

# **OPTICAL DESIGN OF LINEAR SOLAR CONCENTRATORS**

*by*

*Avinash Kumar Singhal*

**THESIS**

*Submitted to the*

*Indian Institute of Technology*

*for the award of the degree of*

**DOCTOR OF PHILOSOPHY**

*In Physics*

Department of Physics

INDIAN INSTITUTE OF TECHNOLOGY, DELHI

April 1982

TO MY PARENTS

## ACKNOWLEDGEMENTS

It is a great pleasure and privilege to express my deep sense of gratitude and profound indebtedness towards Prof. S.S. Mathur and Dr. R.N. Singh for their incessant, valuable guidance, direction and inspiring encouragement given to me, without which it would have been impossible to complete the present work.

I am highly grateful to Dr. T.C. Kandpal for his guidance throughout the work. Dr. Kandpal has always been very informal and cordial to me and extended his friendly help at every step I needed.

I also take an opportunity to sincerely thank Prof. M.S. Sodha, Prof. B.B. Tripathi and Prof. R.D. Garg who have always been a source of encouragement and inspiration for me.

I am also thankful to Profs. H.P. Garg, B.C. Raychowdhary, S.P. Sabberwal and Drs. S.C. Mullick, H.K. Sehgal, N.K. Bansal, R.P. Dhaiya and S.C. Kaushik for their interest in my present work.

My special thanks go to my colleagues Drs. J.K. Nayak, P.K. Bansal, Ashwani Kumar, Messers Chatar Singh, M.S. Sharma, Subhash Bhardwaj, V.K. Sharma, Miss Usha Singh and Neeta for their valuable assistance and fruitful discussions I had during the course of this work. Thanks are also due to Drs. Dilip Ranganathan, G. Bose, Miss Kamana Aggarwal, Mr S.K. Jha and Mrs & Mr Jagdish Rai for their co-operation and help in completing the present work.

Finally the financial support of C.S.I.R., India which enabled me to reach at this stage is also acknowledged.

Avinash Kumar

(A.K. Singhal)

## SUMMARY

The present thesis deals with the optical design of linear solar concentrators. A brief review of several existing types of solar concentrators has been made in the beginning. An analytical formulation for the optimum temperature of a solar thermal power plant for maximum overall efficiency is also presented with some numerical calculations made to exemplify the procedure.

The possibility of using a fin receiver with cylindrical parabolic trough has been explored. Suitable modifications in the reflector design lead to its better performance. The effect of concentrator tracking error and the fin alignment error on its concentration characteristics has also been studied; taking the limb-darkening effect of the Sun into account.

The study of geometrical-optical performance characteristics of an inverted vee type linear Fresnel lens reveals that a significant gain in concentration can be achieved as compared to the flat Fresnel lens. It is also found that an error of +2% in defocusing and  $1^\circ$  in tracking does not affect the concentration characteristics significantly.

A somewhat new design strategy for a linear Fresnel lens/reflector has also been presented in the thesis due to which a more uniform illumination is obtained as compared to the

conventional system. Such modified lens/reflector may be useful for photovoltaic systems.

Finally, results of some optical flux mapping experiments performed on a composite parabolic trough using a calibrated silicon solar cell have been presented. Such a system can be used for those solar thermal as well as photovoltaic applications where moderate concentration is required. Though due to its faceted nature, the concentration obtained is somewhat lower than that possible with perfect design yet the other simplicities, advantages in fabrication and maintenance and a comparatively more uniform illumination over the receiver make it attractive.

o o o o o

## PREFACE

Solar energy has now attained a prominent position as a source of energy for the future. Extensive efforts are being made the world over to collect, store and to convert it into usable forms. Thermodynamically, it is imperative that solar energy be collected at higher temperatures so that the efficiency of conversion to mechanical or electrical forms may be high. Development of solar concentrators, therefore becomes a high priority research area. Solar concentrators are collection devices which produce a higher flux density on the receiver than what exists on the concentrator aperture. Optimal concentration is achieved by using reflecting and/or refracting elements.

