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Extended heat loss and temperature analysis of three linear Fresnel receiver designs

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Abstract

Heat loss prediction models for parabolic trough receivers do not consider the thermal effect of a secondary mirror. As an extension a Thermal Resistance Model (TRM) has been developed at Fraunhofer ISE for the prediction of the heat loss of three different Linear Fresnel Collector (LFC) receiver configurations. In previous investigations we have found the energy balance of a LFC receiver to be strongly influenced by the amount of solar radiation absorbed by the secondary mirror. This absorption provokes an increase of temperature of the secondary mirror and hence a decrease in the total amount of heat loss of a LFC. The size of this effect depends on the receiver geometry and diverse ambient parameters. Investigated parameters are wind velocity, ambient temperature and Direct Normal Irradiance (DNI). This dependency and its effect on heat loss and secondary mirror temperatures are analyzed for three different LFC receiver configurations. As the radiation absorbed by the secondary mirror is affected by the aperture area of the LFC, studies are performed for small-scale and for large-scale collectors.

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Keywords: Linear Fresnel Receiver, Heat Loss, Secondary Mirror Temperatures, Ambient Parameter Study

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Nomenclature

CSP	Concentrated Solar Power
DNI	Direct Normal Irradiation
f_{abs_sec}	Ratio of solar radiation absorbed by the secondary mirror of a LFC
ISE	Fraunhofer Institute for Solar Energy Systems
LFC	Linear Fresnel Collector
PTC	Parabolic Trough Collector
$Q_{abs\_sol\_sec}$	Amount of solar radiation absorbed by the secondary mirror of a LFC
TRM	Thermal Resistance Model developed at Fraunhofer ISE
W_{ap}	Aperture width

1. Introduction

In Concentrated Solar Power (CSP) technology, both optical and thermal performance parameters influence the efficiency of a solar collector. Hence improvements in these parameters contribute significantly to the strengthening of the potential of concentrating collectors. In the field of line-focusing concentrating solar thermal collectors, Linear Fresnel Collectors (LFC), in addition to Parabolic Trough Collectors (PTC), represent an effective technology for the generation of solar power as well as solar process heat. The major difference between these collectors lies in the design of the concentrator optics. Due to intrinsic optical aberrations and the resulting need to improve optical efficiency, a LFC is equipped with a secondary mirror at the receiver. The addition of a secondary mirror contributes to the optical performance, but it also influences the thermal energy balance of the LFC receiver.

Heat loss prediction models for PTC receivers do not consider the thermal effect of a secondary mirror [1]. As an extension a Thermal Resistance Model (TRM) has been developed at Fraunhofer ISE for the prediction of the heat loss of different LFC receiver geometries (see [2]). This model describes the main heat transfer effects in LFC receivers, even though for the single heat transfer coefficients of different heat transport mechanisms, several simplifying approximations are made. In these previous investigations we have found the energy balance of a LFC receiver to be strongly influenced by the amount of solar radiation absorbed by the secondary mirror. This absorption provokes an increase of temperature of the secondary mirror and hence a decrease in the total amount of heat loss of a LFC. This heat loss is defined as the reduction of useful heat transferred to the heat transfer fluid and not as a global heat loss of the receiver to the ambient. The loss mechanism directly connected to the radiation absorbed by the secondary mirror is considered in the optical collector parameters (optical efficiency and Incidence Angle Modifier IAM). The thermal effect of absorbed radiation depends on the receiver geometry and diverse ambient parameters. This dependency and its effect on heat loss and temperatures are analyzed for three different LFC receiver configurations.

2. Methodology

Heat loss and parameter studies are conducted for three exemplary receiver types: (a) an absorber tube with non-evacuated glass envelope, (b) an evacuated absorber tube with secondary mirror and housing and (c) an absorber tube combined with a flat glass cover of the receiver (see Fig. 1).

