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An investigation into the use of water as a working fluid in wraparound loop heat pipe heat exchanger for applications in energy efficient HVAC systems

Hussam Jouhara [a], [*], Richard Meskimmon [b]

[a] Institute of Energy Futures, College of Engineering, Design and Physical Sciences, Brunel University London, UB8 3PH, UK
[b] S & P Coil Products Ltd, SPC House, Evington Valley Road, Leicester, LE5 5LU, UK

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ABSTRACT

Wraparound heat pipes have been used for many years and have found a niche application in outside air handling units in hot and humid climates. They are used in conjunction with primary, chilled water cooling coils to enhance the efficiency of moisture removal and ensure that the process consumes minimal energy. The type of heat pipe employed is a gravity assisted thermosyphon which is formed into a loop and ‘wrapped’ around the main cooling coil.

The traditional working fluid for HVAC heat pipes has been a refrigerant and a replacement fluid is desirable as a short and long-term option. From an environmental standpoint, water is an ideal candidate and many of its thermal transport properties suggest that it should be viable. There are manufacturing issues associated with using water which are not the concern of this paper; the paper's intention is to prove the viability of water and compare its performance with that of traditional refrigerants.

At the conditions used for the experimentation, the results suggest that the use of water in a loop heat pipe can enhance the effectiveness of the arrangement by up to 18% when compared with a conventional refrigerant filled pipe.

The type of thermosyphon, or gravity-assisted heat pipe, that is under consideration has a performance which can be quantified using an effectiveness model. This model has been used in the investigation to compare the performance of identical pipes filled with different working fluids. The effectiveness of the heat pipe is determined by many variables and a good proportion of these are related simply to tube orientation, size and flow path. The application of wraparound heat pipes that is under consideration relies upon specific sizes and orientations of tubes and the conclusions of the report give pointers towards further research which needs to be undertaken, or is currently underway, in order to determine the extents of applicability of water as a working fluid.

1. Introduction

The ventilation of occupied spaces subject to hot and humid climates consumes vast quantities of energy. In such regions, the moisture load is extremely high with external moisture contents of up to 25 g/kg being common. In order to refresh the internal air with air at a lower moisture content, chillers and cooling equipment must be sized to deal with these exceptionally high latent loads. Heat pipes have been utilised in these applications for around 20 years and have realised significant energy savings [1–3].

The dehumidification of outside air involves it being overcooled to remove moisture and then reheated to a suitable supply temperature. The process is energy consumptive and dehumidifier heat pipes are used, wrapped around the primary cooling coil. The heat pipe precools the air prior to it reaching the cooling coil and then reheats it downstream of the cooling coil. In effect the heat pipe transfers heat around the cooling from the warmer upstream air to the cooler air from the cooling coil. This combination of free cooling and free reheating serves to justify the inclusion of the heat pipe in the ventilation system whenever considerable amounts of moisture need to be removed.

A number of studies have been undertaken to describe and quantify the economic benefits of heat pipes in these applications.

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[*] Corresponding author.
E-mail address: hussam.jouhara@brunel.ac.uk (H. Jouhara).

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Nomenclature

Symbol

K	Thermal conductivity (W/m K)
Hfg	Latent heat of vaporisation (kJ/kg)
S	Associated Error
T	Temperature (°C)
Greek Symbols	
ε	Effectiveness
μ	Viscosity (Pa s)
ρ	Density (kg/m^3)
Φ	Figure Of Merit
Subscripts	
l	Liquid

Ahmadzadehtalatapeh and Yau [4–6] reviewed the system performance and enhancements associated with the introduction of the heat pipes based on R134a as the working fluid and concluded that energy savings and enhanced dehumidification are achieved. These studies are based on generic heat pipes and do not comment on the suitability or otherwise of the working fluid.

Jouhara and Ezzuddin [7] and *Jouhara and Meskimmon* [8] determined performance characteristics for the type of heat pipe used for enhanced ventilation i.e. loop type heat pipes wrapped around cooling coils. An experimental arrangement was designed to allow the determination of the overall thermal resistance of the loop heat pipe and these tests were again based on the use of R134a.

Refrigerants were identified as ideal working fluids for heat pipes, operating at temperatures common to air conditioning applications, around 30 years ago. Original fluids included R12 and R22 though these were quickly phased out in most regions and replaced by R134a.

The Montreal protocol, which came into force in 1989, phased out ozone depleting refrigerants such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) and was responsible for the demise of R12 and R22 and the widespread adoption of R134a as the preferred heat pipe working fluid. R134a is a hydrofluorocarbon (HFC) and is the only type of refrigerant currently used for heat pipes in the EU [9,10].

The properties of R134a (1,1,1,2-Tetrafluoroethane) are given in Table 1.

Due to increased regulations regarding the use of fluids with high global warming impact the focus has now shifted to replacing refrigerants such as R134a. The Kyoto protocol established the phase out of HFCs due to their high GWP [16,17]. The European Parliament and the Council of the European Union have issued regulation (EU) No 517/2014 (F-Gas regulations) which dictates the phase out of different fluids for refrigeration and air-conditioning including many applications of R134a [14,17]. Since 2015, R134a has been banned from use in domestic refrigerators and from 2022 for domestic freezers [18].

Table 1
Properties of R134a [9,11–15].