The concentration of solar-energy for generating higher temperatures has long been practised [20]. In recent years many developments in the understanding and use of solar concentrators have been reported [22,32]. The conventional imaging as well as more recently developed nonimaging [37,53] reflecting and/or refracting devices have found applications in solar concentrators of various geometries. Recent investigations have resulted in the development of new solar concentrator designs suitable for specific purposes [29]. Studies have also been made to improve upon the various concentrator designs proposed so far. This necessitates a careful review of the diversified work on solar concentrators so as to select a particular concentrator design

for a certain task. In the present thesis, such a review has been attempted.

A solar concentrator is characterized by several design and performance parameters which define its optical and thermal performance characteristics [23]. Geometrical concentration ratio, local concentration ratio, receiver intercept factor and the optical efficiency are some of the parameters which define the optical performance of a concentrator whereas the thermal performance is characterized by the stagnation temperature, heat loss coefficient and the thermal efficiency. A relationship between any two of the optical and/or thermal performance parameters can be established in terms of other known variables. As the local insolation level affects the performance of any concentrating system efficiently, it will be advantageous to study the effect of insolation on the performance characteristics of a solar concentrator. The overall efficiency of a solar thermal power plant is the product of the efficiencies of the individual components i.e. of the concentrator and the associated engine. As the operating temperature is increased, the efficiency of the engine increases but the efficiency of the concentrator decreases due to the increased heat losses from the receiver at higher temperatures. Therefore, there will be an optimum temperature for obtaining maximum power output from such a combination. These factors have been given due consideration in the thesis in which results of numerical calculations for some main stations in India are also included.

Solar concentrators may broadly be classified as tracking and non-tracking systems [25]. Tracking systems may further be classified as (i) One-axis tracking and (ii) Two-axis tracking systems. Two-axis tracking systems provide high concentrations while one-axis tracking systems are used when intermediate concentration is sufficient to fulfill the requirements. A paraboloid of revolution, central tower receiver, circular Fresnel lens and a hemi-spherical bowl mirror are of two-axis tracking type. One-axis tracking systems are exemplified by a cylindrical parabolic trough, linear Fresnel lens/reflector and Russell's fixed mirror solar concentrator whereas a compound parabolic concentrator, Tabor-Zeimer circular cylinder and V-trough belong to non-tracking systems. However, the cylindrical parabolic trough and the linear Fresnel lens/reflector are the only devices which have achieved any market penetration to date. Uses for these items include irrigation systems, building air conditioning, industrial hotwater and small thermal power plants.

The optical and thermal performance characteristics of a conventional cylindrical parabolic trough have been the subject matter of several research papers [10,40,45,50]. However, the conventional design may be modified to make it suitable for a typical application. For example, a fin receiver (i.e. a flat plate placed along the optical axis) can be used in place of a usual flat plate or a tubular receiver so as to attain higher efficiencies and better output while using it as a photovoltaic

concentrator with double side and multijunction edge illuminated solar cells. Another modification can be the approximation of the single piece parabolic reflecting surface by a composite surface made up of smaller flat mirror elements to simplify the fabrication process [19]. However in each case detailed analysis will have to be made so as to ascertain the merits and demerits of the modified design. In the present work the possibility of using a fin receiver with a cylindrical parabolic trough has been explored and the effects of limb-darkening has been studied.

As an alternative to a curved base linear Fresnel lens a double convex inverted vee type linear Fresnel lens has been suggested [7]. It is made by dividing a flat lens in two halves and sloping them against each other in the form of an inverted vee. The concentration characteristics of such a Fresnel lens in imaging geometry with a flat plate receiver have been presented in the thesis using a simple analytical model.

A conventional linear Fresnel reflector/lens produces a nonuniform illumination over the receiver and suffers from partial blocking of radiation reflected/transmitted from a mirror element/groove by adjacent mirror elements/grooves. A somewhat new design strategy for designing a linear Fresnel lens and a linear Fresnel reflector has been presented. In each case comparatively more uniform illumination is produced and the blocking of radiation is also avoided in case of reflector by assigning a proper value of tilt, width and shift

parameters associated with each mirror element.

