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Design optimization of a tubular solar receiver with a porous medium

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HIGHLIGHTS

- A tubular solar receiver made from stainless steel with a porous medium inside was proposed.
- Porous medium serves to increase contact area between air and solid thus enhance system efficiency.
- Numerical simulation is conducted to pre-evaluate the effect from various controlling parameters.
- The effect of each variable on the maximum temperature and pressure loss has been investigated.
- Optimal design point of the proposed solar receiver concept has been numerically identified.

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ABSTRACT

The main objective of this research is to find the optimal design point of the proposed solar receiver concept to heat up compressed air. Within a tubular receiver made of stainless steel, a porous medium is filled to enhance the heat transfer via the large contact area and thereby to increase the system efficiency. Due to the low melting point associated with the selected material, a numerical simulation is conducted to pre-evaluate the effects of various controlling parameters on the maximum temperature and pressure loss of the system. The design factors expected to influence the system performance were the length, porosity, and thermal conductivity of the porous medium as well as the number of inlet pipes. The effect of each variable on the maximum temperature and pressure drop of the system is numerically investigated and the optimal design point is selected. The results of this study offer a valuable design guideline for future manufacturing processes.

1. Introduction

Recently, energy consumption has been soaring, especially in emerging countries despite the fact that oil prices are high at the time of writing. The amount of CO_2 emissions, which is the main source of global warming, has significantly grown with the ever-increasing energy consumption in modern society. With the intention of saving fossil fuels and reducing CO_2 emissions, many countries have been searching for renewable and clean energy sources such as solar, wind, and geothermal energies for sustainability.

One means of utilizing solar energy is through solar thermal electricity, or concentrating solar power. Highly concentrated solar radiation increases the temperature of a heat-transfer fluid until it is high enough to drive turbines and thus generate electricity. Owing to the possibility of easy hybridization with other thermal sources such as fossil fuels or biomass and dispatchability via thermal storage, concentrating solar power will be very valuable in the renewable energy mix in the future. The solar receiver, basically a heat exchanger that transfers solar energy to a heat-transfer fluid, plays a critical role in determining the type, capacity, and efficiency of concentrating solar power plants. Studies relevant to air solar receivers have been emphasized in an effort to take advantage of air-based concentrating solar power such as abundant and eco-friendly heat-transfer fluid, water usage reduction in arid regions, and realization of the combined cycle.

Schwarzbozl et al. [1] designed and assessed the performance of a solar-hybrid gas turbine system, which uses both solar heat and fossil fuel to heat up compressed air. After a rigorous economic analysis, they validated the economic benefits of this system.

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Nomenclature

D_{i1}	diameter of the large inlet pipe [mm]
D_{i2}	diameter of the small inlet pipe [mm]
D_p	mean particle diameter of porous medium [m]
D_s	diameter of the cylindrical tubular shell [mm]
h	natural convection coefficient [W/m^2 K]
I_r	inertial resistance [1/m]
L_s	length of the cylindrical tubular shell [mm]
q''_{conv}	natural convection [W/m^2]
$q''_{net,in}$	heat flux absorbed to the receiver [W/m^2]
q''_{rad}	radiation from the receiver surface [W/m^2]
q''_{ref}	solar reflection [W/m^2]
q''_{total}	concentrated solar flux [W/m^2]
T_s	temperature of receiver surface [K]
T_∞	temperature of environment [K]
V_r	viscous resistance [1/m^2]
Greek symbols	
α	tubular surface absorptivity
ε	porosity of the porous medium
ε_r	tubular surface emissivity
σ_r	Stefan–Boltzmann constant

Kribus et al. [2] proposed a partitioning approach to reduce energy loss by re-radiation and convection through the receiver aperture. The total area of the aperture was divided into parts to match the exposed levels of different irradiation fluxes. An air exit temperature of up to 1000 °C was achieved with a simple two-stage system. Buck et al. [3] developed both a volumetric receiver and a secondary concentrator (see Fig. 1(a)) that are suitable for modular design in central-receiver-system plants and demonstrated that they could increase the air temperature to 800 °C at a pressure of 15 bars. Heller et al. [4] used essentially same design as Buck et al.'s [3] except for the use of two different types of tubular receivers of high and low temperature to heat compressed air and fed it into a volumetric receiver. They attained an air temperature of 1000 °C and succeeded in generating electricity of 230 kW with a combined gas turbine cycle.

