International Journal of Thermal Sciences 126 (2018) 152–161

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Phase change heat transfer characteristics of porous wick evaporator with bayonet tube and alkali metal as working fluid

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ARTICLE INFO

Keywords:
Porous wick evaporator
Bayonet tube
Alkali metal
Phase change heat transfer
Numerical simulation

ABSTRACT

Porous wick evaporator is an important power source of alkali metal thermal to electric converter (AMTEC) available for different kinds of energy sources including renewable energy. A bayonet tube structure is adopted in porous wick evaporator which is based on the principle of capillary pumped loop (CPL). The phase change heat transfer characteristics in the evaporator were numerically studied and the impact of the bayonet tube was investigated. The working fluid temperatures on two feature lines were selected to analyze the effect of bayonet tube on temperature of porous wick evaporator. The results show that for the evaporator using alkali metal as working fluid, a stable vapor-liquid interface is maintained at wick-groove interface. The bayonet tube divides the working fluid flow in porous wick into two parts, and the temperature change rule inside the bayonet tube is different from that outside the bayonet tube. The bayonet tube structure in the evaporator causes the temperature distribution in liquid channel to become more uniform and the maximum temperature to be decreased. The fluid temperature in the evaporator, especially in the liquid channel, can effectively be affected by the thermal resistance per unit area, length and diameter of bayonet tube. These parameters for bayonet tube must be limited within acceptable ranges in a specific operating condition, and there are optimum values to guarantee the best performance of the evaporator.

1. Introduction

The alkali metal thermal to electric converter (AMTEC) is a thermally regenerative device using alkali metal as the working fluid for direct conversion of heat to electrical energy, which is applicable to different kinds of energy sources, such as solar, fossil fuel and nuclear energy etc. Owing to its high efficiency, low energy consumption, no noise and good reliability, AMTEC, as a new energy conversion technology, has a wide range of application prospect, especially in the field of future space power [1,2]. A parabolic dish solar thermal equipment was proposed as the energy source of AMTEC system, and its performance and efficiency were evaluated in theory [3,4]. Considering the advantages of capillary pumped loops (CPL), the system adopting porous wick evaporator based on CPL principle to provide the power for the circulation of working fluid has been proposed. Compared with the split structure evaporator equipped at AMTEC currently, the porous wick evaporator based on CPL principle is available for the situation with larger capacity and greater heat flux, since only a part of region contains porous media. In the AMTEC system, the liquid alkali metal from the condenser flows into porous wick evaporator along the liquid channel. The resulting working fluid absorbs heat supplied from the external heat source, leading to the evaporation of the liquid alkali metal inside the porous wick. The meniscus formed at the surface or inside the porous wick establishes a capillary head to guarantee the cycle of the working fluid. Detailed descriptions of AMTEC system and specific working principles of the evaporator can be found in Ref. [2]. Porous wick evaporator receives external energy and provides the power for the working fluid circulation, which plays a crucial role in the whole AMTEC system.

At present, some related researches have been carried out on porous wick evaporator with methanol or ammonia as the working fluid. And heat and mass transfer characteristics of porous region have attracted widespread attention in particular [5–9]. A continuum model and a pore network model were presented to describe phase change heat transfer within the porous wick section by Figus et al. [5]. The result showed that the pore network model is more applicable while the continuum model is not available for the case with varied pore sizes. By dividing porous wick into liquid, two-phase and vapor parts, Huang et al. [6] developed a three-region model to analyze the transport process in CPL. The heat and mass transfer in the porous structure was

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https://doi.org/10.1016/j.ijthermalsci.2017.12.035
Received 17 June 2017; Received in revised form 18 November 2017; Accepted 31 December 2017
Available online 09 January 2018
1290-0729/

also numerically studied by Kaya and Goldak [7]. They established mathematical models for both vapor-liquid and all-liquid wick cases respectively. Boubaker et al. [8] developed a separate phase model to investigate the phase change heat transfer characteristics in unsaturated porous wick of CPL evaporator. The result illustrated that there is a vapor region under the casing fin, and the region is expanded when the heat load is increased. Moreover, Li and Peterson [9] and Zhang et al. [10] extended their work to a three-dimensional geometry to analyze flow and heat transfer in the evaporator, which was coupled with flow in the vapor groove and heat conduction in the casing. Nishikawara [11] also developed a three-dimensional numerical model to analyze the impact of parameters on the performance of evaporator by using a pore network model.

In some cases, in order to improve the performance of the porous wick evaporator, another structure is also adopted, in which a bayonet tube structure is added in the liquid channel. Waston [12] established a model to explore the impact of bayonet tube, and the research indicated that the maximum temperature in the liquid channel was reduced with bayonet tube in the evaporator. Qian [13] took a study on CPL evaporator with bayonet tube, the result showed that the bayonet tube structure can prevent vaporization in the liquid channel, which earns the risk of "vapor-blockage". Despite these facts, the detailed investigations about the impact of bayonet tube on the porous wick evaporator with alkali metal as working liquid are very limited. Cao [14] established an axisymmetric geometry to study the performance of the evaporator using alkali metal as working liquid. However, Cao [14] only focused on the regions of liquid channel and porous wick. It is necessary to develop a global model to have a detailed analysis in the evaporator. Therefore, in this work, considering liquid channel, bayonet tube, porous wick, vapor groove and casing as a whole, a three-dimensional global numerical model is established. One of the goals of the present study is to research the flow and phase change heat transfer characteristics in porous wick evaporator, which is based on the principle of the CPL and takes alkali metal as working fluid. Another goal is to analyze the role and impact of bayonet tube on phase change heat transfer of porous wick evaporator.

