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A comparative study of water as a refrigerant with some current refrigerants

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SUMMARY

Water as a refrigerant (R718) is compared with some current natural (R717 and R290) and synthetic refrigerants (R134a, R12, R22, and R152a) regarding environmental issues including ozone depletion potential (ODP) and global warming potential (GWP), safety (toxicity and flammability), operating cost, refrigeration capacity and coefficient of performance (COP). A computer code simulating a simple vapour compression cycle was developed to calculate COPs, pressure ratios, outlet temperatures of the refrigerants from the compressor, and evaporator temperatures above which water theoretically yields better COPs than the other refrigerants investigated. The main difference of this study from other similar studies is that both evaporator temperature and condenser temperature are changed as changing parameters, but the temperature lift, which is the temperature difference between condenser and evaporator, are held constant and the irreversibility during the compression process is also taken into consideration by taking the isentropic efficiency different from 100%. It is found that for evaporator temperatures above 20°C and small temperature lift (5 K), R718 gives the highest COP assuming exactly the same cycle parameters. For medium temperature lifts (20–25 K), this evaporator temperature is above 35°C, whereas for even greater temperature lifts it decreases again. Furthermore, with increased values of polytropic efficiency, R718 can maintain higher COPs over other refrigerants, at lower evaporator temperatures. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: refrigeration; refrigerants; water; comparison; compressor; cycle; heat pump; air conditioning; properties

1. INTRODUCTION

Water as a refrigerant is one of the oldest refrigerants being used for refrigeration applications down to about the freezing of water. When water is coupled with protective solutions to prevent freezing (i.e. propylene or ethylene glycol), it can be used well below water's normal freezing point in applications such as ice slurries. Water is easily available and has excellent thermodynamics and chemical properties. Beside these advantages, there are technical

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challenges that result from its high specific volume at low temperatures. These challenges include high pressure ratios across the compressor and high compressor outlet temperatures. These challenges have been overcome by designing and manufacturing special compressors for water vapour compression applications.

Water vapour compression applications can mainly be classified in heat pump, water chiller, vacuum ice production, drying and separation (Madsboll *et al*., 1994). The application range also includes the applications for district cooling (thermal storage and chilled water), agriculture, gas turbine inlet cooling and industrial process cooling (Elovic and Holmes, 1996).

Water vapour compression applications can also be classified according to the compressor types used in the refrigeration cycle, which include single and multistage centrifugal, multistage axial, roots, liquid ring, cycloid, and jet/ejector compressors (Wight *et al*., 2000). Most of the studies in the literature were based on the applications in which centrifugal compressors have been used (Madsboll *et al.,* 1994; Elovic and Holmes, 1996; Madsboll and Minds, 1993; Albring, 1994; Albring and Heinrich, 1996; Koren and Ophir, 1996; Albring and Heinrich, 1998; Müller, 2001).

There have been some studies in which using water vapour as a refrigerant has been compared with other refrigerants through evaluating their coefficient of performances (COPs), refrigeration capacities, compression ratios, and compressor outlet temperatures. Water has also been directly compared with other refrigerants through computer programming which has been developed to determine the thermodynamic properties of the more common working fluids used in similar vapour compression refrigeration cycles (de' Rossi *et al*., 1991). This study has shown that water and ammonia perform better than the other refrigerants in regards to their potential latent enthalpy. Orshoven *et al*. (1993) have compared water vapour as a refrigerant to other refrigerants including R12, R22, R502, and R717, with respect to their COPs, by using several commercial programs. They used a simple refrigeration cycle model, assuming no pressure drop through the cycle, no subcooling between the condenser outlet and expansion valve, and no superheating between evaporator outlet and compressor inlet. Paul (1994) compared water (R718) as a refrigerant with R134a, R290 (propane), and R717 (ammonia). His comparison was based on qualitative and quantitative assessment including current environmental issues like the global warming potential (GWP) and the ozone depletion potential (ODP), operating and maintenance cost, design complexity, regulations, codes and standard, etc. Madsboll and Elefsen (1993) have compared cooling plants using water as a refrigerant with traditional ammonia cooling plants through a dynamic computer model developed. They also mentioned that the potential energy saving in the cooling plant with water as refrigerant is 50% more compared with traditional ammonia cooling plants. By using a numerical simulation model, (Chen *et al*., 1997) analysed a thermal storage system of an air-conditioning system with water vapour and R22 as the refrigerants. He directly compared their COPs under different evaporator and condenser temperatures.

