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Experimental investigation of effect of heat load on thermal performance of natural circulation steam generation system as applied to PTC-based solar system

Meng Hua [a], Liang Zhang [a,b,c,*], Liwu Fan [a], Yu Lv [d], Hai Lu [a,e], Zitao Yu [a,*], Kefa Cen [b]

[a] Institute of Thermal Science and Power Systems, College of Energy Engineering, Zhejiang University, Hangzhou 310027, PR China
[b] State Key Laboratory of Clean Energy Utilization, Zhejiang University, Hangzhou 310027, PR China
[c] Key Laboratory of Efficient Utilization of Low and Medium Grade Energy (Tianjin University), Ministry of Education of China, Tianjin 300072, PR China
[d] Department of Mechanical Engineering, Stanford University, Stanford, CA 94305, USA
[e] Electric Power Research Institute, Yunnan Electric Power Test and Research Institute (Group), Kunming 650217, PR China

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ABSTRACT

An indoor experimental test rig of parabolic trough collector (PTC)-based natural circulation steam generation system consisting in a thermosyphon loop was presented. A series of five heat loads (0.6–1.2 kW) were applied to investigate effect of heat load on thermal performance of the system. Effect of heat load on flow pattern, thermal efficiency and two phase heat transfer coefficient was discussed, respectively. An extended correlation equation was provided for two flow patterns, which is characterized by heat pipe thermal resistance. The critical heat pipe thermal resistance for flow pattern transition was ranged from 34.37 K/kW to 33.35 K/kW. Simultaneously, thermal efficiency shows a continuous increase as heat load kept rising. The effect of backflow was found to be negligible when heat load increased to 1.1 kW. Additionally, the average two-phase heat transfer coefficient in receiver also went up with the rising of heat load for the same flow pattern. Due to the flow pattern transition, which resulted in a dryness fraction drop in receiver, a maximum heat transfer coefficient of 285.86 $W/m^2\,K$ was obtained at heat load of 1.0 kW under a steam discharging pressure of 0.15 MPa.

1. Introduction

Solar energy is regarded as one of the main contributors to the world's clean energy supply due to its wide and abundant availability. Investment of solar energy has accounted for nearly 37% of global clean energy market, reaching to over 130 billion U.S. dollars in 2011 [1]. Besides of photovoltaic technology, solar thermal technologies are getting more and more important for solar energy utilization. Moreover, solar thermal power technology was characterized as the roadmap of high-grade and efficient large-scale industrial applications [2,3]. The development of the major solar thermal technologies was reviewed by Thirugnanasambandam and Iniyan [4].

Since the first commercial solar thermal power plant developed in the 1980s, parabolic trough collector (PTC) power technology has been recognized to be reliable [2]. Nevertheless, solar thermal power technology is still a governmentally subsidized activity due to its low annual solar thermal electricity efficiency (∼10% for PTC power technology) and high investment cost. If there are no government policy grants, solar thermal power plant hardly has capacity to be a rival to the traditional power plants. Therefore, efficiency improvement and cost reduction are urgent for the development of solar thermal energy technologies.

For conventional forced convection PTC solar thermal systems, the working fluid must usually be pumped to fulfill the circulation. Besides of additional power consumption, this kind of forced circulation, however, is confronted with system reliability and safety issues when the operation temperature is increased to obtain a higher efficiency. The efficient direct steam generation (DSG) system is a typical example [5–8].

In consideration of the good thermal performance and simple structure, the thermally-driven natural circulation thermosyphon or heat pipe systems, provide a potential option to solar thermal utilization. The study of the subject of natural circulation solar heat pipe (thermosyphon) water/steam systems has been carried out for a century [9]. Thermal performances and thermosyphonic flow characteristics of the natural circulation solar heat pipe thermal

* Corresponding authors at: Institute of Thermal Science and Power Systems, College of Energy Engineering, Zhejiang University, Hangzhou 310027, PR China (L. Zhang). Tel./fax: +86 571 87952378.
E-mail addresses: jackway@zju.edu.cn (L. Zhang), yuzitao@zju.edu.cn (Z. Yu).

