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Effect of compressed thickness on hydraulic and thermal characteristics of metal felt wick

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ABSTRACT

The influence of compressed thicknesses on hydraulic and thermal characteristics of metal felt used in high temperature heat pipe solar receiver was investigated by hydraulic characteristic experiment with water and thermal numerical simulation in annular porous media with liquid metal sodium. The experimental results showed that the capillary pumping amount first increased and then decreased, and capillary force increased as compressed thickness decreased. The effective capillary radiuses were 69 μm at 1 mm, 176 μm at 2 mm, 218 μm at 3 mm and 274 μm at 4 mm, in good agreement with calculated values. The simulation results showed that the drag coefficient and Nusselt number were increased by decreasing compressed thickness. To obtain the large capillary force, high liquid storage capacity, small flow resistance and good thermal performance, the optimum compressed thicknesses of metal felt were 2–3 mm, which were 33–50% of initial thicknesses, and could well adapt to heat pipe solar receivers in high heat flux working condition.

1. Introduction

Receiver is a core component of dish solar thermal power generation system, which absorbs the concentrated beam of solar energy, converts it to heat, and transports solar heat to the heat engine with minimized heat loss. Heat pipe receivers for dish solar thermal power generation system has been widely concerned because of the efficiency and reliability. It is composed of a cavity receiver, thermal energy storage and sodium heat pipes [1,2]. Wicks in high temperature heat pipe directly affect thermal performance of heat pipe. For the complex conditions of high and variable heat fluxes, it is important to choice a wick with excellent hydraulic and thermal characteristics.

Generally, there are wire mesh, groove, sintered metal powder, metal felt [3,4] and composite wick [5–7] as heat pipe wicks. Recent investigations of heat transfer in metal felt with open cell micro-structure indicate that such material offers more promising prospects. Qu et al. [8] integrated high thermal conductive porous media fiber felt and high latent heat phase change materials (PCMs) to efficiently improve the effective thermal conductivity. Harris et al. [9] made metal fibers and other selected particulates to be a composite material with high void volume for chemical processing application.

Measurements of the metal felt characteristics are presented in many researches. Williams et al. [10] tested metal felts fabricated from 316L stainless steel or Haynes 188 fibers in the in-plane and cross-plane orientation to get liquid permeability and effective pore size. These felt materials performed as well or better than traditional wicking materials (screens and powders). Li et al. [11] investigated the capillary pumping characteristics of porous wicks by analyzing the real time capillary pumping amount changing curve with different working fluids, which can be described with an exponential increase equation. Tang et al. [7] used infrared (IR) thermal imaging to identify and locate the liquid meniscus of novel sintered-grooved composite wick structures with ethanol as the working fluid. The optimal powder size of composite wick was suggested to be 80–110 μm among 40–60 μm to 110–140 μm. Canti et al. [12] used commercial sintered porous media and gauzes to measure their thermal and hydraulic parameters. U-tube was employed in the capillary force experiment. Therefore, the way of measuring capillary height and capillary amount in porous medium to get hydraulic characteristics such as capillary force and effective radius is feasible.

When high temperature heat pipe is in steady state operation, the wick not only provides capillary pressure differences across the liquid–vapor interface in the evaporator and condenser, but also is used for the liquid flow duct. Vapor flows in the central core

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Nomenclature

c^p	specific heat capacity at constant pressure J/(kg·K)
d	the diameter of the metal particle or wire μm
D_h	hydraulic radius m
g	gravitational acceleration m/s^2
h	wetted height m
K	permeability of wick m^2
P	axial pressure Pa
Q	the capillary pumping amount g
q	heat flux W/m^2
r_{eff}	the effective capillary radius μm
r	radius m
S	source term
t	time s
T	temperature K
v	rising velocity of wetted height m/s
w	the flow rate in z-direction m/s

Greek symbols

β	contract angle
Γ	diffusion coefficient
ε	porosity
θ	radian
λ	thermal conductivity W/(m·K)
μ	dynamic viscosity of working liquid Pa·s
ρ	fluid density kg/m^3
σ	surface tension N/m
ϕ	dependent variable

Subscripts

1	inner radius
2	outer radius
m	average
lg	liquid–gas
sl	solid–liquid
sg	solid–gas

of the heat pipe with the opposite direction of liquid. Therefore, liquid metal flow and heat transfer in wicked heat pipe can be simplified to flow in annular porous media.

