Applied Thermal Engineering 108 (2016) 641–649

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

The flow distribution in the parallel tubes of the cavity receiver under variable heat flux

Yun Hao, Yueshe Wang *, Tian Hu

State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, 710049 Xi'an, China

HIGHLIGHTS

- An experimental loop is built to find the flow distribution in the parallel tubes.
- With the concentration of heat flux, two-phase flow makes distribution more uneven.
- The total flow rate is chosen appropriately for a wider heat flux distribution.
- A suitable system pressure is essential for the optimization of flow distribution.

ARTICLE INFO

Article history:
Received 16 April 2016
Revised 15 July 2016
Accepted 24 July 2016
Available online 25 July 2016

Keywords:
Solar cavity receiver
Flow distribution
Parallel tube
Variable heat flux
Experimental study

ABSTRACT

As an optical component of tower solar thermal power station, the heliostat mirror reflects sunlight to one point of the heated surface in the solar cavity receiver, called as one-point focusing system. The radiation heat flux concentrated in the cavity receiver is always non-uniform temporally and spatially, which may lead to extremely local over-heat on the receiver evaporation panels. In this paper, an electrical heated evaporating experimental loop, including five parallel vertical tubes, is set up to evaluate the hydrodynamic characteristics of evaporation panels in a solar cavity receiver under various non-uniform heat flux. The influence of the heat flux concentration ratio, total flow rate, and system pressure on the flow distribution of parallel tubes is discussed. It is found that the flow distribution becomes significantly worse with the increase of heat flux and concentration ratio; and as the system pressure decreased, the flow distribution is improved. It is extremely important to obtain these interesting findings for the safe and stable operation of solar cavity receiver, and can also provide valuable references for the design and optimization of operating parameters solar tower power station system.

1. Introduction

A solar cavity receiver is an essential apparatus to achieve the solar-thermal conversion in the tower solar thermal power station. From 1980s, more and more countries have paid attentions to the water/steam cavity receiver of tower solar thermal power station Consequently, it has been used in many successful demonstration plants sequentially, in which the working fluid of cavity receivers is water/steam, such as CESA-1 in Spain, PS10 (11 MW, the first solar commercial tower power station completed in 2007) and PS20 in Spain (20 MW, accomplished in 2009), and DAHAN power plant in China (1 MW, the largest tower solar thermal power station in Asia, constructed in 2012) [1–3]. In the solar concentration system, one-target focus type of the heliostat field is prevalent and feasible, in which a sole predetermined target is stationary relative to the heliostat field and the sunlight is reflected in a fixed direction. Due to the astronomical feature of the sunlight, it is very difficult for heliostats to track the sun path in real-time because of the clunky and complicated controlling system, and the heat flux distribution of the beam spot focused on the inside surface of the receiver varies widely in time and space. It showed in many literatures that the heat flux distribution on the surface of receiver presented two dimensional normal distribution for one-target focus type, studied by the ray tracing method, theoretical analysis and experimental research [4–7]. That is to say, the heat flux in the center of the beam spot is far above the average heat flux, and is almost zero in the edge of the spot. Comparing with the traditional fossil fuel boiler, the nonuniformity of heat flux is more severe and prominent, which results in the flow rate maldistribution of working fluid in the parallel tubes of evaporation panel. This phenomenon may lead to the burst or erosion on certain tubes of

* Corresponding author.
E-mail address: wangys@mail.xjtu.edu.cn (Y. Wang).

http://dx.doi.org/10.1016/j.applthermaleng.2016.07.168
1359-4311/

evaporation panel due to the local over-heat under extreme situation, which may affect the safe and stable operation of whole cavity receiver system then [8]. Various work has revealed that the flow rate of working fluid in the tubes of evaporation panel are greatly different caused by the non-uniform heat flux distribution [9,10].

Most numerical or experimental studies on the flow distribution of working fluid in the parallel tubes have focused at the conventional boilers [11]. Marchitto et al. [12] reported the measurements of two-phase air-water distributions, which occurs in a cylindrical horizontal header supplying 16 vertical channels for upward flow. The effect of operating conditions on the header-channel distribution area ratios and the inlet port orifice plates were investigated. Ablanque et al. [13] developed a numerical model to predict the thermal and fluid-dynamic behavior of two-phase flow distribution in the system with multiple branching tubes like manifolds. Zhong et al.[14] researched the distribution of heat flux and flow distribution of manifold and derived the relationship between the heat flux and the flow distribution of manifold in the header system of boiler. Yang et al. [15] established the mathematical model for predicting the profile of water wall flow rate and temperature, taking account of mass momentum and energy conservations.

