figure 20 whose value of the gradient was calculated as 4, an equation relating the shape factor and the parabolic equation coefficient used in designing a PTC can be expressed as:

$$s = \frac{1}{4a}, \tag{4.1}$$

From equation 3.2 it can be noted that the shape factor and the focal length of a PTC are equal. Thus:

$$f = s, \tag{4.2}$$

The relationship of the design parameters of a solar PTC can therefore be known from equations 4.1 and 4.2 and their influence on the performance of a PTC be explained.

When the parabola coefficient ‘a’ approaches zero the parabola widens and becomes flat when a= 0 and the shape factor becomes infinite. At this point the PTC becomes a flat plate reflector such that all incident radiation do not converge at any point and are reflected parallel, assuming that the reflecting surface is smooth leading to regular reflection. For very small values of parabolic equation coefficient ‘a’, for instance, when a=0.00625, the focal line falls outside the PTC. When focal line of the PTC is not within the concentrator, then such a device cannot be effectively used in an open environment due to great convective heat losses.

On the other hand, as the parabola coefficient ‘a’ increases, the PTC aperture and the shape factor decreases. The PTC closes when the shape factor becomes zero, implying the reflector or concentrator is non-existent. A PTC designed from a large value of parabola coefficient has a very short focal length and cannot produce very useful temperature. It is important to note that the focal length of a parabolic concentrator varies inversely with the parabola coefficient.

From our definition of the shape factor and its relationship with the parabolic equation coefficient ‘a’ as expressed in equation 4.1, the aperture width of the PTC which determines the amount of inlet solar radiation to be concentrated and converged to a focus can be expressed in terms of the parabolic equation coefficient using equation 4.3 as:

$$d = \frac{h}{2a}, \qquad (4.3)$$

From equations 3.3 and 4.2, the focal line of a PTC can also be located from the measurements of the aperture width and depth of the concentrator as:

$$f = \frac{d}{2h}, \qquad (4.4)$$

Thus, even without knowing the equation of a parabola used in designing a PTC, the focal line where maximum concentrated radiation temperature is obtained, can be more conveniently located. This is done simply by measuring the aperture width and depth of the PTC and using the relationship of those parameters shown in equation 4.4.

In order to assess the performance of solar energy conversion systems such as solar concentrators, terrestrial solar radiation has to be defined. This is because the solar radiation is attenuated when it passes through the earth’s atmosphere. The attenuation of solar radiation is due to the scattering and absorption by air molecules, dust particles, and aerosols in the atmosphere. Particles such as steam, oxygen, carbon IV oxide cause absorption which is wavelength selective and therefore results in gaps in the spectral distribution of the solar radiation.

The most important parameter that determines the solar irradiance under clear sky conditions is the distance that the sunlight has to travel through the atmosphere. This distance is the shortest when the sun is at the zenith, i.e. directly overhead. The ratio of an actual path length of the sunlight to this minimal distance is known as the optical air mass. When the sun is at its zenith the optical air mass is unity and the radiation is described as air mass one (AM1) radiation. When the sun is at an angle θ to the zenith, the air mass is given by

$$air\ mass = (\cos\theta)^{-1}, \tag{4.5}$$

For example, when the sun is 60^o from the zenith, the radiation is described as AM2.

The solar radiation spectrum is also a function of air mass, (Concise Encylopaedia, 1994).

Thus due to such variations of solar radiation, average focal line temperatures of the solar PTCs were analysed for solar radiation intensity within the range of 500-740W/m^2. Such a range of solar radiation produced almost equal temperatures within prevailing weather conditions during the research period as shown in figure 21. It is important to note that variation of solar radiation intensity is quite instantaneous and does not simultaneously cause temperature variation of the absorbers within the solar concentrators.