The overall objective of the present study is to compare extensively water as a refrigerant (R718) to the other traditional the refrigerants like R717, R12, R22, R134a, R152a and R290. The comparison is based on environmental issues (ODP and GWP), safety (flammability and toxicity), COP of the refrigerant in the refrigeration cycle and cycle parameters like specific volume, pressure ratio and discharge temperature. The effects of temperature lift and polytropic efficiency on the COPs obtained with the refrigerants are also investigated. For this study, a computer code was developed to calculate COPs, pressure ratios, compressor outlet temperatures of the refrigerants, and evaporator temperatures above which water as a refrigerant has a higher COP than the other refrigerants. A commonly available refrigerant library was used to calculate the thermodynamic properties of the refrigerants.

2. QUALITATIVE COMPARISON OF THE REFRIGERANTS

Refrigeration industries including compressor manufacturers, refrigerant producers and refrigeration system producers have been investigating new refrigerants and replacement refrigerants. Their investigations have been generally based on the environmental concerns, refrigeration capacity and performance, safety, chemical stability under extreme temperature and pressure conditions in the system, suitability for materials and refrigeration oil in the system, and reasonable price. Under these aspects the refrigerants R718, R717, R12, R22, R134a, R152a and R290 have been investigated. Some of them have been used for many years, some are current refrigerants, and some have been considered as replacement refrigerants. A brief description of these refrigerants follows.

R717 (ammonia) is one of the oldest refrigerants used in vapour compression and absorption refrigeration systems. Lorentzen (1988) summarized advantages of R717. The advantages are that they have a lower molecular weight, wide range of working temperature because of its high critical point, high latent heat of vapourization and easy leak detection. It shows a relatively high (or the highest COP for high polytropic compressor efficiencies like $\eta_{\mathrm{p}} = 0.9$) COP compared to the other refrigerants. Among the refrigerants that are investigated here, only water (R718) shows an even higher COP than R717 at higher evaporator temperatures. However, R717 also has some disadvantageous, especially as human health, safety and material consideration are taken into account. Dincer (2003) presented many disadvantages of R717, especially related to the human health, those including the harmful effects to the eyes, throat, skin and lung.

R12 is still being used in small refrigerators and freezers, automotive air-conditioning, chillers and applications of transported food refrigeration in available units in some countries but it has been replaced by R134a in the U.S.A. and European countries. Dossat and Horan (2002) have presented some of the advantages including non-flammable, non-explosive, non-toxic, chemically stable under extreme working conditions and some disadvantageous including high ODP = 1, GWP = 8500 and toxicity when it comes in contact with a heat source.

R134a is the long-term replacement refrigerant for R12 because of having nearly zero ODP and similar thermodynamic properties. But, it has also economical disadvantages (Wylie and Davenport, 1996) like higher cost compared with other HCFCs because of a two-step production process and a requirement of larger capacity compressor to achieve the same cooling capacity, especially as it is considered as a replacement refrigerant for R22.

R152a has been used in blends. Because of having a relatively low GWP and thermodynamic properties well matched with R134a, it has been considered a replacement refrigerant for R134a. It even yields a higher COP than 134a. But, it is a flammable refrigerant and it is not advisable to use it in refrigeration systems having very high compressor discharge temperature.

Although R22 was developed for low temperature refrigeration applications including domestic, commercial and industrial systems, it is extensively used in window and split type air-conditioners because of requiring small compressor displacements, especially as compared with R12 and R134a. But, it still has a relatively high ODP = 1900 and a GWP = 0.034 (IIR, 1992), which is a disadvantages compared with R718 (ODP = 0 and GWP = 0).

Table I. Refrigerant properties related to the environmental concern, safety and refrigeration cycle characteristics based on $T_e = 10°C$, $T_c = 50°C$ and $\eta_{is} = 1$.

Ref	ODP	GWP	Safety group	Ref. Cap. (kj kg^{-1})	COP	Spec. vol. (m^3 kg^{-1})	π	Comp. out. temp. (°C)
R718	0†	0†	A1*	2309	5.70	106.4	10.0	223
R717	0†	0†	B2*	102.9	5.96	0.205	3.03	99
R12	1‡	8500‡	A1*	106.5	5.70	0.0409	2.88	55
R22	0.034‡	1900‡	A1*	145.6	5.60	0.0347	2.85	67
R290	0‡	20‡	A3*	250.1	5.42	0.0725	2.66	54
R134a	0‡	1600‡	A1*	131.9	5.54	0.0491	3.18	62
R152a	0‡	190‡	A2*	228.0	5.88	0.0865	3.15	52

A and B represents the toxicity limits. Toxicity increases from A to B. 1, 2 and 3 represents the flammability limits. Flammability increases from 1 to 3.
*Ashrae Standard 34 (1994).
† Dincer (2003).
‡ Calm and Hourahan (1999), ODP and GWP are given relative to R11 and R744 (CO_2), respectively.

