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Modeling and design guidelines for direct steam generation solar receivers

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HIGHLIGHTS

- A computational model for solar receiver for direct steam generation is developed.
- Experiments are conducted and used to validate the model.
- Practical designs, operational conditions and material choices are investigated.
- Model provides design tool for direct steam generation solar cavity receivers.

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ABSTRACT

Concentrated solar energy is an ideal energy source for high-temperature energy conversion processes such as concentrated solar power generation, solar thermochemical fuel production, and solar driven high-temperature electrolysis. Indirectly irradiated solar receiver designs utilizing tubular absorbers enclosed by a cavity are possible candidates for direct steam generation, allowing for design flexibility and high efficiency. We developed a coupled heat and mass transfer model of cavity receivers with tubular absorbers to guide the design of solar-driven direct steam generation. The numerical model consisted of a detailed 1D two-phase flow model of the absorber tubes coupled to a 3D heat transfer model of the cavity receiver. The absorber tube model simulated the flow boiling phenomena inside the tubes by solving 1D continuity, momentum, and energy conservation equations based on a control volume formulation. The Thome-El Hajal flow pattern maps were used to predict liquid-gas distributions in the tubular cross-sections, and heat transfer coefficients and pressure drop along the tubes. The heat transfer coefficient and fluid temperature of the absorber tubes' inner surfaces were then extrapolated to the circumferential of the tube and used in the 3D cavity receiver model. The 3D steady state model of the cavity receiver coupled radiative, convective, and conductive heat transfer. The complete model was validated with experimental data and used to analyze different receiver types and designs made of different materials and exposed to various operational conditions. The proposed numerical model and the obtained results provide an engineering design tool for cavity receivers with tubular absorbers (in terms of tube shapes, tube diameter, and water-cooled front), support the choice of best-performant operation (in terms of radiative flux, mass flow rate, and pressure), and aid in the choice of the component materials. The model allows for an in-depth understanding of the coupled heat and mass transfer in the solar receiver for direct steam generation and can be exploited to quantify the optimization potential of such solar receivers.

1. Introduction

Concentrated solar technologies offer promising opportunities for efficient solar-driven power generation systems (e.g., concentrated solar power (CSP) [1–5], solar thermochemical fuel production (STFP) [6–10], or solar driven high-temperature electrolysis (SHTE) [11]). The solar receiver is a key component in these applications converting solar energy efficiently into thermal energy. Numerical models offer an effective pathway for the characterization and quantification of the optical, thermal, and fluid flow behavior of receivers [12–18]. When steam is used as the working fluid (CSP application) or as the reactant in high-temperature systems (STEP and SHTE applications), the understanding of the complex two-phase flow boiling process inside the absorber tubes of the direct steam generation receiver is important for identifying local hot spots, and designing and predicting receiver performance. The modeling approach for the coupled heat transfer and fluid flow problem in direct steam generation solar receivers can be inspired by the design of conventional steam generators or evaporators

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Nomenclature

Latin symbols

A	area (m^2)
a	thermal diffusivity (m^2/s)
c_p	heat capacity (W/kg/K)
d	diameter (m)
E	two-phase convection multiplier
F	view factor
Fr	Froude number
f	friction factor
g	acceleration of gravity (m/s^2)
H	height (m)
h	heat transfer coefficient ($W/m^2/K$)
$\bar{h}$	averaged heat transfer coefficient ($W/m^2/K$)
h_g	enthalpy for gas (kJ/kg/K)
h_{lg}	latent heat (kJ/kg)
h_l	enthalpy for liquid (kJ/kg/K)
J	radiosity (W)
k	thermal conductivity (W/m/K)
L	length (m)
$\dot{m}$	mass flow rate (kg/s)
$\dot{m}''$	mass flux ($kg/m^2/s$)
Nu	Nusselt number
P	tube perimeter (m)
Pr	Prandtl number
p	pressure (Pa)
p_r	reduced pressure
$\dot{Q}$	heat rate (W)
q'''	heat sink (W/m^3)
q_w	heat flux (W/m^2)
Ra	Rayleigh number
r_{ij}	distance (m)
r_{turn}	helical turning radius (m)
S	boiling suppression factor
T	temperature (K)
$\bar{T}$	averaged temperature (K)
t_{wall}	thin wall thickness (m)
v	velocity (m/s)
We	Weber number
x_g	vapor quality

Greek

β	thermal expansion coefficient (1/K)
δ	standard deviation (m)
δ_{ij}	visibility
δ_{lf}	liquid film thickness (m)
ε_g	void fraction
ν	kinematic viscosity (m^2/s)
ξ_{ph}	liquid-vapor interfacial friction factor
ρ	density (kg/m^3)
σ	Stefan-Boltzmann constant ($5.67e^8$ $W/m^2/K$)
σ_t	surface tension (N/m)
η_{STT}	solar-to-thermal efficiency
θ	tube inclination angle (rad)
θ_{dry}	dry angle (rad)
θ_{strat}	stratified angle (rad)
μ	dynamic viscosity (Pa s)
τ_w	shear stress (Pa)
φ	receiver tilt angle (rad)

Subscripts

amb	ambient
ap	aperture
cb	convective boiling
cav	cavity
cond	conduction
conv	convection
crit	critical value
DNB	departure from nucleate boiling
dry	dry-out
g	gas phase
in	inner
IA	intermittent flow to annular flow
i, j	location index
insu	insulation material
l	liquid phase
max	maximum value
min	minimum value
mist	mist flow
nb	nucleate boiling
nc	natural convection
rerad	reradiation
strat	stratified flow
wavy	stratified-wavy flow

in coal-fired boiler power plants [19,20], pressurized water reactors (PWR) in nuclear power plants [21–23], and vapor-compression refrigeration system [24,25]. The development of a full 3D mechanistic model of the flow boiling process is challenging [26] due to the complex nature of the processes involved (activation of nucleation sites, bubble dynamics, and interfacial heat transfers) and the computational needs required for the solution of the direct numerical problem, which incorporates a large number of bubbles and surfaces with complex geometries [27,28]. To overcome this challenge, semi-mechanistic approaches are proposed [29–34]. For example, Kurul and Podowski developed a 3D model which couples an Euler-Euler two-phase flow model (for bulk fluid flow) with a wall boiling model. The wall boiling model partitioned the heat flux between the tube wall and the fluid into three parts: liquid phase convective heat flux, quenching heat flux, and evaporation heat flux (wall boiling phenomena), predicting each heat flux by empirical and mechanistic correlations. Due to the numerical instability and large computational cost of the wall boiling model, a bulk boiling model was used instead and coupled with an Euler-Euler two-phase flow model in the modeling of a PWR nuclear steam generator [21]. The bulk boiling model agreed well with the experimental data. In the engineering design of evaporators and steam generators, the wall-fluid heat transfer is more important in determining the thermal performance than the detailed in-tube liquid-vapor interfacial heat and mass transfer. Hence less computationally expensive 1D two-fluid (separated or homogeneous) two-phase flow models with empirical correlations (single equation correlations [35,36] and flow pattern based correlations [37,38]) for the wall-fluid heat transfer coefficients are commonly employed [39–41] without resolving the local non-uniformity of the wall-liquid heat transfer. An obvious disadvantage of a simplified 1D two-phase model with empirical correlations is that the local heat transfer and temperature distribution cannot be accurately captured. However, this might be extremely important for the determination of the critical point. Oliet et al. [24] proposed an integrated model for a fin-and-tube evaporator by linking a fin-and-tube