The solar radiation absorbed by the secondary mirror is influenced by several parameters like the Direct Normal Irradiance (DNI), the reflectance and absorptance of the secondary mirror, the aperture area of the primary mirrors, the sun position etc. To take these relations into account, for fixed geometrical and material parameters of all three receiver configurations, an absorption factor f_{abs_sec} is calculated via ray tracing simulations and integrated in the TRM according to the equation:

$$Q_{abs\_sol\_sec} = f_{abs\_sec} \cdot W_{ap} \cdot DNI \quad (1)$$

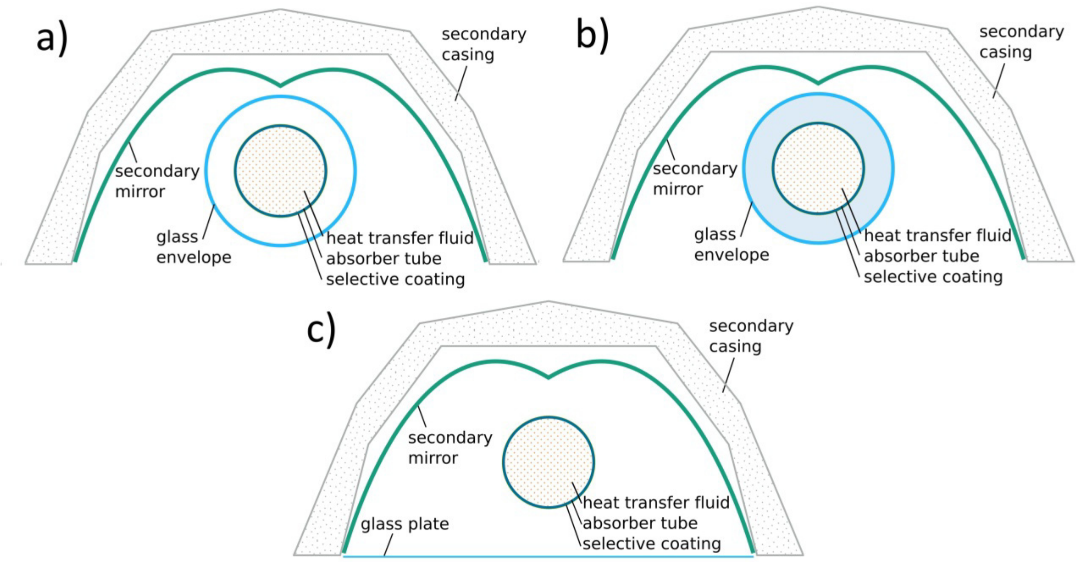

Fig. 1: Sketch of the different LFC receiver configurations analyzed: a) an absorber with non-evacuated glass envelope, b) an evacuated tube absorber and c) an absorber with a flat glass receiver cover (extended sketch based on [2])

The corresponding geometrical and material parameters implemented in these ray tracing simulations are shown in Table 1. Exemplary ray tracing results for small- and large-scale collectors are given in Fig. 2, the configuration used in the simulation is the receiver type with a glass plate cover (receiver 'c' from Fig. 1).The difference in radiation absorbed by the secondary mirror is mainly due to the larger primary field aperture of the large-scale collector. A further reason is that the optical errors are exacerbated in the large-scale setup due to the longer path of reflected light from the primary field.

The heat flux resulting from absorbed radiation is not equally distributed along the secondary mirror. The total short wavelength radiation absorbed $Q_{abs\_sol\_sec}$ is obtained by integrating the heat flux along the secondary mirror surface. Setting DNI equal to 750 W/m² yields $Q_{abs\_sol\_sec}$-values of 240 W/m and 580 W/m (meters of receiver length) for small-scale and large-scale collectors, respectively. $Q_{abs\_sol\_sec}$ is then assumed to be equally distributed along the secondary mirror, leading to an average, homogeneous temperature of the secondary mirror.

This approach allows for an evaluation of the effect of the DNI on the absorbed solar radiation of the secondary mirror, hence on the temperature of the secondary mirror and finally on the heat loss of the LFC receiver. Further parameters included in the parameter study are ambient parameters like wind velocity and ambient temperature.

Table 1: Geometrical and material parameters implemented in ray tracing simulations

	Small-scale collector	Large-scale collector
Number of mirrors	8	16
Width of mirrors	0.8 m	0.8 m
Height of receiver	4.5 m	8 m
Reflectance primary field	0.91	
Reflectance secondary mirror	0.89	
Transmittance of glass (at perpendicular incidence)	0.96	