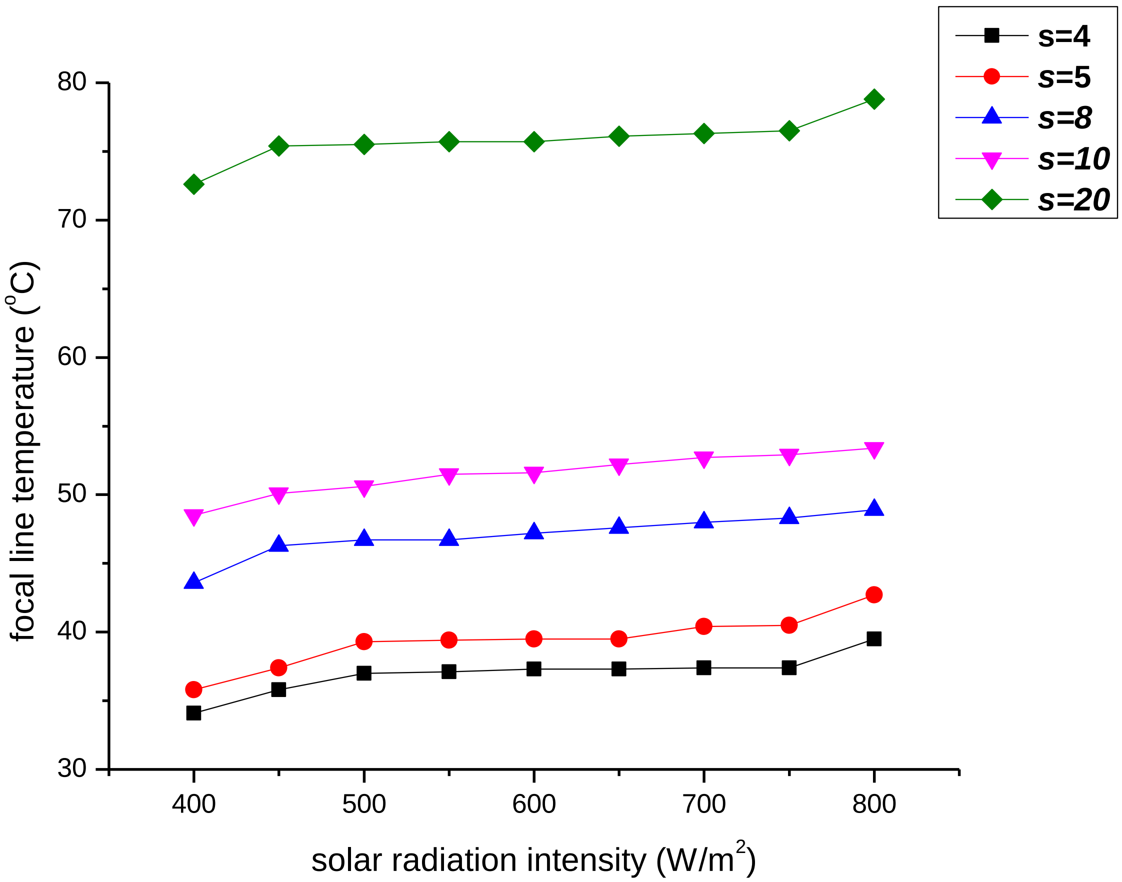

Figure 21: Average focal line temperature of different PTCs at different solar radiation intensities.

Our experimental results using the various solar PTCs indicated that solar radiation intensity of between 500W/m^2 to 740W/m^2 produced almost uniform focal line temperature. The focal line temperature dependence on the shape factor of the solar PTC at an average solar radiation intensity of 620W/m^2 was graphically represented as shown in figure 22. The experiment was done assuming conductive, radiative and convective losses.