Propane (R290) has been used in industrial refrigeration around world because of having zero ODP and no direct global warming effect. It is also a natural refrigerant like R718 and R717. It has operating pressures and COP comparable to R22. For these reasons, according to the some studies (Meyer, 2000, 2001), it has been recommended as an alternative refrigerant for R22.

R718 is an excellent refrigerant. It is an environmentally safe (ODP = 0 and GWP = 0), non-toxic, non-flammable, non-explosive, easy available, and the cheapest refrigerant. It has also the highest COP at higher evaporator temperatures.

Table I gives the most important properties of the refrigerants together with the performance data and cycle parameters. A simulation software (CoolPack, 2001) was used to obtain the results shown in the table for a theoretical vapour compression refrigeration cycle (no pressure drop, no subcooling and superheating). This cycle has the operating conditions of an evaporator temperature $T_e = 10°C$, a condenser temperature $T_c = 50°C$, and an isentropic efficiency $\eta_s = 1$.

According to Table I, R718 is the best refrigerant as ODP, GWP, safety and mass specific refrigeration capacity are taken into consideration. When COPs are compared, R718 is the third best for the specific operating conditions selected for Table I. This study finds a set of combinations that include evaporator temperature, condenser temperature and polytrophic efficiency, at which R718 gives the best COP. However, the other considered refrigerants have some technical advantages over R718 as far as specific volume, pressure ratio and compressor outlet temperature are considered. As mentioned earlier, these challenges for R718 have been overcome by designing and manufacturing special compressors for water vapour compression applications.

3. THEORETICAL MODEL

The model used to compare water as a refrigerant with R717, R290, R134a, R12, R22, and R152a, is based on a one stage simple vapour compression refrigeration cycle consisting of compressor, condenser, thermostatic expansion valve and evaporator. The schematic and pressure–enthalpy (P–h) diagram of this cycle are shown in Figure 1.

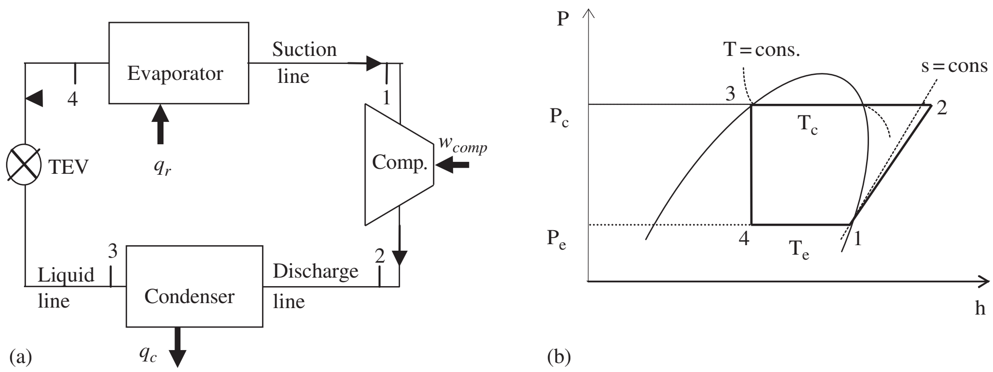

Figure 1. One stage vapour compression refrigeration cycle: (a) schematic of the cycle; (b) P–h diagram of the cycle.

In this theoretical vapour compression cycle, the refrigerant enters the compressor at state 1 at low pressure, low temperature, and saturated vapour state. From state 1 to 2, the refrigerant is compressed by the compressor and is discharged at state 2 as a high pressure, high temperature and superheated vapour condition. At state 2, it enters the condenser where it releases heat to the environment. The refrigerant leaves the condenser at state 3 at high pressure and saturated liquid state. From state 3, the refrigerant enters the expansion valve where its pressure is reduced in a throttling process from high pressure (condenser pressure) to low pressure (evaporator pressure). After this it enters state 4 (the evaporator) where it absorbs heat from the conditioned space and it leaves the evaporator at low pressure, low temperature and saturated vapour state. In the theoretical cycle, it is also assumed that there is no superheating in the suction line, no subcooling in the liquid line and no pressure drop through the cycle.

