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Comparative study on evaporator heat transfer characteristics of revolving heat pipes filled with R134a, R22 and R410A ☆

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ABSTRACT

Heat pipes are used extensively in various applications including the heating, ventilating and air conditioning (HVAC) systems. The high thermal conductivity of the device, attributed from the two-phase heat transfer processes within the heat pipe, made them superior heat exchanger devices. Heat pipes had been widely used in HVAC applications in energy conservation, dehumidification enhancement, heat dissipation, etc. A number of researches have been conducted to expand the applicability of heat pipes in HVAC in Malaysia, especially in air-to-air heat recovery using stationary heat pipes. However, the potential usage of rotating heat pipe in heat recovery in tropical countries like Malaysia was yet to be explored. Hence, the potential of rotating heat pipe in the HVAC systems used in tropics was explored through a parametric study that incorporates rotational speeds, off-axis displacements and varied refrigerants. The rotating heat pipes charged with R134a, R22 and R410A were tested with varied radial displacement from the rotational axis. The straight and leveled heat pipe with the furthest radial displacement yields the most significant heat transfer, which was attributed to the magnitude of the generated centrifugal force, and effective distribution of liquid in the evaporator.

1. Introduction

The need of reducing the consumption of the depleting energy resources and production of the greenhouse gasses that resulted in global climate change has been deemed necessary for a creating a sustainable future. Energy was extensively used in the heating, ventilating and air conditioning of a building to provide a comfortable environment for the occupants residing within it. Hence, the need of heat recovery devices, such as heat pipes, arises to reduce the energy consumption of the HVAC systems. Heat pipes are generally two phase heat transfer devices with very high thermal conductance. The heat pipe primarily consists of three main components; which are the container, working fluid and the wicking structure. Heat pipes transport heat by absorbing heat when the working fluid liquid evaporates at the evaporator and releasing the heat when the vapor condensates at the condenser as illustrated in Fig. 1(a).

The working fluid, which is the heat transport medium, is the most important component of the heat pipe. A good working fluid should be compatible with the heat pipe materials, have good thermal conductivity and stability, high latent heat of evaporation, high surface tension, low liquid and vapor viscosities, good wettability, reasonable vapor pressure over operating temperature range and suitable freezing point. Working fluids such as water, ammonia, methanol and ethanol have been proven useful in the comfort temperature range in the past. Refrigerant such as Freon was used in the heat pipe for air conditioning back in the 1980s [1]. However, the HCFC refrigerants replaced CFC refrigerants were subjected to phase-out under the Montreal Protocol due to its ozone-depleting potential.

Nowadays, refrigerants such as R22, R134a, R407C and R410A are common in the HVAC equipments and these refrigerants are readily available in the market for a reasonable price. Some of these refrigerants have been used in the heat pipe researches, such as the study of R22-charged thermosyphon solar collector done by Than et al. [2]. A performance study of R134a-filled thermosyphon was done by Ong and Haidar-E-Alahi [3]. An experimental investigation of convective heat transfer coefficient during downward laminar flow condensation of R134a in a vertical smooth tube has been conducted by Dalkilic et al. [4]. Esen and Esen [5] have conducted a study of R134a, R407C and R410A thermosyphon solar water heater. Akhavan-Behabadi et al. [6] have also studied the condensation heat transfer of R-134a inside a microfin tube with different tube inclinations. The results from their study revealed that the tube inclination angle affects the condensation heat transfer coefficient in a significant manner. Jung et al. [7] also have presented a comparative study they have conducted flow condensation heat transfer coefficients of R22, R134a, R407C, and R410A inside plain and microfin tubes. The results from their study show that the heat transfer coefficient of a microfin tube was 2–3 times higher than those of a plain tube and they show that the heat transfer enhancement factor decreased as the mass flux increased for all refrigerants tested. The advantage of using these refrigerants can be summarized by their suitable operating temperature in the comfort range, ease in charging heat pipe from pressurized cylinder, availability and cost.

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Nomenclature

a_c	centrifugal acceleration (m/s^2)
ASCII	American Standard Code for Information Interchange
CFC	Chloro Fluoro Carbon
h	Heat Transfer Coefficient
HCFC	Hydro Chloro Fluoro Carbons
HFC	Hydro Fluoro Carbon
HVAC&R	Heating, Ventilating and Air Conditioning and Refrigeration
N	Rotational Speed (Hz)
Nu	Nusselt Number
Pr	Prandtl Number
$\dot{q}$	Heat Rate per Unit Area
r	Radius of Curvature (m)
Re	Reynolds Number
RHP	Rotating Heat Pipe
RPM	Round Per Minute
v	Instantaneous velocity (m/s)
ΔT	Evaporator test chamber air temperature difference
Greek	
Ω	Angular Velocity (rad/s)

Rotating heat pipes (RHP) are the types of heat pipes that utilize centrifugal force generated by the rotating motion to return the condensate as shown in Fig. 1(b). The container of the conventional RHP is slightly tapered axially to promote better condensate return. An RHP with taper angle of α and rotating at angular velocity ω will generate centrifugal acceleration $r\omega^2 \sin \alpha$on the condensate along the container wall and hence, the presence of the centripetal force onto the heat pipe enhances the return of the liquid significantly. Conventional RHP has both the condenser and evaporator on axis of the rotation.