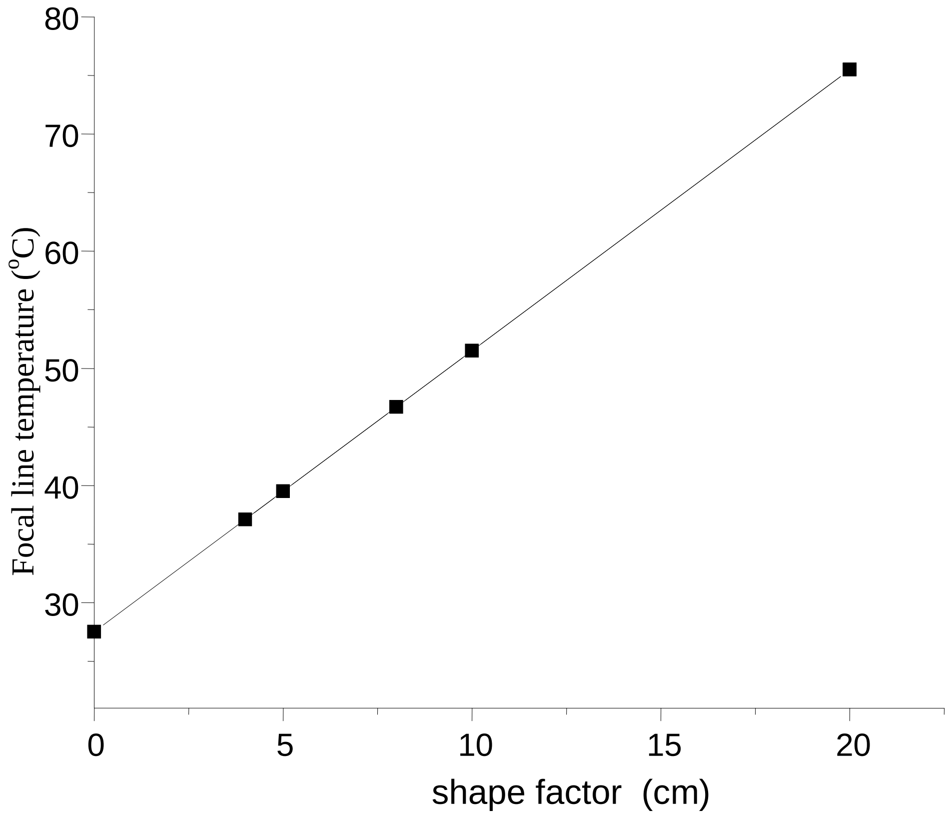

Figure 22: Focal line temperature variation with shape factor of a solar PTC for average solar radiation intensity of 620 W/m2.

From the graph in figure 22 above it can be noted that the focal line temperature increases with increase in its shape factor, which is a function of aperture width within a given limit of parabolic equation coefficient. Hence the focal line temperature of a parabolic trough concentrator increases with increase in its aperture width, (Amara et al, 2001). Thus the size of aperture width of the concentrator determines the amount of incident radiation entering the device, such that the wider the concentrator aperture (opening), the greater the concentration ratio. This in turn affects the temperature at the focal line which is directly proportional to the aperture width of any type of solar concentrator within a given range of parabolic equation coefficient below which the sharpness of focus of incident radiations on the PTC are greatly affected by spherical aberration, such that below a certain value of parabolic equation coefficient, the PTC focus is so much affected by spherical aberration that the focal line temperature is lowered despite the large aperture width.

From the graph in figure 22, the temperature of the receiver placed at the focal line of a solar PTC can be determined from a given ambient temperature T_O using the expression:

$$T = T_O + s\frac{dT}{dx}, \qquad (4.6)$$

It is important to note that the orientation of the PTC from which the shape factor is defined as given in equation 2.2.25 gives the shape factor a unit of length.

From equation 4.2 the focal line temperature of a PTC is affected by its focal length. Thus the focal line temperature of the PTC can be expressed in terms of focal length f as shown in equation 4.7 below:

$$T = T_O + f\frac{dT}{dx}, \qquad (4.7)$$

where $\frac{dT}{dx}$ is the temperature gradient whose value is 2.4^o C/cm

Focal line temperature of a PTC can also be affected by the parabolic equation coefficient 'a' since the shape factor, focal length and coefficient 'a' are related as seen in equations 3.2, 4.1 and 4.2. Thus substituting equation 4.1 into 4.6 gives focal line temperature in terms of parabolic equation coefficient as:

$$T = T_O + \frac{1}{4a}\frac{dT}{dx}, \qquad (4.8)$$

Since the design parameters of a solar PTC such as aperture width d, height h, and the focal length f are interrelated as shown in equation 4.4, the focal line temperature can also be determined from their interrelationship as:

$$T = T_O + \frac{d}{2h}\frac{dT}{dx}, \qquad (4.9)$$

Thus from a given ambient temperature the focal line temperature of a PTC can be precisely predicted from the dimensions of the concentrator.

Thus the position of the focal line of a solar PTC and its corresponding temperature at a given ambient temperature can be easily determined from its dimensions.

Another design parameter affecting the performance of a PTC is the rim angle, which is an angle between the principal axis and aperture width or rim of the PTC as shown in figure1.

The rim angle just like the shape factor also affects the extent of curvature of a reflecting surface of PTC. Hence the rim angle affects both the quality of focus and the magnitude of the focal length of the concentrator as illustrated in figure 2. A PTC with a small rim has a large shape factor, and long focal length. However the focal line temperature of the PTC increases with increase in focal length within a given range of both parabolic equation coefficient and rim angle.

