



Investigation of low Global Warming Potential working fluids for a closed two-phase thermosyphon



Robert W. MacGregor^{a,*}, Peter A. Kew^c, David A. Reay^b

^a AECOM, 1 Tanfield, Edinburgh EH3 5DA, UK

^b David Reay & Associates, PO Box 25, Whitley Bay, Tyne & Wear NE26 1QT, UK

^c Heriot-Watt University, Dubai Campus, Dubai International Academic City, PO Box 294345, Dubai, United Arab Emirates

HIGHLIGHTS

- ▶ Study of low GWP working fluids for thermosyphons.
- ▶ Thermal conductivity tested for four different working fluids.
- ▶ Validity of prediction models for the experimental results reviewed.
- ▶ Water–5% ethylene glycol can outperform R134a with a suitable temperature drop.
- ▶ The prediction model was found to have mixed results dependent on working fluid.

ARTICLE INFO

Article history:

Received 5 May 2012

Accepted 28 October 2012

Available online 7 November 2012

Keywords:

Two-phase thermosyphon

Working fluids

Performance comparison

ABSTRACT

Two-phase thermosyphons are devices offering very high thermal conductance. The study reported here examined two-phase thermosyphons of length 2200 mm and external diameter 15.9 mm. Potential applications include air to air heat exchangers with operating temperature ranges of -10 – 50 °C for the ambient (cold) side and 60 – 80 °C for the hot side.

The work is prompted by the fact that R134a, used in similar units, will be subject to a ban in the future as it has a high Global Warming Potential. A shortlist of potential replacement fluids was drawn up, and considering the environmental, operating and storage conditions, and cost, five were selected for tests in representative thermosyphons.

The results of the experimental work showed a water–5% ethylene glycol mixture was a suitable replacement fluid, although under certain conditions its performance was less than that of R134a. The tests also showed water alone can give the highest heat transfer, although it is not suited to the target temperature range, and methanol did not perform as well as R134a for most of the experimental range.

A predictive model based on the equations published by ESDU International was developed. It was found to give good results for water, workable results for water–5% ethylene glycol, be of limited use for methanol and be unsuitable for R134a.

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1. Introduction

Two-phase thermosyphons are devices offering high heat transfer rates, and are essentially sealed hollow tubes containing a working fluid in liquid and vapour forms. They have many applications, including as elements in heat exchangers.

The thermosyphons in an air–air heat exchanger application currently use R134a as the working fluid for the target temperature

ranges of -10 – 50 °C on the cold side and 60 – 80 °C on the hot side. Storage temperatures can be as low as -30 °C. While performance is adequate with R134a, there are compelling reasons to investigate a replacement:

- At the upper end of the operating temperature range, the vapour pressure reaches about 30 bar.
- R134a is one of the replacement refrigerants for the CFCs but it has a large Global Warming Potential (GWP).
- Fluids such as R1234ze [22] have been proposed as replacements for HFCs.
- Theory suggests other fluids could perform better.

* Corresponding author. Tel.: +44 7988 392 559.

E-mail addresses: rwm1974@yahoo.co.uk, robert.macgregor@aecom.com (R.W. MacGregor).

Nomenclature (Based on ESDU (5))		ΔT_h	mean temperature difference due to hydrostatic head K
A	cross-sectional area, $\pi D^2/4 \text{ m}^2$	z	thermal resistance K W^{-1}
c_p	specific heat capacity $\text{J kg}^{-1} \text{K}^{-1}$	λ	thermal conductivity $\text{W m}^{-1} \text{K}^{-1}$
D	internal diameter m	μ	dynamic viscosity N s m^{-2}
D_o	external diameter m	ρ	density kg m^{-3}
f_1, f_2, f_3	functions in flooding limit	σ	surface tension N m^{-1}
F	liquid fill = fraction of evaporator covered by static pool	ϕ_2	figure of merit for condensation $\text{kg K}^{0.75} \text{s}^{2.5}$
g	acceleration due to gravity m s^{-2}	ϕ_3	figure of merit for nucleate boiling
h	heat transfer coefficient, wrt internal diameter $\text{W m}^{-2} \text{K}^{-1}$	Subscripts	
L	latent heat of vaporisation J kg^{-1}	c	condenser
l	length m	e	evaporator
p_a	atmospheric pressure Pa	f	liquid film
p_p	pressure at the bottom of the pool Pa	h	hydrostatic head
p_v	vapour pressure Pa	l	liquid
Q	rate of heat transfer W	max	maximum
Re_f	liquid film Reynolds number in adiabatic section	o	external dimension
S	surface area = $\pi D l \text{ m}^2$	p	pool nucleate boiling
T	temperature K	si	heat sink
ΔT (dT on graphs)	effective overall temperature difference (T_{so} – T_{si} – ΔT) K	so	heat source
		v	vapour
		x	container wall

