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A two-phase closed thermosyphon with an adiabatic section using a flexible hose and R-134a filling

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ABSTRACT

This research aimed to investigate the effects of bending and tilting in a flexible hose thermosyphon (TS) on thermal performance. The adiabatic section of the TS was constructed of a Teflon hose with an inner diameter of 12.7 mm, while the evaporator and condenser were made of straight copper tubing with an identical diameter of 17.4 mm. The proposed TS was charged with R-134a refrigerant. The effects of bending positions and tilt angles on evaporator temperature, flow resistance, overall thermal resistance and heat transfer characteristics (Q/Q_{90}) were tested in comparison with a TS that is vertically oriented. At the same tilt angle, bending at the upper end of the flexible hose would decrease TS performance more than bending at the lower end. Bending at both ends would result in the lowest TS performance. The optimum tilt angle for most cases was 45°, except for the case with bending at both ends, which was 60°.

1. Introduction

Effective heat transfer devices, such as heat pipes, are indispensable components in modern electrical appliances. In addition to being energy-efficient, a heat pipe is a maintenance-free device with a long lifespan. In general, the design of a heat pipe depends upon heat load, surface area in contact with the heat pipe and operating temperature. The single thermosyphon (TS) is a subset of heat pipes and the simplest heat transfer device used extensively in various applications. Most studies of TS heat pipes involve TS performance, which can be considered in terms of heat transfer limit, range of operating temperature and overall thermal resistance. There are several factors having a significant influence on TS performance, namely filling ratio, aspect ratio (L_E/d_i), and heat load, as well as mass flow rate and inclination angle, according to Aniket and Ravindra [1]. The effects of coolant mass flow rate and the filling ratio of R-134a on the performance of a vertically-oriented TS heat pipe were also investigated experimentally by Ong and Haider-E-Alahi [2]. In addition to vertical orientation of the TS and R-134a, Payakaruk et al. [3] studied the effect of aspect ratio (L_E/d_i) on heat transfer characteristics of an inclined TS filled with R22, R123, R-134a, ethanol and water. It was found that the filling ratio had no effect on the ratio of heat transfer at any angle to that of the vertical position (Q/Q_{90}), but the working fluid affected the maximum of Q/Q_{90} at an inclination angle from 40° to 60°. Their developed correlation between Kutateladze number (Ku) and aspect ratio could be used to predict Q_{max}/Q_{90}. Noie [4] also reported the optimum filling ratio at which a vertical TS, filled with distilled water, operates at its best conditions for a certain aspect ratio. The enhancement of TS heat pipe efficiency with nanofluids (R11 + titanium nanoparticles) was presented by Naphon et al. [5,6]. Thermal efficiency was adequately higher than the based working fluid. The optimum tilt angle of the TS was 60° for pure refrigerant and 45° for mixture working fluid. The use of R-134a TS heat pipe for solar pond applications was examined with an inclination of 60°, Tundee et al. [7]. As those presented in [3,5–7], it can be seen that an inclination angle ranging from 40° to 60° has a good effect on the high performance of the TS for any working fluid. Further investigation on bending, in addition to inclination of the heat pipe, was done by Odhekar and Harris [8]. The experiments were conducted with sintered-metal felt wick heat pipe, of which the adiabatic section was bendable. Bending of the adiabatic section would affect the buildup of evaporator temperature at constant heat input and the reduction of heat pipe performance. Schweickart and Bunchko [9] presented the application of flexible wick heat pipe using ammonia as the working fluid for cooling inside the space camera. The results showed that the temperature drop was based on the average evaporator and condenser temperatures, as well as the derived conductance requirement of 5.5 W/K prior to dry-out at 30 W. The effects

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Nomenclature

A	cross-sectional area $\left(\pi d_i^2/4\right)$ (m^2)
b	arc of circle (mm)
c_p	specific heat capacity (kJ/kg °C)
d	diameter (mm)
E	electric voltage (V)
$f_1 f_2 f_3$	function of entrainment or flooding limit
FR	filling ratio (V_l/V_t)
g	gravity acceleration (9.81 m/s^2)
h_{fg}	latent heat of vaporisation (kJ/kg)
I	electric current (A)
K	modified Kutateladze number (0.135)
L	length (mm)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (Pa)
Q	heat transfer rate (W)
q	heat flux (kW/m^2)
R	bend radius (mm)
S	surface area $(\pi d_o L)$ (m^2)
T	temperature (°C)
V	volume (ml)
Z	overall resistance (K/W)