Molar mass (g/mol)	102.03
Appearance	Colourless gas
Density (g/cm^3)	0.00425
Boiling point (°C)	−26.3
Solubility in water (wt%)	0.15
Flash point (°C)	250
ASHRAE safety classification	A1
100-year global warming potential (GWP)	1300
Ozone depletion potential (ODP)	0
Latent heat of vaporisation (kJ/kg)	217.16
Liquid specific heat capacity (kJ/kg K)	1.34
Vapour specific heat capacity (kJ/kg K)	0.90
Liquid thermal conductivity (W/m K)	0.092
Vapour thermal conductivity (W/m K)	0.01151

As refrigerant R134a has been heavily used for a wide range of domestic and industrial applications, its ban and strict use requires that an alternative working fluid be found. The replacement working fluid must have low GWP to minimise environmental damage, high heating and cooling capacities and zero ozone depletion potential (ODP), making it very challenging to find a replacement fluid, not only in heat pipes but for air conditioning systems in general.

The development of alternative fluids for use in air conditioning and refrigeration is well underway. *Aprea* et al. [17] investigated the potential to replace R134a with HFO1234ze in a domestic refrigerator. The findings suggest that HFO1234ze in domestic applications performs as well as R134a. Other refrigerants such as R1234yf and R1234ze have been investigated by *Sethi* et al. [14] in small refrigeration systems and are finding use in the automotive industry in particular. Both refrigerants show promising results with an improved performance compared to R134a and similar thermodynamic properties. The use of alternative refrigerants appears promising, but there are other issues with many of the replacement refrigerants, particularly stability and flammability. While the replacement refrigerants have GWP values which are extremely low they are not zero meaning that it is likely that at some point in the future they will be outlawed by legislation. Investigations into alternative refrigerants continue but the use of refrigerants with a non-zero GWP will always carry a risk in terms of them becoming obsolete [18,19].

Gedik et al. [20] investigated the thermal performance of a gravity assisted heat pipe system charged with R134a and R410a. The investigation involved the placement of a heat pipe bundle within a duct and the monitoring of the heat recovered in the condenser section. R410a shows good performance but it is not a suitable replacement for R134a due to the reasons cited regarding stability and flammability. *Eidan* et al. [21] investigated a heat pipe based air conditioning system for sub-tropical climates. Water, Methanol, Ethanol, Acetone, Butanol and R134a were all investigated in a gravity assisted system and the results primarily focused on the dehumidification properties and associated effectiveness. The working fluids investigated all showed good operation, with fluids such as butanol and distilled water showing an equal performance with R134a for dehumidification and energy saving. Single pipe systems have been investigated, comparing the performance of water and R134a [22] but no previous investigation of the loop heat pipe comparing water to R134a has been undertaken.

Water has thermal transport properties which make it suitable as a heat pipe working fluid though its applicability across a temperature range in different heat pipe manifestations has not been fully developed. The zero ODP and GWP values of water future proof it so its suitability in terms of performance needs to be assessed. The drivers which pointed heat pipe pioneers towards the use of refrigerants and not water were largely the ease of manufacture of refrigerant based heat pipes. Water at normal temperatures is at very low pressure inside a heat pipe and manufacturing issues related to removing all the air from a water filled pipe made fabrication very expensive. Recent advances in manufacturing technology mean that water filled heat pipes can now be manufactured at a cost similar to that for refrigerant heat pipes [14].

The findings presented in this paper reflect the potential of using water within a Wraparound Loop Heat Pipe instead of conventional refrigerants. The proposed heat pipe was charged with distilled water and tested within HVAC systems operating in hot and humid conditions.

2. Experimental apparatus

2.1. The WLHP design

2.1.1. Heat pipe design

The wraparound loop heat pipes (WLHP) used commercially are described as thermosyphons and rely on gravity for the return of condensed liquid rather than on capillary or other forces. The pipes are constructed from ACR grade copper tubes but they are internally grooved rather than plain. The grooving does not provide any significant capillary advantage but does provide enhanced boiling and condensation of the working fluid and an increased internal surface.

The heat pipes used in the experimentation are 12 mm o/d copper tubes, internally grooved. The tubes are expanded into continuous aluminium fins in an identical fashion to conventional coil blocks and surrounded in a rudimentary sheet metal casing to provide support. Wraparound heat pipes consist of two identical blocks which are joined by wraparound pipes. The tubes within the fin blocks run horizontally while the connecting pipes slope upwards from the precool side to the reheat side to provide an upward path for the vapours and a downward return for the condensed liquid. When used as wraparound heat pipes the fin blocks are typically 1 or 2 rows deep and these are the incarnations used in the tests. Heat pipes can be manufactured with larger numbers of rows; these are only typically used for heat recovery applications and involve the transfer of heat between two separate airstreams.

Fig. 1 shows an example of a single heat pipe loop; two tubes in the precool section connected to two tubes in the reheat section via wraparound pipes. This figure only shows the copper tubes, the continuous aluminium fins have been omitted for clarity.

Fig. 2 (a) is discussed later but shows the actual orientation of the array of heat pipe loops expanded into fins and fitted inside the sheet metal casing. Fig. 2 (b) shows the actual mechanical design of the wraparound heat pipe.

2.1.2. Figure of merit

Thermal transport properties: latent heat of vaporisation, thermal conductivity, surface tension, and viscosity are the main considerations for selecting the heat pipe working fluid.

