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A model of a solar cavity receiver with coiled tubes

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ABSTRACT

A model of a solar cavity receiver using helically coiled tubes as heat absorber is developed. The receiver geometry of the model mimics that of an experiment for a Cross Linear concentrating system, although the model has a potential for application to the same type of receivers. From solar flux distribution incident on the inner walls of the receiver, which is obtained from optical simulation, absorbed flux distribution is derived. Ignoring the convective heat loss from the cavity, temperature distribution of the heat transfer fluid and the coiled tubes in the steady state is calculated. The outlet temperature, the maximum temperature of the coiled tubes, the pressure drop, the heat losses, the receiver efficiency and the pumping power required for compressing the heat transfer fluid (air in this work) are assessed. The efficiency decreases when the receiver temperature is high or when the total incident energy is small for the receiver temperature. The conductive heat loss through insulators around the coiled tubes is negligible among the total incident energy for the present receiver configuration. The pumping power demand is sufficiently small compared with the expected electric power output. Finally, the absorptivity of the ceiling of the receiver could scarcely influence the outlet temperature as long as the difference of the absorptivity between visible and infrared light of the coiled tubes and the conductive heat loss are negligible.

1. Introduction

Solar thermal energy is one of the most promising energy resources among renewable energy. In order to utilize solar thermal energy, concentrating and collecting systems are important. At the concentrating system, solar light is highly concentrated by plane or concave mirrors. Then, the concentrated light is converted into heat at the collecting system. Here, receivers are addressed as the collecting system, where the collected heat is extracted through a thermal medium or a heat transfer fluid. In most of the existing solar thermal power plants, molten salt, synthetic oil or steam is utilized as the heat transfer fluid in the receiver (Behar et al., 2013). However, nowadays air is being recognized as an option for the heat transfer fluid of high temperature receivers because of chemical stability, availability and no toxicity (Bader et al., 2010; Ávila-Marín, 2011). In order to get solar thermal energy with high efficiency, development of highly efficient receivers is expected.

Cavity receivers are considered to be highly efficient receivers, where heat loss is suppressed by insulating their surfaces except an aperture, and the heat transfer efficiency to the thermal medium can become higher. Its principle consists in high probability reabsorption of radiation until escaping through the aperture. Since the radiative heat loss decreases as the aperture becomes narrower, cavity receivers are effective for highly solar concentrating systems, such as point-focusing systems (e.g., dishes and towers) (Bader et al., 2010).

In this study, a helically coiled tube is addressed as heat absorber in a cavity receiver because of its interesting feature: the centrifugal force acting on a fluid flowing within a coiled tube induces a pair of counter-rotating vortices on the cross-section perpendicular to the mainstream, which is known as Dean effect (Dean, 1928). These vortices enhance the heat transfer between the fluid and the coiled tube, and moreover have a stabilizing effect on the flow, which keeps the pressure drop of the fluid small. For this reason, a heat exchanger exploiting helically coiled tubes has previously existed, which is applied to our solar thermal receiver. In the last decade, solar cavity receivers using helically coiled tubes as heat absorber have been intensively investigated by numerous authors (Prakash et al., 2009; Wang et al., 2013; Prakash, 2014; Good et al., 2015; Qiu et al., 2015; Zhu et al., 2015; Wang et al., 2015; Daabo et al., 2016; Loni et al., 2016a; Daabo et al., 2017). Some variants of the absorber tube for a solar cavity receiver have been also presented: Neber and Lee (2012) used a helically coiled square duct, while Le Roux et al. (2014, 2016b,c) studied a rectangular cavity-shaped coiled tube.