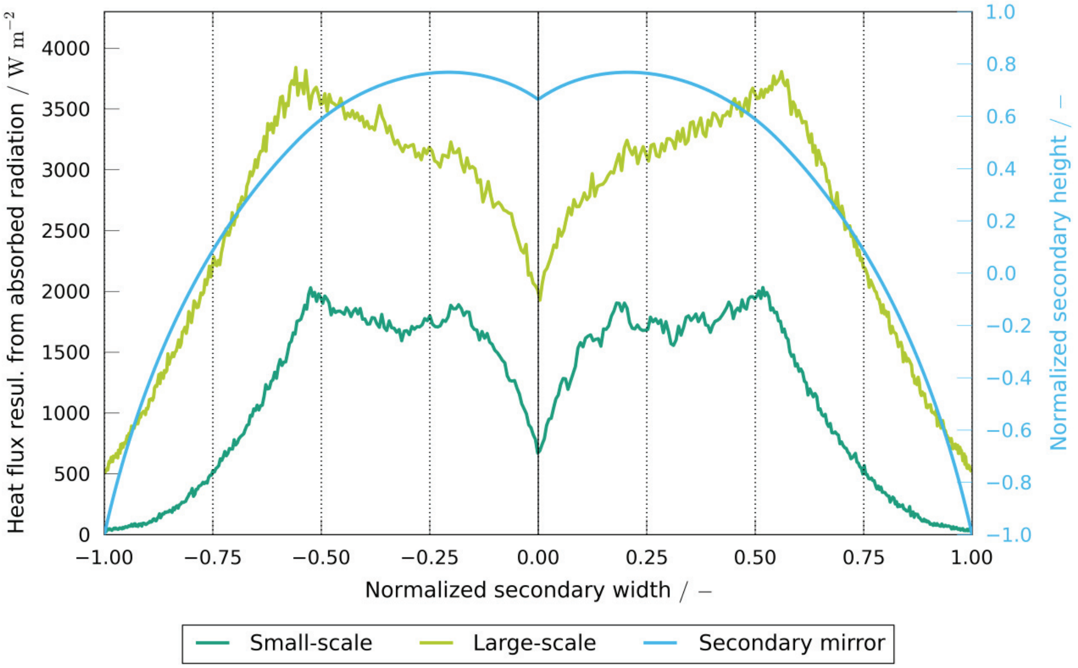

Fig. 2: Results of a ray tracing simulation of radiation absorbed by the secondary mirror for a glass plate receiver configuration. (Left vertical axis) Heat flux resulting from radiation absorbed by the secondary mirror in watts per square metre of secondary mirror area. The light and dark green lines represent resulting heat flux in large- and small-scale collectors, respectively. (Right vertical axis) The light blue line gives the normalized coordinates of the secondary mirror.

3. Results and conclusion

3.1. Analysis under standard operation conditions

To evaluate the effect of the absorbed radiation of the secondary mirror on heat loss for the different receiver configurations, standard operation conditions are selected. Table 2 shows the assumed ambient and operational conditions. As small-scale collectors have a smaller concentration ratio, less radiation is incident on the secondary mirror and hence less radiation absorbed by the secondary mirror. This effect is accounted for by considering a smaller aperture width of the collector as well as analyzing different ranges of working temperatures. Small-scale collectors operate in a range of 100 °C to 250 °C fluid- or absorber temperature, whereas large-scale collectors provide working temperatures typically in a range of 250 °C to 550 °C.

Table 2: Considered standard operation and ambient conditions for the heat loss calculation.

	Small-scale collector	Large-scale collector
DNI	750 W/m²	
Wind velocity	2 m/s	
Ambient temperature	25 °C	
Aperture width	6,4 m	12,8 m
Absorber temperature	100 – 250 °C	250 – 550 °C