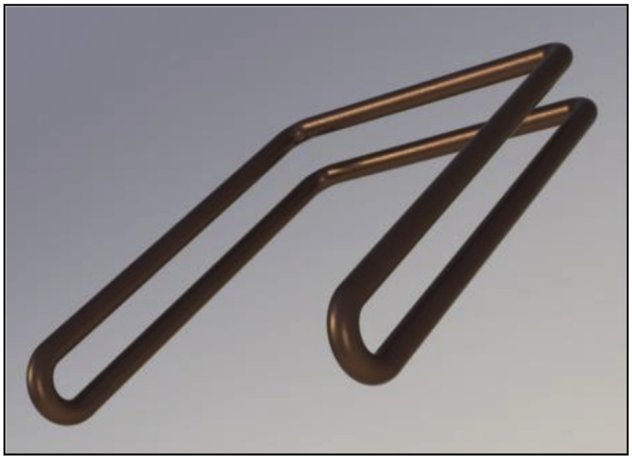

Fig. 1. Single wraparound heat pipe loop.

The influence of the thermophysical properties of the working fluid on the temperature drop for a certain heat transfer rate in a thermosyphon is represented by a Figure Of Merit [23]:

$$\Phi = \left(\frac{h_{fg} k_l^3 \rho_l^2}{\mu_l}\right)^{1/4} \left(\frac{\mathrm{kg}}{\mathrm{K}^{3/4}} \mathrm{s}^{5/2}\right) \qquad (1)$$

A higher merit number suggests a smaller temperature drop along the thermosyphon.

The thermal properties of water and R134a are presented in Table 2.

The variation of the Figure of Merit with operating temperature of the working fluid is illustrated in Fig. 3.

It can be observed from Fig. 3 that the merit number of water increases with increasing operating temperature until it reaches a peak of 7543 kg $\mathrm{K}^{-3/4}$ $\mathrm{s}^{-5/2}$ at 175 °C, while the merit number of R134a decreases with increasing operating temperature reaching a value of 274 kg $\mathrm{K}^{-3/4}$ $\mathrm{s}^{-5/2}$ at 100 °C. In comparing the merit number of water and R134a it can be noted that the merit number for water is 6–24 times higher than for R134a in the operating temperature range of 0–100 °C. In other words, a heat pipe charged with water can transport the same amount of heat against a lower temperature drop than with a heat pipe charged with R134a. The operating pressure of a water heat pipe will be less than that of a corresponding refrigerant pipe at the same temperature due to water's lower saturated vapour pressure. The low operating pressure results in the potential to decrease the wall thickness of the heat pipe which reduces the overall weight and the cost of the system. Furthermore, water is inexpensive, safe, and environmentally-friendly which overcomes the economic and environmental disadvantages of R134a.

2.2. Test rig design

A test rig was developed to demonstrate the wraparound heat pipe and evaluate its thermal performance. A schematic of the test rig is presented in Fig. 4 and exploded assembly details are shown in Fig. 2. The heat pipe system was installed in rectangular galvanised ducting and an axial fan installed at the end of the duct to draw air through. The chiller and cooling coil are used for the experimentation in cooling mode (Fig. 5), these were replaced with an electrical heater (Fig. 4) between the two legs of the heat pipe in the heater mode set up. In the latter method the inlet air passes through the condenser leg of the heat pipe first, it then passes through the evaporator leg after it has been heated by the electrical heater.

Both modes of testing will provide the same challenges for the heat pipe. The cooling mode directly reflects the application whereby a temperature drop is imposed on the air by the cooling coil. Heating mode increases air temperature but it is the temperature difference between the two sides of the heat pipe which affects heat pipe performance rather than the direction of temperature difference so both methods are equally valid. The heating method was used for the first batch of testing which was undertaken prior to the chiller and related equipment being available.

As the gravity assisted heat pipes rely on a slope in the wraparound pipes upwards from evaporator to condenser section this slope needs to be reversed between heating and cooling testing modes.

The air temperature was measured using K-type thermocouples at four positions: before and after each leg of the heat pipe. Two radiation shields were installed between the heat pipe legs and the