2. Physical and mathematical model

The sketch diagram of porous wick evaporator with bayonet tube is shown in Fig. 1, and a cross section of the evaporator is also depicted. It consists of liquid channel, bayonet, porous wick, vapor grooves and casing, which absorbs heat from external energy source. Compared with actual structure of porous wick evaporator, the aspect ratio of the model is reduced to lower the grid number and numerical simulation workload. Of course, as long as the similarity principle in heat transfer between model and actual structure is satisfied, the calculation results can be applied to the actual process. Meanwhile, the evaporator is simplified as four channel evaporator. Taking the symmetry of the evaporator structure into account, the physical model is provided in Fig. 2 with an outer diameter of $d_e = 14$ mm and length of $L_e = 15$ mm. Fig. 2(a) is one-eighth of the overall model and Fig. 2(b) is the cross section at outlet of vapor groove. The porous wick inside the evaporator has an outer diameter of $d_{wo} = 9$ mm and a thickness of $\delta = 3$ mm. The length and diameter of liquid transport line are $L_0 = 100$ mm and $d_0 = 2$ mm. Similar to previous investigations in Refs. [7,8,14], the mathematical model is based on the following assumptions:

① The process is in steady state;
② Gravitational and radiative effects are negligible;
③ The working fluid is Newtonian fluid and has constant properties for liquid, vapor and solid respectively;
④ Porous wick is homogenous and isotropic, and there is local thermal equilibrium between working fluid and porous structure;
⑤ Evaporation occurs only on the liquid-vapor interface, while no boiling is inside the liquid.

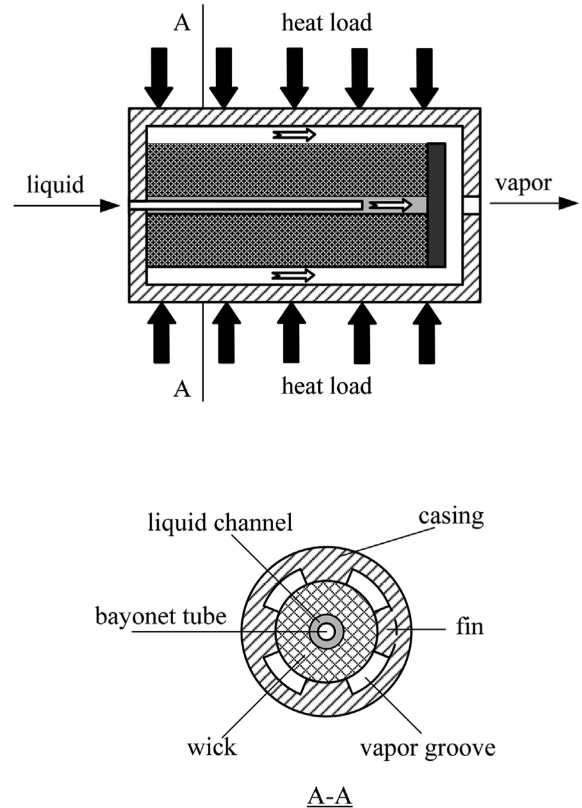

Fig. 1. Sketch diagram of porous wick evaporator with bayonet tube.

Based on the physical model of porous wick evaporator and assumptions mentioned above, the local governing equations for fluid phases and solids are written as follows:

① Continuity equation

Liquid phase region

$$\nabla\cdot(\alpha_l \rho_l \boldsymbol{v}_l) = -\dot{m} \tag{1}$$

Vapor phase region

$$\nabla\cdot(\alpha_v \rho_v \boldsymbol{v}_v) = \dot{m} \tag{2}$$

where the mass source term $\dot{m}$ is used to deal with the mass transfer on the phase change interface, α is volume fraction of working fluid. The subscripts "l" and "v" represent liquid phase and vapor phase respectively.

② Momentum equation

Porous wick part

$$\frac{\rho_f}{\varepsilon^2}\boldsymbol{v}\cdot\nabla\boldsymbol{v} = -\nabla\boldsymbol{P} - \frac{\mu_f}{K}\boldsymbol{v} + \boldsymbol{F} \tag{3}$$

where ε and K are the porosity and permeability of porous wick respectively; $\boldsymbol{F}$ is the momentum source term, which is used to deal with surface tension; μ_f is the coupling dynamic viscosity coefficient of fluid, which is defined as

$$\mu_f = \alpha_l \mu_l + \alpha_v \mu_v = \mu_v + \alpha_l(\mu_l - \mu_v) \tag{4}$$

Non-porous wick part (liquid transport line, liquid channel, bayonet tube and vapor groove)

$$\rho_f \boldsymbol{v}\cdot\nabla\boldsymbol{v} = -\nabla\boldsymbol{P} - \mu_f \nabla^2\boldsymbol{v} + \boldsymbol{F} \tag{5}$$

③ Energy equation