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Experimental investigation on startup and thermal performance of a high temperature special-shaped heat pipe coupling the flat plate heat pipe and cylindrical heat pipes

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ABSTRACT

A high temperature special-shaped heat pipe (HTSSHP) coupling the flat plate heat pipe (FHP) and cylindrical heat pipes (CHPs), respectively as the thermal receiver and heat transfer unit, is proposed as the key component in a solar thermochemical reactor. The startup characteristics, isothermal performance, and thermal resistance variation of HTSSHP were experimentally investigated and analyzed. The results show that heat transfer limits are not encountered in tests and HTSSHP can startup effectively. The continuum flow transition temperature of sodium vapor in FHP and CHPs are 426.0 °C and 442.3 °C respectively and the startup behavior of HTSSHP differs from the flat-front phenomenon in a traditional high temperature cylindrical heat pipe with a constant transition temperature each part. However, the temperature difference response in startup can be employed to indentify the sodium melting and the flow regime transition in FHP and CHPs, validating its startup law. HTSSHP possesses the potential to inhibit the hotspots on heat absorber surface and meanwhile improve the temperature distribution in reaction chamber. The overall thermal resistance in HTSSHP reduces with increasing operating temperature, ranging from 0.12 to 0.19 °C/W that is in the same order of magnitude in a typical heat pipe. Furthermore, the various heat inputs and cooling rates have considerable effect on the thermal resistance in cooling side. This work is helpful for establishing the preliminary understanding of the operating characteristics on HTSSHP and provides some suggests for its normal operation and structure optimization.

1. Introduction

Solar thermochemical processes, or artificial photosynthesis as they are usually called, proceeding in solar thermochemical reactors (or solar reactors) can directly transform solar energy to chemical energy stored in solar fuels [1,2]. Splitting water for producing hydrogen is the main technological route in common solar thermochemical processes. Hydrogen has been identified as the most promising candidate for replacing fossil fuels as its positive features concerning efficiency, ease of storing and transporting, and environmental issues [1,3]. The current solar hydrogen production is mostly performed by two-step thermochemical cycles using metal oxide particles as the medium. The first step of a typical water-splitting cycle is thermal reduction of the metal oxide particles, which is driven by concentrated sunlight in a solar thermochemical reactor with a temperature that can be as low as 1200 K. And then in the second step, the reduced metal oxides spontaneously substitute the oxygen in water where hydrogen is released [4,5]. Hitherto, the proved redox pairs for water-splitting include ZnO/Zn, Ce_2O_3/CeO_2, Fe_2O_3/FeO, TiO_2/TiO_x and Sn/SnO_2 [4].

Solar reactors are essentially some special types of solar receivers where the high temperature thermochemical processes are carried out. They have been widely studied with the increasing development of solar thermal utilization technologies. According to the heat integration mode into the reaction chamber, solar reactors are grouped into indirectly and directly irradiated [6].

Direct solar reactors feature highly efficient heat transfer as the reactants inside are directly irradiated and heated by incoming solar radiation typically via an apparent quartz window [6]. Steinfeld et al. [7,8] made some initial study in this field. In 1998, a 5 kW direct solar reactor prototype called SynMet with a cylindrical reaction cavity was fabricated and tested by them. It was conceived for continuous co-production of Zn and synthesis gas with a gas–particle vortex flow. Its maximum reaction temperature achieved 1600 K and the conversion of Zn from ZnO reached 90%.

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Nomenclature

d	inner diameter of pipe, m
D	minimum dimension in vapor flow passage, m
h_f	pipe flow resistance, J/kg
k	Boltzmann constant, 1.38×10^{-23} J/K
Kn	Knudsen number
l	length, m
P_{sat}	saturation pressure, Pa
q	heat flux, W/m^2
Q	heat input, W
R_c	thermal resistance at cooling side, °C/W
R_e	thermal resistance in FHP, °C/W
R_t	overall thermal resistance, °C/W
T	temperature, °C
T_a	temperature at adiabatic section, °C
T_c	temperature along CHPs, °C
$\overline{T}_c$	average temperature at cooling side, °C
T_e	temperature on heat absorber surface, °C
$\overline{T}_e$	average temperature on heat absorber surface, °C
T_f	temperature on FHP upper surface, °C
T_r	continuum flow transition temperature, °C
$T_{r,c}$	transition temperature in CHPs, °C
$T_{r,f}$	transition temperature in FHP, °C
T_w	operating temperature, °C
u	velocity, m/s
Greek symbols	
λ	mean free path of vapor molecular, m
σ	effective molecular diameter, m
τ	time, s
ζ	frictional factor