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Nomenclature

Bo	boiling number, $(q/(Gi_g))$
c_1,c_2	constant value in Eq. (4)
C_1–C_5	constant value in Eq. (8)
Co	convection number, $\left(\left(\frac{1-x}{x}\right)^{0.8}\left(\frac{\rho_g}{\rho_l}\right)^{0.5}\right)$
D	diameter, mm
DN	nominal diameter, mm
e	error deviation, dimensionless
FR	filling ratio, dimensionless
Fr_L	Froude number $(G^2/\rho_l^2 gD_i)$
F_{fL}	fluid dependent parameter in Eq. (8)
g	gravitational acceleration, (9.8 m/s^2)
G	mass flow velocity, kg/m^2 s
G_{sc}	solar constant, (1367W/m^2)
h	convective heat transfer coefficient, W/m^2 K
$\bar{h}$	average convective heat transfer coefficient, W/m^2 K
i_g	latent heat of vaporization, J/kg
I	current, A
I_c	perpendicular solar irradiation, W/m^2
I_r	direct solar irradiation, W/m^2
L	heating length of receiver, m
m	mass of discharging steam, kg
n	geometric concentration ratio, dimensionless
P	pressure, Pa
q	heat/electrical power, W/m^2
$\bar{q}$	average heat/electrical power, W/m^2
q''	heat flux, W/m^2
q_{el}	heat loss power of heat furnace, kW
R_{HP}	total heat pipe thermal resistance, K/kW
T	temperature, °C
$\bar{T}$	average temperature, °C
ΔT	temperature difference, °C
Δt	time interval, s
U	voltage, V
V	volume, ml
x	dryness fraction, dimensionless

Greek letters

β	slope, °
ϕ	latitude, °
ρ	density, kg/m^3
θ	incident angle, °
η	efficiency, dimensionless
δ	declination, °
ω	hour angle, °

Subscripts

A–G	cross section A–G of receiver
Cin	coil inlet
Cout	coil outlet
F	working fluid
FT	falling tube
i	inner
insulation-f	pipe insulation of field system
insulation-in	pipe insulation of indoor system
L	liquid
noon	noon
o	outer
opt	optical
pipe	thermosyphon loop pipe
P1,P2	two thermocouples positions of falling pipe
Rin	receiver inlet
Rec	receiver
Rout	receiver outlet
Sat-pipe	related saturated vapor temperature in thermosyphon loop pipe
steam	vapor steam
t	total
TP	two phase

systems have been presented by various researchers [10–29]. Recently, Ayompe and Duffy [20] investigated the thermal performance of a solar water heating system with heat pipe evacuated tube collector over a year-long field trail. Thermal performance of evacuated heat pipe solar water system was measured in different regional climates by Redpath [21]. Azad [22] evaluated three types of heat pipe solar collectors. Wang et al. [23] proposed a newly façade-based solar loop heat pipe water heating system. Aung and Li [24] investigated the effect of riser diameter and inclination angle in a closed loop thermosyphon solar water system. Brashim et al. [25] investigated thermal performance of a screen mesh heat pipe solar collector incorporating fins arrays into the condenser region. Chen [26,27] and Zhang et al. [28] developed a novel solar thermal conversion system based on supercritical natural convection of CO_2 in a loop thermosyphon. Koffi et al. [29] presented a theoretical and experimental analysis of the thermal performance of a solar water heater prototype with an internal exchanger using thermosyphon system. Nevertheless, the working temperature of these systems was restricted by either thermal properties of working fluid or peak heat flux of receiver.

In order to satisfy a higher-temperature circulation efficiently to meet the requirements for application in building heating, heat-powered air conditioner, seawater desalination, industrial heating, etc., Pei et al. [30] proposed a compound parabolic concentrator (CPC)-type solar water heater system with a U-pipe. Moreover, in view of efficiency and commercial valuation, solar cogeneration (even solar thermal steam) seems to be more competitive than solar thermal electricity [31,32]. Liu et al. [33–36] proposed an evacuated tubular high temperature air solar collector integrated with simplified CPC and special open thermosyphon. Fadar et al. [37,38] proposed a conceptual parabolic trough collector based solar adsorptive cooling system coupled with a water–stainless steel annular heat pipe. In the previous work of the present research group, a U-type natural circulation heat pipe system was designed, constructed and applied to a parabolic trough solar collector for generating mid-temperature steam. Thermal performance of the heat pipe steam generation system and heat losses of the heat pipe receiver were investigated experimentally, and a correlation for the total heat pipe thermal resistance was fitted [39,40]. However, in our recent work, two kinds of flow instabilities were obtained in thermosyphon by an indoor experimental test rig of a two-phase loop thermosyphon (TPLT)-based natural circulation steam generation system [41]. Thermal performance of the system at two different heat flux conditions was investigated in a preliminary work [43]. In consideration of the complicated heat transfer mechanism of loop heat pipe system [42], the availabilities of the present correlation for heat pipe thermal resistance and thermal performance characteristics for different flow patterns should be verified. This paper is devoted to extending the work on the effects of heat load on the thermal