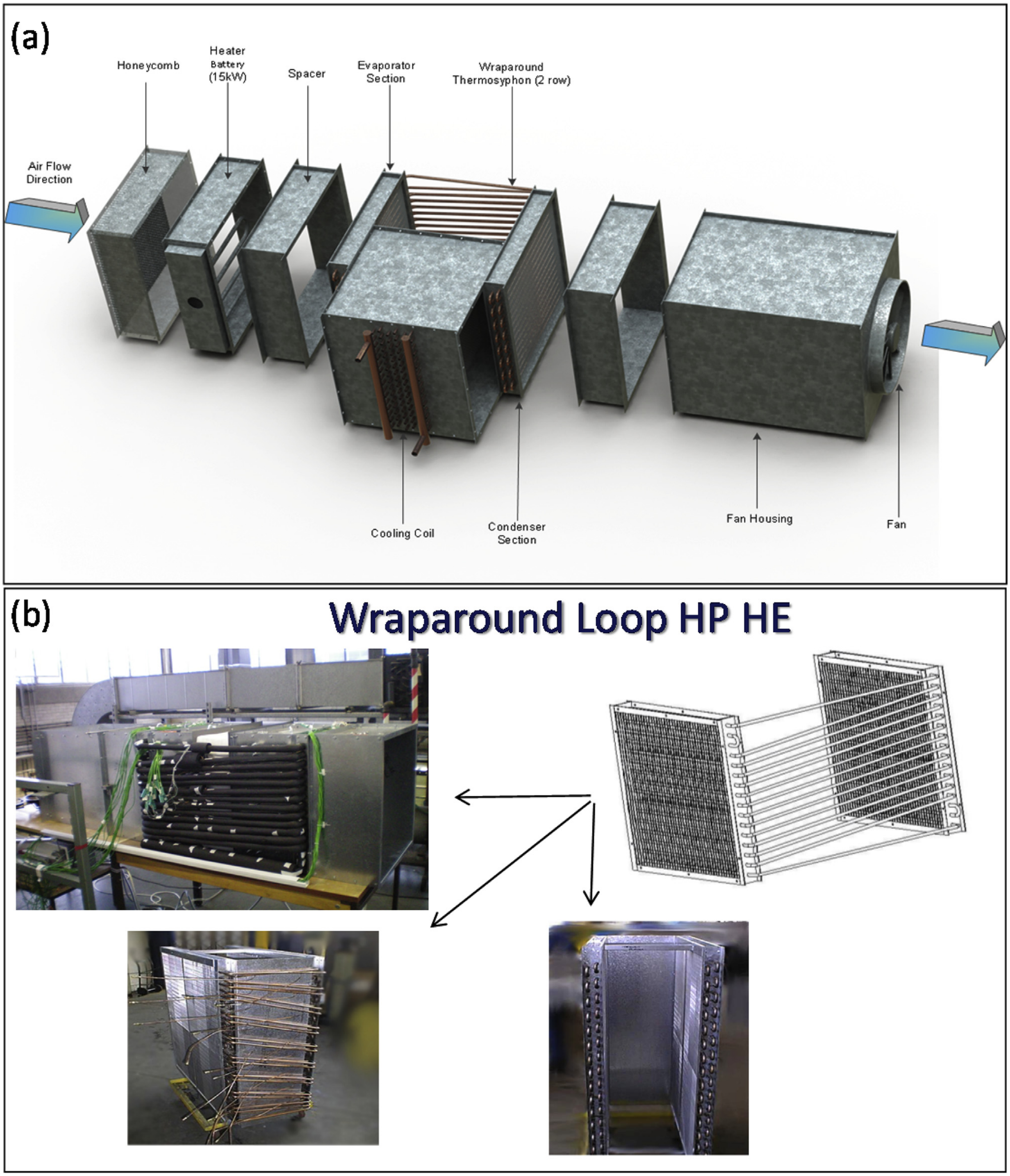

Fig. 2. (a) Exploded assembly details, (b) Actual mechanical design of the wraparound heat pipe.

Table 2
Water and R134a thermal properties [3,24,25].

Working fluid	Melting point°C	Boiling Point°C	Critical Point°C	Triple point°C	Useful range°C	Latent heat of vaporisation (kJ/kg)	Merit Number at operating temperature 20 °C
R134a	−101.1	−26.5	100.9	−103.3	−75 to 50	216	528
Water	0	100	373.95	−0.05	10 to 287	2258	4777

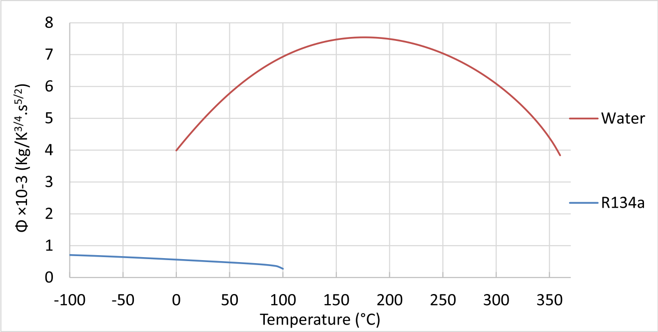

Fig. 3. Variation of the figure of merit for water and R134a with operating temperature.

heaters to prevent heat transfer by radiation and to measure the air temperature without it being influenced by radiation from the high temperature surfaces of the heater.

The two legs of the heat pipe are exposed to the same air flow with no moisture condensing on the heat pipe legs. Accordingly, the heat pipe performance is examined by measuring the change in the air temperature only at a certain value of air velocity. As a result, an accurate evaluation of the heat performance can be achieved without the need to measure the relative humidity of the air.

The heat pipe was tested at constant heater output at two fan speeds.

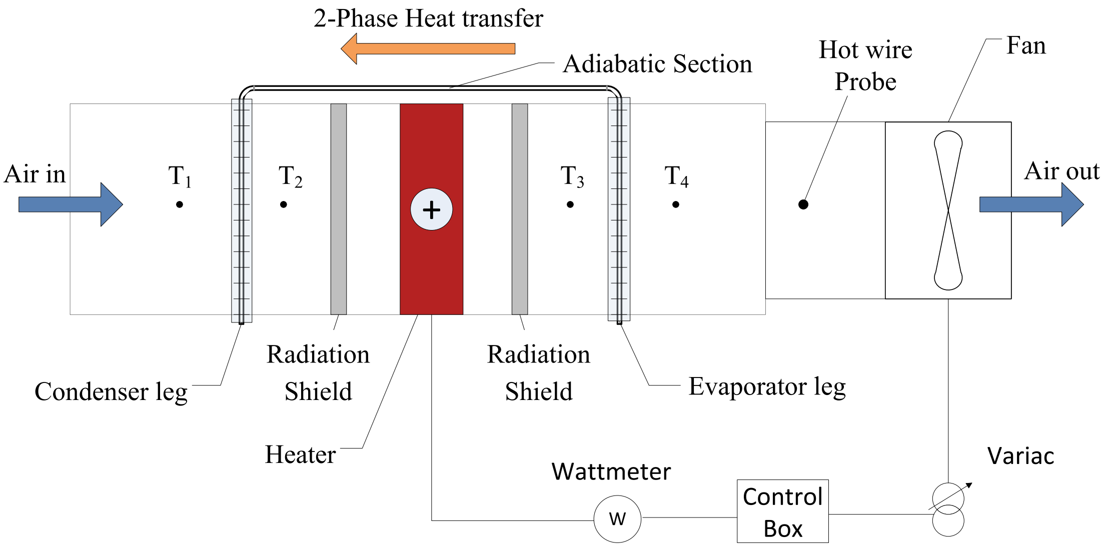

Fig. 4. Schematic of test rig with heater set up.