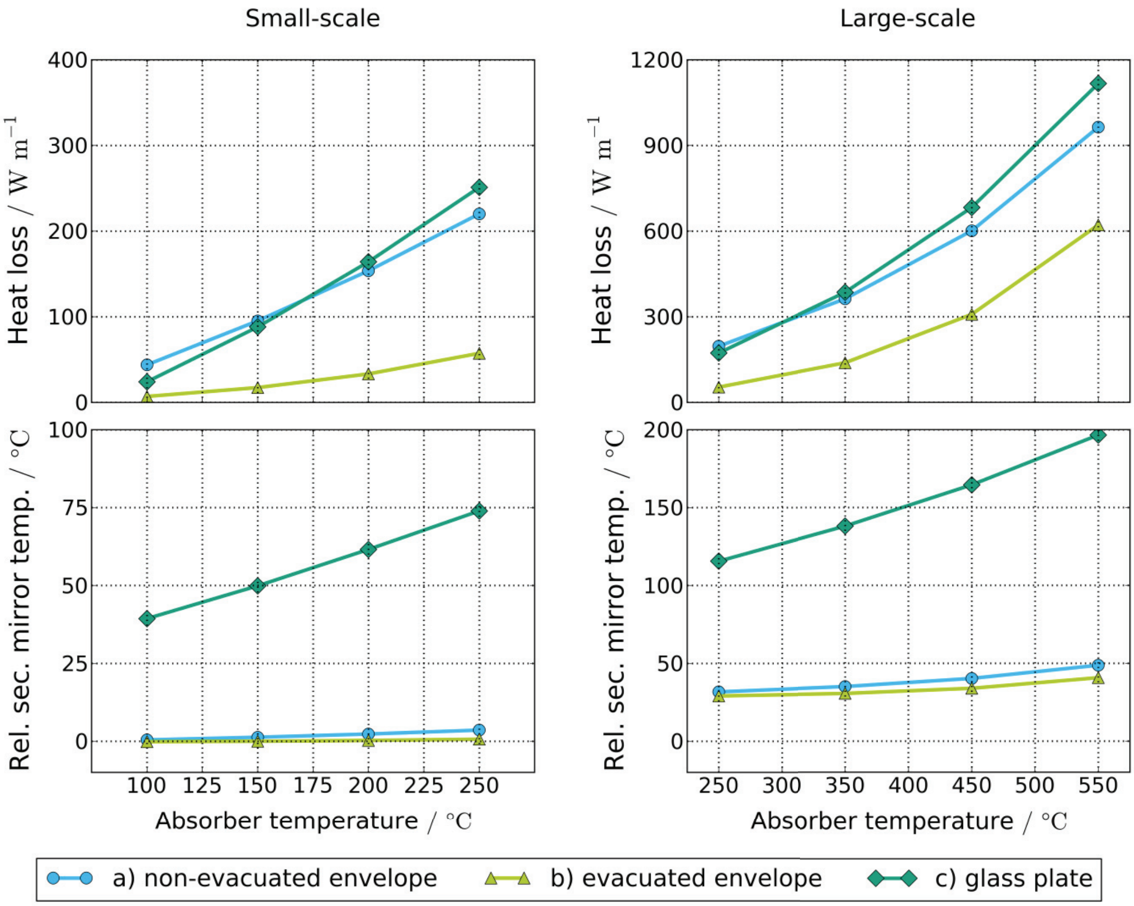

Fig. 3: Heat loss and relative secondary mirror temperatures vs. absorber temperature for small- and large-scale collectors in dependence of three different LFC-receiver configurations. The temperature of the secondary mirror is given as relative increase with respect to the temperature at the lowest absorber temperature investigated (evacuated glass envelope configuration at absorber temperature of 100°C).

Fig. 3 depicts the dependence of heat loss and secondary mirror temperatures on the absorber temperature for the three receiver types. Heat loss is given in watts per meter receiver length. Due to the fact that the TRM contains several simplifying assumptions and absolute temperatures will in any case depend on many details of geometry and materials, the temperature increase with increasing absorber temperature is given as relative increase of mirror temperature with respect to the mirror temperature at the lowest absorber temperature investigated (in this case evacuated glass envelope configuration at absorber temperature of 100°C). It shows that both heat loss and secondary temperatures are lowest for the evacuated glass envelope configuration (light green line with triangles) as expected. The configuration with a non-evacuated glass envelope (light blue line with circles) shows a heat loss similar to that of the configuration of an absorber tube with glass plate cover (dark green line with diamonds). For large-scale collectors, heat loss of the glass plate receiver type is slightly higher for higher working temperatures, whereas in the case of small-scale collectors heat loss can be lower than the one of a non-evacuated glass envelope, especially for lower working temperatures This makes the glass plate receiver configuration a reasonable alternative to the non-evacuated glass envelope receiver.

As direct radiative and convective heat exchange between the absorber and the secondary mirror surface is possible for the glass plate configuration, higher operational fluid temperatures resulting in higher absorber temperatures are heating up the secondary mirror. This heat exchange results in multiple higher secondary mirror temperatures of the glass plate configuration in comparison to the envelope configurations, where direct convective heat exchange between absorber and secondary mirror is not possible (see Fig. 3 lower plots). The most critical increase of secondary mirror temperature occurs for the case of large-scale collectors at higher absorber temperatures, where temperatures become significantly higher as compared to initial values. Furthermore, the possibility of direct radiative and convective heat exchange between secondary mirror and absorber in the glass plate configuration enables a second effect: the optically lost radiation absorbed by the secondary mirror serves as an additional heat source. This leads to lower heat loss of the glass plate configuration in comparison to calculations without considering $Q_{abs\_sol\_sec}$ in a similar range of heat loss occurring in the non-evacuated glass envelope configuration. This fact provides further evidence that the amount of solar radiation absorbed by the secondary mirror cannot be neglected in energy balance calculations with this receiver type.

