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Simulation on a novel solar high-temperature thermochemical coupled phase-change reactor

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Abstract

Solar high-temperature thermochemical process is a promising concept to produce hydrogen as well as basic chemical materials by concentrated solar energy. An important feature of this technology is the design of a satisfactory reactor. A novel solar high-temperature thermochemical coupled phase-change reactor based on a special-shaped high-temperature heat pipe (SHHP) receiver is presented. The SHHP integrated with phase-change heat transfer, temperature leveling of heat pipe and heat plate (flat plate heat pipe) separates the upper reaction chamber and the lower solar absorber. In this manner, radial temperature gradient in absorber and axial temperature gradient in reaction chamber will be lowered, thus to enhance safety and thermochemical conversion efficiency of the solar reactor. A three-dimensional model of the reaction chamber coupling heat transfer with nitrogen as working fluid instead of reactants is developed to optimize geometry configurations. The temperature distribution of the reactor wall and the working gas are presented. The impact of the inlet/outlet configurations and arrangement of heat pipes in heat plate are investigated. The results show that different inlet/outlet positions has significant influence on the thermo-fluid behavior, and the existence of the heat pipes on heat plate enhances the heat transfer in reaction chamber.

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Keywords: Solar energy; High-temperature thermochemical reactor; Heat pipe (heat plate); Thermal performance

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1. Introduction

Concentrated solar energy can be used to provide the heat necessary to drive high-temperature endothermic chemical reactions for renewable fuel production including direct thermolysis of water, reduction of metal oxides or hydrogen production for thermochemical water splitting cycles, and gasification of biomass, coal or other carbonaceous materials to produce synthesis gas [1-3]. Both solar energy and fossil resources (including water or biomass) are upgraded through this integrated process [4-6]. The solar high-temperature reactor is one of the keys to this process. Most of the reactors are derived from solar cavity-type collectors （also known as solar absorbers or receivers） commonly used in solar tower or dish concentrating power generation. Cavity-type receiver [7] is basically an enclosure designed to effectively capture the incident solar radiation entering through a small opening (the aperture). Directly irradiated reactors [2, 8-10] provide a very rapid and efficient means of heat transfer directly to the reaction site. However, the reactors require high thermal shock resistance since it is directly subjected to severe thermal shocks that often occur in applications with transient high-flux irradiation. Overheating or “hot spots” in partial region [11, 12] can be easily found because of nonuniform fluxes, which further lead to reactants or catalyst sintering. Another drawback when working with reducing or inert atmospheres is the requirement for a transparent window, which is a critical and troublesome component in high-pressure or severe gas environments.

One solution is an indirectly irradiated reactor [5, 6, 13, 14] with the introduction of either absorbing tubes or a separate cavity. With this arrangement, the inner cavity serves as the solar receiver, radiant absorber, and radiant emitter. Thus, the safety and reliability of the reactor can be improved. But the indirect heat transfer between absorber cavity, reactants and intermediate heat transfer fluid results in large thermal gradients inside the reactor that can lower system thermal efficiency and chemical conversion.

The high temperature metal heat pipe with excellent heat transfer characteristic is an approach to the indirect solution, while maintaining an indirectly irradiated reactor [15-18]. In this manner, liquid metal contained in an evacuated chamber evaporates under the effect of concentrated solar radiation impinging on solar-heated surface of the containment in absorber cavity. The metal vapor condenses on the reactor tubes or separate wall in the reaction chamber and energy is transferred to the reactants. Condensed liquid then flows back to the wick-covered evaporator surface under the influence of gravity. Since the metal is in a saturated state, temperatures within the reactor are uniform. Therefore, thermal stresses are minimized.

A novel solar reactor integrated with heat pipe technology is proposed to conduct high-temperature thermochemical reactions. In order to improve the design of the solar reactor, the present study focuses on investigating the effects of different geometrical parameters such as inlet/outlet configurations and arrangement of heat pipes in heat plate on the thermal behavior in reaction chamber.

2. Solar high-temperature thermochemical coupled phase-change reactor

A schematic of the solar high-temperature thermochemical coupled phase-change reactor [19] configuration is depicted in Figure 1. It features two cavities in series, with the upper cavity functioning as the reaction chamber, and the lower cavity as the solar absorber. These two cavities are separated by a special-shaped high-temperature heat pipe (SHHP). The upper, an insulated cylindrical cavity with inlet/outlet ports for reactants and products respectively. The lower comprises an aperture with a quartz window mounted on a pair of flanges, and inlet/outlet ports for an inert SHHP-cooling/window-cooling carrier gas. The solar flux concentration may be further augmented by incorporating a compound parabolic concentrator (CPC) in front of the aperture. The SHHP is a heat exchanger which consists of one cylindrical heat plate (flat plate heat pipe) and more heat pipes, as shown in Figure 2. The inner cavity of SHHP is an evacuated chamber containing sodium. In operation, concentrated sunlight heats the front circular plane (evaporator surface or solar-heated surface) of heat plate in absorber, and vaporized sodium. Sodium vapor condensed on the rear circular plane of heat plate and heat pipes (condensing surfaces) in reaction chamber, releasing latent heat and returning to the absorber by the capillary pumping action of wick structure. A groove wick with triangular cross-section and metal felt were chosen to form a combined wick for the SHHP.