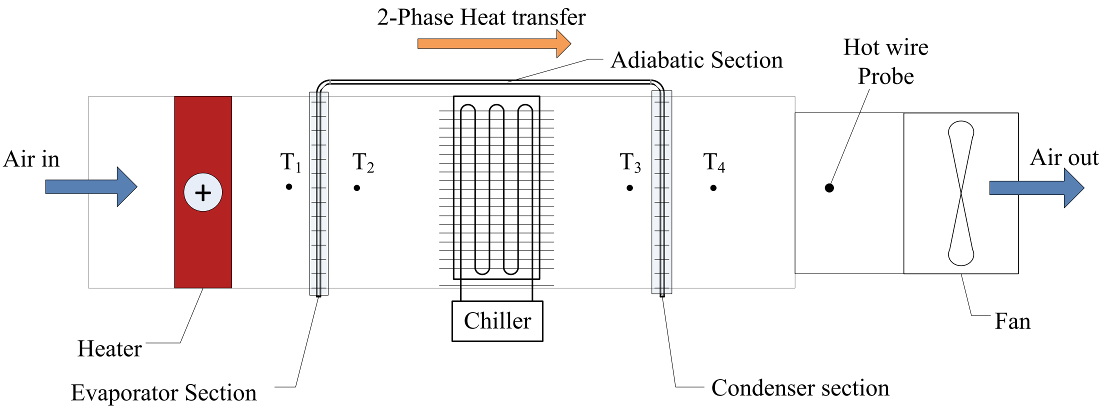

Fig. 5. Schematic of test rig with chiller set up.

2.3. *Instrumentation*

On the airside the testing apparatus consisted of a cased axial fan which draws air through the assembly of the wraparound heat pipe, cooling coil/heater and various ductwork parts. Also included, on the inlet side with the chiller set up, is an electric heater used to bring the air up to that required for testing i.e. the design condition for a hot and humid climate of around 50 °C. The ductwork is drilled in appropriate places to allow the placement of K type thermocouples which are used to measure the air temperature. Air temperature was measured at 4 positions; immediately upstream and downstream of the precool leg and immediately upstream and downstream of the reheat leg. Air off the precool leg corresponds to air onto the cooling coil and air off the cooling coil corresponds to air onto the reheat leg. A total of 3-off temperatures were monitored at each plane and averaged to take account of any temperature stratification within the ducting; this is shown in Fig. 6 (a).

Heat pipe test pieces were of a constant 600 mm × 600 mm cross section and all utilised 0.15 mm thick ripple pattern continuous aluminium fins spaced at 2.1 mm. Both 1 and 2 row versions of the heat pipes were tested at two different air velocities typical of actual velocities found within air handling units. Velocity measurements were taken using a hot wire anemometer and again these measurements were averaged from a spread as shown in Fig. 6 (b).

3. Experimental results and discussion

Wraparound heat pipe performance can be characterised by effectiveness. This is the actual temperature difference across one leg of the heat pipe divided by the maximum temperature difference between the air entering one leg of the heat pipe and air entering the other leg of the heat pipe. Based on the temperatures as shown in Fig. 5 the effectiveness is equal to:

$$\varepsilon = \frac{(T_1 - T_2)}{(T_1 - T_3)} \text{ or } \varepsilon = \frac{(T_4 - T_3)}{(T_1 - T_3)} \tag{2}$$

The two formulations are theoretically equal as the temperature drop across the precool section should be just equal to the temperature rise across the reheat section in order to maintain an energy balance.

3.1. Temperature data

3.1.1. Heater case

The heat pipe charged with water and R134a was tested at two different air velocities; 2.56 m/s and 2.6 m/s respectively. The temperatures of the air and the effectiveness of the heat pipe are illustrated in Table 3. The air temperature after the heater was maintained as a constant by using a control system to vary the electrical input of the heater based on the air velocity.

The effectiveness of the heat pipe charged with R134a and water versus the air velocity is presented in Fig. 7. It can be noted that the effectiveness decreases with increasing air velocity. The effectiveness of the heat pipe charged with water varied between 20.14% and 19.61%, while it varied between 13.76% and 13.25% for the one charged with R134a. Based on these results the effectiveness of the water heat pipe was 46–48% higher than R134a.

3.1.2. Chiller case

The data obtained from testing one and two row heat pipes charged with R134a and water at an air speed of 2.3 m/s are presented in Table 4. The air temperature before the evaporator leg varied between 46.2 °C and 47.4 °C between the two tests. The air temperatures before and after the heat pipe legs for the R134a and water heat pipes are illustrated in Figs. 8 and 9, respectively. It can be noted that the difference between the air temperature before and after the evaporator leg was close to the temperature difference before and after the condenser leg.