1.1. Background

Thermosyphon tubes typically have two sections, the evaporator where heat is applied, causing the liquid to evaporate, and the condenser where the evaporated vapour is cooled and condenses to a liquid. Some units have an adiabatic section located between the evaporator and condenser. Liquid formed in the condenser runs back down the tube walls to the evaporator section. For the liquid to run back to the evaporator solely through the influence of gravity, in conventional thermosyphons the condenser must be positioned above the evaporator [1].

To compare the performance of different fluids, the overall performance is best understood in terms of the thermal resistance. Thermal resistance is given by:

$$z = \frac{\Delta T}{Q} \quad (1)$$

ESDU [5] proposes a description of how to find z , for circular cross-section pipes, with single component working fluids. The thermosyphon is viewed as a series of thermal resistances that can be individually calculated and then combined to give the overall figure. This is discussed in Section 2.

1.2. Previous work on thermosyphons

There have been many previous studies of thermosyphon performance. The most relevant are discussed below and are tabulated later in the paper (Table 3) where their reported results may be compared with the data from this study.

Dobson and Pakkies [6] used an experimental design similar to the test rig for this study. They selected R134a as the working fluid and found heat transfer capabilities of 400–1500 W, for ΔT of 10–50 °C. Internal heat transfer coefficients were 2–10 $\text{kW/m}^2 \text{K}$ for the evaporator and 1–4 $\text{kW/m}^2 \text{K}$ for the condenser.

Tundee et al. [24] studied the use of heat pipe heat exchangers (acting as thermosyphons) to remove heat from the bottom of solar ponds also using R134a as the working fluid. The temperature range of the heat source (the lake) was 26 °C–70 °C.

Nguyen-Chi and Groll [7] carried out research on a 2.5 m long, 20 mm diameter copper thermosyphon with water fill. They measured performance across a range of thermosyphon inclination angles, but no measurements were made on vertical units. They used an 88 g fill of water, giving a fill ratio of 0.38, the fill ratio being the ratio of the working fluid volume in liquid state to the volume of the evaporator.

Joudi and Witwit [8] used various lengths of 20 mm internal diameter copper pipe, with water fill. The evaporator and condenser lengths were kept constant at 100 mm and 150 mm, while the adiabatic section was changed, values of 100, 300 and 700 mm were chosen. A much longer thermosyphon was examined by Wright [9] who tested a 16 m thermosyphon also with water fill. This was analysed using ESDU data [5]. It was found that the results were not in good agreement with the ESDU equations for the condenser, the experimental unit having 3–4 times the predicted resistances. It was suggested that incomplete wetting may have been the reason.

Ong and Haider-E-Alalhi [10] looked at hysteresis in thermosyphons using R22, R134a and water. A 780 mm long and 28 mm diameter thermosyphon was tested with ΔT s ranging from 0 to 25 °C, while Nuntaphan et al. [11] studied the higher temperature (>100 °C) use of a mixture of triethylene glycol (TEG) and water. It was found that the mixture performed well, and can extend the flooding limit. It was also found that the ESDU equations were effective in predicting the performance of the mixture.

The use of thermosyphons where freezing might be expected is in permafrost regions. Ammonia is the fluid of choice, as in the trans-Alaska pipeline [1] and more recent work by Zhang et al. [25] on the use of such ammonia thermosyphons to prevent subsidence over the permafrost region of the Qinghai-Tibet Plateau section of a major rail link confirmed their effectiveness. Mixtures were considered, however – including the use of ethylene glycol mixtures as discussed below.

Other work on mixtures included that of Imura et al. [12] who examined start up behaviour from the frozen state of thermosyphons using water–ethylene glycol mixtures of various concentrations. They found that glass test tubes cooled to –20 °C and –40 °C did not break when ethylene glycol was present in concentrations as low as 1%. Further work was carried out using

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