HIGH TEMPERATURE SOLAR CONCENTRATORS

Robert Pitz-Paal
Institute of Technical Thermodynamics, German Aerospace Center (DLR), Germany

Keywords: Optical concentration ratio, central receiver systems, dish/Stirling, solar furnace, selective surface, imaging / non-imaging concentrators

Contents

Summary

The use of solar energy in technical applications is often constrained due to its low energy density relative to the conventional sources of energy. Optical concentration is one option to increase the energy density of the solar radiation resulting in the possibility to use absorbers with small surfaces. Higher temperatures can be achieved under concentrated conditions, because heat losses are proportional to the absorber surface. If the final objective is to convert the solar energy into work, the thermodynamics suggests that it can be done more efficiently the higher the temperature is.

In order to understand the design of different high temperature solar concentrators, this chapter gives an comprehensive insight into the fundamentals of optical concentration systems by introducing the definition of the concentration ratio and its limits and gives examples of imaging and non-imaging systems. When analyzing the conversion of radiation energy to heat, the collector performance equation of concentrated solar high temperature systems is presented and the impact of the concentration ratio, temperature and absorber properties is discussed.

One part deals with the conversion of heat to mechanical work starting with the discussion of the Carnot cycle. As typical examples for solar high temperature applications, the Rankine cycle, the Brayton cycle and the Stirling cycle are discussed.

The combination of power cycle attributes and receiver performance characteristics is presented to show the optimization potential.

In the scope of this chapter only three dimensional concentration concepts using two axis tracking are investigated, since they offer an application temperature clearly beyond 500 °C. Two axis tracking systems are dealt elsewhere. Three technical concepts for high temperature solar concentrators are presented: dish/Stirling systems acting in the power size below 25 kW_e and central receiver systems ranging from the 10 MW to 100 MW are concepts used today mainly for high temperature power production purposes, whereas the third option, a solar furnace, is utilized as a research tool to apply very high energy densities to materials or processes under investigations. For all three options the system design and a description of different components are presented together with an analysis of the system performance and loss mechanisms. The state of the art of existing facilities is demonstrated and further development directions are pointed out.

1. Introduction

This chapter focuses on 3D two-axis tracking systems with concentration ratios higher than 500 for the generation of high temperatures beyond 500 °C. Linear one-axis tracking concentrators are presented in (*Medium Temperature Solar Concentrators (Parabolic Troughs Collectors*).

High temperature solar concentrator concepts were already known by the ancient Greeks that enlightened the Olympic fire using a burning mirror. Leonardo da Vinci proposed a technique to weld copper using concentrated solar radiation in the 15th century. In the 18th century first technical prototypes of parabolic dish concentrators were used to generate steam driving steam engines. However, when oil and natural gas became available to serve as fuels to operate engines, the interest in high temperature solar concentrators vanished due to obvious reasons. In the late 1960s and early 1970s, when it became clear that fossil fuel resources are limited and their unequal distribution lead to strong dependencies, systematic research work was started in a number of industrialized countries. Today's concepts are based on the experiences gained with a variety of prototype and research installations that were mainly erected in the 1970s and 1980s. First commercial systems were put into operation in the beginning of the 21st century.

In order to understand the technical options offered by high temperature solar concentration, Section 2 of this chapter deals extensively with the relevant fundamentals. It covers the basics of optical concentration, the conversion of radiation to heat as well as the thermodynamic cycles to convert heat to mechanical power.

In Section 3 three technical concepts of high temperature solar concentrators are presented; dish/Stirling systems and central receiver systems are applied mainly on the field of electricity production whereas solar furnaces are utilized as a research tool to apply very high energy densities to materials or processes under investigation.

2. Theoretical Background

2.1. Concentration of Radiation

Radiation energy Φ measured in W that is emitted from a source is diluted with increasing distance. This means that the energy density E measured in W m^{-2} is reduced with increasing distance, because the emitted energy is distributed over a larger surface area. Concentration of radiation aims at increasing the energy density E of the radiant energy, in order to allow a better use of it.