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Nomenclature

Latin characters

A	outer surface area
c_p	constant pressure specific heat
D	coil inner diameter
d	tube diameter
F	view factor; function
f	conductive heat loss fraction; function
H	coil height
h	heat transfer coefficient; distance
H'	parameter in view factor
i	coiled tube index
l	length
$\dot{M}$	total mass flow rate
$\dot{m}$	mass flow rate per coiled tube
N	number of segments
$\mathbf{n}$	surface normal vector
Nu	Nusselt number
P	parameter in view factor
p	coil pitch; pressure
Pr	Prandtl number
$\dot{Q}$	heat transfer rate
R	coil radius
$\mathbf{r}$	direction vector
R'	parameter in view factor
R_{air}	gas constant of air
Re	Reynolds number
S	inner surface area; Sutherland's constant
T	temperature
t	thickness; parameter of position vector
u_m	mean flow velocity
$\dot{W}_p$	pumping power
x	Cartesian x-coordinate
$\mathbf{x}$	position vector
y	Cartesian y-coordinate
Z	parameter in view factor
z	Cartesian z-coordinate

Greek symbols

α	visible light absorptivity; angle at adjacent tube center
β	coil curvature ratio; angle at adjacent tube center
γ	ratio of linear interpolation
ε	infrared light absorptivity; specific pumping power demand
ζ	friction factor
η	efficiency
θ	circumferential angle
κ	specific heat ratio
λ	thermal conductivity
μ	dynamic viscosity
ρ	density; tube radius
ρ_m	mirror reflectivity
σ	Stefan-Boltzmann constant
ϕ	ray angle
Ψ	difference between azimuthal angles
ψ	azimuthal angle

Subscripts and superscripts

0	reference value; tube center; segment edge
a	ambient
ab	absorption
av	average
b	insulating board
c	coiled tube; critical
$cond$	conduction
eff	effective
f	fluid
i	insulating cover; coiled tube index
in	inner; inlet; incident
j	segment/cross-section index
k	segment/cross-section index
l	segment/cross-section index
max	maximum
O	tube center
out	outer; outlet; heat loss
p	isentropic pumping
rad	radiation
rec	receiver
ref	reflection
s	solid; side; segment
t	top; commencement of turbulence; parameter of position vector
$th\text{-}el$	thermal-to-electric conversion
x	x component
y	y component
z	z component

In order to design and quantitatively evaluate a cavity receiver with coiled tubes, which has the above characteristics, its modeling is desirable. The alternative approach is to conduct a Computational Fluid Dynamics (CFD) analysis, consuming very expensive computational cost (Prakash, 2014; Qiu et al., 2015; Daabo et al., 2016; Daabo et al., 2017). In the modeling approach, a heat transfer coefficient between the tube and the fluid within it is prescribed instead of solving the bulk equations of the fluid as in the CFD approach (Good et al., 2015; Le Roux et al., 2014; Loni et al., 2016a; Loni et al., 2016b; Loni et al., 2016c). In the present case, the geometry of the receiver is so simple that the modeling approach is applicable.

The goal of the present paper is to construct such a model for a Cross Linear (CL) concentrating system, which has been recently developed (Tamaura et al., 2014a; Tamaura et al., 2014b; Aiba et al., 2015). In the CL system, a linear receiver line lies on the east-west axis and mirror lines lie on the north-south axis. All the mirrors on one mirror line reflect the solar radiation to the one point of the receiver. Thus, linear receiver and point concentration are combined in the CL system. A feasibility study on a 20 MWe CL concentrated solar power plant was carried out by Aiba et al. (2016), showing cost competitiveness of a CL plant. In order to demonstrate this, a test site for a CL plant has been set up in Minamisoma, Fukushima, Japan, where a cavity receiver, using air as the heat transfer fluid, is adopted, because the CL system possesses a point-focusing characteristic and a high degree of the solar concentration, and hence a cavity receiver is suitable for a CL concentrated solar light collector, as mentioned above. In addition, there are some advantages of a cavity receiver compared to a conventional tubular receiver (Bader et al., 2010): (i) an area on which light is incident becomes larger than that of a tubular receiver; (ii) an amount of the radiative heat loss is regarded as comparable to that of a tubular receiver, because the radiative heat loss is only from the aperture under proper thermal insulation; (iii) wavelength selective coatings, applied to a tubular receiver, are difficult to function and retain their durability in high temperature, where solar and non-solar radiation overlaps (recently, solar heat has tended to high temperature for importance of heat storage). Since