Since the promising results by Heller et al. [4], many researchers have sought better performance and understanding of air solar receivers. Becker et al. [5] theoretically and numerically found that flow instability in porous materials used for volumetric solar receivers can be avoided by the proper selection of material parameters. Wu et al. [6] proposed a pressure drop model for ceramic metal foams and suggested foams with a hole bored in them for improved penetrability. Hischier et al. [7] suggested a novel receiver design in which air flows through annular reticulate porous ceramic foam bounded by two concentric cylinders while concentrated solar flux is incident on the inner cylindrical cavity (See Fig. 1(b)). Lee et al. [8] applied optical simulation results for the consistent boundary conditions of heat transfer equations and demonstrated via a parametric study that the absorber emissivity mainly influenced the receiver performance. Cho et al. [9] devised a tubular receiver in which two concentric tubes form a cavity wall, inside which flow channels are fabricated. Compressed air enters the channels and is effectively heated up while passing through the extended surface, i.e., fins.

We propose a new design for a compressed air solar receiver, as shown in Fig. 1(c). We exploited the concept of the tubular receiver as in Cho et al. [9]. Tubular receivers are usually made of stainless steel or metal alloy tubes, and concentrated solar flux is incident on the tube surface while the heat-transfer fluid flows inside it. Compared to the volumetric receiver, the tubular receiver has advantages in terms of machinability, the sealing of compressed air, and no requirement to handle a fragile quartz window. As shown in Fig. 1(c), a tubular shell is filled with porous metal foam and the front surface of the shell is exposed to concentrated solar flux. Compressed air from a piston compressor with a 500 L capacity at the rear through several inlet pipes hits the shell front surface from the inside and is injected into the metal foam. After passing through the metal foam, the heated air exits through an outlet pipe. A modular design for easy scale-up is also adopted in such a way that solar receivers in the form of a cylindrical unit module can be stacked in parallel contact.

The main objective of this research was to find the optimal design point of the proposed solar receiver concept. The higher the temperature of the compressed air is, the higher the efficiency of the power plant becomes. However, the exposed surface temperature of the tubular shell must be held at below its melting temperature for safety and durability, which is one of main restrictions associated with the tubular receiver. We focused on identifying the proper combinations of the controlling parameters and on minimizing the maximum temperature and pressure loss. We used numerical simulations to pre-evaluate the effect of various controlling parameters. The design factors expected to influence the temperature of the materials as well as the pressure loss were carefully chosen. After fixing the geometrical size of the proposed solar receiver according to manufacturing constraints, we chose the following controlling variables: the length and properties of the porous medium, the number, location and size of the inlet pipes, the mass flow rate, the emissivity of the receiver surface, and the concentrated solar flux. The effect of each variable on the maximum temperature and pressure drop of the system were numerically investigated.

2. Numerical procedure

We used the commercial software FLUENT for the current numerical simulation. Conventional continuity, momentum, and energy equations were solved with a porous medium inside. Because the Reynolds number of the air inside the receiver is high enough, the porous medium used in this research could be modeled with additional terms to the standard fluid flow equations. The viscous and inertial loss term was added as a source term in the momentum equation. The viscous and inertial resistances of the porous material in FLUENT were set from equations (1) and (2):

$$V_r = \frac{150}{D_p^2}\frac{(1-\varepsilon)^2}{\varepsilon^3} \tag{1}$$

$$I_r = \frac{3.5}{D_p}\frac{(1-\varepsilon)}{\varepsilon^3} \tag{2}$$

Here, D_p represents the mean particle diameter of the porous medium, which can be calculated from the porosity (ε) and the density of the pores in the unit length (ppi). In this study, a ppi of 45 #/in was used, which is a conventional value of popular materials. For the energy equation, the effective conductivity and transient term for the thermal inertia of the solid region was used to account for the porous medium.

Our intention was to pre-evaluate various design factors for the development of a prototype receiver. Because of restrictions associated with the experimental test facility such as the concentrated beam area and power input as well as certain manufacturing constraints, some design parameters of the proposed solar receiver