The effectiveness for the water heat pipe was 16.9% which was higher than the R134a heat pipe which was 14.3%.

The comparison of the data obtained from testing one row heat pipes at two different air velocities is presented in Table 5. Fig. 10 presents the effectiveness of one row heat pipes versus the air speed during the chiller tests.

It can be noted from Fig. 10 that the effectiveness of the heat pipe decreases with increasing air speed, similarly to the heater test. The effectiveness of the water heat pipe varied between 16.9% and 16.4%, while it varied between 14.3% and 14% for R134a. It was observed that the performance of the water heat pipe was 17.7% better than R134a.

Table 6 presents the data obtained from testing two row heat pipes in the chiller test rig. The effectiveness versus air speed is illustrated in Fig. 11. It can be seen that the effectiveness of the water heat pipe reached 23.6% at 2.3 m/s which was 18.7% higher than the effectiveness of the R134a pipe. Fig. 11 shows that the effectiveness of both heat pipes decreases with increasing air speed.

By comparing the data obtained from the heater test with the chiller test, it can be observed that the effectiveness of the water heat pipe was higher in the heater test than the chiller test. In contrast, The R134a heat pipe achieved higher performance in the chiller test than the heater test. This is due to the fact that the air temperature before and after the heat pipe legs in the heater case was higher than in the chiller case. The corresponding difference of the merit number value of the two working fluids plays a significant role at these two conditions. As is shown in Fig. 3, the merit number of water increases significantly with increase in temperature while it decreases for R134a. As the merit number increases, the temperature drop between the two legs of the heat pipe decreases. Hence the temperature of the condenser of the heat pipe becomes higher and the heat pipe is capable of transporting more heat at the same air temperature. It can be concluded that the experimental

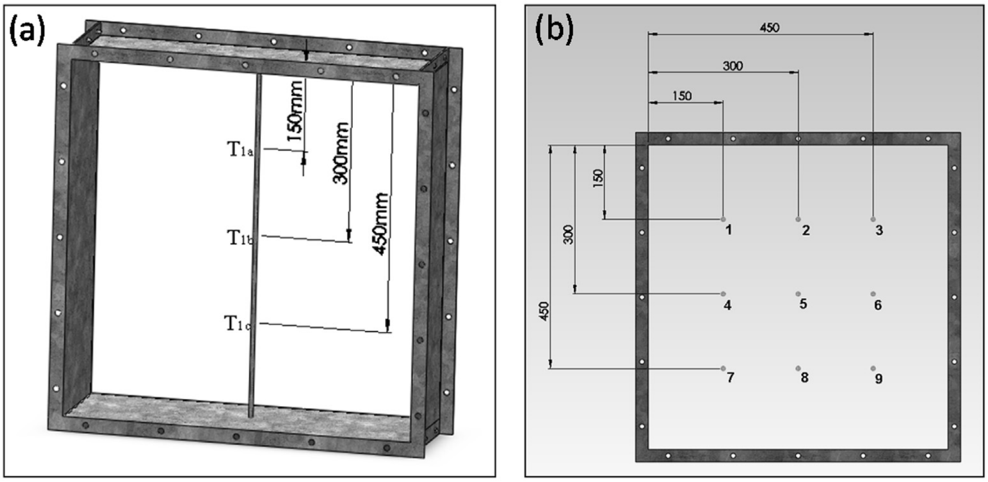

Fig. 6. (a) positions of thermocouples, (b) positions of air velocity measurements.

Table 3
Experimental data and results in heater case for heat pipe using R134a and water.

T3 °C	55.03	55.67	55.28	54.83
Variac voltage (V)	220		240	
Air velocity (m/s)	2.56		2.6	
Mass flow Rate (kg/s)	0.753		0.767	
Working Fluid	**R134a**	**Water**	**R134a**	**Water**
(T3-T4)	3.86	5.37	3.65	5.22
(T3-T1)	28.06	27.16	27.56	26.38
Effectiveness (%)	13.76	20.14	13.25	19.61
% Increase	46.4%		48. %	

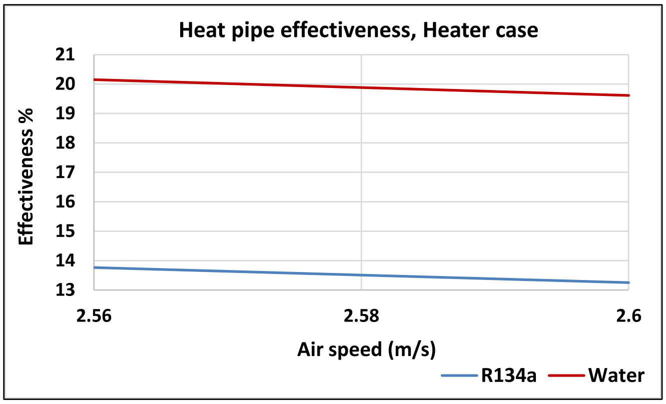

Fig. 7. Heat pipe effectiveness versus air speed for R314a and Water in the heater case.

Table 4
Average data for 1 row heat pipe at 2.3 m/s using R134a and Water.

Working Fluid	R134a	Water
Air velocity	2.3 m/s	
Average Temperature (°C)		
Air temperature (T1)	46.2	47.4
Pre Cool Temperature (T2)	40.6	40.6
Off Cool Temperature (T3)	12.7	12.7
Reheat Temperature (T4)	17.5	18.6
(T1-T2)	5.6	6.8
(T4-T3)	4.8	5.8
Effectiveness	14.3%	16.9%

results agree with the discussion in section 2.1.2.

