Renewable Energy 35 (2010) 2501–2513

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

The impact of geometrical parameters on the thermal performance of a solar receiver of dish-type concentrated solar energy system

Mo Wang, Kamran Siddiqui*

Department of Mechanical and Materials Engineering, University of Western Ontario, London, Ontario N6A 5B9, Canada

ARTICLE INFO

Article history:
Received 9 December 2009
Accepted 11 March 2010
Available online 21 April 2010

Keywords:
Solar energy
Parabolic dish concentrator
Receiver
Thermal performance

ABSTRACT

A three-dimensional model of parabolic dish-receiver system with argon gas as the working fluid is designed to simulate the thermal performance of a dish-type concentrated solar energy system. The temperature distributions of the receiver wall and the working gas are presented. The impact of the aperture size, inlet/outlet configuration of the solar receiver and the rim angle of the parabolic dish are investigated. The results show that the aperture size and different inlet/outlet configuration have a considerable impact on the receiver wall and gas temperatures, but the rim angle of the parabolic dish has negligible influence.

1. Introduction

Concentrated Solar Energy (CSE) systems operate on the principle of concentrating the incident solar irradiation into small enclosures via parabolic reflectors. The solar receiver or the enclosure is located at the focal point or focal line of the parabolic reflector. Conventional CSE systems consist of three different configurations: parabolic dish, parabolic trough and central tower. Parabolic dish systems are considered to be the most efficient of all solar technologies [1]. A parabolic dish system consists of a parabolic dish with an array of mirrors and a receiver located at the focal point of the dish (see Fig. 1). The solar radiation incident on the dish are reflected toward the focal point of the dish where the receiver is located. Highly concentrated solar radiations enter the receiver through a small opening and significantly increase the temperature of the receiver and the receiver fluid. Comparing to the parabolic trough system with the concentration ratio of 100 Suns and the central tower system with the concentration ratio of 1000 Suns, the parabolic dish system can achieve concentration ratio of 10,000 Suns [2]. Therefore, high collection efficiencies can be achieved in a parabolic dish system due to its high concentration ratio. In addition, the quality of the thermal energy in this system is high because the receiver has very small opening and could be assumed as a blackbody [3]. Thus, the temperatures inside the receiver are considerably higher than other types of CSE systems. Receiver fluid temperature of over 2000 K has been suggested in previous studies [2,4]. Due to higher achievable temperatures and higher heat fluxes in the receiver, such systems could be used in a wide range of applications. Few of these applications are thermochemical reactions that involve production of synthetic gas and hydrogen [2], production of hybrid solar-fossil fuel [5], and solar thermal detoxification and recycling of waste materials [6].

There are relatively few studies on the thermo-fluid analysis of the solar receiver/reactor. Meier et al. [7] simulated the fluid particle flow and convective heat transfer in a high-temperature solar chemical reactor by using a CFD code CFDS-FLOW3D. The converged solutions were found by using the standard k-ε turbulence model and the maximum temperature reached 1200 K. However, they did not model the solar radiation as it reflects from the three-dimensional parabolic concentrator but rather assumed uniform heat flux at the aperture. Palumbo et al. [8] analytically and conceptually illustrated the parameters that are important for designing solar thermal chemical reactors. It includes geometry, feed conditions, materials' emissivity, thermal conductivity and heat capacity. They suggested the matching of decomposition reaction kinetics with the heat transfer processes so that large fraction of solar energy entering the reactor could be converted into chemical energy. Stephane et al. [4] presented a simplified two-dimensional model of a solar reactor. The chemical reaction is simulated using FLUENT. They observed that for the complete chemical reaction with initial metal oxide particle diameter of 1 μm, the particle temperature must exceed 2200 K. In their simulations, the solar flux was applied directly on the inner wall to simplify the radiation model without taking into consideration the complex radiation path from the sun to the parabolic dish and the solar receiver. Shuai et al. [9] used the Monte Carlo ray-tracing

* Corresponding author. Tel.: +1 519 661 2111x88234; fax: +1 519 661 3020.
E-mail address: ksiddiqui@eng.uwo.ca (K. Siddiqui).

0960-1481/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.renene.2010.03.021