Variation of temperature of concentrated solar radiation with distance from both below and above the focal line within solar PTCs of shape factors 8, 10 and 20 was also investigated. The remaining PTCs of shape factors 4 and 5 were not used due to their short focal lengths. Thus they could not contain the equal number of aluminium plates placed at 2 cm interval on both sides of the focal line perpendicular to the PTC principal axis. Thus temperature distributions obtained from those aluminium plates was as shown in figure 23. It was observed that temperature decreased with increase in distance either below or above the focal line perpendicular to the solar PTC principal axis. This temperature variation from the focal line of each of the solar PTCs was almost equal on either side, that is, above or below the focal line. However, it was noted that the focal line temperature increases with increase in the shape factor of the PTC. Thus a PTC with a large shape factor or aperture width has along focal length and high focal line temperature. Such a concentrator is suitable for both high and low temperature applications. This is because various temperature values can be obtained from such a device by varying the receiver positions from the focal line.

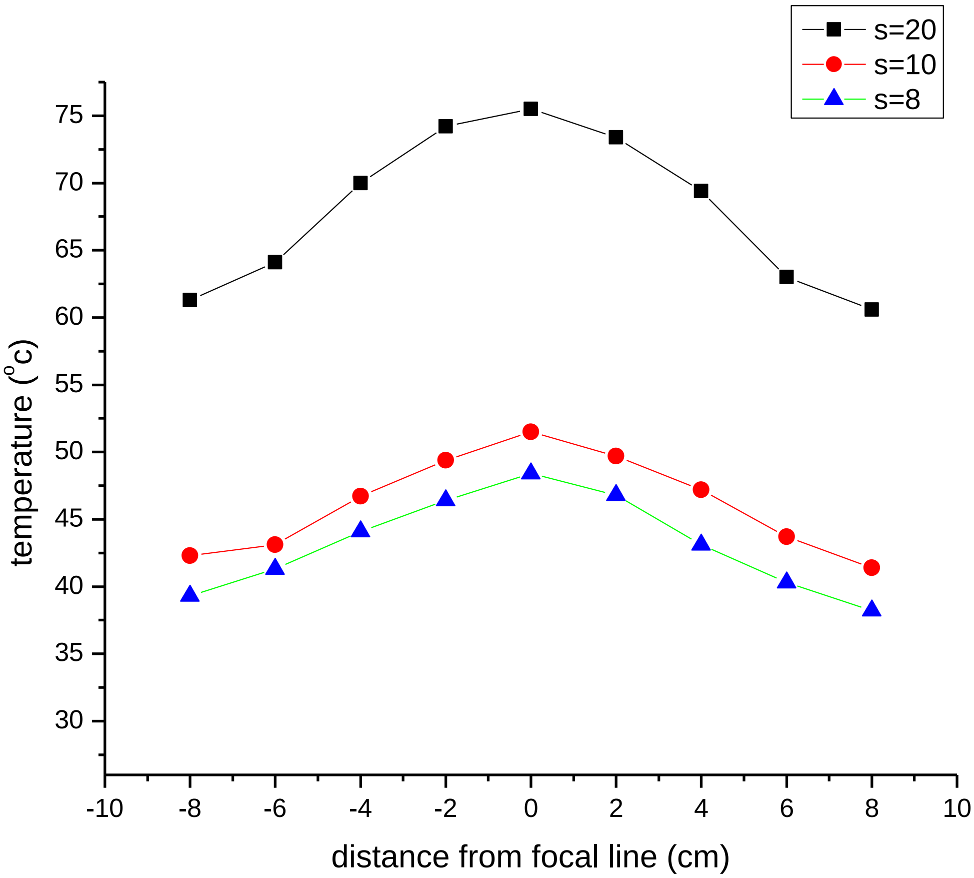

Figure 23: Temperature distribution of concentrated solar radiation within various solar PTCs.

A shape factor of 20 produced an average focal line temperature of 75.5°C at an average solar radiation intensity of 620 W/m^2 while a shape factor of 8 at the same radiation intensity produced an average temperature of 46.7°C. However, there were instances when focal line temperature reached 95°C for the larger shape factor when incident solar radiation reached about 1050 W/m^2. It can also be noted that a PTC with a large shape factor is more suitable for high temperature applications than those with small shape factors, which produce lower temperatures. Thus solar PTCs of low shape factor are suitable for low temperature applications such as drying.

However, temperature variation with distance from the focal line of a PTC is not uniform hence it is not easy to precisely predict the temperature from either side of the focal line.