It is also assumed that steady state and uniform flow conditions exist throughout the elements of this simple vapour refrigeration cycle and changes in kinetic, potential energies, and heat loss from the compressor are neglected. Therefore, specific work of compression w_{comp} for the compressor can be written as

$$w_{\text{comp}} = h_2 - h_1 \tag{1}$$

where h_1 and h_2 are the enthalpies of refrigerant at the compressor inlet and exit, respectively. The refrigerants are simulated as ideal gases during compression process. Hence the specific work of compression can also be expressed by

$$w_{\text{comp}} = \frac{c_{\text{p}} T_{(\text{comp})i}}{\eta_{\text{is}}} [\pi^{(k-1)/k} - 1] \tag{2}$$

where π, $T_{(\text{comp})i}$ are the pressure ratio (the ratio of the condenser pressure to the evaporator pressure), and the temperature at compressor inlet, respectively, while η_{is} is the isentropic efficiency of the compressor, c_{p}, and k are constant pressure specific heat, and specific heat ratio of the refrigerant. Isentropic efficiency of the compressor can be expressed in terms of polytropic efficiency, η_{p}, pressure ratio and specific heat ratio:

$$\eta_{\text{is}} = \frac{\pi^{(k-1)/k}}{\left[\pi^{(k-1)/k\eta_{\text{p}}} - 1\right]} \tag{3}$$

During the throttling process in the expansion valve, it is assumed that there is no heat transfer to the environment, which results in

$$h_3 = h_4 \tag{4}$$

The refrigeration capacity of the cycle can be calculated from the rate of enthalpy change in the evaporator

$$q_r = (h_1 - h_4) \tag{5}$$

where q_r is the specific refrigeration load of the refrigeration cycle. The COP of the refrigeration cycle is then calculated by

$$\mathrm{COP} = \frac{q_r}{w_{\mathrm{comp}}} \tag{6}$$

Based on the above model a computer program was developed to calculate COPs for all refrigerants and their absolute differences to those COPs obtained for R134a. The computer code uses a commonly available data bank for refrigerant properties of such as P, T, h, s.

For this investigation, three parameters were mainly varied or held constant. They are evaporator temperature T_e, temperature lift TD, and polytropic efficiency of the compressor η_p. The refrigerants R718, R717, R290, R134a, R12, R22, and R152a are compared.

3.1. Validation of the theoretical model

To show the validation of the vapour compression refrigeration cycle model that we developed, we compared our model with the models in the literature (Chen and Parasad, 1999; Haberschill *et al*., 2002; Aprea and Renno, 2004; Spatz and Yana Motta, 2004).

After simulating the operating conditions of the recent models by using the model developed in this study, we obtained the COPs of the cycle for the same operating conditions. The results and operating conditions mentioned in the literature are tabulated in Table II. Table II shows the COPs of the recent refrigeration cycle models and our model for certain operating conditions. The COP values in parentheses in Table II denote the COPs derived from our model for the same operating conditions. The COPs of the refrigerants are common in the recent models and our model were selected for comparison.

The minimum and maximum per cent COP differences between the models in the literature and the model in this study are about 0.2 and 4.3, respectively, when R12 is taken into consideration. For R134a, these differences are 0.6 and 3.3 while the differences are −1.2. and 12.1 for R22. The per cent COP difference for R290 is about 5 at a specific operating condition in Table II.

4. RESULTS AND DISCUSSION

With the computer code the evaporator temperature was increased from 0 to 45°C while the temperature lift and polytrophic efficiency were held constant. Absolute COP values (and their absolute differences to the COPs of R134a) of the refrigerants were determined as a function of evaporator temperature. This has been performed with different temperature lifts between 5 and 30 K and polytropic efficiencies between 0.5 and 0.9.

Table II. Comparison of the COPs of the recent vapour compression refrigeration cycle models with the model that is developed in this study.

Ref.*	Ref.*	Ref.†,‡,§	Ref.§
R12	R134a	R22	R290
3.8* (3.97) $T_e = 0°C$, $T_c = 40°C$ $\eta_{is} = 0.7$	3.7* (3.383) $T_e = 0°C$, $T_c = 40°C$ $\eta_{is} = 0.7$	2.6† (2.569) $T_e = -14.43°C$, $T_c = 43.03°C$ $q_r = 151.75\ \mathrm{kj\,kg^{-1}}$, $w_{comp} = 59.21\ \mathrm{kj\,kg^{-1}}$ $\dot{m} = 0.228\ \mathrm{kg\,s^{-1}}$	2.83§ (2.697) $T_e = -6.7°C$, $T_c = 43.3°C$ $\eta_{is} = 0.65$ $TD_{sh} = 5.6°C$, $TD_{sc} = 8.3°C$
3.3* (3.375) $T_e = -5°C$, $T_c = 40°C$ $\eta_{is} = 0.7$	3.25* (3.241) $T_e = -5°C$, $T_c = 40°C$ $\eta_{is} = 0.7$	2.75‡ (3.13) $T_e = -14.61°C$, $T_c = 46°C$, $\eta_{is} = 1$ 3‡ (3.31) $T_e = -12.41°C$, $T_c = 46°C$, $\eta_{is} = 1$	
2.8* (2.896) $T_e = -10°C$, $T_c = 40°C$ $\eta_{is} = 0.7$	2.75* (2.77) $T_e = -10°C$, $T_c = 40°C$ $\eta_{is} = 0.7$	3.35‡ (3.49) $T_e = -10.28°C$, $T_c = 46°C$, $\eta_{is} = 1$	
2.5* (2.506) $T_e = -15°C$, $T_c = 40°C$ $\eta_{is} = 0.7$	2.4* (2.386) $T_e = -15°C$, $T_c = 40°C$ $\eta_{is} = 0.7$	2.87§ (2.56) $T_e = -6.7°C$, $T_c = 43.3°C$, $\eta_{is} = 0.65$ $TD_{sh} = 5.6°C$, $TD_{sc} = 8.3°C$	