Recently, many theoretical, numerical and experimental studies on convective heat transfer in porous media have been reported in literatures. The geometry of flow duct can be parallel-plate channel [13–18], square annulus [19,20], circle duct [21–25] and annular duct [26–31], that partially or fully filled with porous media. Annular duct is widely used in thermal storage systems, electronic cooling, inert gas insulation of high-voltage electric and other applications. Thermal performance of annular ducts have been obtained in the above researches by considering the fully developed laminar mixed convection [26], natural convection [27,28], analytical solution [29,30], non-Darcian flow [30], vertical annulus [26,28,31,33], viscous dissipation [32] and power-law fluid as working fluid [33].

Compressed thickness is one of the most important parameters in the porous media. Adkins et al. [34] showed that the permeability was extremely sensitive to the level of compaction in the wick. A half-millimeter reduction in the thickness can cause a 150 μm^2 drop in the permeability. Several researchers focused on the compressed thickness of gas diffusion layers, which greatly affected the performance of polymer electrolyte membrane fuel cells. Gostick et al. [35] studied in-plane and through-plane permeability of gas diffusion layers, and found that compression of a sample to half its initial thickness resulted in a decrease in permeability by an order of magnitude. Sadeghi et al. [36,37] measured the effective thermal conductivity and thermal contact resistance between the gas diffusion layers and adjacent surface/layers in vacuum and ambient conditions under varying compressive loads. The effective thermal conductivity increases with the compressive load and decreases with operating temperature increasing, and it is relatively insensitive to ambient air pressure. However, few researches take into account the impact of compressed thickness on the hydraulic and thermal characteristics of metal felt. In the actual operation of the high temperature heat pipe, different compressed thicknesses lead to rearrange the fluid channel inside metal felt, and cause corresponding changes of the porosity and permeability that directly affect the flow and heat transfer of liquid sodium in metal felt wick.

In this study, the effect of compressed thicknesses on the hydraulic and thermal performance of metal felt wick is considered. The capillary pumping amount, capillary force and effective capillary radius are tested at different compressed thicknesses in hydraulic characteristic experiment, and effective capillary radiuses are compared with the results from empirical formula. The flow resistance and thermal performance within annular metal felt wick are numerically simulated and validated by literature data. Finally, considered hydraulic and thermal characteristics, the optimum compressed thickness of metal felt wick is obtained to improve the performance of high temperature heat pipe solar receiver.

2. Hydraulic characteristics

2.1. Experimental design

The test apparatus of hydraulic characteristic experiment is showed in Fig. 1. It consists of sample fixing device, reservoir, electronic balance and computer. A steel stand, bench vice, ruler and two slide glasses are combined to a fixing device. The accuracy of ruler is 1 mm. The readability of the electronic balance (FA2004) used in this experiment is 0.1 mg with the accuracy class 0.5.

The material of metal felt used in heat pipe is the type of WB 08/300, which was made of 316L stainless steel and produced by Bekaert Company in Ukraine. The first number in this type designation is the wire diameter in micrometers, and the second number is the surface density of the felt in grams/meter^2. The initial thickness and typical scanning electron microscope-scanned microstructure of the metal felt is presented in Fig. 2, which illustrates that the fibers are distributed in a stochastic way. 4 samples were cut to the same initial dimensions, with length 80 mm, width 10 mm and initial thickness 6 mm which contains two layers. They will be compressed to 1–4 mm respectively. The specifications of all samples are shown in Table 1.

At first, a sample was fixed in fixing device by two slide glasses into 4 mm thickness, and hanged to the experimental stand in vertical. Put amount of water in the reservoir, and then place it on the electronic balance gently. The level of water can be read by a rule