International Communications in Heat and Mass Transfer 69 (2015) 18–22

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Numerical study of flat plate solar collector with novel heat collecting components☆

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ARTICLE INFO

Available online 19 October 2015

Keywords:
CFD simulation
Corrugated surface
Flat plate solar collector
Heat pipe structure

ABSTRACT

In this paper, a novel design of heat collecting component for a flat plate solar collector is presented and a numerical study on this solar collector collection efficiency by computational fluid dynamics (CFD) method is conducted. The new heat collecting component consists of a corrugated upward surface and a flat downward surface. The significant influences of the tilt of solar collector, the mass flow rate of inlet water and the distance of air gap on the solar collector collection efficiency are investigated by CFD-simulation. Simulation results reveal that the optimum values of the three factors are the tilt of 10° for April to September, 30° to 35° for the rest months (in Guangzhou of China), the mass flow rate of inlet water 0.15 kg/s and the distance of air gap 20 mm, respectively. Finally, the maximum instantaneous efficiency of 85.1% and the total heat loss factor of 3.127 are obtained by fitting the instantaneous efficiency curve of this solar collector.

1. Introduction

The utilization of solar energy has become an eye-catching subject in the past few decades due to the energy crisis and environmental protection. As known, the photo-thermal [1], photo-voltaic [2] and photo-chemical [3] conversion formed the basis of the solar energy utilization. Among them, the key of the photo-thermal utilization is exploring the best method to directly convert the solar radiation into thermal heat. The core device of photo-thermal utilization is solar collector, including flat plate solar collector and vacuum tube solar collector. Comparing to the vacuum tube solar collector, the flat plate solar collector has many obvious advantages, such as simple structure, uniform collection of solar radiation, and most especially can integrate with building. However, the conventional flat plate solar collector has some drawbacks. For instance, the structure of water pipe will be frozen to crack while the ambient temperature is below zero and the working fluid tend to reflux at night. All of these drawbacks will hinder the popularization of the flat plate solar collector.

To overcome the above disadvantages, heat pipe flat plate solar collector which introduces heat pipe into the heat collecting component offers a best way. Heat pipe is a high-efficiency heat transfer element, which utilizes the phase change of working fluids to transfer a great quantity of heat quickly [4]. At present, the utilization of different kinds of heat pipes in flat plate solar collectors has been studied experimentally. For example, gravity heat pipe, sintered heat pipe, oscillating heat pipe and micro channel array heat pipe have been reported in literatures. Samuel Luna Abreu et al. [5] designed a kind of gravity heat pipe with a straight line evaporation section and a semi-circular condensation section. Mehmet Esen and Hikmet Esen [6] examined a gravity heat pipe with three different kinds of refrigerants R410A, R407C and R-134a as working fluids in a flat plate solar collector. H.M.S. Hussein and H.H. El-Ghetany et al. [7] experimentally studied the copper–water gravity heat pipe with round, oval and semielliptical sectional shape under different liquid filling rates in a flat plate solar collector. S.A. Nada and H.H. El-Ghetany et al. [8] experimentally investigated the effect of cooling water mass flow rate and the number of gravity heat pipe on the flat plate solar collector collection efficiency. Dazhong Yuan et al. [9] designed an improved structure, called large integrated wickless heat pipe, instead of side-by-side separate heat pipe in the flat plate solar collector. M. Hammad [10] experimentally researched a sintered heat pipe with aluminum sintered powder and R-12 working fluid in a flat plate solar collector. S. Rittidech and S. Wannapakne [11] experimentally investigated a closed-end oscillating heat pipe flat plate solar collector with R134a as the working fluid and an inner diameter of 0.003 m. The heat pipes used in the flat plate solar collectors mentioned above employed copper as wall material. As we know, copper is not easy to be processed and its price is quite expensive, but aluminum does not have these problems. Sergii Khairnasov et al. [12] proposed the application of extruded

☆ Communicated by W.J. Minkowycz.

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2015.10.012
0735-1933/

aluminum alloy made heat pipes of original cross-sectional profile with wide fins and longitudinal grooves. Yaohua Zhao et al. [13,14] presented a novel flat plate solar collector with aluminum micro-channel heat pipe array (MHPA-FPC).

In the aspect of theory study, H.M.S. Hussein et al. [15–17] analyzed the energy balance of the gravity heat pipe flat plate solar collector and improved its collection efficiency through parameter optimization [18]. Lan Xiao et al. [19] and Azad [20] researched the gravity heat pipe flat plate solar collector based on the ε-NTU method.

Aluminum made heat pipes used in the flat plate solar collectors have been reported by many researchers. In contrast with copper, aluminum has the advantages of easier processing and lower price. This paper develops a novel aluminum heat collecting component with heat pipe structure, which is easy to be processed by extrusion technology. And then, the effects of the tilt of solar collector, the mass flow rate of inlet water and the distance of air gap on this solar collector collection efficiency are investigated by CFD-simulations.