A generic concentrator (see Figure 1) consists of a concentrator entrance aperture area A (in m^2) which the radiant energy enters through and an exit aperture A' from where the radiation energy leaves the concentrating system.

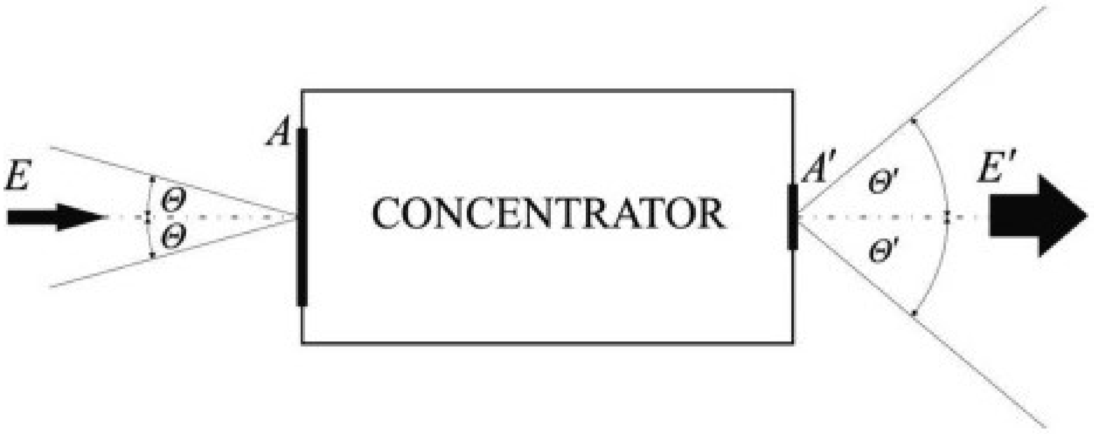

Figure 1: Scheme of a generic concentrator showing relevant aperture areas (A and A'), radiation densities (E and E') and half angles of the radiation cones (Θ and Θ')

Provided that no losses occur in the concentrator, the energy conservation principle leads to the conclusion that the concentration factor C, defined as the ratio of the outgoing energy density E' to the incoming energy density E, can also be described by the inverse ratio of the respective aperture areas:

$$C = \frac{E'}{E} = \frac{A}{A'} \qquad (1)$$

A burning glass is a simple example of a concentrator. The entrance aperture is the circular area described by the diameter of the lens, the output aperture can be arbitrarily chosen, e.g. by an orifice behind the lens, through which the radiation passes to be utilized for instance by a photovoltaic cell. An ideal lens would concentrate incoming parallel rays to a mathematical point, resulting in an infinite concentration ratio. However, in reality the focus point has finite dimensions (thus being a focal spot) so that a minimum diameter of the orifice is required to make sure that all radiation can pass. One essential reason for this is that the incoming radiation is generally not parallel but can be described by a cone with a half angle Θ. For solar energy applications on earth the sun's radiation cone with its half angle of 4.653 mrad is the relevant quantity. In complex thermodynamic considerations (cf. Welford et al., 1978) it can be shown that ideal concentrators conserve a quantity called *Etendue*, the product of aperture area and sinus square of the half angle of the radiation cone:

$$A \cdot \sin^2 \Theta = A' \cdot \sin^2 \Theta' \qquad (2)$$

Employing this law the concentration ratio of an ideal concentrator can be specified by

$$C = \frac{A}{A'} = \frac{\sin^2 \Theta'}{\sin^2 \Theta} \qquad (3)$$

For a burning glass used to concentrate the sunlight, Θ equals the sun's half angle, whereas Θ' is described by the rim rays of the lens to the focal point. For a given opening angle Θ the maximum concentration is achieved if $\sin^2\Theta' = 1$ or rather $\Theta' = 90°$. Thus, for the sun's half angle of 4.653 mrad the theoretical maximum of the concentration ratio is 46 200. From this principle the conclusion can be drawn that the concentration ratio of a burning glass is higher the smaller the ratio of focal length f to lens diameter D is, because Θ' is increased further towards 90°. However, even with a perfect burning glass the theoretical limit can not be reached. Optical errors, like the fact that parallel rays which are not parallel to the optical axis do not coincide in on single point ("off-axis aberration"), limit the capability to achieve the theoretical concentration limit.