*Chen and Parasad (1999).
†Haberschill *et al.* (2002).
‡Aprea and Renno (2004).
§Spatz and Yana Motta (2004).

Figure 2 shows the variation of COP_{abs} (the absolute difference between the COP of the refrigerant and the COP of the reference refrigerant R134a) versus evaporator temperature for different TD values and constant polytropic efficiency. While the COP of R134a (COP_{R134a}) is given by the right ordinate, the absolute COPs for the other refrigerants can be calculated by adding COP_{abs} from the left ordinate to COP_{R134a}.

For the shown temperature range, with increasing evaporator temperature, the COPs of the refrigerants increase with exception of R22 and R290. As shown in Figure 2(c), for a high TD = 30 K, the COP of 134a also decreases at evaporator temperature above 23°C. Furthermore, Figure 2 shows that R718 has the steepest increase in COP_{abs} for all TD ranges and also the potential for higher economic benefits over the other refrigerants if the evaporator temperature can be raised. As TD values decrease, the temperature range at which R718 shows the best COP increases. The evaporator temperatures, above which COP_{abs} of R718 is higher than that of the other refrigerants, are 34°C for TD = 30 K, 30°C for TD = 10 K and 20°C for TD = 5 K. Below these evaporator temperatures, R717 produces a better COP. However, despite that ammonia does not deplete the ozone layer (ODP = 0) and does not directly contribute to the greenhouse effect, ammonia still has a sharp rank smell, is toxic, and explosive in certain mixtures with air. Water (R718) is free of these serious disadvantages. For certain operating conditions at the lower evaporator temperatures, R718 is still advantageous over some of the refrigerants. For example, above 9°C for TD = 5 K, COP values of R718 are better than R12, R22, R290 and R134a.

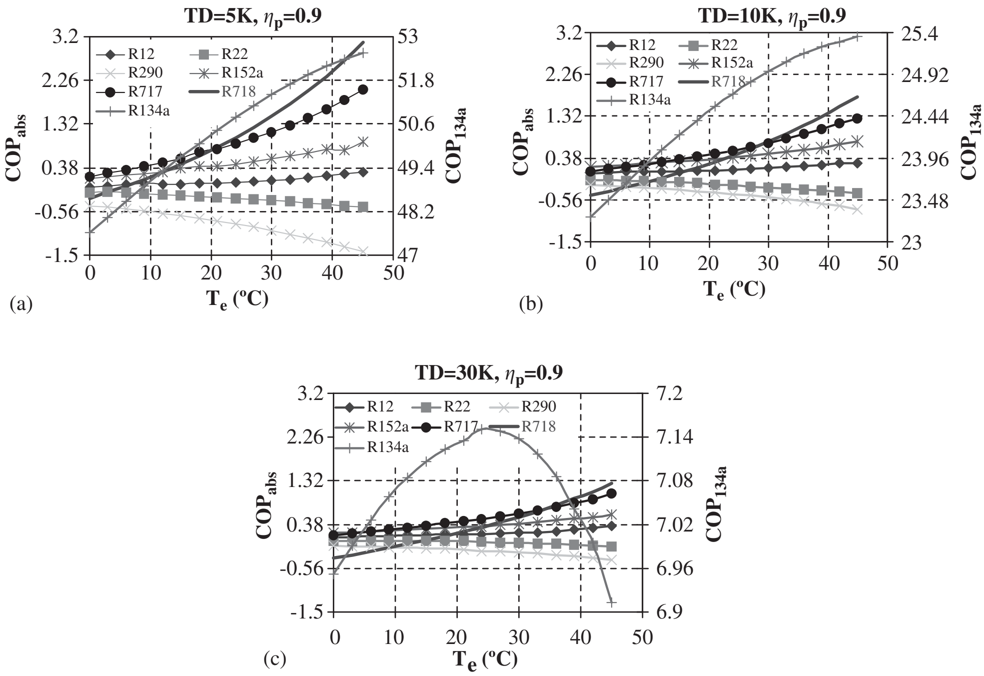

Figure 2. COP_{abs} as a function of evaporator temperature for different TD values: (a) TD = 5 K; (b) TD = 10 K; (c) TD = 30 K.