However, the direct exposure of reaction chamber to high solar flux may bring about hotspots and thus the sintering problem in reaction layer or burnout failure because of the transient nature of solar radiation and the inherent error of focusing system [9]. Thereby, Haueter et al. [10] proposed a rotating conical cavity solar reactor (ROCA) for thermal dissociation of ZnO. The ZnO particles in ROCA were confined to the inner surfaces of reaction chamber by centrifugal forces from a rotating component, allowing the reaction layer served simultaneously as the thermal insulator. For this reason, the capacity of ROCA to withstand transient thermal shock was enhanced. However, the poor flow characteristic of reactants in ROCA led to an overall conversion efficiency as low as 35%. In order to overcome the drawbacks, Muller et al. [11] proposed a reactor evolved from ROCA, referred to as ZIRRUS. Both the reaction chamber shape and reactants feeder were optimized, providing an even reactant flow and consequently higher efficiency. The testing results showed that the conversion of Zn from ZnO exceed 90% in ZIRRUS, greatly exceeding that in ROCA. The direct solar reactors have been extensively studied, however, their scale-up are limited for commercial production due to the use of rotating component and quartz window [9,12].

Most of indirect solar reactors adopt heat exchanger tubes as reaction chamber, and their flow characteristics and thermal shock resistance are remarkably improved as compared to direct solar reactors. However, the multiple heat transfer by pure heat conduction from heat absorber surface to reaction site in indirect solar reactors is thermally inefficient, which may lead to a large temperature drop and hence the lower conversion efficiency [12–14]. Anyway, the existing solar reactor technologies are difficult to promote the market permeation of solar thermochemical processes. It is urgently necessary to develop a reactor with better efficiency and reliability.

A heat pipe is a heat transfer device with extremely high thermal conductivity and isothermal performance, through which heat is transported by phase change of working fluid circulating in a sealed container [15,16]. Recently, the heat pipes have been widely studied and used in solar thermal utilization at middle-and-low temperature [17–19]. In high temperature field, the Sandia National Laboratory [20,21] and Kribus et al. [22] have developed several solar dish–stirling systems using heat pipes as the thermal receiver. The test results indicate that the overall performance of these systems were notably increased in comparison to traditional dish–stirling systems. However, there are limited publishing literatures on heat pipe type solar reactors.

To get over the poor reliability and inefficiency problems, the excellent isothermal performance and high conductivity of heat pipes are incorporated into solar thermochemical processes in this paper and a solar thermochemical coupling phase change reactor (STPCR) is proposed. Besides, the key heat transfer component in STPCR – a high temperature special-shaped heat pipe (HTSSHP) coupling the flat plate heat pipe (FHP) and cylindrical heat pipes (CHPs) was fabricated and tested. Its startup characteristics, isothermal performance, and the effect of heat inputs and cooling rates on thermal resistance were experimentally investigated. The results can establish preliminary understanding on the thermal characteristics of HTSSHP and provide suggestions for the operation and optimization of STPCR.

2. Experimental investigation

2.1. Description of STPCR

STPCR is a type of solar reactor incorporating the high temperature heat pipe technology, in which an FHP is employed as the thermal receiver to inhibit the formation of hotspots at heat absorber surface and the CHPs work as heat transfer components at reaction side to improve the uniformity of temperature distribution. It is designed for producing Zn from thermal reduction of ZnO particles in solar dish systems. STPCR consists mainly of a

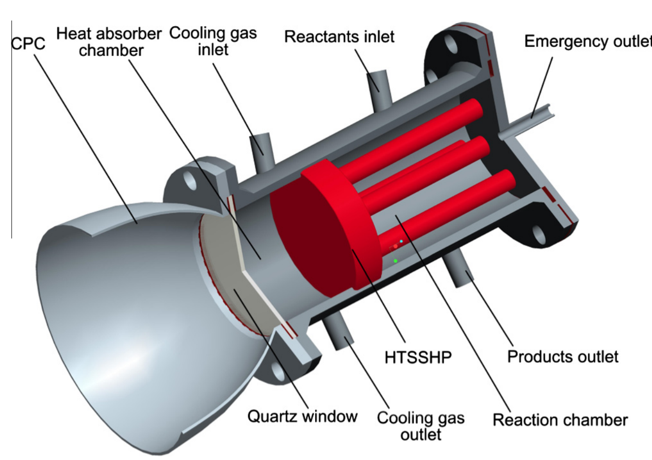

Fig. 1. Schematic view of STPCR.