In the analysis of concentrators it is important to distinguish between imaging and non-imaging systems. In imaging designs like the burning glass, telescopes, microscopes or parabolic shaped mirrors all rays leaving from a point of an object and entering into the aperture will be imaged on one single point in the exit aperture independently of their way through the optical systems. That is how an image can be generated. Like the example of a burning glass given above shows, inherent optical errors do not allow imaging systems (with constant refractive properties and a finite number of reflector elements) to achieve the maximum theoretical concentration ratio. For instance the simple and often applied concentrator design of an ideal 3D parabola can only reach one fourth of the theoretical limit.

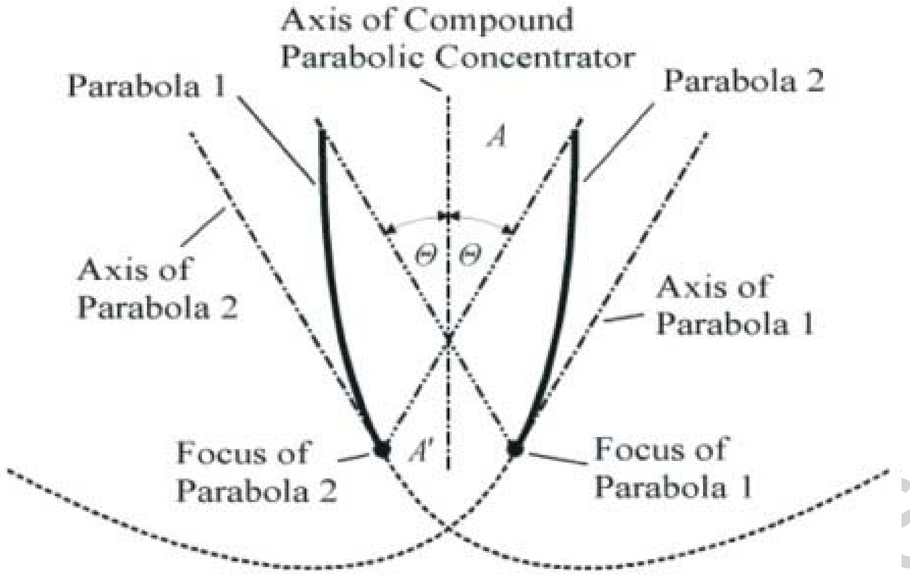

Figure 2: Compound parabolic concentrator (CPC)

Non-imaging systems only require that all rays entering the entrance aperture leave the exit aperture somewhere. It may be not surprising, that the fewer constraints of non-imaging systems lead to a higher flexibility concerning the concentrator design so that higher concentration ratios can be achieved. A simple (but sub-optimal) example is a truncated cone with reflective inner surfaces, where the radiation enters through the larger opening and leaves through the smaller one. A very efficient design of a non-imaging concentrator is a cone with a specific shape forming a segment of a parabola. Such a concentrator is called compound parabolic concentrator (CPC) (see Figure 2**.** This design can approach the theoretical concentration limit very closely. The conservation of the *Etendue* implies that for a given ratio of exit to entrance apertures of the CPC, only rays in a cone with an half angle of

$$\Theta = \arcsin\sqrt{\frac{A'}{A}} \qquad (4)$$

will be accepted by the concentrator.

