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Hydrothermal model for small-scale linear Fresnel absorbers with non-uniform stepwise solar distribution

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HIGHLIGHTS

- Model for hydrothermal behaviour of the working fluid in a Linear Fresnel Collector.
- Stepwise distribution of the solar flux along the absorber axis was considered.
- Experimental data of different prototypes were used for model validation.
- Low and medium-high mass flow situations were simulated with good results.
- A parametric study was conducted to evaluate the performance of small scale LFCs.

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ABSTRACT

The study of the hydrothermal behaviour of water-steam is a key topic in direct steam generation through solar concentrators. The hydrothermal behaviour is affected by the non-uniformity in the solar flux distribution along the axis of the linear absorber. The non-uniformity produces non-illuminated regions at the absorber ends (especially in small Linear Fresnel Collector prototypes or in non-rectangular configurations of Fresnel systems), and partially illuminated regions due to the gradual contribution of the mirror rows to the reflected solar radiation in the absorber. The aim of this paper is to present a new general hydrothermal model for linear absorbers that accounts for this non-uniformity and allows simulating Linear Fresnel systems of any size, mirror field geometry, and working conditions. The present model considers both, one phase flow—for heating/cooling of the liquid or the superheated steam—and two-phase flow—for describing boiling or condensation mechanisms—using a homogeneous mix model. The model was validated against experimental data from prototypes under different working conditions. Infrared thermography was used to measure the absorber temperature profile. A good agreement between experimental and predicted datasets was found, which confirmed the reliability of the model.

1. Introduction

Linear solar concentration is a viable and cost-effective technology with a promising future. It is characterized by a linear absorber in which the working fluid – water or synthetic oil – is heated at high temperatures by the concentrated solar radiation. If the working fluid is water, steam can be directly generated in the absorber without the need of using costly intermediate heat exchangers. Depending on the reflector field and absorber geometry, two types are commonly developed by industry: parabolic trough (PTC) and Linear Fresnel (LFC). Both have been extensively studied and characterized, with special interest devoted to large-scale systems for on-grid electricity generation [1–6]. On the opposite, studies on small-scale concentrating systems – which provide heat outputs in the range of 150–300 °C are scarce. These systems have promissory applications in combined heat and power generation [7], water desalination [8], heating/cooling of buildings [9–10], advanced absorption air cooling using Solar-GAX cycle [11], domestic water heating [12–13], steam generation for mining, and also in textile, paper and chemical industries, timber, food, and agriculture [14–15]. In the last decade, in Europe about 27% of the overall final energy requirement is accounted for by industrial process heat, and about 30% of this requirement occurs at temperatures below 100 °C and a further 27% occurs in a range between 100 and 400 °C [16]. This consumption could be partially covered by small-concentrating solar systems thus reducing the consumption of fossil fuels and the emission of greenhouse gases to the environment. The great potential of this

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Nomenclature

A	cross sectional area of tube (m^2)
d_i	inner diameter of tube (m)
d_o	outer diameter of tube (m)
D	horizontal distance between a mirror centerline and the solar absorber line projected on the aperture plane (m)
DNI	Direct Normal Irradiance (W/m^2)
e	total energy (J/kg)
F_c	cleaning factor of mirrors
F_W	shading factor on mirror' surfaces caused by the absorber cavity
h	enthalpy (J/kg)
h_c	convective heat transfer ($W/m^2\,K$)
H	absorber height (m)
k_w	thermal conductivity of tube (W/m K)
L	absorber length (m)
L_{ext}	extra length of absorber (m)
L_m	mirrors length (m)
$\dot{m}$	mass flow rate (kg/s)
N_m	number of mirrors
N_t	number of tubes
Nu	Nusselt number
p	pressure (Pa)
P	perimeter of pipes (m)
Pr	Prandtl number
P_{th}	thermal power (kW)
Q''	heat flux rate (W/m^2)
Re_D	Reynolds number
T	temperature (°C)
u	velocity (m/s)
U_L	overall heat loss coefficient ($W/m^2\,K$)
v	specific volume (m^3/kg)
v_w	wind velocity (m/s)
W_m	mirror width (m)
x	steam quality
y	direction across absorber tubes
z	direction along tubes