As TD increases, the pressure ratio increases and in turn the compressor power increases. Simultaneously, with increasing pressure ratio the refrigeration effect decreases. Together, they result in a reduced coefficient of performance as can be seen by comparing the plots in Figure 2. Figure 3 summarizes this effect for R718, being representative for evaporator temperatures between 0 and 45°C.

The variation of COP_{abs} values with respect to the evaporator temperature for three different polytropic efficiencies and constant TD = 20 K is shown in Figure 4. Isentropic efficiency is mainly a function of pressure ratio and polytropic efficiency. Isentropic efficiency can be determined as a function of the compressor outlet temperature as the pressure ratio is held constant at a constant evaporator temperature. As polytropic efficiency increases at a constant evaporator temperature, both the compressor power and compressor outlet temperature decrease. Therefore, the COP of the refrigeration cycle increases. Figure 4 compares the refrigerants' COPs under constant TD and at a constant evaporator temperature value. In other words, for constant evaporator and condenser temperatures (no change in refrigeration capacity), the COPs of all of the refrigerants increase as the polytropic efficiencies η_p increase. R718 still shows the steepest increase in its COP values between any two successive polytropic efficiencies (0.5–0.7 or 0.7–0.9), compared to other refrigerants. This shows that for R718 systems which require high pressure ratios, it is extremely advantageous to develop compressors with high polytropic efficiencies. As the polytropic efficiencies increases, the temperature range at which R718 has advantages over the other refrigerants also increases. For a TD = 20 K, the

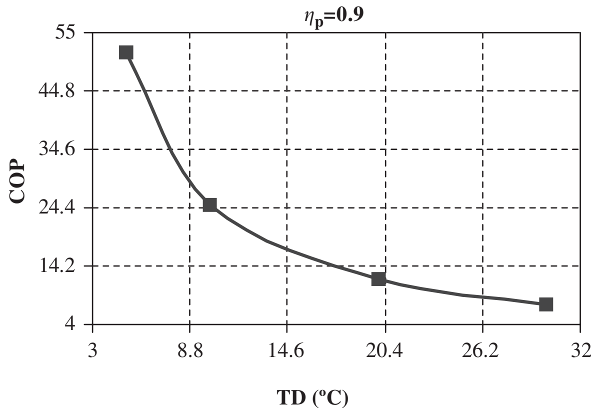

Figure 3. COP of R718 as a function of temperature lift representative for 0...45°C.