A stand-alone CPC is not well suited for high temperature solar concentration, because its length needs to be very high compared to its aperture diameter to achieve high concentration ratios. However, the use of a CPC as a 3D terminal concentrator in imaging solar concentrator applications is beneficial, because it boosts the overall concentration ratio of the system by a factor of 2 to 8.

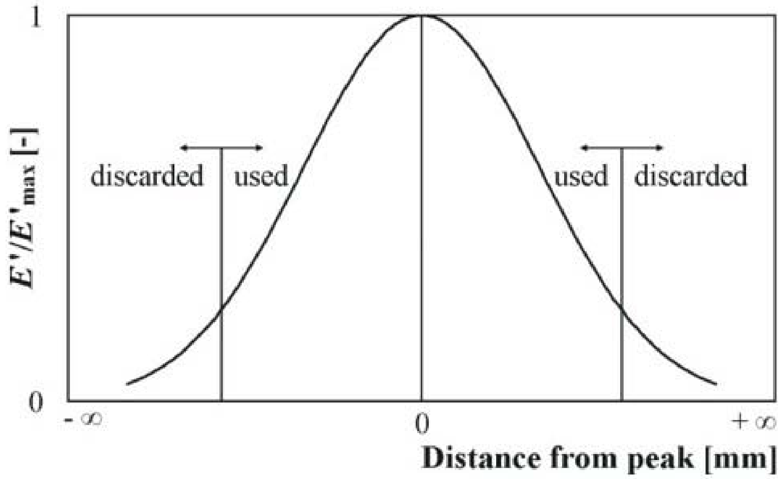

Figure 3: Gaussian distribution showing the relative radiation density (the radiation density E' related to its maximum) as a function of the distance to the center of the peak

In practice, imaging mirror concentrators rather than lens concentrators are applied as primary concentrators for solar high temperature systems, due to their better outdoor durability and lower specific costs. Their design generally approximates the parabolic shape in a continuous or segmented way (see details in the subsequent paragraphs). The image of the sun if generated by such a mirror reflector is blurred by the intrinsic optical imperfections of the imaging parabola concentrator concept (off-axis aberration) and by imperfect surface characteristics. The resulting image, in particular if it consists of superimposed images of individual concentrator segments, can often be well approximated by a Gaussian distribution (see Figure 3). Thus, the energy density at the exit aperture of an imaging concentrator is not constant but varies from a peak value to zero at an infinite distance. For practical applications it makes sense to use only the central part of the Gaussian profile and to discard the rest. The amount of discarded energy is the outcome of an economic optimization process. Typical values range between 2 % and 10 %.

2.2. Conversion of Radiation to Heat

The device that is used in high temperature solar concentrators for the conversion of concentrated solar radiation to heat is called “receiver”. It is designed to absorb the concentrated solar radiation and to transfer as much energy as possible to a heat transfer fluid. Losses originate from the fact, that the absorbing surface may not be completely black, that it emits thermal radiation to the environment, because it has an elevated temperature, and that convection as well as conduction occur. Assuming that the receiver is not protected by a transparent cover the useful heat collected by the receiver Q can be calculated as

$$Q = A_{\mathrm{Ap}} \cdot [\alpha \cdot C \cdot E^{\mathrm{S}} - \varepsilon \cdot \sigma \cdot T_{\mathrm{A}}^{4} - U_{\mathrm{L}} \cdot (T_{\mathrm{A}} - T_{\mathrm{a}})] \qquad (5)$$

with A_{Ap} being the aperture area, α being the average absorptivity of the absorber with respect to the solar spectrum, C the concentration factor, E^{S} the radiation density of the direct solar radiation and ε the average emissivity of the absorber with respect to the black body radiation at the absorber temperature T_{A}. σ stands for the Stefan-Boltzmann constant. U_{L} is the heat loss coefficient due to convection and conduction. Thermal radiation input from the ambient (with the ambient temperature T_{a}) to the receiver is neglected.