Theoretical distribution of concentrated solar irradiance on the receiver placed on both sides of the focal line of a solar PTC for various aperture sizes is as shown in the figure 24 below, (Sammouda et al, 1999).

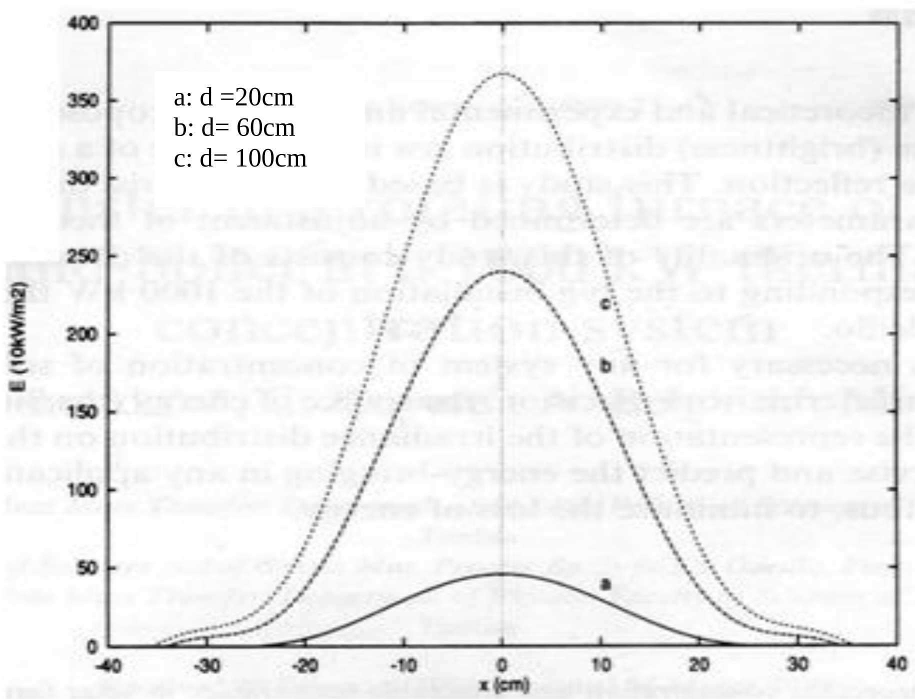

Figure 24: Theoretical distribution of concentrated solar irradiance on the receiver plane at various distances for different aperture widths, (Sammouda et al, 1999).

From figures 23 and 24, it is evident that the amount of heat received by the absorber within the PTC depends on incident solar intensity, aperture size which determines the amount of solar radiation entering the PTC, and the relative distance of the absorber from the focal line.

However temperatures shown in above graphs in figures 21, 22 and 23 could be higher if better reflective material other than aluminium was used as in our case. For example, a 1000 kW thermal solar concentration system of CNRS at Odeillo (France), which consists of a system for double reflections can generate a focal spot energy power of 1000 kW and a temperature of 3200^{o}C from 80 cm diameter concentrator, (Sammouda et al, 1999).

Temperatures could also be low as a result of surface errors due to dust particles or roughness, tracking error, as well as receiver losses. Thus it should be covered by a selective material to eliminate such losses.

It was also noted that the upper part of the reflector has very little effect on the concentration of the radiation as earlier reported by Duffie and Beckman, 1980. Thus the temperatures at the upper part of the concentrator were very close or at times equal to ambient temperatures. This implies that there is very little solar radiation energy concentration at the upper part of the PTC. However the focal line temperature remained maximum but decreased symmetrically with increase in distance on either side of focal point.

A factor such as solar radiation intensity, which affects ambient temperature also has an impact on the focal line temperature of a PTC as indicated by equations 4.3 and 4.4 above. Thus in designing such a device factors such as average ambient temperature and shape factor must be considered for the desired focal temperature.

It is important to note that real PTC solar concentrators have an optical error ∂_{opt}.

(Rabl A., 1985). This is the sum of individual errors, that is,

$$\partial_{opt}^2 = 4\partial_{contour}^2 + \partial_{specular}^2 + \partial_{displacement}^2 + \partial_{tracking}^2 , \quad (4.10)$$

where ∂, represents the standard deviation for each respective error arising from the indicated subscript. However, the total optical error takes into account the standard deviation of the angular intensity distribution of the sun's disc as

$$\partial_{tot}^2 = \partial_{opt}^2 + \partial_{sun}^2 , \quad (4.11)$$

The effect of the total optical error on the optical efficiency of a PTC solar collector using values of ∂_{tot} in the range $0 \leq \partial_{tot} \leq 0.025$ rad is as shown in figure 25.The average clear sky has a value of $\partial_{sun} = 4 \times 10^{-3}$rad, (Rabl and Bendt, 1982).