3.2. Analysis under extreme ambient conditions (worst case study)

The higher secondary temperatures of a glass plate receiver configuration have to be considered when choosing secondary mirror materials, as they have to withstand these temperature conditions. As a material selection does not only depend on standard conditions, but also on possible extreme conditions, a further temperature analysis for a worst case ambient scenario is conducted. Table 3 shows the ambient conditions for this worst-case study. Fig. 4 illustrates the secondary temperatures for these extreme ambient conditions.

It shows that in this particular example for small-scale collectors, the secondary mirror material has to withstand temperatures up to 150°C. For large-scale collectors, secondary mirror temperatures can even reach up to around 300°C. As explained above, the modeling simplifies the radiation absorbed by the secondary mirror, considering it as uniformly distributed along the surface. The simplification results in constant temperature contributions. As shown in Fig. 2, in reality there are zones under high heat flux, and consequently these zones may be subjected to even higher temperatures. The temperature values derived here may still serve as indicating reference for secondary mirror material selection. Materials typically selected for the secondary mirror are anodized aluminum or silvered glass. Anodized aluminum withstands temperatures up to 300°C [3], whereas silvered glass withstands temperatures up to 400°C [4]. It is not expected that the reflecting properties of anodized aluminum will suffer from degradation in small-scale collectors. However in large-scale collectors - depending on the conditions and model parameters (and the receiver specifics of a real receiver) - the maximum temperatures may reach or even exceed allowed operating temperature of mirror materials recommended by the manufacturer. In this case, the secondary mirror material has to be properly selected in order to ensure good operational conditions during the expected life of the collector.

For both, temperature levels and absolute numbers of heat loss depicted above and below, it should be noted that all calculations were performed using a simplifying model with specific parameter and geometry assumptions. Actual heat loss values and temperatures arising in a real LFC receiver will always strongly depend on many specifics of a particular LFC design as well as on the materials chosen and specific site conditions, and should be investigated in more detail for each specific 'real' collector.

Table 3: Considered extreme ambient conditions for worst case analysis of secondary temperatures.

	Small- / large-scale collector
DNI	1000 W/m²
Wind velocity	0 m/s
Ambient temperature	40 °C