Taking into account, that for the heat transfer from the absorber to the heat transfer fluid a temperature difference is required, the following expression also holds for the useful energy:

$$Q = A_{\mathrm{Ab}} \cdot U_{\mathrm{I}} \cdot (T_{\mathrm{A}} - T_{\mathrm{F}}) \tag{6}$$

with U_{I} being the inner heat transfer coefficient from the absorber to the fluid, T_{F} being the average temperature of the heat transfer fluid and A_{Ab} being the absorber area. Using both equations, the energy balance equation can be rewritten replacing the absorber temperature by the fluid temperature:

$$Q = A_{\mathrm{Ap}} \cdot [F \cdot \alpha \cdot C \cdot E^{\mathrm{S}} - F \cdot \varepsilon \cdot \sigma \cdot T_{\mathrm{F}}^4 - F \cdot U_{\mathrm{L}} \cdot (T_{\mathrm{F}} - T_{\mathrm{a}})] \tag{7}$$

with the heat removal factor F, also known from the energy balance of flat plate collectors, that is defined as

$$F = \frac{A_{\mathrm{Ab}} \cdot U_{\mathrm{I}}}{A_{\mathrm{Ab}} \cdot U_{\mathrm{I}} + A_{\mathrm{Ap}} \cdot U_{\mathrm{L}} + A_{\mathrm{Ap}} \cdot 4 \cdot \sigma \cdot T_{\mathrm{F}}^3} \tag{8}$$

The thermal efficiency of the receiver η_{th} is defined by the ratio of the useful heat to the incoming solar radiation in the aperture.

$$\eta_{\mathrm{th}} = \frac{Q}{A_{\mathrm{Ap}} \cdot C \cdot E^{\mathrm{S}}} = F \cdot \alpha - \frac{F \cdot \varepsilon \cdot \sigma \cdot T_{\mathrm{F}}^4}{C \cdot E^{\mathrm{S}}} - \frac{F \cdot U_{\mathrm{L}} \cdot (T_{\mathrm{F}} - T_{\mathrm{a}})}{C \cdot E^{\mathrm{S}}} \tag{9}$$

The efficiency is plotted for several concentration factors in Figure 4 as a function of the fluid temperature T_{F}.

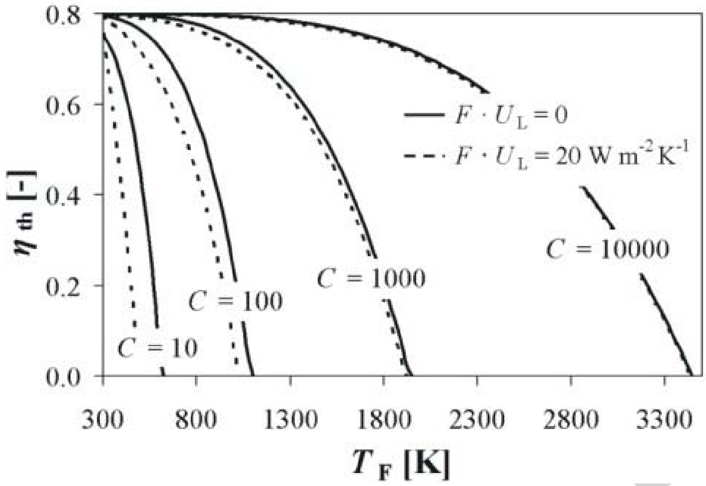

Figure 4: The thermal efficiency of a receiver η_{th} as a function of the fluid temperature T_{F} and the concentration factor C ($F \cdot \alpha = 0.8$, $F \cdot \varepsilon = 0.8$, $E^{\text{S}} = 800$ W m^{-2}, $T_{\text{a}} = 300$ K)

Several messages can be derived from this figure:

- Higher fluid temperatures lead to lower efficiencies
- Higher concentration factors lead to higher efficiencies
- Convection and conduction losses are of minor importance at high concentration factors

Other than for flat plate collectors or parabolic trough receivers the use of transparent covers is not so common in high temperature solar concentrators due to the limited temperature stability and other design constraints of glass covers. In principle it could increase the useful energy gain by a term describing the emission of the hot cover towards the absorber; however, the details of the calculations are complex so that it is referred to the literature (e.g. Winter et al., 1991) here.

