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Experimental investigation of a two-phase closed thermosyphon charged with hydrocarbon and Freon refrigerants

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HIGHLIGHTS

- Study of HCs and Freon as TPCT working fluids for renewable energy applications.
- Experimental performances of TPCTs were studied with eight working fluids.
- R245fa/R152a, R600a, and R1234ze were recommended as substitutes for R134a.
- Suitability of typical HTC correlations were analysed for the TPCT working fluids.
- A simplified Rohsenow correlation was developed to further improve accuracy.

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ABSTRACT

Two-phase closed thermosyphons (TPCTs) are simple, efficient, and low cost heat exchangers. They have been explored for use in the renewable energy resource utilization marker and low grade thermal energy heat recovery systems. Freon R134a has been extensively used in refrigeration systems and researched as a working fluid of TPCTs; however; it has high global warming potential and operating pressure. In this paper, an experimental investigation of the performance of TPCTs charged with eight working fluids: R134a, R601, R245fa, R600a, R1234ze, R152a, R245fa/R152a, and R601/R245fa have been carried out. The experimental results showed that R245fa/R152a offered the best performance in maximum heat transfer rate. R134a outperformed the other pure working fluids, while R600a and R1234ze had close performances to that of R134a. R245fa showed marginal improvement at higher operating temperatures. The predictions of six evaporation heat transfer coefficients (HTCs) correlations, including Imura, Shiraishi, Labuntsov, Kutateladze, Cooper, and Rohsenow were compared with the experimental results. In the five constant coefficients and powers correlations, the Shiraishi and Cooper correlations had superior accuracy. The coefficients and powers of the Rohsenow correlations fitted based on the experimental data, while they had the best accuracy. Nusselt and Hashimoto-Kaminaga correlations were chosen to predict the condensation HTCs. Both of them tend to over-predict the condensation HTCs in low heat fluxes while under-predicting in high heat fluxes. The experimental results had greater agreement with Hashimoto and Kaminaga correlations.

1. Introduction

The two-phase closed thermosyphons (TPCTs) have been extensively used in a wide range of engineering applications [1,2]. With energy savings and environmental protection being increasingly important, the TPCTs have been explored and applied in renewable energy resource utilizations [3–16] and electronic equipment cooling systems [17–19], etc. There has been much research and investigation into the effect of various parameters such as working fluids, filling ratios, inclination angles, aspect ratios, geometries, and vibration with respect to the performances of TPCTs. The properties of working fluids play an important role in the performance of TPCTs. For operating conditions in the medium temperature region, purified water is usually recommended as the preferred working fluid. However, in some applications, water is not suitable for its low operating pressure and high freezing temperature [20]. Freon refrigerants, methanol, ammonia, CO_2, etc. have been explored as working fluids of TPCTs in low to medium temperature regions.

In oilfields, some researchers have applied long scale TPCTs, which are made of coupled hollow sucker rods to transfer heat

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Nomenclature

c_p	specific heat capacity (kJ kg^{-1} K^{-1})
D_i	internal diameter (mm)
D_o	external diameter (mm)
g	gravitational acceleration (ms^{-2})
HTC	heat transfer coefficient (Wm^{-2} K^{-1})
h	heat transfer coefficient (Wm^{-2} K^{-1})
h_{fg}	latent heat of vaporization (J kg^{-1})
K	thermal conductivity (Wm^{-1} K^{-1})
L	length (m)
L_b	Bubble length scale (m)
m	mass flow rate (kg s^{-1})
P	pressure (Pa)
Q	heat transfer rate (W)
q	heat flux (Wm^{-2})
T	temperature (°C)
T_e	average temperatures of inner/outer wall of the TPCT in evaporator section (°C)
T_c	average temperatures of inner/outer wall of the TPCT in condenser section (°C)
T_v	saturated temperature of working fluid/average temperature of outer wall in the adiabatic section (°C)

Greek symbols

μ	dynamic viscosity (Nsm^{-2})
ν	kinematic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})
σ	surface tension (Nm^{-1})

Subscripts

a	average
atm	atmospheric
b	water bath
c	condenser section
e	evaporator section
exp	experimental
i	inlet
l	liquid
o	outlet
pred	predicted
sat	saturation
v	vapour
w	water

from the wellbore bottom crude oil to the wellbore top crude oil. This application of TPCTs can effectively improve the temperature of crude oil and save a large amount of steam. Wu et al. [3,4] have evaluated the performances of water, R113, and methanol, while methanol was recommended for its good performances. Zhang et al. [5] investigated the performances of a TPCT with a length of 770 m and ammonia as the working fluid. The results showed average wellhead temperature of the TPCT well at approximately 63 °C and 10 °C higher than the regular well. Jia et al. [6] applied a near 1600 m long TPCT with a mixture as the working fluid to improve wellhead crude oil temperatures from 22 °C to 39 °C when the wellbore bottom crude oil temperature was 66.9 °C at the depth of 1600 m.