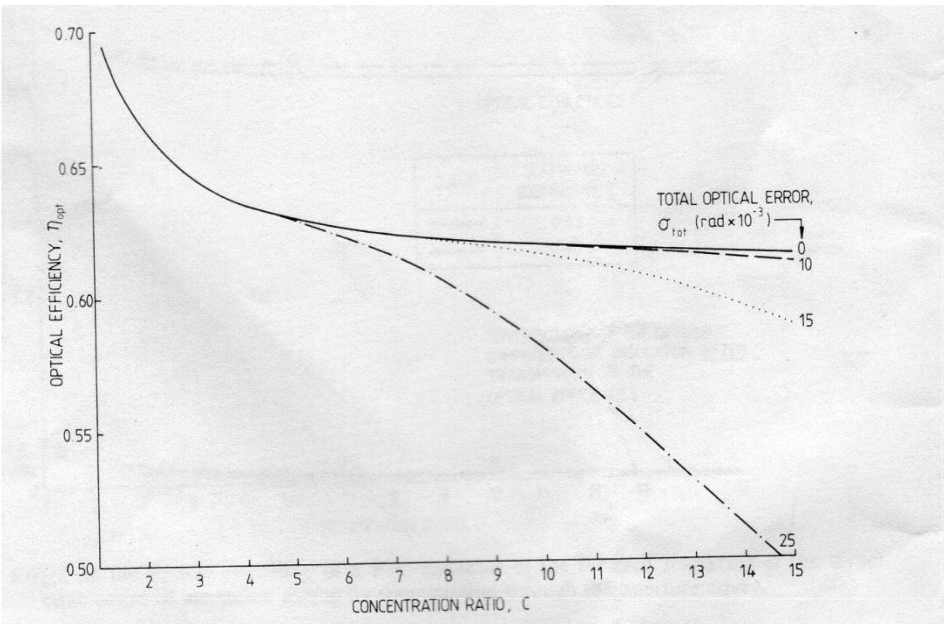

Figure 25. The effect of the total optical error on the optical efficiency of a PTC collector

From figure 25 above it can be noted that optical efficiency is insensitive to optical errors at low concentration ratios. However as the concentration ratio increases the efficiency diminishes, (Prapas et al,1987).

Due to such errors, the experimental focal length of our PTC had an error falling within ± 2.5 cm as shown in table 5

Table 5: Theoretical and experimental values of focal lengths of PTCs used.

Parabolic equation coefficient, a ($x10^{-2}$)	**Theoretical focal length, f (cm)**	**Experimental focal length, f (cm)**
1.25	20	22.0
2.5	10	12.0
3.125	8	6.5
5.0	5	6.2
6.25	4	3

CHAPTER FIVE: CONCLUSION, RECOMMENDATIONS AND SUGGESTIONS FOR FUTURE WORK

5.1 Conclusion

The main purpose of using of a solar concentrator is to obtain a temperature higher than ambient temperature that is appropriate for intended application. Certain applications such as burning and heating require higher temperatures than those which involve drying. Thus a solar PTC should be appropriately designed so that the desired temperature can be obtained. The maximum concentrated solar radiation temperature is obtained at the focal line of the PTC. However the value of the focal line temperature of the PTC is mainly affected by the incident solar radiation intensity which determines the ambient temperature. A solar concentrator is therefore a radiation exchange device involving the source, aperture and absorber. Thus, the ambient temperature and aperture width or shape factor affect the temperature of the absorber placed within the PTC.

The value of the focal line temperature of a PTC is also affected by the design parameters such as the shape factor as a function of aperture width, parabolic equation coefficient, focal length, rim angle and others. Most of these design factors are interrelated. For instance, the value of parabolic equation coefficient affects the aperture width of the parabola. The aperture width of a parabolic part of the PTC varies inversely with parabolic equation coefficient. The PTC becomes a flat plate reflector when the value of parabolic equation coefficient ‘a’ reduces to zero. On the other hand as the value of the parabola coefficient ‘a’ increases, the aperture width of the PTC decreases. The position of the focal line of the PTC and its corresponding temperature are also affected by the value of the coefficient ‘a’ in the same inverse proportionality manner.