Based on Eq. (9), highest efficiencies can be achieved for $\alpha = 1$, $\varepsilon = 0$ and $U_{\text{L}} = 0$. While the latter is of minor importance for high temperature concentrators, the choice of α and ε is crucial. However, an independent and arbitrary selection of both quantities is limited by Kirchhoff's law, which requires that for a specific wavelength λ, the absorptivity equals the emissivity:

$$\alpha(\lambda) = \varepsilon(\lambda) \tag{10}$$

If the solar spectrum and the spectrum of the emitted thermal radiation are sufficiently different the possibility exists, to make use of the strongly wavelength-dependent characteristics of α to achieve high values of the averaged overall absorptivity α and low values for the average emissivity ε.

In order to find the optimal spectral characteristic for a given high temperature concentrator it is helpful to calculate the radiance temperature T as a function of the wavelength λ of both spectra. $T(\lambda)$ is defined as

$$T(\lambda)=\frac{h\cdot c}{k\cdot\lambda\cdot\ln\left(1+\frac{2\cdot\pi\cdot h\cdot c^2}{E_\lambda\cdot\lambda^5}\right)} \qquad (11)$$

where h is the Planck constant, k the Boltzmann constant, c the vacuum light velocity and E_λ the spectral energy density of the radiation. For blackbody radiation the radiance temperature is constant over all wavelengths and equal to the black body temperature.

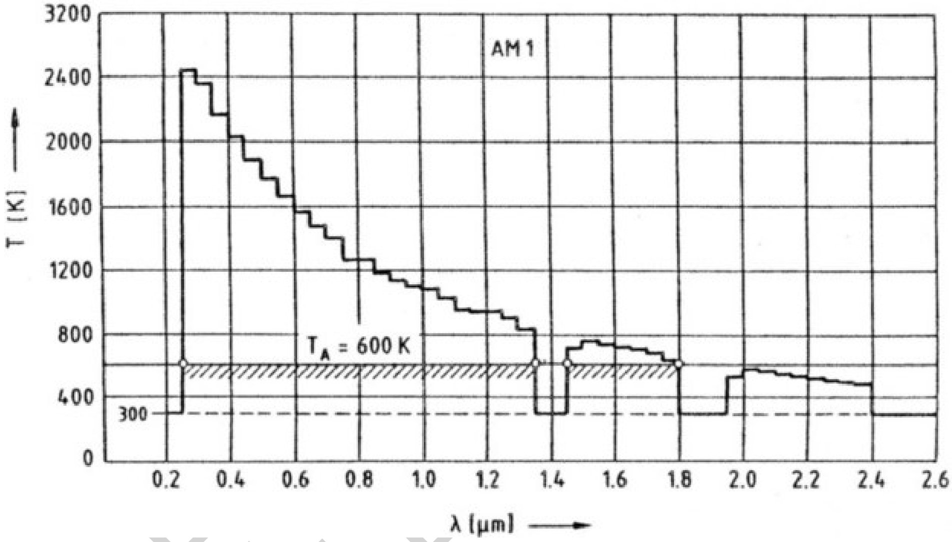

Figure 5: The radiance temperature distribution
(Source: Sizmann et al., 1991. With kind permission of Springer Science and Business Media.)

In Figure 5 the radiance temperature distribution for a real solar spectrum at perpendicular incidence (AM1) is plotted as a function of the wavelength and compared to the radiance temperature of a black absorber at $T_\mathrm{A}=600\,\mathrm{K}$. In the spectral region where the radiance temperature of the solar spectrum is above of that of the absorber, the emission spectrum should be equal to one, since the gain by solar absorption is higher than the loss by thermal emission. In all other regions the situation is vice versa, so that $\alpha(\lambda)=0$ is desirable.

