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Research Paper

An experimental work on thermal features of the miniature revolving heat pipes

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HIGHLIGHTS

- The thermal features of MRVHPs have been experimentally investigated.
- Thermal resistance of MRVHPs reduces with increases rotational speed and heat load.
- The influence of capillary structure on MRVHPs is taken into consideration.

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ABSTRACT

As the traditional rotating heat pipe, the condensate film is transported from condenser to evaporator by centrifugal force in the revolving heat pipe (RVHP), however, there is an eccentric distance between the rotational axis and its central axis. An experimental investigation is conducted on thermal features of the miniature revolving heat pipes (MRVHPs), at rotational velocities ranging from 1000 to 3000 rpm, and heat loads ranging from 2.5 to 30 W, the influence of the capillary structure is taken into consideration as well. The results show that the outer surface temperature of heat pipe wall decreases with the increases rotational velocity. The main axial temperature difference and the corresponding thermal resistance reduce as the rotational velocity increases. Based on the experimental data, a novel correlation of the Nusselt number on the condenser surface of the ordinary-wick MRVHP and the rotational Reynolds number is obtained. The results of the comparative experiments show that the capillary structure has contributed to the uniformity of circumferential temperature and evaporation heat transfer in MRVHPs, however, the main axial temperature difference and the corresponding thermal resistance are enlarged because of the existence of the capillary structure.

1. Introduction

A rotating heat pipe (RHP) is heat pipe rotating about its own axis, including three sections, the evaporator, the adiabatic section and the condenser. Heat is transferred from the evaporator to the condenser through phase changes of the working fluid. According to Gray [1], the backflow of the working fluid in wickless RHP is mainly pumped by centrifugal force instead of capillary action. As a specific type of the RHPs, the revolving heat pipes (RVHPs) inherit all the features of the RHPs excepting there is an eccentrical distance between the rotational axis and the geometric axis [2]. The RVHPs are extremely applicable in those situations that heat sources distance away from the rotating axis, for instance, the cooling of rotating electrical machines, heat exchangers, turbine spindles [3,4].

The existing research results of the RHPs are reviewed here from the aspects of theoretical study, numerical simulation and experimental investigation. A rotating wickless heat pipe was analyzed theoretically and experimentally by Daniels et al. [5], a theoretical Nusselt type analysis was proposed for the condensate film taking into account the drag effects of contra-flowing vapor and experimental investigation tests for Arcton 113 and 21 fluids showed fine agreement with the theoretical results. Investigations of these wickless heat pipes had found that the liquid flow can be classified into different flow patterns depending on the magnitude of the centrifugal force relative to gravity [6,7]. The vapor flow in an axially rotating heat pipe had been numerically analyzed using a two-dimensional axisymmetric model in cylindrical coordinates, a parametric study was conducted for axial Reynolds number of 0.01, 4.0 and 20.0, and rotational speeds ranging from 0 to 2800 rpm. The numerical results indicated that the pressure and the axial, radial, and tangential velocities are significantly affected

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Nomenclature

C	constant
D	heat pipe diameter, m
h	convective heat transfer coefficient, W/(m²·°C)
k_f	air conductivity, W/(m·°C)
L	length, m
Nu	Nusselt number
P	heat load, W
Q	heat flux input, W
R	radius of rotation, m
Re	Reynolds number
R_{th}	thermal resistance, °C/W
T	temperature, °C
t	thickness, m