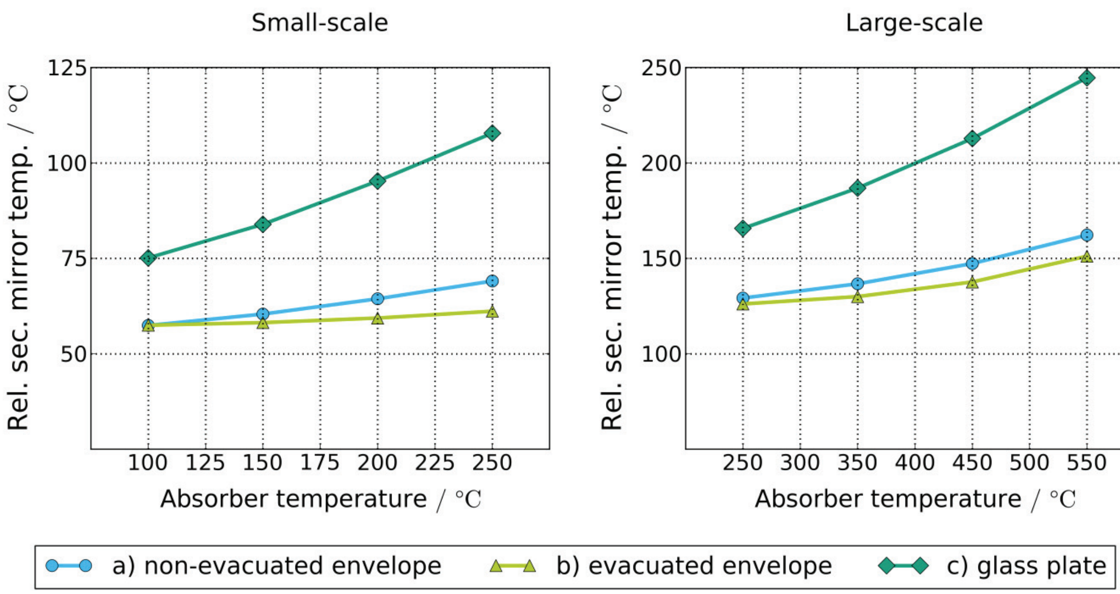

Fig. 4: Worst case study of relative secondary mirror temperatures vs. absorber temperature for small- and large-scale collectors in dependence of three different LFC-receiver configurations. The temperatures are given as relative increase with respect to the temperature at the lowest absorber temperature investigated and plotted in Fig.3. The secondary mirror temperatures are significantly higher as compared to the standard operating conditions.

3.3. Analysis for varying ambient conditions

While analyzing heat loss for different receiver configurations, various ambient parameters have to be considered. As such parameters vary continuously during collector operation, the effect of these variations on the heat loss of the different configurations is studied. To cope with the differences in operational conditions between small-scale collectors versus large-scale collectors, the ambient parameter study has been performed at different absorber temperatures. For small-scale collectors a standard operation temperature of 200 °C is assumed, while for large-scale collectors the absorber temperature is set to 500 °C.

3.3.1. Varying wind velocity

Wind velocity varies in a range from 0 m/s to 5 m/s. Results for heat loss versus wind velocity are plotted in Fig. 5. The TRM considers thermal effects of wind in a simplified way. Therefore, the results represent, to a certain degree, the model which is implemented in the TRM and are indicative only as far as absolute values are concerned. Yet, the dominating effects can be identified and investigated. The graphs show that the heat loss of an evacuated glass envelope configuration is only slightly affected by the wind, as expected. In this geometry, the heat loss is dominated and limited by the radiative heat exchange between absorber and envelope. Heat loss of the glass plate configuration shows a notable dependency on the wind, but the non-evacuated glass envelope receiver is affected the most by the wind velocity. Under high wind conditions, the heat loss of the non-evacuated glass envelope configuration may even exceed heat loss of the glass plate configuration. The wind dependency, when viewed relative to heat loss, is more significant for small-scale collectors than for large-scale collectors.

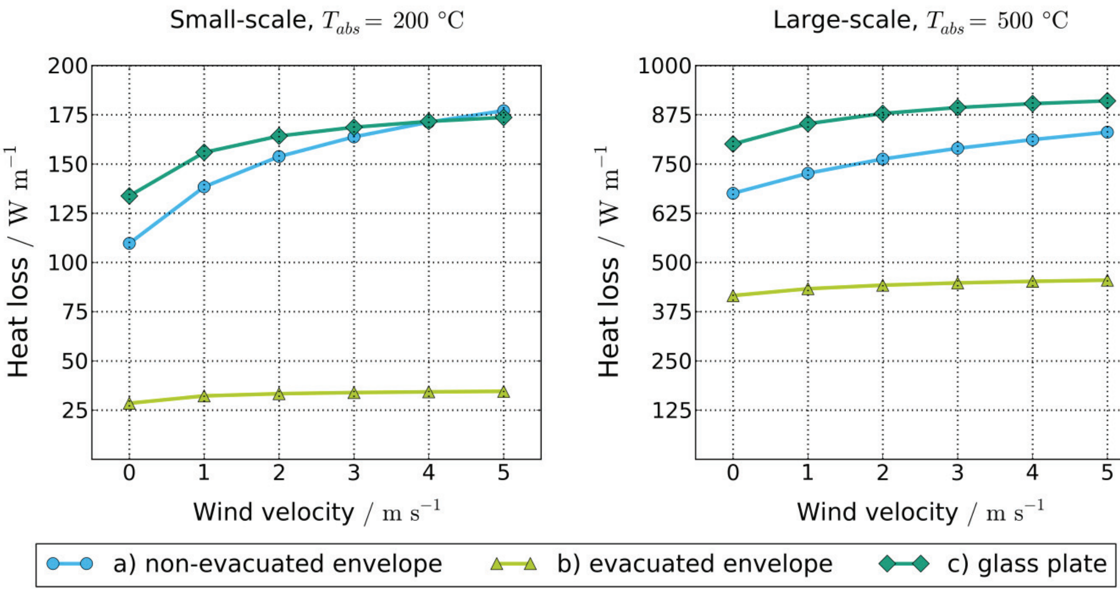

Fig. 5: Influence of wind velocity on the heat loss of three different LFC-receiver configurations for small- and large-scale collectors.