The relationship between the focal length and the parabolic equation coefficient is shown in equation 3.2. Shape factor is related to focal length as expressed in equation 4.2. Thus the focal line where maximum temperature is obtained can be easily located from the measurements of the aperture width and depth of the PTC. It should also be noted that there are many equations of the parabola, depending on different orientations of the parabola. This in effect results in diverse ways of locating the focus of the parabola.

Rim angle affects the quality or sharpness of the focus of the PTC as shown in figure 2. Thus effect of spherical aberration is more pronounced when the rim angle is very small, hence reducing the sharpness of focus. Therefore a PTC should be designed from a suitable range of parabolic equation coefficient in order to produce corresponding suitable rim angle. A solar PTC suitable for high temperature applications should have a focus. The performance of a PTC is also dependent on factors such as: the acceptance angle, which is the angular range over which radiation is accepted without moving all or part of the collectors, (Prapas,et al,1987). Other factors are concentration ratio, reflectivity of the mirror, the tracking system and aperture width, (Rabl, 1976). Thus a PTC can produce high temperature if the area of solar radiation concentration is large. Therefore in order to achieve large concentration ratio required for high efficiency of the PTC, the receiver size should be reduced relative to the aperture area. In any concentrating device, the radiation is concentrated to a central receiver using mirrors or refractive optics. Concentrators therefore require direct solar illumination, and the optics or mirrors must move during the course of the day to track the sun's trajectory for high efficiency of the system.

Therefore for high efficiency to be achieved, it requires large field of view as well as good tracking system. This is because the effective incoming radiation to the aperture plane is the beam radiation which is concentrated by the PTC. The focal length is a determining factor in the image size and the aperture is the determining factor in the total energy, (Amara et al 2011). Hence the higher the shape factor, the larger the aperture, which in turn improves the efficiency of the system. Parabolic-trough systems have been used to concentrate the sun's energy through long rectangular, curved (U-shaped) mirrors. The mirrors are tilted toward the sun, focusing sunlight on a pipe that runs down the center of the trough. The pipe normally carries oil which is heated. The hot oil then is used to boil water in a conventional steam generator to produce electricity, (Salomoni et al 2009).

It was also noted that there is focal line temperature variation with the shape factor and focal length of the PTC. The focal line temperature of a PTC varies directly with shape factor or focal length provided that ambient temperature is constant. Graphical representation of focal line temperature variation with shape factor led to an establishment of constant temperature gradient of 2.4^{o}C/cm, which can be used to predict focal line temperature of a PTC at a given ambient temperature as expressed in equations 4.6 and 4.7. Hence by measuring the aperture width and depth of the PTC, the focal line can be easily located and its corresponding temperature predicted provided ambient temperature is known.

There is also symmetric temperature drop on both sides of focal line of a solar parabolic trough concentrator (PTC). Equal temperatures can therefore be obtained from corresponding equal distances from the focal line of the PTC. Thus receivers can be placed on either side of the focal line of the PTC to obtain desired temperatures. Our experimental temperature distribution curves in figure 23 were symmetric about the focal line just as the theoretical graph shown in figure 24.

It can also be noted that the research was successful in meeting the set objectives, in that, the extent to which the ambient temperature affects the focal line temperature of a PTC was determined. The effect of the shape factor, as a function of both the aperture width depth on the focal line temperature of the PTC was also successfully investigated and determined. The relationship of the design parameters of a PTC such as parabolic equation coefficient, shape factor and focal length was investigated and determined as intended. Both experimental and theoretical results on temperature variations from the focal line showed symmetric temperature drop with increase in distance from both sides of the focal line within certain solar intensity range.

However the effect of instantaneous solar radiation intensity on temperature of the plates used in the PTC could not be precise since temperature and solar radiation intensity changes do not occur at the same time interval.

5.2 Recommendations

Solar energy has vast potential towards the world's energy market contribution, especially in Kenya which has long sunshine duration due to its equatorial location. Thus the Kenyan government and other development agencies should give support to research programs in solar energy technology.

A lot of countries are now focusing more on renewable energy, for instance, in the US President Barack Obama chose a group of people to run his Energy Department, hailed by known as the "Green Team". Besides tackling the climate change, the team is also responsible to venture into new technologies. In 2008 alone, it is reported that the total global investment in renewable energy has reached approximately USD120 billion, led by the US, Spain, China and Germany, (Muhammad et al 2008).