Greek symbols

ν	kinematic viscosity, m²/s
ω	rotational velocity, rad/s

Subscripts

a	ambient
c	condenser of heat pipes
e	evaporator of heat pipes
v	vapor channel

by the rotational speed and the radial Reynolds number [8]. A detailed transient numerical simulation of the RHP was proposed by Harley and Faghri [9], the two-dimensional axisymmetric formulation accounts for the thin liquid condensate film on the inner surface of the rotating pipe wall, the vapor flow in the vapor space, and the unsteady heat conduction in the pipe wall. It was shown that the complex vapor flow patterns in RHP influence the vapor temperature and thus the performance of the heat pipe, the effect of interfacial vapor shear stress on the liquid film thickness and subsequent thermal resistance across the film was also discussed. A theoretical model was established by Lin et al. [10] that describes the evaporating film flow in a rotating miniature heat pipe with an axial triangular grooved internal surface, the effects of disjoining pressure, surface tension and centrifugal force on the flow were discussed. Results showed that the influence of centrifugal force on the liquid film flow and evaporation heat transfer in the micro region was not significant, and the film thickness and apparent contact angle increased with an increase of superheat. A complete model had been developed by Song [11] to predict the performance of high-speed RHPs with centrifugal accelerations up to 10,000*g*, the flow and heat transfer in the condenser was modeled using a conventional modified Nusselt film condensation approach, while the heat transfer in the evaporator had previously been modeled using a modified Nusselt film evaporation approach. It was found the natural convection in the liquid film becomes more significant at higher accelerations and larger fluid loadings. The predictions of the model were in reasonable agreement with existing experimental data. An experimental study on the moderate-speed RHP was conducted by Song et al. [12] for heat transfer mechanism in the evaporator section of non-stepped rotating heat pipes at rotational speeds of 2000–4000 rpm, and evaporator heat fluxes up to 100 kW/m². The results indicated that natural convection heat transfer occurred in the liquid layer of the evaporator section under these conditions. The heat transfer measurements were in reasonable agreement with the predictions from an existing RHP model that take into account the effect of natural convection in the evaporator section. A numerical model was developed for the simulation of the two-phase flow and heat transfer phenomena during the operation of a RHP [13], a novel phase-change model by Sun [14] was introduced to predict the evaporation and condensation processes in the RHP while the balance between evaporative and condensing masses was considered. The simulation results were compared with experimental data and a satisfactory agreement was observed, which indicated that the model is feasible to predict the heat and mass transfer processes in RHP.

In consideration of the excellent heat transfer capability of RHPs, the application of the RHPs in cooling electric machines, motors and generator was explored by Oslejsek, Groll, and Thoren et al. [15–17]. Ponnappan [18,19] published the test results of high speed rotating heat pipes (HSRHPs) for possible cooling applications in rotating electrical machines required for design of the more-electric aircraft. The stainless steel 316-methanol and stainless steel 316-water HSRHPs which were tested at the speeds up to 30,000 rpm, the inducting heater in the temperature range of 20–250 °C and power levels from 250 to 1300 W. Jankowski [20,21] delivered comprehensive experimental works on a curved rotating heat pipe used for cooling of superconducting machines, the heat pipe was bended so that both the condenser and evaporator sections are parallel to the axis of rotation. The test data indicated that the working fluid continued to circulate, resulting in heat transfer with a high effective thermal conductivity, with the curved rotating heat pipe operating under the influence of centrifugal accelerations approaching 400*g*. Chen [22] investigated on the heat transfer of a RHP cooling system in dry abrasive-milling of Ti-6Al-4V, different cooling conditions, filling ratios and feed speeds were taken into consideration. The optimal heat transfer performance could be obtained with a cooling pressure of 0.36 Mpa and a filling ratio of 16.4%, the temperature in the evaporator section was lowered by approximately 65.7% compared to the same machining process without heat pipe. The feasibility of a novel aero-engine nose cone anti-icing system for a typical turbofan based on an axially RHP was experimentally demonstrated by Lian and Xuan [23], the actual anti-icing capability of the prototype was tested in an icing wind tunnel. The wind tunnel conditions, including the wind speed, the ambient temperature, the liquid water content, and the average diameter of the water droplets, were employed based on the actual flight conditions of the aero-engine. The fabricated prototype based on RHP was verified to have a satisfactory anti-icing performance.

As reviewed above, there are lots of intensive studies focusing on RHPs, nevertheless, only few investigations are concentrated on the eccentric rotating of heat pipes (RVHPs). The effects of operating parameters on the heat transfer and liquid film thickness of RVHP were theoretically analyzed by Hassan et al. [24], they found that the liquid film thickness increases with the decrease in temperature difference and with the increase in the mass of fluid. The maximum heat transfer increased with the increase in the rotation speed. Hassan and Harmand [25] conducted an experimental investigation on the effect of the radius of rotation on the thermal performance of RVHP, the experiment was carried out at different rotational velocities, different radii of rotation, and different input powers to the evaporator. As the results showed, at high rotational velocities, the radius of rotation and rotational speed had no significant effect on the heat pipe temperature, the thermal resistance of RVHP decreased with increasingly rotational velocity, and the radius of rotation has no sensible effect on the maximum Nusselt number of the RVHP at high input power.

To the author's best knowledge and from the previous research review, there is scarcely any study focusing on the heat transfer performance of the miniature revolving heat pipes (MRVHPs). Whereas it has great potential in design of heat dissipation system for small-size rotating electrical machines, such as the internal cooling of high speed motorized spindle. In the present work, we conduct experiments concentrating on the thermal features of the MRVHPs and the contribution