The generated centrifugal force due to the rotating motion could be utilized for the return of the liquid condensate from the condenser to the evaporator section [8]. They can quickly transfer heat in any rotary equipment and at any orientation. However, there are also RHPs that have the evaporator or even the condenser being off-axis from the rotational axis. These RHPs have been called revolving heat pipe in some past researches [9,10]. Song et al. [11] presented an experimental investigation on the heat transfer characteristics of axial rotating heat pipes. The comparison study between the test results and the predictions from previous models showed that the natural convection in the liquid film at the heat pipe evaporator played an important role in the heat transfer mechanism at high rotational speeds. A numerical study has been presented by Nobari and Gharali [12]. In this study, they have simulated the flow and heat transfer in internally finned rotating straight pipes and stationary curved pipes. The use of RHP in cooling electrical motors has been explored in the past researches, which includes the incorporation of rotating heat pipe in the motor shaft and radially displaced RHP on the motor armature [13–15]. The application of radially displaced RHP in rotary heat exchangers for high temperature applications has also been explored by Okamoto [16]. However, the integration of radially displaced RHP in centrifugal blowers operating in comfort temperature ranges was yet to be fully explored. Generally, the liquid film thickness in the evaporator section of RHPs is usually much smaller than the film thickness in other heat pipes. It is usually smaller than the diameter of typical vapor bubbles (0.1–1 mm) [17]. Therefore, the film evaporation would occur rather than nucleate boiling.

Unfortunately, literature survey shows that a comparison heat transfer study between three different refrigerants, namely R134a, R22, R410A in the inclined revolving heat pipes has not been done up to this point. This study gives comprehensive information of the potentials of using revolving heat pipes in the HVAC systems, especially in heat recovery, dehumidification enhancement and cooling of machineries.

2. Overview of the theory relevant to the present research

The theory relevant to the present research was described in [18]. The details are repeated here for convenient reference. The literature review shows that many early studies had been focused on the single-phase heat transfer of fluids flowing in a smooth tube. They have been conducted to develop a correlation in order to model the heat transfer coefficients in other geometries. Among all, the most widely used single-phase correlation in a pipe is the well-known Dittus–Boelter equation [19]:

$$Nu = 0.023\, Re^{0.8}\, Pr^{0.4} \tag{1}$$

where Re represents the fluid Reynolds number, Pr is the Prandtl number, and Nu is the Nusselt number. The two-phase heat transfer coefficient modelling has been done by Bergles and Rohsenow [20]. The experimental data for evaporation of refrigerant R134a, R22 and R410A in a straight revolving heat pipe heat exchanger of this study can be used in developing a more precise two-phase flow correlation. The thermodynamic and transport properties of the refrigerants used in this study are presented in Table 1 [21,22]. Generally, the heat transfer coefficient, h, is defined by the following equation:

$$h = \frac{\dot{q}}{\Delta T} \tag{2}$$

where $\dot{q}$ is the heat rate per unit area and ΔT is the evaporator test chamber air temperature difference. Since the heat pipes are revolving, the centrifugal acceleration that pressed the liquid refrigerant against the container walls could be generally represented by Eq. (3).

$$a_c = \frac{v^2}{r} = \omega^2 r = 4\pi^2 N^2 r \tag{3}$$

The centrifugal force acting on the return flow of the working fluid liquid back to the evaporator was dependent to the radius of rotation and square of rotational speed. The increase in the radial displacement or rotational speed will promote better liquid return to the evaporator and would improve the heat transfer capabilities. However, this relation was not necessarily applicable for all the cases, as the heat transfer characteristic depends on the heat pipe orientation on the rotational axis.

The centrifugal force generated from the rotating heat pipe will tend to push the denser fluid, which was the liquid, away from the rotational axis. However, there was also gravitational force that constantly acted upon the liquid, which will always pull the liquid towards the center of the Earth. Hence, the heat pipe will be required to rotate fast enough to generate enough centrifugal force to maintain a liquid film that was always situated away from the rotational axis. The liquid film was important in analyzing the liquid flow within the straight heat pipe.

An operational rotating heat pipe will absorb heat at the evaporator section through the evaporation process and dissipate heat at the condenser section through the condensation process that occurred within the heat pipe. The liquid film on the evaporator section thins when the liquid evaporates from the inner surface of the container and the liquid film on the condenser section thickens when the vapor condensates. The level difference of the liquid films and hydrostatic head generated from the rotating motion produces a pressure difference within the liquid that subsequently induced the liquid flow that returns