Greek symbols

ρ	density (kg/m^3)
σ	surface tension (N/m)
β	tilt angle (°)
Δ	difference
μ	viscosity (Pa s)

Subscripts

a	adiabatic
ave	average
b	boiling
C	condenser
$crit$	critical
E	evaporator
e	entrainment
i	inner
in	input, inlet
l	liquid
max	maximum
o	outer
out	output, outlet
s	sonic
t	total
v	vapor
w	water

of bending on a counter-current motion inside a TS heat pipe could be visualized using the neutron radiography technique proposed by Tsuji et al. [10]. The adiabatic section was inclined to an angle of 45°, while the evaporator and condenser were vertically oriented.

As mentioned earlier, study of the effects of working fluid, pipe geometries, inclination, fixed bending and filling ratio on the performance of TS has been conducted extensively. However, there have been few such studies on a flexible hose TS. In practice, limitations exist on the use of heat pipes in several applications to remove heat from areas difficult to access to mount the pipes. In many cases, various components must be added to an electrical cabinet to serve clients' additional demands. This results in higher heat load. As the heat load in the cabinet increases and exceeds the capability of the existing heat removal system, an auxiliary heat removal system becomes essential. Thus, a flexible hose that can be bent repeatedly has been selected for this research study. The current research aims to investigate the effects of bending position and tilt angle on the efficiency of a TS with a flexible hose adiabatic section that is bendable and filled with R134a.

2. Experimental apparatus and test procedure

2.1. The fabrication of a TS with a flexible hose adiabatic section

Fig. 1 presents the schematic and dimensions of the TS in this research work. The proposed TS was constructed of three sections: the evaporator, adiabatic and condenser sections with a total length of 1050 mm. This TS with a length to diameter ratio (L_t/d_i) of 77 and L_a/d_i of 55 could be classified as part of the same group of long pipes that was proposed by many researchers with the pipes having L_t/d_i of 33 [11], 40 [12], 94 [13] and 188 [14]. The evaporator section is fabricated from a straight copper tube with a 17.4 mm inner diameter. It is 100 mm in length and connected to the adiabatic section by a taper joint. The heat flux is enhanced by a bell mouth (taper joint) installed at the vapor entrance, which is better than having no bell, Inoue and Monde [15]. The adiabatic section is made from a Teflon hose with 12.7 mm inner diameter, 18.5 mm outer diameter and 700 mm length. The Teflon hose is sheathed in a stainless steel flex pipe to provide additional strength, but the effect of the polymer on the heat transfer characteristics was not a consideration. The condenser section is fabricated from a straight copper tube 150 mm in length and with a 17.4 mm inner diameter, and retained inside a cooling chamber. In this study the inner diameter of the adiabatic section is different from those of the evaporator and condenser sections. This is because the electrical cabinet in practice needs a large boiling area, but it has a narrow space for bending the pipe to reject heat on the outside of the cabinet. Therefore, the experimental under additional pressure losses from the different diameters it must be choice.

2.2. Experimental setup

The experimental apparatus consists of a TS, an electric heater, a cooling system and a data acquisition system. The evaporator of the pipe was inserted into the cylindrical electrical heater, which was insulated on the outside surface. The heat supplied to the evaporator was regulated by an AC power supply. The pipe was laid on the test rig. The inclined angle, with respect to the horizontal plane, was adjustable, as shown in Fig. 2. During operation, the condenser section was cooled down by flowing cold water from a cold water tank through a control valve for heat exchange in a condenser section before returning to the storage tank. The outgoing water from the condenser was controlled by a control valve and converted to mass flow rate using a digital weight balance with an accuracy of ±1.0%. The cold water storage tank had a capacity of 0.15 m^3. A type K thermocouple with an accuracy of 0.1% was used to measure the temperature.

2.3. Testing condition

The experiment was carried out with the flexible TS consisting of an adiabatic section that was bendable. R-134a was charged into