Furthermore, the effectiveness of the heat pipes was higher in the case of two rows in comparison to one row for the both working fluids. This can be explained by increasing the number of rows of the heat exchanger increases the heat transfer area and enhances the heat transfer coefficient in forced convection between the air medium and the heat pipe. As a results the heat transfer rate through the heat exchanger increases in comparison to the same maximum available heat.

4. Error analysis

The level of uncertainty for the calculated effectiveness come from the temperature measurements of T_1, T_2, T_3, T_4, which were made using K-type thermocouples (NiCr/NiAl) and a data logger (MSI Datascan). The uncertainties associated with these readings are estimated to be ±(0.05% rdg+0.3 °C).

According to [26], the propagation of uncertainties associated with the calculated effectiveness values (S_ε) can be calculated from:

$$S_\varepsilon = \varepsilon \cdot \sqrt{\left(\frac{S_{(T_3-T_4)}}{T_3-T_4}\right)^2 + \left(\frac{S_{(T_3-T_1)}}{T_3-T_1}\right)^2} \tag{3}$$

Where:

$$S_{(T_3-T_4)} = \sqrt{S_{T_3}^2 + S_{T_4}^2} : \text{The error associated with}(T_3 - T_4) \tag{4}$$

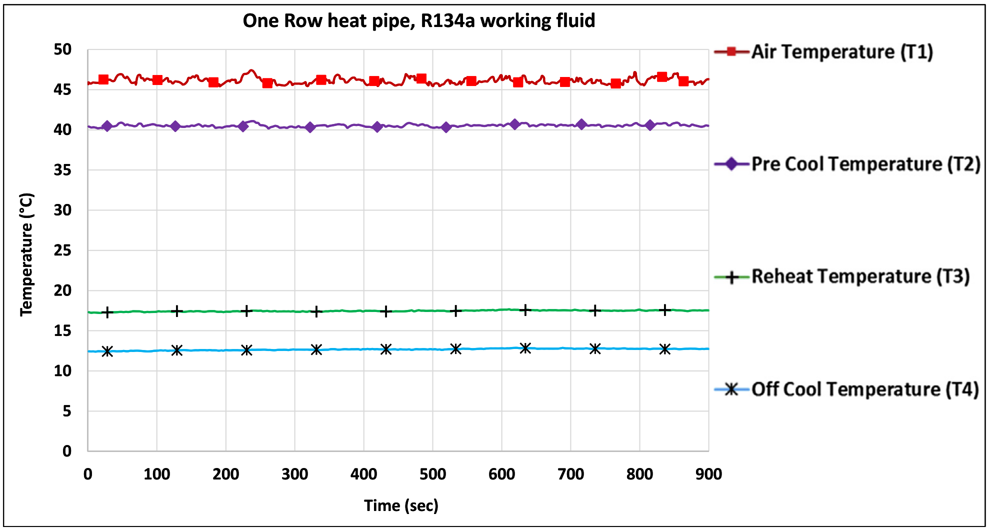

Fig. 8. 1 row heat pipe, 2.3 m/s, R134a.

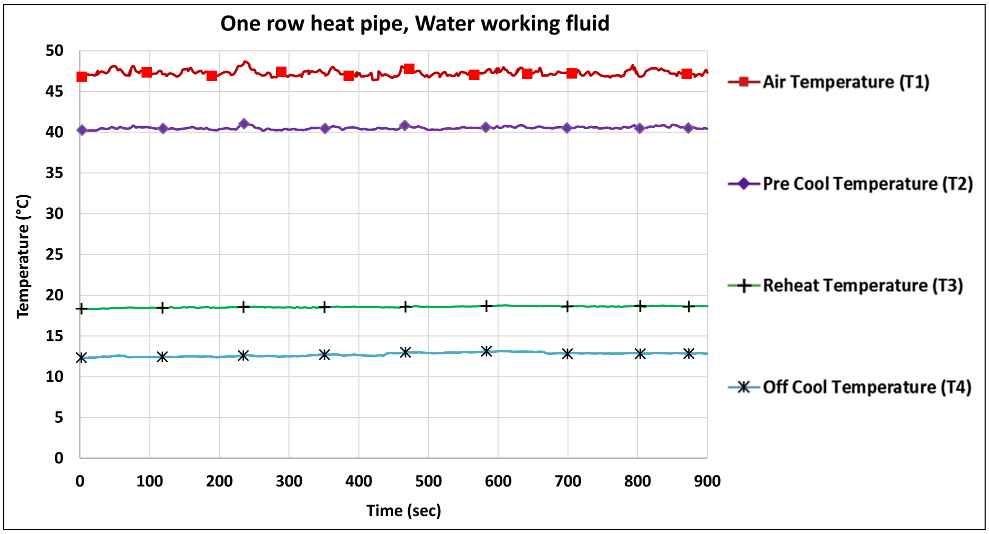

Fig. 9. 1 row heat pipe, 2.3 m/s, water.

Table 5
1 row heat pipe data.