3.3.2. Varying DNI

The results of the heat loss analysis for standard operation conditions in Section 3.1 have shown that the radiation absorbed by the secondary mirror has a significant effect in the glass plate configuration. As the amount of absorbed radiation depends on the incident radiation, varying DNI is studied. Results are presented in Fig. 6. They show the expected effect that the heat loss decreases with increasing DNI for a glass plate receiver. This effect is equally dominant in small-scale as in large-scale collectors. Fig. 6 also indicates, that the receiver configuration with an evacuated glass envelope is hardly affected by the DNI, in agreement with results from the standard operational conditions analysis, as there is no direct heat exchange between absorber tube and secondary mirror. Hence the absorbed radiation does not affect heat loss significantly for this configuration. For the non-evacuated glass envelope receiver a small dependency of the heat loss on the DNI is determined.

3.3.3. Varying ambient temperature

Heat loss is analyzed in dependence on the ambient temperature in a range between 10 °C to 45 °C; results are illustrated in Fig. 7. The graphs show that the heat loss of the evacuated glass envelope receiver is again hardly affected by a change in ambient temperature, for both small- and large-scale collectors. For the non-evacuated glass envelope and the glass plate receiver types, heat loss decreases with increasing ambient temperature. This effect is more significant for small-scale collectors than for large-scale collectors.

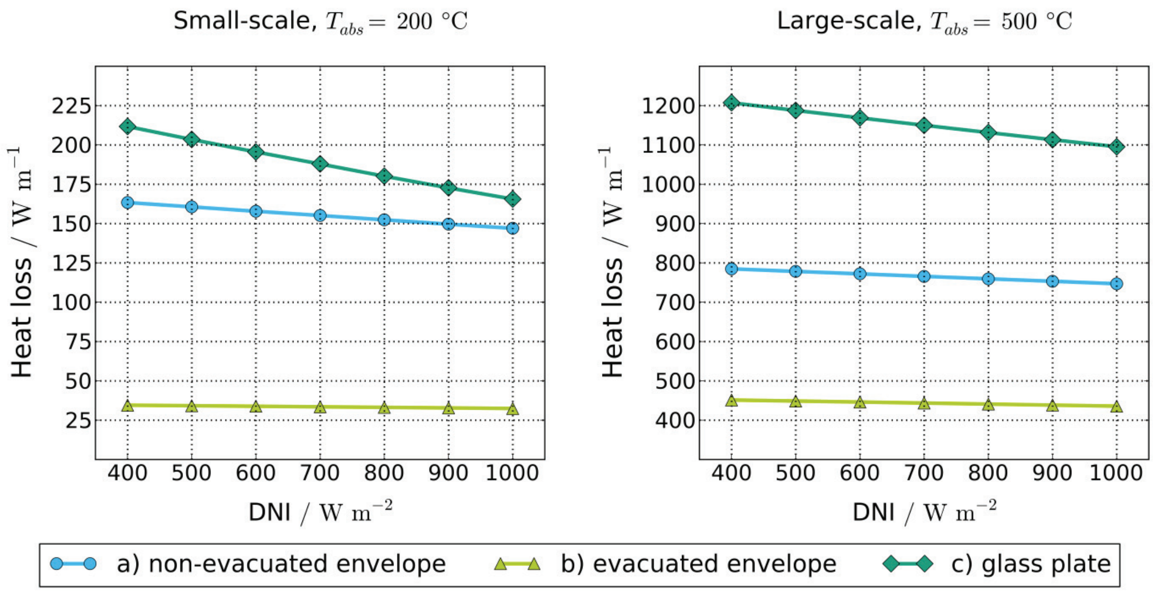

Fig. 6: Influence of Direct Normal Irradiation on the heat loss of three different LFC-receiver configurations for small- and large-scale collectors.