However, the heat fluxes in the spot center area can reach to 800 kW/m^2 focused by a highly focused heliostat field [16]. And the non-uniform coefficient, which is the ratio of the heat flux of the center of a light spot to one around its edges, is approximately 18 times than that of the conventional boiler [17]. Jones and Lior [18] presented the numerical investigations of flow distribution in solar collectors without considering thermal effects, which consists of two horizontal manifolds connected by a number of parallel riser tubes. Gunnewiek et al. [19] analyzed the flow distribution by using a computational fluid dynamics (CFD) model, and the effect of wind on flow distribution in unglazed transpired plate collectors was studied. Weitbrecht et al. [20] investigated isothermal flow distribution in solar collectors with laminar flow conditions by means of LDV (laser Doppler velocimetry) measurements and numerical analysis. Chen et al. [21] put forward a non-linear dynamic model to obtain the effects of non-continuous step change radiation flux and step change feed water flow on the receiver performance by a sequential modular approach. Regarding to DAHAN tower plant in China, In order to investigate its dynamic characteristics Yu et al. [22] developed an integrated receiver model for actual operation conditions, in which a large and fast real-time disturbance of sunlight were accounted. Fan et al. [23] theoretically and experimentally investigated the flow and temperature distribution in a solar collector panel with an absorber consisting of horizontally inclined fins. They found that there was a good degree of similarity between the measured and calculated fluid temperatures for high flow rates, by comparing CFD simulations and the thermal measurements.

As mentioned above, although it is crucial to understand the flow characteristics of evaporation panel for improving its thermal performance and operation safety, little available study focused on the flow distribution of parallel tubes under non-uniform heat flux. In this paper, an experimental loop of hydrodynamic characteristics in the parallel tubes (evaporation panel of solar cavity receiver) is set up, consisting of five parallel vertical upward tubes. By allotting the spacing between any pair of electrodes (positive and negative electrode plates), which are assigned on the wall of parallel tubes and adjusting the currency intensive varied by the transformer, which other ends of electrodes are connected to, the heat flux distribution with different concentrated intensities can be obtained. The flow distribution in the parallel tubes is gauged under different heat flux concentration ratio, total flow rate, and system pressure. These research findings are not only helpful for the safe and stable operation of whole solar tower power system, but also beneficial to the design and optimization of operating parameters in the solar tower power station system.

2. Experimental loop

The cavity receiver consists of several panels, which are in turn comprised of an array of thin-walled tubes (stainless steel or alloyed) that are typically arranged to shuttle the working fluid in multiple passes through incident concentrated sunlight [24–26]. Tubes in the same panel have fluid flows in the same direction and have approximately the same flux distribution. The use of numerous tubes effectively acts as a mechanism to enhance heat transfer, much like fins are used to increase surface area. In this paper, the prototype of the cavity receiver is from the 1 MW pilot solar power station located in Yanqing County, Beijing, China, in which the evaporation panels has seven panels with vertical pipe bundles that were weld together to form a membrane wall [22].

An overall sketch of the experimental loop is given in Fig. 1, in which five parallel vertical tubes are arrayed to simulate an evaporation panel of cavity receiver. U-type and Z-type flow directions are the most commonly used configurations for parallel tubes and normally the flow distribution of U-type is more uniform than Z-type at the same flow area ratio [27,28]. Thus, the U-type flow direction is adopted in the experimental loop.

Working fluid flowing in the test loop is depicted as the following. Deionized water packed in a water supply tank is transported to a heat exchanger by a vertical multi-stage centrifugal pump, and the bypass valve installed in the pump discharge is used to regulate the flow rate entering the test section. After being preheated by backflow fluid from the outlet of the test section in the exchanger, water is pumped into the test section. Then flowing through a lower header and being distributed into five parallel tubes, water is heated further into an boiling state while such variables as temperature, pressure and rate are measured separately. After measured, water in five separate tubes is collected into an upper header. And it sequentially backflows to the water supply tank after flowing through an exchanger and a cooler. To guarantee a relatively constant pressure, a counterbalance valve is set in the outlet of test section. The cooling water of cooler is from tap water by use of an additional circulation system, which consisted of a cooling pump, a cooler, a cooling tower, and a cooling water tank.

The test section is shown schematically in Fig. 2, which is composed of five parallel vertical stainless steel tubes. Each tube is 12 mm in diameter, 1 mm in thickness and 3 m in length. The water from the exchanger is gathered in the lower header, and then distributed to five parallel tubes (marked as Tube 1 to Tube 5 sequentially from the far end of the inlet in the lower header). After heated in five tubes individually the water is combined in the upper header, and finally flows into the exchanger. Because of one-target focusing of the heliostat field in CSP, the energy strength of a beam spot focusing on the heated surface of the receiver presents asymptotic from-strong-to-weak changing from its center to its edge along two individual vertical and horizontal directions. The concentrated heat along the vertical direction is absorbed by one individual tube of parallel tube bundles. In spite of its nonuniformity, its thermal effect converted into the enthalpy of working fluid in individual tubes should be equivalent to the uniform heat flux. However, for the horizontal direction, the neighbouring tubes could be irradiated by gradual concentrated solar radiation energy, which would leads to different thermal and hydrodynamic characteristics in parallel tubes. That is the objective of this study. Comparing to the heat flux distribution along the vertical direction of parallel tubes, the nonuniform heat