Air Velocity (m/s)	2.3		2.5	
Working Fluid	R134a	Water	R134a	Water
$(T_1 - T_2)$	5.6	6.8	5.2	5.8
$(T_4 - T_3)$	4.8	5.8	4.4	5.1
Effectiveness (%)	14.3	16.9	14	16.4
% Increase	17.7%		16.4%	

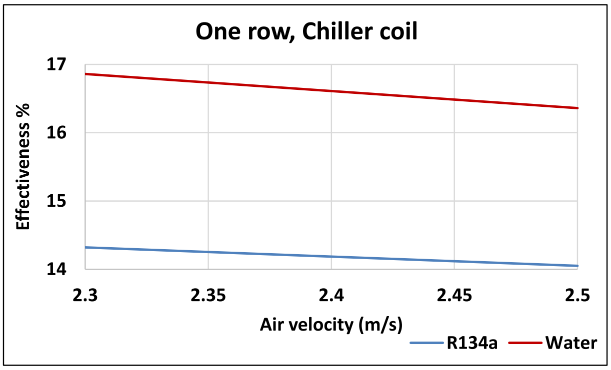

Fig. 10. The Effectiveness of one row heat pipes versus air speed in chiller test.

$$S_{(T_3-T_1)} = \sqrt{S_{T_3}^2 + S_{T_1}^2} : \text{The error associated with} (T_3 - T_1) \qquad (5)$$

By calculating S_ε from Eq. (3), for the experimental range considered, the following table reflects the calculated errors:

From the calculated results in Table 7, the maximum experimental uncertainty associated with the effectiveness values obtained is around 13%, which is an acceptable uncertainty value in engineering applications.

The air velocity was measured using a hot-wire probe (VelociCalc Plus 8386) which measures the air velocity with uncertainty of ±3% rdg.

5. Conclusion

The data clearly demonstrate that, under the constraints of the testing, there is always a performance benefit associated with using water as the working fluid. While this benefit is not great it is sufficient to indicate that the use of water as an alternative heat pipe working fluid is feasible at the temperatures in question. When tested in a standard orientation with a cooling coil between the legs of the heat pipe, performance enhancements of 18% were recorded when using water compared to R134a. Earlier tests using an electric heater between the legs of the heat pipe suggest that improvements of up to 40% are possible. Some of this increased enhancement can be understood as being due to the enhanced thermal transport properties of water at the somewhat elevated temperatures used in the heater tests and the correspondingly reduced thermal transport properties of R134a. As the tests which predict an increase of 18% were conducted under arrangements

Table 6
2 row heat pipe data.

Air Velocity (m/s)	2.3		2.5	
Working Fluid	R134a	Water	R134a	Water
$(T_1 - T_2)$	6.2	7.7	5.2	6.8
$(T_4 - T_3)$	6.1	7.3	5.6	6.6
Effectiveness (%)	19.9	23.6	19.5	22.8
% Increase	18.7%		16.8%	

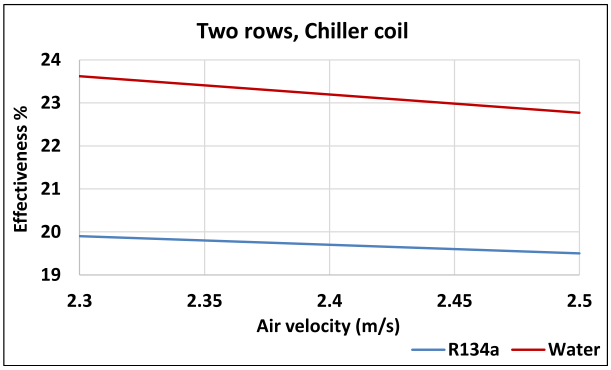

Fig. 11. The Effectiveness of two row heat pipes versus air speed in chiller test.

which directly reflect those used in actual air handling units, the authors wish to advertise this as the headline figure; thermosyphons are extremely sensitive to orientation and application.

The testing does not provide a carte blanche assurance of the suitability of water at other conditions or arrangements of tubes and further investigation is required. The theoretical basis for expecting an increased performance when using water i.e. determination of the Figure of Merit has been validated experimentally and the expected variation in performance with fluid temperature is reflected in the results. The Figure of Merit cannot be expected to fully characterise the relative performance of fluids used in this type of wraparound loop thermosyphon heat pipe; it was developed for classical, wicked type heat pipes and pays no attention to size, aspect ratio, fill ratio, orientation, hydrostatic heads or the possibility of geyser boiling, all of which are worthy of consideration for thermosyphons which have pooled liquid at the bottom of the pipe; a classical heat pipe will just have a saturated wick.

The results are applicable as far as the conditions used for testing and the orientation and design of the pipes match those used in actual systems. The result given above was determined using a testing set-up which complies with these requirements and hence can be applied. This type of heat pipe, used at different temperatures, or variants on the heat pipe design used at the same temperature will need to be the subject of further testing as an extrapolation of the results beyond reasonable limits will result in significant error with this type of equipment.

It has been shown that water as a working fluid not only possesses more sustainable credentials but also provides some performance enhancement in this application. When combined with the current state of the art in terms of manufacturing it means that there are no further impediments to the use of water as a working fluid in the application considered. Its use in heat pipes for other air conditioning systems, however, must be carefully considered and tested.

Table 7
Maximums error associated with the experimental results.

Effectiveness, ε	Maximum error, S_ε	Maximum error, $S_\varepsilon/\varepsilon$ (%)
0.1962	±0.0177	±9.00%
0.2015	±0.0177	±8.8%
0.1325	±0.0170	±12.8%
0.1376	±0.0167	±12.1%
0.1432	±0.0131	±9.2%
0.1686	±0.0127	±7.6%

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