Greek symbols

α	absorptance of the absorber tubes
θ	incidence angle (°)
θ_z	zenital angle (°)
γ	azimuth of surface (°)
γ_s	sun azimuth (°)
β	surface tilt (°)
η_{th}	thermal efficiency
τ	transmittance of glass cover
ρ	fluid density (kg/m^3)
ρ_m	reflectance of mirrors
ϕ_{tp}^2	two phase multiplier
τ_w	shear stress (N/m^2)

Subscripts

abs	absorbed by the fluid
amb	ambient
f	fluid
g	vapour phase
i	corresponding to *i*-mirror
in	input
l	liquid phase
lo	liquid only
loss	loss
out	output
TP	two phase
w,o	external wall of tube

technology was highlighted by Rawlins and Ashcroft [17] who predict a growth of small-scale systems for industrial processes of about 2.5 (globally) and 4.6 (in Latin America and Africa), from now to 2050. The large variety of possible applications of small systems is promissory, but further research is needed in order to characterize their thermodynamic and energy behaviour.

In comparison with large LFC systems, small-scale ones must face two main issues that affect their energy performance: the non-uniformity of solar flux reaching the absorber and the lower flow of the working fluid. The main source of non-uniformity of solar flux along the absorber length -not very significant in large systems but crucial in small ones- is the optical end loss, which can account for as much as 33% of the total optical loss [18–19]. It is caused by "shaded" zones at the ends of the absorber that are produced by the position of the sun in the sky for given latitude, day and hour. In these zones and depending on the fluid conditions, a not-desired condensation process could start in short absorbers, which is very unlikely to occur in large ones. Besides, small systems are generally built with components with lower costs, including those in the reflector field, which decrease the optical performance of the system in terms of reflectivity and shape accuracy [7]. Thus, the use of common non-white flat mirrors -manually curved to obtain a quasi parabolic profile- usually produces a slight "deformation" of the reflected sun ray that causes a meandering line on the absorber and contributes to the non-uniform distribution of the solar radiation. Thereby, all the mentioned effects cause non-uniform solar radiation to reach the different points of the absorber. These local inhomogeneities can lead to instability in the operating conditions and even to damage of the absorber material. Finally, the second issue to be investigated in short LFC systems is related to the working conditions. While in large absorbers -mostly designed for electricity generation- the vapour flow is high, in short ones the vapour/water flow is generally lower. Whereas experimental data found in the literature cover high flow conditions, the available data for low flow and with the associated phase change is very limited. Moreover, experimental data on the temperature profile along the absorber length was not found in the literature. Both issues are addressed in this paper.

The axial non-uniformity in solar flux distribution in LFC absorbers was studied by several authors who investigated both, the optical end losses [19–22] and the anomalies caused by the mirrors optical behaviour. For example, Barbón et al. [14] studied through numerical simulation the influence of geometrical parameters (receiver height and mirror dimensions) on the end losses and on the energy absorbed by a small-scale LFC. A decrease of 59% in the absorbed energy was found for a decrease of 30% in the mirror width for a small-scale system for building applications in Spain. Hongn et al. [22–23] proposed a simplified least square fitting expression that estimates the average annual end loss for any latitude – between 0° and ± 40° – and for any LFC azimuth. The integration of the optical performance and fluid thermodynamics is a step forward in LFC simulations, for which two groups of thermodynamic models are used depending on the uniformity of the solar flux distribution. For uniform flux, 1-D homogeneous and heterogeneous models are mostly used. For non uniform solar flux, time consuming 3-D ray tracing methods are coupled to simplified homogeneous thermodynamic models. Thus, pioneering work was made in Australia by Reynolds et al. [24], who proposed a hydrodynamic homogeneous model for uniform solar flux to determine one and two