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Thermal performance of rotating closed-loop pulsating heat pipes: Experimental investigation and semi-empirical correlation

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ABSTRACT

A rotating closed loop pulsating heat pipe (RCLPHP) was experimentally investigated as a passive heat sink for rotary equipment cooling. The effects of heat input, rotational speed, filling ratio, and working fluid on the thermal resistance of RCLPHP were studied. Pure water and ethanol were used as working fluids with filling ratios of 30%, 50%, and 70% by volume, and the RCLPHP was tested at four rotational speeds: 200, 400, 600, and 800 rpm. The results showed that the best filling ratio for both water and ethanol is 50% and proved that the RCLPHP is able to work efficiently in a wide range of rotational speed. Moreover, it was observed that at the optimum filling ratio for ethanol and water, which is 50%, the decrease in thermal resistance at 800 rpm compared to 200 rpm was 5.4% and 13%, respectively. Such an enhancement in thermal performance indicates that these types of heat pipes are applicable for the purpose of cooling rotating devices. Moreover, a correlation is presented to estimate the amount of heat flow in RCLPHP with a maximum estimated error of 20%.

1. Introduction

The high thermal conductance of heat pipes as two-phase heat transfer devices, makes them favorable equipment in thermal management to dissipate the generated heat in rotating devices such as rotating parts of electrical machines and generators. There is a wide variety of applications for heat-pipes in rotating equipment [1], high speed cutting operations [2], drilling applications [3], and electric motors [4].

Film cooling is a cooling method used in virtually all of today's power-generation turbine engines. It is applied to nearly all the external surfaces of the airfoils that are exposed to hot combustion gases. In film cooling, cool air is bled from the compressor stage, passed through the turbine blades, and discharged through small holes in the blade walls. This air provides a thin, cool, layer along the external surface of the turbine blade. In this method, due to the use of compressor for cooling, the total efficiency of turbocompressor declines. Cooling internally through a series of internal channels is another method used in industrial gas turbine (IGT) blades. The channels carry air that circulates and protects the blades from damage caused by elevated temperatures. Finding new and innovative methods of cooling these blades has triggered research on other methods of dissipating heat, such as heat pipes.

One of the latest designs of heat pipes is the pulsating heat pipe which was invented by Akachi in 1990 [5]. Its structure comprises a meandering tube of small capillary dimension which must be evacuated of air and filled partially with working fluid. A Closed Loop Pulsating Heat Pipe (CLPHP) [6,7] is a long capillary tube which is bent into a meandering shape with tube ends are connected to each other in an endless loop. It does not include an additional capillary structure (wick).

Accordingly, it is not subjected to some restrictions associated with conventional heat pipes. CLPHPs are partially filled with a working fluid. Due to the surface tension effect, the working fluid distributes through the CLPHP's channel in the form of liquid slugs and vapor plugs. Heat is transferred from the evaporator region to the condenser region by fluid oscillation. As the fluid receives heat in the evaporator, steam pressure of the bubble in the evaporator increases and this causes a force to move the liquid slugs toward the condenser. As the bubble reaches the condenser, it condenses and the liquid moves back to evaporator. As a result, a steady oscillating flow is evident in CLPHP that results in its continuous operation [8]. High durability and reliability of CLPHPs make them ideal choices for heat transfer applications.

Quite a few experiments have been conducted to investigate the effective parameters of pulsating heat pipes' (PHPs') thermal

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Nomenclature

c_p	specific heat capacity (J/kg.K)
D	Diameter (m)
g	Gravity acceleration (m/s^2)
h_{fg}	vaporization enthalpy (J/kg)
k	Thermal conductivity (W/m.K)
L	Length (m) and length primary dimension
Q	Heat input (W)
q''	Heat flux (W/m^2)
T	Temperature (K) and temperature primary dimension
R	Thermal resistance (K/W)
N	Number of turns
T	Time (s) and time primary dimension
M	Mass primary dimension
J	Energy primary dimension
Bo	Bond number
Ja	Jacob number
Fr	Froude number
Ku	Kutateladze number
Mo	Morton number
Pr	Prandtl number

Greek symbols

Δ	Difference
μ	Viscosity (Pa.s)
σ	Surface tension (N/m)
ρ	Density (kg/m^3)
ω	Rotational speed (rpm)
φ	Filling Ratio (liquid volume to total volume)