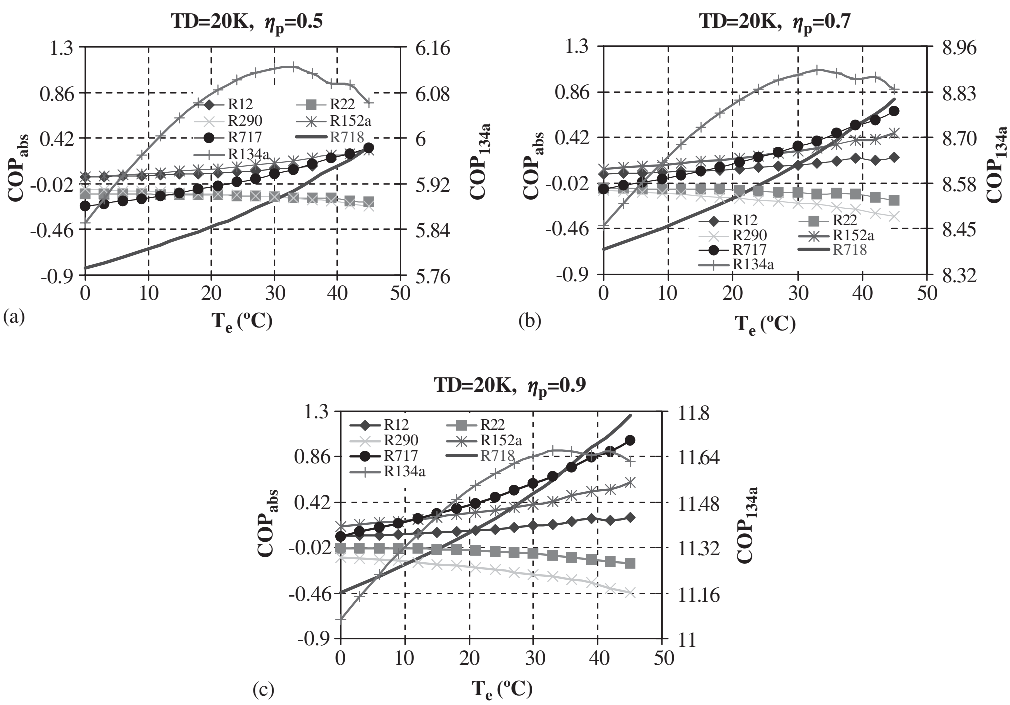

Figure 4. COP_{abs} as a function of evaporator temperature for different η_p values: (a) η_p = 0.5; (b) η_p = 0.7; (c) η_p = 0.9.

evaporator temperatures, above which the calculated COP_{abs} of R718 is higher than those of the other refrigerants, are 45°C for $\eta_p = 0.5$, 39°C for $\eta_p = 0.7$ and 33°C for $\eta_p = 0.9$.

The increase of refrigerant temperature at the compressor outlet (discharge temperature T_2) with increasing evaporator temperature is shown in Figure 5, for a temperature lift of TD = 20 K and a polytropic efficiency $\eta_p = 0.9$. The compressor-outlet temperature of water (R718) is given

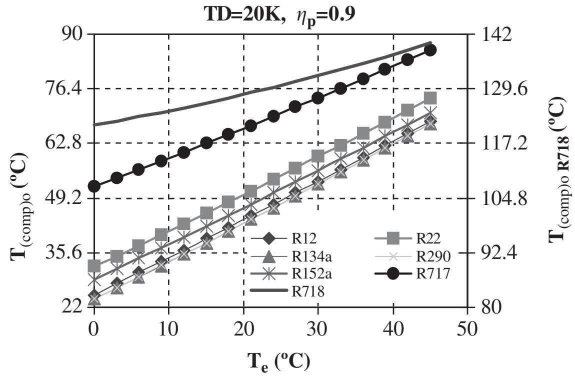

Figure 5. Discharge temperature versus evaporator temperature.

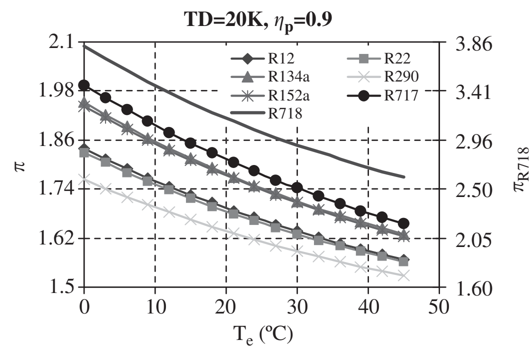

Figure 6. Pressure ratio as a function of evaporator temperature.

from the right ordinate in Figure 5. R134a yields the lowest compressor-outlet temperature, while R718 yields the highest. The temperatures of R134a, R290 and R12 are very close to each other. The high compressor-outlet temperature of water is mainly due to the high pressure ratios, which require a high compressor work. This disadvantage can be reduced by designing special compressors and applying suitable cooling methods like intercooling for multistage compressors. As mentioned above, this has been realized with centrifugal compressors for water vapour compression applications.

Figure 6 shows the cycle pressure-ratio versus evaporator temperature for a temperature lift of TD = 20 K and polytrophic efficiency $\eta_p = 0.9$. The high pressure ratio for R718 is shown on the right ordinate. When the evaporator temperature increases, the evaporator pressure increases due to the constant temperature lift. However, the ratio of the increase in evaporator pressure to that of increase in condenser pressure is always greater than 1. Therefore, the ratio of condenser pressure to the evaporator pressure decreases with increasing evaporator temperature. R290 has the lowest pressure ratio, while R718 has the highest pressure ratio. As shown in Figure 6, R22 and R12, as well as R134a and R152, show almost the same pressure ratios, in the lower mid range.

Table III. Evaporator temperatures above which in a simple refrigerant cycle with $\eta_p = 0.9$ R718 gives a better COP than R290, R22, R134a, R12, R152a, R717.