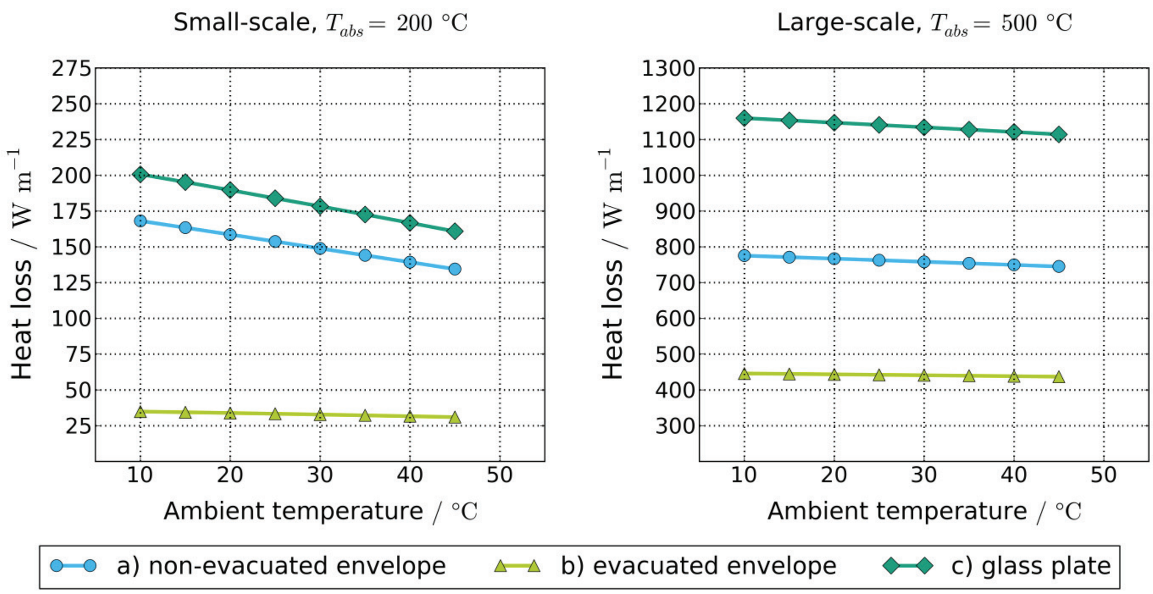

Fig. 7: Influence of ambient temperature on the heat loss of three different LFC-receiver configurations for small- and large-scale collectors.

4. Summary and outlook

In the present publication, a comprehensive heat loss and temperature analysis of three different LFC receiver types is performed, considering the thermal effect of a secondary mirror and including solar radiation absorbed by the non-ideal secondary mirror in the energy balance. For standard operation conditions, the heat loss of the glass plate configuration is similar to the non-evacuated envelope receiver, making it a considerable alternative in the choice of a LFC receiver design. As a consequence of the absorption of solar radiation, higher temperatures of the secondary mirror have to be noted particularly for the glass plate receiver type in large-scale collectors. A worst-case ambient scenario for the secondary mirror temperature shows that temperatures may reach values close to or even may exceed temperature limits for operational temperatures of materials, depending on the particular geometry and parameter details. This effect has to be thoroughly considered in the material selection of the secondary mirror and receiver design.

A parameter study of ambient parameters indicated, that the ambient parameters have a marginal effect on the heat loss of an evacuated glass envelope receiver. In contrast, the LFC configuration with a non-evacuated glass envelope showed a high dependency on the wind velocity, leading to a similar heat loss as the glass plate receiver type. At high wind velocities for the non-evacuated glass envelope even higher heat loss may occur in a small-scale collector. A variation of ambient temperature showed little effect on the receiver geometries without vacuum. The impact of variations in DNI on heat loss proved to be most significant in the glass plate configuration. This relation provides further evidence that the amount of solar radiation absorbed by the secondary mirror cannot be neglected in energy balance calculations with this receiver type in any attempt to correctly describe or predict heat loss and resulting material temperatures.

The results presented here are obtained from a thermal resistance model (TRM) containing several simplifying assumptions and results have been calculated for specific geometries and input parameters. Therefore, all absolute values given are indicative only, but still allowing to investigate and to show the relevant effects. Yet, for a given 'real' collector, detailed investigations should be made to obtain reliable results also in terms of absolute numbers.

While interpreting the results of the presented parameter study, recall that they represent individual parameter studies, i.e. that each parameter was analyzed while holding the others constant. Therefore interactions between parameters were not considered. Such interactions are accounted for in a global sensitivity analysis, that is currently implemented at Fraunhofer ISE and is an object of current research. Results of a global sensitivity analysis as an enhancement of the present parameter study will be published in the near future to indicate interactions effects, especially of ambient parameters. Their influence on heat loss correlations, which are used to parametrically describe heat loss in collector performance evaluations or yield simulations, will also be presented in upcoming publications.

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