In all the above analytical formulations the following simplifying assumptions have been made ;

- (i) The concentrator is perfectly tracking the Sun.
- (ii) The apparent angular diameter of the Sun ( $2\theta$ ) is 32 minutes of an arc and the solar disc has a uniform spatial intensity distribution.
- (iii) The reflector surface is specularly reflecting and the reflectivity is independent of angle of incidence.
- (iv) The diffraction effects, blocking and edge losses and the groove depth are negligible in case of Fresnel lens
- (v) The manufacturing defects in the concentrator are negligible.

A chapter-wise summary of the thesis is given below:

#### CHAPTER I

This chapter presents a review on solar concentrators including all existing important types of concentrators. A survey of recent available literature has been made. The specific aspects covered in writing the review are (i) design (ii) fabrication (iii) optical performance and (iv) tracking. A comparative study of such concentrators has also been attempted.

## CHAPTER II

Generalized curves representing the relationships between concentration and temperature are given in the IIInd chapter. The effect of local isolation level on the performance of concentrating system coupled with an engine has been studied. Results of some sample calculations are plotted graphically and discussed.

## CHAPTER III

The design features and concentration characteristics of a cylindrical parabolic trough using a fin receiver are the subject of this chapter. It has been found advantageous to eliminate a portion of the trough near the apex of the parabola so as to eliminate large tails in the distribution of local concentration ratio. The eliminated portion may be characterized by a chopping angle. For each value of rim angle the corresponding value of chopping angle is calculated numerically so as to provide maximum possible concentration. The effect of limb darkening on the concentration characteristics alongwith the effect of concentrator tracking error and the lateral shift of the fin receiver has also been presented in this chapter.

## CHAPTER IV

This chapter presents the optical design and performance characteristics of an Inverted vee type linear Fresnel lens. Such a lens provides a higher concentration as compared to a

conventional flat Fresnel lens. An increase in concentration has been found with the increase in slope angle of the lens. The effects of transverse tracking and receiver defocusing errors on its concentration characteristics have also been studied. It is observed that a transverse tracking error of  $1^\circ$ , and the defocusing of the receiver by +2% does not affect the concentration characteristics significantly.

#### CHAPTER V

The design and performance characteristics of a modified linear Fresnel lens has been described in this chapter. The width, and tilt associated with each groove is so chosen that the intercept produced is equal to the width of the receiver. An illumination more uniform than that produced by a conventional Fresnel lens is found over a flat plate receiver placed in the focal plane of the modified Fresnel lens.

The geometrical characteristics of linear Fresnel reflector using a fin receiver with a similar design strategy have also been discussed in this chapter. Results of some numerical calculations made for some typical concentrator receiver systems have been plotted graphically and discussed.

#### CHAPTER VI

The geometrical optical performance characteristics of a composite parabolic trough (CPT) with a flat and also with a

fin receiver have been studied analytically. Results of some optical flux mapping experiments performed on the CPT are also presented in the chapter. The CPT is fabricated using locally available material and the flux mapping is done by a calibrated silicon solar cell sensor. Measurements have been made over the focal plane and as well as on a plane perpendicular to it containing the optical axis. Attempts have also been made to simulate the optical performance in presence of a finite tracking error and a small defocusing of the receiver.

The above mentioned work has partially appeared in the following publications;

(A) Papers Accepted / Published in Journals

1. Influence of errors of trough pointing and fin alignment on the geometrical concentration ratio of focusing parabolic concentrators; Int. J. Energy Research, Vol. 5, 277-287 (1981).
2. Performance of a cylindrical parabolic trough using a fin receiver: Limb-darkening effects; Int. J. Energy Research, In press (1982).
3. A modified linear Fresnel lens; Int. J. Energy Research, In press (1982).
4. Optical design and performance characteristics of an inverted vee type linear Fresnel lens; Applied Energy, In press (1982).

5. Geometrical optical performance studies of a composite parabolic trough with a fin receiver; Applied Energy, In press (1982).