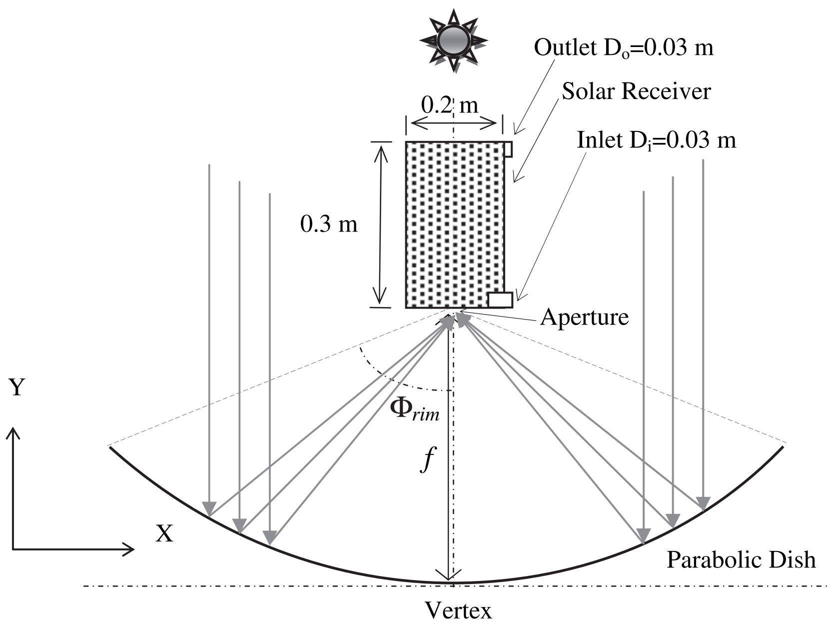

Fig. 1. Schematic of the parabolic-dish CSE system.

method to investigate radiation performance of a parabolic dish with simplified cavity-receiver. They suggested that the spherical receiver has relatively good radiation performance and proposed an upside-down pear-shaped receiver that could achieve almost uniform flux distribution. An experimental model of a solar chemical reactor consisting of a cylindrical cavity-receiver containing a tubular ceramic absorber coupled with elliptical mirror as concentrator is reported by Melchior et al. [3]. They found that the inner absorber surface could reach up to 2500 K in the presence of argon gas (working fluid) at a flow rate of 1.0 l/min. Their experimental results show a good agreement with the numerical simulations developed using Monte Carlo and finite difference techniques in a two-dimensional domain.

As the above literature review shows, the studies on the detailed investigation of thermal and optical behavior of coupled parabolic dish-receiver system are scarce. Furthermore, no detailed investigation of the thermal and radiative performance of a parabolic dish-receiver system in the presence of the working fluid has been conducted. As a result, the impact of different geometrical parameters on the net radiation influx into the receiver is not well understood. The understanding of the temperature distribution in such a system is vital in order to improve the design of the solar reactor. Some important parameters, such as the aperture size of the receiver which allows concentrated solar radiation to enter the receiver, have significant influence on the radiant heat flux. The configurations of fluid inlet and outlet in the receiver also have a considerable impact on the thermo-fluid behavior inside the receiver and has a direct impact on the overall performance of the parabolic dish CSE system. The present research is focused on investigating the effects of different geometrical parameters such as the aperture size, inlet/outlet configuration of the solar receiver and the rim angle of the parabolic dish on the thermal behavior inside the solar receiver.

2. Numerical simulations

A three-dimensional model of parabolic dish-receiver concentrated solar energy system is developed in a commercial software FEMAP. The schematic is shown in Fig. 1. The model consists of two key components, a parabolic dish concentrator and a cylindrical solar receiver. The parabolic dish is designed from the standard parabolic equation. The focal distance (f) is set to 1 m and the rim angle (Φ_{rim}) is set to 45°. The diameter of the dish is equal to 1.68 m and its surface area is 2.3 m^2. The concave surface of the disk is considered to be highly reflective, while the back surface is considered to be adiabatic due to insignificant effects of conduction and convection. The radiation source is the sun with constant beam flux distributed in the visible spectrum. Since the radiation is only in the visible solar spectrum, emissivity and reflectivity in the infrared band are not considered. As the parabolic dish mainly reflects solar irradiation, the temperature of the parabolic dish does not increase significantly thus, the infrared radiation emitted by the parabolic dish that reaches the solar receiver is not significant and is ignored.

The solar receiver is cylindrical in shape with the diameter of 0.2 m and height of 0.3 m (see Fig. 1). The outer surface of the solar receiver is considered to be adiabatic. The aperture of the cylinder is located at the focal point of the parabolic dish. For the initial configuration, the solar receiver has tangential inlet and outlet of diameter 0.03 m and length 0.1 m. These configurations are modified later to investigate their impact on the thermo-fluid behavior inside the solar receiver. The receiver wall is made of ceramic material (Al_2O_3). Argon is considered as the working gas that enters the receiver through the inlet and leaves through the outlet. The argon gas inside the receiver and the surrounding air between the parabolic dish and receiver are considered to be non-participating mediums for the radiation exchange.

The location is defined as Mexico City with the latitude of 19°. The simulations are conducted at the local solar time of 12:00 PM on 1st day of January and the sky is considered to be clear. Ambient temperature and pressure are considered as 298.15 K and 101 351 Pa, respectively. The simulations are initially set at the following conditions: reflectivity of the parabolic dish = 0.9, emissivity of the solar receiver = 0.8, absorptivity of the solar receiver = 0.8, argon gas at ambient conditions enters at a constant flow rate of 1.15×10^{-4} kg/s, and leaves through the outlet which exposes to the ambient conditions, buoyancy effects are considered. Some of these parameters are modified later to investigate their impact on the thermo-fluid behavior inside the solar receiver. The convergence criteria is set to 2×10^{-4}. Second Order Upwind method is chosen to compute the flow domain.