In the application of geothermal energy utilization, TPCTs and loop types have been explored to extract heat from geothermal energy for district heating. Mochizuki et al. [7] developed a large scale loop type TPCT that was 150 m in length and had a 150 mm outer diameter to extract heat from underground water. It extracted 90 kW of heat at an 80 °C working temperature that used water as the working fluid. Carotenuto et al. [8] utilized a geothermal convector (GTC), which is a special TPCT, to withdraw heat from aquifers. The depth of the well was 20.3 m; the aquifer thickness was 8.3 m, while R11 was chosen as the working fluid. The temperature of the geothermal fluid entering the evaporator was in the range of 54 °C–70 °C and the maximum value of heat flow was approximately 25 kW. Ebeling et al. [9] have experimentally and theoretically investigated the performances of two types of geothermal TPCTs with a length near 400 m, which transferred the heat extracted from soil for use by heat pumps for district heating. CO_2 was selected as the working fluid, and the design heat load was 25 kW for both of the TPCTs.

There exist a number of applications for TPCTs in the solar energy field. The use of TPCT collectors in solar water heating systems has gradually increased to solve problems like corrosion, fouling, and freezing that occur in traditional ones [21]. Commonly, the operating temperature of working fluid is in the range of 40 °C–70 °C. Acetone [21], petroleum ether [21], ethanol [22], distilled water [23], and recently nanofluids [24] have been investigated as working fluids. While Freon refrigerants for their non-toxic, low freezing point, stable, good material compatibility, etc., have been more extensively used in thermosyphon collectors. In the early stages of research, chlorofluorocarbons (CFCs) and hydrochloro-fluorocarbons (HCFCs) refrigerants including R11 [25], R113 [26], R123 [27], etc. were researched and evaluated. With CFCs and HCFCs gradually phased out, the non-ozone depleting potential alternative HFC refrigerants have been introduced. Samanci and Berber [10] compared the performance of an R134a TPCT flat-plate solar collector (FPSC), with a length of 780 mm and inner diameter of 25.5 mm, to that of a traditional one. The results showed that the efficiency was substantially increased by using the TPCT collector. Esen and Esen [11] investigated three TPTC-FPSCs, with a length of 1050 mm and outer diameter of 6.32 mm, using R134a, R407C, and R410A as the working fluids, respectively, while R410A offered the highest efficiency. Ordaz-Flores, etc. [12] investigated the performance of R410A, acetone, and R134a in TPCT-FPSCs. The results showed that R410A and R134a offered equivalent performances compared to single phase water, but their operating pressures were high. Acetone showed lower performances but had a suitable operating pressure. Enaburekhan and Yakasai [13] evaluated the performances of R134a, R12, and ethanol as the working fluids in a TPCT-FPSC, with a length of 1150 mm and outer diameter of 2.5 mm, which concluded that R134a provided the best performance. HFC refrigerants are also used as working fluids when TPCTs are explored in solar cookers [14], salinity-gradient solar ponds [15], and other solar applications.

In other applications, Zhang et al. [17] conducted tests on a TPCT exchanger, with a length of 870 mm and inner diameter of 16 mm, used for cooling a communication base station in replacement of the current air conditioning system. R134a was used as the working fluid in the exchanger. The experimental results proved that the TPCT exchanger could reduce the run time and operating cost of the air conditioning system. Further calculations showed that an 18.7%–48.6% annual electricity savings rate could be achieved among the five selected cities. Jouhara and Robinson [18] experimentally investigated the performances of a small diameter and compact thermosyphon, with a length of 200 mm and inner diameter of 6 mm, for electronics cooling with water and dielectric fluids including FC84, FC77, and FC3283. MacGregor et al. [19] experimentally researched a TPTC, with a length of 2200 mm and outer diameter of 15.82 mm, for potential applications including air to air heat exchangers. Five working fluids were

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