(B) Papers presented in conferences

1. An inverted vee type Fresnel lens linear solar concentrator; 8th All India Conf. of O.S.I. (1980).
2. Geometrical optical performance studies of a composite parabolic trough with a fin receiver; 8th All India Conf. of O.S.I (1980).
3. Defocusing and transverse tracking error effects in case of vee type linear Fresnel lens; Proceeding Indian National Solar Energy Convention, Annamalai (1980).
4. Optical performance characteristics of a cylindrical parabolic concentrator using a fin receiver; 9th All India Symposium on Optics (1980).

(C) Communicated

1. Geometrical concentration characteristics of a linear Fresnel reflector using a fin receiver.

(D) Other papers published

1. An application of white light multiexposure speckle photography; Optica Applicata Vol X No. 3 (1980).
2. Formation of Laser speckles under extra-axial aberrations; Optical & Quantum Electronics, 12, 519 (1980).

## TABLE OF CONTENTS

	Folio
PREFACE	1
CHAPTER 1 A REVIEW ON SOLAR CONCENTRATORS	
1.1 Introduction	10
1.2 Solar Concentrators	14
1.3 Parameters Characterising Concentrators	15
1.4 Classification	17
1.5 Tracking Concentrators	18
1.5.1 One-Axis Tracking Concentrators	18
1.5.1(a) Cylindrical parabolic trough	18
1.5.1(b) Linear Fresnel lens/reflector	22
1.5.1(c) Russel's fixed mirror solar concentrator (FMSC)	26
1.5.2 Two-Axis Tracking Concentrators	27
1.5.2(a) Paraboloid of revolution	27
1.5.2(b) Central tower receiver	30
1.5.2(d) Hemispherical bowl mirror	35
1.6 Non-Tracking Concentrators	39
1.6.1 Tabor-Zeimer circular cylinder	39
1.6.2 Compound parabolic concentrator	40
1.6.3 V-trough	44
CHAPTER 2 MAXIMUM POWER FROM A SOLAR THERMAL POWER PLANT	
2.1 Introduction	47
2.2 A Solar Thermal Power Plant	48
2.3 Analysis	50
2.3.1 Low and intermediate operating temperatures	51
2.3.2 High operating temperatures	53

	Folio
2.4 Relation between Concentration Ratio and Operating Temperature	54
2.5 Results and Discussion	55
 CHAPTER 3 USING A FIN RECEIVER WITH CYLINDRICAL PARABOLIC TROUGH	
3.1 Introduction	59
3.2 Analysis	60
3.2.1 Geometrical concentration ratio	60
3.2.2 Local concentration ratio	67
3.2.3 Effect of tracking and fin alignment errors	70
3.3 Results and Discussion	73
 CHAPTER 4 AN INVERTED VEE TYPE LINEAR FRESNEL LENS	
4.1 Introduction	76
4.2 Analysis	77
4.2.1 Groove angles	77
4.2.2 Transmission characteristics	78
4.2.3 Local concentration ratio	81
4.3 Results and Discussion	86
 CHAPTER 5 A MODIFIED LINEAR FRESNEL LENS AND A FRESNEL REFLECTOR	
5.2 Introduction	89
5.2 A Modified Linear Fresnel Lens Using Flat Receiver	90
5.2.1 Geometrical design analysis	90
5.2.2 Transmission and concentration characteristics	93
5.2.3 Results and discussion	94

	Folio
5.3 A Modified Linear Fresnel Reflector Using Fin Receiver	96
5.3.1 Geometrical design analysis	96
5.3.2 Local concentration ratio	100
5.3.3 Results and discussion	102
5.3.4 Concluding remarks	104
 CHAPTER 6 A COMPOSITE PARABOLIC TROUGH	
6.1 Introduction	105
6.2 Analysis	106
6.2.1 Local Concentration ratio	106
6.2.2 Tracking and receiver displacement errors	112
6.3 Experimental Verification	114
6.4 Results and Discussion	115
6.5 Concluding Remarks	117
 REFERENCES	119