The spectrum generated by a solar concentrator can be approximated by the spectral emissive power of a black body at a temperature of 5700 K multiplied with the dilution factor f taking into account, that the energy density is reduced due to the large distance of the radiation source:

$$f = \frac{C}{C_{\max}} = \frac{C}{46\,200} = C \cdot 2.165 \cdot 10^{-5} \qquad (12)$$

Applying the concept of the radiance temperature to this distribution and comparing it to radiant black body temperature of the absorber lead to the definition of a cut-off wavelength λ_{C} where the absorber's absorptivity should fall from $\alpha(\lambda < \lambda_{\mathrm{C}}) = 1$ to $\alpha(\lambda > \lambda_{\mathrm{C}}) = 0$ to achieve the best performance.

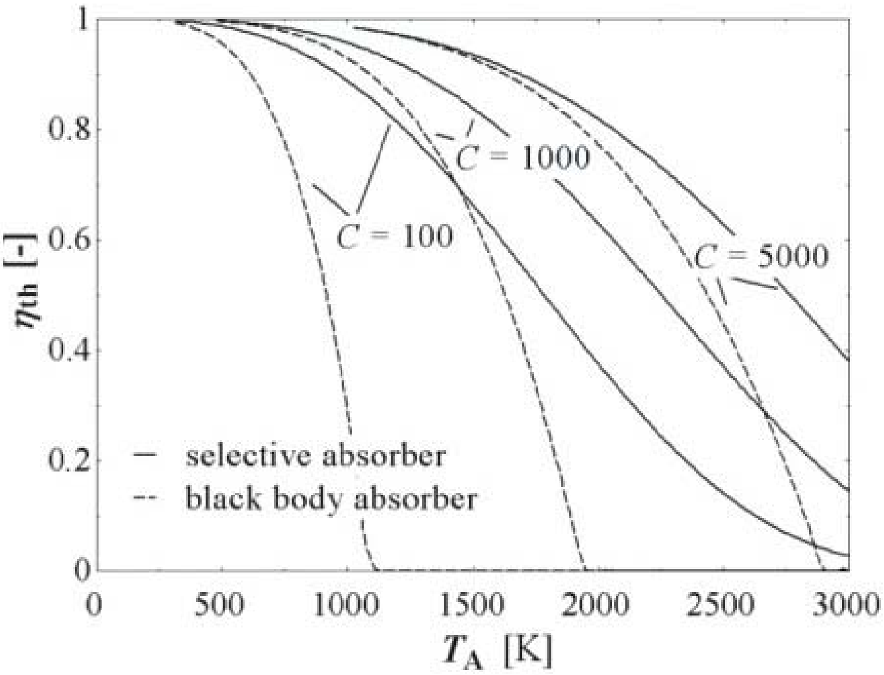

Figure 6: The thermal efficiency of a receiver η_{th} as a function of the absorber temperature T_{A} and the concentration factor C considering the use of a selective absorber and a black body absorber respectively. Convection heat losses are neglected.

Utilizing Figure 6 the efficiency of such a selective absorber can be compared to the efficiency of an ideal black absorber for different concentration factors and as a function of the absorber temperature. Here the convection heat losses are neglected. Based on this figure it can be concluded that selective absorber properties significantly increase the receiver performance, specifically in case of low concentrating systems and high temperatures.

In practice selective coatings are only available up to a temperature of 800 K. High temperature stability in atmospheres containing oxygen is still limited, so that today selective coatings are irrelevant for high temperature solar concentrators.

Finally the impact of the heat removal factor F in Eq. (7) has to be discussed. F should ideally be close to 1. This can only be achieved, if the product of the inner heat transfer coefficient U_{I} and the absorber area in Eq. (8) is an order of magnitude larger than the product of the aperture area with the sum of the convective heat loss coefficient U_L and the radiation loss coefficient $4 \cdot \sigma \cdot T_F^3$. The latter increases drastically with the temperature. That may pose a severe constraint on F for high temperature solar concentrators for the case that the aperture area and the absorber area are the same.