Subscripts

vap, v	Vapor
l	Liquid
c	Condenser
e	Evaporator
Th	Thermal

performance, and the results show that the most important parameters that affect the thermal capability of PHPs include working fluid, filling ratio (FR) and geometrical properties of PHP. In order to investigate the influence of working fluid on the performance of PHPs, Kolkova and Malcho [9] conducted an experiment on distilled water, ethanol and acetone in a range of 0–80% of filling ratios. They reported that distilled water exhibited the best thermal performance. Furthermore, their experiment showed a reduction in the thermal performance of PHP out of the range of 30%–70%. Some researchers have attempted to improve PHP performance by mixing common working fluids [10,11]. For this purpose, Pachghare and Mahalle [10] employed water, methanol, ethanol and acetone and also binary mixtures (1:1 by volume) of water-ethanol, water-methanol and water-acetone as working fluids. They found that the water-acetone binary mixture had the best thermal performance among the other options. Han et al. [12] investigated the effects of thermo-physical properties of fluids on the operation of PHP; they deemed that the start-up and oscillation speed depend heavily on the dynamic viscosity of the fluid and this dependence weakens with an increase in heat input. Moreover, they observed that the heat transfer capability of fluids is characterized by their specific heat and latent heat of vaporization, and at low filling ratios, a heat pipe with a lower boiling point and lower latent heat of vaporization of working fluid is more susceptible to drying out. In addition, various studies have also shown that the performance of PHP is sensitive to the value of filling ratio [13]. At lower filling ratios, the volume of vapor plugs is larger compared to that of the liquid slugs. Consequently, the vapor plug driving force to push a small amount of liquid slugs is larger. Moreover, lower filling ratios lead to a lower friction force between fluid slugs and pipe wall, and facilitate fluid motion. On the other hand, at lower filling ratios, due to the smaller amount of liquid, the sensible heat transfer from evaporator to condenser decreases resulting in dry-out and malfunctioning of the PHP. When the filling ratio is high, the liquid slugs are long, and a higher-pressure difference is needed to push the larger liquid slugs between evaporator and condenser sections. Since this pressure difference is not obtainable, the PHP does not operate properly. In summary, by considering both hydrodynamic and heat transfer effects, the optimum filling ratio has been reported to be about 50% [14]. Qu and Wang [15] reported the best filling ratio for water and ethanol to be 40%.

Yang et al. [16] utilized R123 with 30, 50 and 70% in order to investigate the effect of filling ratio, and found the best CLPHP performance at 50%. In addition, according to their studies, the early dry-out occurred at lower heat inputs and 30% filling ratio. Other important factors affecting CLPHPs performance are geometrical parameters such as CLPHP channels orientation with respect to the gravity direction, channel configuration, and size.

In 2013 Burban et al. [17] investigated the thermal performance of a PHP at different inclination angles. Their results showed that the PHP is able to work even at unfavorable orientations. Mameli et al. [18] tested a PHP in micro and hyper gravity conditions and discovered that the thermal characteristics of PHP are strongly affected by variations in gravity field. According to their observations, the CLPHP is more stable and efficient in vertical operation with bottom heat mode compared to horizontal operation. The vertical operation with bottom heat mode is heavily dependent on the initial distribution of vapor plugs and liquid slugs, and requires larger heat inputs to start up. Changing gravity to hyper gravity or micro gravity, moreover, only affects the vertical operation. In micro gravity operation, the CLPHP experiences a sudden temperature rise. According to reference [18], the magnitude of external force (gravity) acting upon liquid slugs and vapor plugs affects the startup, static pressure distribution and steady function in pulsating heat pipes. If the gravitational force acts in the direction of a heat pipe toward its evaporator, the thermal performance of the heat pipe will improve significantly. Therefore, it has been deduced that the centrifugal force, like the gravitational force, improves the thermal performance of PHPs since it always acts in the pipe direction toward the evaporator.

Employing the centrifugal force is a way to enhance heat transfer in internal flows. According to reference [19], centrifugal force improves the limitation of heat transfer in conventional heat pipes, including startup, dry-out, and limited temperature difference between evaporator and condenser. The temperature difference between the evaporator and condenser can be significantly greater in magnitude in rotational heat pipes with higher rotational speed than in conventional heat pipes.

Yan and Soong [20] conducted an investigation on the influence of Coriolis and centrifugal buoyancy forces on friction factor (fRe) and Nusselt number (Nu) in radially rotating rectangular ducts. According to their findings, Coriolis and centrifugal buoyancy forces