	Evaporator temperature (°C)					
	R718					
Temperature lift (K)	R290	R22	R134a	R12	R152a	R717
TD = 5	0	3	6	7	12	20
TD = 10	7	10	14	16	23	29
TD = 15	10	14	16	20	26	33
TD = 20	11	15	16	21	26	35
TD = 25	11	15	15	20	26	35
TD = 30	10	14	14	19	25	34
TD = 35	8	13	11	17	23	33
TD = 40	6	11	9	15	21	32

Table III shows the evaporator temperatures above which the theoretic cycle calculation gives a higher COP for R718 than for the other considered refrigerants, for a polytropic efficiency $\eta_p = 0.9$ and temperature lifts 5–40 K. The table shows that R718 is especially advantageous for low (5–10 K) and high (TD > 30 K) temperature differences, whereas for mid range temperature lifts of 15–25 K the evaporator temperatures, above which R718 shows the best COP, are the highest. Table III shows that R718 always gives higher COPs than R290, R22, and R134a for evaporator temperatures above 16°C. R12 and R152a are included for evaporator temperatures above 25°C and above 35°C evaporator temperature R718 gives even better COP than R717 (ammonia). Table III gives a guideline for which combinations of evaporator temperatures and temperature lifts using R718 instead of the other refrigerants can enhance the COP. For example, a less advantageous operating point for R718, at an evaporator temperature of 20°C and condenser temperature of 40°C, would result in a temperature lift of 20 K; R718 still yields a better COP than R290, R22, and R134a.

5. CONCLUSIONS

Water as a refrigerant (R718) is directly compared to current refrigerants, including R717, R290, R134a, R12, R22, and R152a by using a computer code for the calculations of a simple vapour compression refrigeration cycle and refrigerant properties.

The presented results are in good agreement with the studies in the literature. The per cent COP differences between the models in the literature and the model in this study are about: 0.2(min.) and 4.3(max.) for R12, 0.6 and 3.3 for 134a, -1.2 and 12.1 for R22, and 5 for R290.

The computed results show that the use of water as a refrigerant can result in higher COP over the other traditional refrigerants at evaporator temperatures above 35°C and at lower evaporator temperatures with either relatively small temperature lift ($\leqslant 10$ K) or relatively high temperature lift ($\geqslant 30$ K). Furthermore, the presented results always show a higher COP for water vapour (R718) over R134a, R290, and R22 at evaporator temperatures above 16°C, irrespectively of the magnitude of the temperature lift.

The disadvantage of water vapour as a refrigerant are its high specific volume, the required high pressure ratio, and resulting high compressor outlet temperatures. It has been demonstrated that these technical challenges can be overcome with specifically developed compressors, especially multi-stage turbo compressors with intercoolers between stages. In today's world, a refrigeration system with a high COP is the primary target, but it is not the only factor in deciding which refrigerant is to be used. Environmental parameters like ODP and GWP are becoming more and more restrictive. Furthermore, the economic costs and safety properties of refrigerants are heavily taken into consideration. With regards to all of these aspects and the specific operating conditions mentioned above, water is the superior refrigerant.

NOMENCLATURE

c_p	= constant pressure specific heat of ($\mathrm{kj\,kg^{-1}\,K^{-1}}$)
COP	= coefficient of performance
$\mathrm{COP_{abs}}$	= coefficient of performance absolute to the COP of R134a
h_1	= specific enthalpy of refrigerant at the compressor outlet ($\mathrm{kj\,kg^{-1}}$)
h_2	= specific enthalpy of refrigerant at the compressor outlet valve ($\mathrm{kj\,kg^{-1}}$)
h_3	= specific enthalpy of refrigerant at the condenser outlet ($\mathrm{kj\,kg^{-1}}$)
h_4	= specific enthalpy of refrigerant at the evaporator inlet ($\mathrm{kj\,kg^{-1}}$)
k	= ratio of constant specific heats
$\dot{m}$	= mass flow rate of refrigerant ($\mathrm{kg\,s^{-1}}$)
η_{is}	= isentropic efficiency of the compressor
η_p	= polytrophic efficiency of the compressor
q_c	= specific condenser capacity ($\mathrm{kj\,kg^{-1}}$)
q_r	= specific refrigeration capacity ($\mathrm{kj\,kg^{-1}}$)
P	= pressure (kPa)
π	= pressure ratio
s	= specific entropy ($\mathrm{kj\,kg^{-1}\,K^{-1}}$)
T	= temperature (°C)
TD	= temp. lift (temperature difference between condenser and evaporator) (K)
$\mathrm{TD_{sc}}$	= degree of subcooling
$\mathrm{TD_{sh}}$	= degree of superheating
w	= specific work of compression ($\mathrm{kj\ kg^{-1}}$)

Subscripts

c	= condenser
comp	= compressor
e	= evaporator
i	= inlet
o	= outlet

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