A possible solution is the use of a cavity receiver. The concentrated radiation enters through a small aperture in a thermally insulated cavity. The actual absorbers are distributed on the inner cavity walls so that the aperture area and the absorber area feature different values. While cavities reduce the problem to achieve sufficiently high F-factors, they destroy the option to benefit from a selective absorber characteristic, due to the inherent characteristics of their apertures approximating a black body, independent of their specific inner surface properties.

-
-
-

Bibliography

Grasse W. (1988). Entwurfsgrundlagen für solarthermische Kraftwerke – Ergebnisse und Erfahrungen aus demBetrieb von Experimentalanlagen. In: VDI-Gesellsch. Energietechnik (Ed.). *VDI-Berichte 704 Solarthermische Kraftwerke zur Wärme- und Stromerzeugung*. Düsseldorf, Germany: VDI-Verlag. (page 184, figure 7)[Report about the operation of pilot solar power plants (e. g. Solar One).]

Mancini T., Heller P. (Eds.) (2003). Dish-Stirling Systems: An Overview of Development and Status. *Journal of Solar Energy Engineering* **125**, 135-151.[Review of different dish/Stirling systems including technical and economical details.]

Mancini T. (Ed.) (2000). SolarPACES Technical Report No. III – 1/00. Catalog of Solar Heliostats, 32 pp.[This catalog comprehends an overview about heliostats purchasable in 2000 with detailed information.]

Plataforma Solar de Almería (Ed.) (2004). *Annual Report 2004*, 102 pp. Tabernas, Spain. (page 20, figure 17)[Presentation of PSA with detailed information about the facilities, infrastructures and R&D projects in 2004.]

Romero M., Buck R., Pacheco J.E. (2002). An Update on Solar Central Receiver Systems, Projects and Technologies. *Journal of Solar Energy Engineering* **124**, 98-108.[Review of different Solar Central Receiver projects and plans.]

Sizmann R., with contributions by Köpke P. and Busen R. (1991). Solar Radiation Conversion. In: Winter C.-J., Sizmann R.L., Vant Hull L.L. (Eds.). *Solar Power Plants. Fundamentals, Technology, Systems, Economics*. Berlin, Germany: Springer. (page 50, figure 2.24)[Textbook about solar power plants: this chapter provides information about solar radiation, its conversion to heat or electricity, and its use in photochemical processes.]

Stine W.B., Harrigan R.W. (1985). *Solar Energy Fundamentals and design*, 536 pp. New York: Wiley & Sons.[Textbook about Solar Energy.]

Welford W.T., Winston R. (1978). *The Optics of Nonimaging Concentrators. Light and Solar Energy*, 200pp.San Diego, CA, USA: Academic Press.[Book about non-imaging concentrators (e. g. compound parabolic concentrators) implying basic geometrical optics and applications.]

Winter C.-J., Sizmann R.L., Vant Hull L.L. (Eds.) (1991). *Solar Power Plants. Fundamentals, Technology,Systems, Economics*, 424 pp. Berlin, Germany: Springer.[Comprehensive textbook about solar power plants.]

Biographical Sketch

Prof. Dr.-Ing. Robert Pitz-Paal is head of the Solar Research Unit at the German Aerospace Center (DLR) and Professor for Solar Technology at the Technical University in Aachen. He has been working in the field of concentrating solar systems for more than 15 years. He has served as the Operating Agent for Task III of the SolarPACES (Solar Power and Chemical Energy Systems) implementing agreement of the International Energy Agency and is its Vice Chairman today. He is also member of the editorial board of the ASME Journal of Solar Energy Engineering. His team has been awarded the title “Center of Excellence” in the field of Concentrating Solar Technology by DLR Board of Directors in 2006.