2. Novel aluminum heat pipe heat collecting component

Heat collecting component is the key element of a flat plate solar collector. Fig. 1 shows the schematic diagram of the novel aluminum heat pipe heat collecting component. Its upward surface is corrugated and is plated with solar spectrum selective absorption coating, which converts the solar radiation into thermal heat. The downward surface is flat so as to contact the flat surface of the heat exchanger perfectly. Pipelines exist in the middle of the heat collecting component protrusions by aluminum extrusion technology. The pipelines are pumped vacuum and filled with working fluid; both ends were closed to form the heat pipe structures.

3. Model description

3.1. Physical model

The flat plate solar collector with novel aluminum heat pipe heat collecting components is shown in Fig. 1. This collector is 1960 mm length and 1000 mm width, with 20 pieces of the novel aluminum heat pipe heat collecting components continuously placed along the length direction. The pipe diameter of the heat exchanger is 24.5 mm, the thickness of the insulation layer on bottom wall is 50 mm, and the thickness of insulation layer on around wall is 30 mm. The solar absorptivity of the solar spectrum selective absorption coating is 94%, while its thermal emissivity is 7%. The thermally conductive silica gel is set between the novel heat collecting component and the heat exchanger in order to reduce the contact thermal resistance. The solar transmissivity and absorptivity of glass cove are 92% and 5% respectively. The other physical thermal parameters are listed in Table 1.

After projecting onto the selective absorbing films on the surfaces of a novel heat pipe, the sunlight which is called radiation energy can be transformed into heat energy, which will be transferred to the condenser section of the heat pipe quickly through the phase-change heat transfer in heat pipes. Then this heat energy transfers to the water pipe and heats the water. The heated water flows out from the outlet to the water storage tank and blends with cool water in the storage tank. The mixed water flows to the water pipe inlet of the collector. It will be heated again by absorbing the heat energy again. In this cycle, water in the storage tank can be continuously heated.

Table 1
Physical thermal parameters on the flat plate solar collector with novel aluminum heat pipe heat collecting components.

	Density (kg/m^3)	Specific heat (J/kg K)	Thermal conductivity (W/m K)
Air	Boussinesq	1006.43	0.0242
Water	1000	4182	0.6
Insulation layer	30	1380	0.04
Novel heat collecting component	2719	871	Axial: 30,000 Radial: 202
Heat exchanger	2719	871	202
Glass cover	2500	840	0.76

Under different inlet mass flow rates and different inlet water temperatures, the Reynolds numbers of water are varied from 2055 to 53,176, which indicate that the water flow belongs to turbulent flow. In comparison with the standard k–ε turbulence model, the RNG k–ε turbulence model shows improving accuracy and can be used for low Reynolds number fluid flow, therefore, the RNG k–ε model is selected for the water flow in this paper. DO radiation model is chosen to calculate the radiation, and the Solar Ray Tracing algorithm to calculate the heat flux on boundary surface.

3.2. Boundary conditions

(1) Inlet flowing boundary condition: constant mass flow rate and temperature of inlet water. (2) Outlet flowing boundary condition: fully-developed assumption. (3) Glass cover surface: $h = 5.7 + 3.8v$ [21], where v is the wind velocity. The other surfaces that contact with ambient air are $h = 2.8 + 3.8v$ [21]. The solar energy flux distribution is calculated by Solar Ray Tracing algorithm, while the rest contact surfaces are couple conditions.

3.3. Numerical methods

FLUENT software is employed to discretize the governing equations by the finite volume method. The PRESTO! algorithm is used to ensure the coupling between velocity and pressure. And the terms in momentum, energy and k–ε equations are discretized with the second upwind scheme. DO radiation equation is discretized with the first upwind scheme. The convergence criterion for energy and radiation is 10^{-7} and 10^{-6} respectively, and the convergence criterion for other variables is 10^{-3}.

ICEM software is applied to draw structure mesh for calculation domain. Boundary layer method is used to increase the density of mesh near the fluid flow walls. Several grid systems with 4,522,452, 5,369,788 and 6,152,643 nodes are selected to test the grid independence. It is found that the grid system with 5,369,788 nodes is adequate, since the average temperature of outlet water varies less than 2%. The CPU is Intel i5 and each case needs 2.5h CPU time.

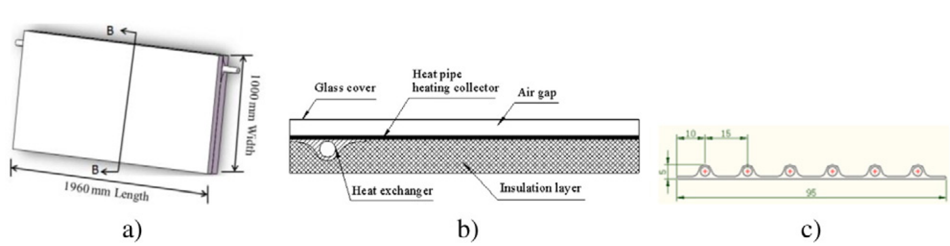

Fig. 1. (a) Schematic of the flat plate solar collector with novel aluminum heat pipe; (b) B–B cross-section view; (c) cross-section view of the novel aluminum heat pipe.