Solar energy is one of the alternative energies that has vast potential. It is estimated that the earth receives approximately 1000W/m^2 amount of solar irradiation in a day, Winston et al, 2005. This amount of irradiation could generate around 85,000TW and it is estimated that the current global energy consumption is about 15TW. Taking into account the power obtained from all renewable resources as illustrated in Table 6.

Table 6: Power available from renewable resources, (Winston et al, 2005).

Energy Source	**Max Power (TW)**
Total surface solar	85000
Desert solar	7650
Ocean thermal	100
Wind	72
Geothermal	44
River hydroelectric	7
Biomass	7
Open ocean wave	7
Tidal wave	4
Coastal wave	3

Therefore the solar energy alone has the capability to meet the current energy demand, (Abbott, 2009). It is also estimated that by harnessing the solar energy from eight different solar power plant sites throughout the world, the energy generated from these plants has the capability to supply more than enough electricity to satisfy the present global energy utilization. These sites are located in the deserts in Southwest Asia, China, Australia, Southern South America, United States and Mexico, (Liu et al, 2009).

From our research the following recommendations can be made:

1. A PTC should have a large shape factor and hence long focal length. The large shape factor contributes to a high focal line temperature of the PTC within a given range of parabolic equation coefficient values. Such a concentrator is more appropriate for high

temperature application than one with a small shape factor. The long focal length allows various temperature values to be obtained within the PTC for various applications.

2. When designing a PTC, it is important to know the average solar radiation intensity and the resulting ambient temperature of the place where the device would be used. This is useful in predicting the focal line temperature.
3. The dimensions, that is, aperture width and depth of the PTC should be indicated so that the focal line where maximum temperature is obtained, can be easily located.
4. Temperature gradient from the PTC focal line should be known. Thus temperature calibrations should be indicated on the concentrator where specific temperatures can be obtained within the PTC.

5.3 Suggestions For Future Work

Some work needs to be done to formulate the relationship between the area of solar concentration, concentrated solar thermal energy and temperature which can be obtained within solar concentrators.

The time lag between temperature and solar radiation intensity changes needs to be determined in the next research to establish more accurately the experimental results where both temperature and solar radiation are involved.

Some improvements are required on the design of the PTC used in this study to reduce heat losses in order to obtain higher temperature

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APPENDICES

Table A: Variation of parabolic equation coefficient, a with the shape factor,s.

Parabolic equation coefficient, a	0.0125	0.025	0.0135	0.05	0.0625
Shape factor, s (cm)	20	10	8	5	4
s^{-1} (cm^{-1})	0.05	0.10	0.125	0.20	0.25

Table B: Temperature variation with distance from various PTC focal line.

Shape factor, s (cm)										
20	Distance (cm)	-8	-6	-4	-2	0	2	4	6	8
	Temperature (^{0}C)	56.6	61.1	66.1	70.7	75.5	70.7	65.9	61.1	56.3
10		32.1	36.8	41.4	46.3	51.0	46.2	41.4	36.6	31.8
8		27.0	32.0	36.8	41.6	46.7	41.4	36.6	32.1	27.0

Table C: average focal line temperatures of various PTCs at different solar radiation intensities.

Shape factor, s										
20	Radiation intensity (W/m^2)	400	450	500	550	600	650	700	750	800
	Focal line temperature (^{o}C)	72.5	73.3	75.2	75.5	75.5	75.5	75.6	75.6	76.3
10	Radiation intensity (W/m^2)	400	450	500	550	600	650	700	750	800
	Focal line temperature (^{o}C)	48.8	50.1	50.9	51.6	51.7	51.7	51.8	51.8	54.4
8	Radiation intensity (W/m^2)	400	450	500	550	600	650	700	750	800
	Focal line temperature (^{o}C)	44.7	45.5	46.6	46.6	46.7	46.7	46.7	46.9	48.2

Table C cont.

Shape factor, s										
5	Radiation intensity (W/m^2)	400	450	500	550	600	650	700	750	800
	Focal line temperature (^oC)	38.1	38.3	39.4	39.6	39.6	39.7	39.7	39.7	41.4
4	Radiation intensity (W/m^2)	400	450	500	550	600	650	700	750	800
	Focal line temperature (^oC)	35.1	35.6	36.5	36.5	36.6	36.6	36.8	36.8	37.1