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THE VIABILITY OF CAPACITY CONTROL OF HIGH TEMPERATURE HEAT PUMP WATER HEATERS OPERATING NON-AZEOTROPIC MIXTURES.

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ABSTRACT

A high temperature electrically-operated heat pump water heater is evaluated in terms of the viability of employing capacity control using non-azeotropic refrigerant mixtures (NARMs). The system coefficient of performance (COP) is improved by introducing capacity control, which offers continuous modulation by varying heat pump capacity to match the load. This is accomplished by using a non-azeotropic refrigerant mixture (NARM) and changing the composition (x) of the circulating mixture. The NARM R-22/ R-142b is selected due to the requirement for a high condensing temperature and a wide capacity range. The life-cycle cost effectiveness of this heat pump is compared with that of a conventional heat pump (operating a pure fluid). Computer simulations show that the capacity-controlled heat pump, operating between compositions of 100% R-22 and 70% R-22, shows a 29.6% improvement in energy conversion when compared with a conventional R-22 heat pump water heater. The payback periods of the capacity-controlled systems, are strongly dependent on electricity tariff, additional system cost, and period and duration of heat pump operation.

NOMENCLATURE

C	Additional purchasing and installation cost of a capacity-controlled heat pump ($)
COP	Coefficient of Performance (-)
C_p	Specific heat value for water at constant pressure (kJ/kg °C)
E	Monthly energy consumption (kWh)
l	Volume of hot water consumption per day (l)
$\dot{m}$	Mass flow rate (kg/s)
PP	Payback period (years)
Q	Heating capacity (kW)
S	Annual saving on electricity ($)
T	Runtime (h), Temperature (°C)
$\bar{T}_{EXIT}$	Average water exit temperature
$\bar{T}_{FEED}$	Average feedwater (source) temperature (°C)
W	Electrical energy input (kW)
x	Mass fraction of low boiler (fraction)

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INTRODUCTION

The search for alternatives to the fully-halogenated chlorofluorocarbons (CFCs) as refrigerants, is motivated by the Montreal Protocol. Alternatives are being sought among the partially-halogenated hydrocarbons, mixtures, as well as among different classes of organic compounds (Cavallini, 1996; Spauschus, 1991). For the widely-used hydrochlorofluorocarbon (HCFC), R-22, there is currently no non-flammable single-component alternative with similar pressure/ temperature characteristics.

All the current available synthesized chlorinated-alternative refrigerants are based on HCFCs, and intended to serve as short-term quasi drop-in replacements for CFCs with minor system modifications. These alternative fluids are all in the form of NARMs or NEARMs (Near Azeotropic Refrigerant Mixtures), and the majority of these are ternaries containing R-22; Either R-32 or R-143a are present in all of these mixtures, even though both these fluids are moderately flammable.

The use of mixtures as working fluids expands the number of alternatives from which an alternative fluid may be selected. Non-azeotropic refrigerant mixtures (NARMs) used as working fluids in a heat pump cycle, offer two characteristics not available from pure fluids. These unique features are (1) gliding temperature phase-change processes in the heat exchangers, and (2) variable composition (and variable fluid density) with temperature change. These features allow for the increase in system efficiency (or COP) and the possibility of exercising heating capacity control.

With the correct selection of a NARM, a heat pump water heater (HPWH) may be afforded a much increased water delivery temperature, typically 100 °C (212 °F) condensing temperature compared to approximately 60 °C (140 °F) for current industrial HPWHs operating with R-22. This would of course ensure an extension of the application range of heat pumps.

Exploitation of a HPWH using a NARM would require certain system modifications, such as the inclusion of accumulators and servovalves, and the use of a microprocessor-based controller to facilitate the optimization of heat pump performance over the entire design range, and to enable continuous capacity modulation.

High condensing temperatures normally apply to industrial applications, which provide more freedom in the choice of working fluid/s, since the problems of toxicity and flammability are generally not as severe as in space heating applications or in the food industry; Many industries are accustomed to working with flammable and toxic substances.

This paper investigates the viability of using the NARM R-22/ R-142b for use in a high condensing temperature (i.e. > 100 °C (212 °F)) industrial heat pump water heater employing capacity control. The use of R-22/ R-142b meets with the short term goals of the Montreal Protocol; Although R-22 is to be phased out before the year 2020, this paper focuses on the benefits of using a binary NARM (which includes R-22), especially from an electrical energy consumption point of view.

NON-AZEOTROPIC REFRIGERANT MIXTURES (NARMs)

A non-azeotropic refrigerant mixture (NARM) of two substances is one which can be separated into its constituent components by distillation (i.e. mixtures that do not form azeotropes). Compared to a pure working fluid, a NARM undergoes a temperature change (also called a *gliding temperature*) during evaporation and condensation, due to changing mole fractions in liquid and vapour phases as phase change takes place, which implies changing bubble points.

SELECTION OF A NARM FOR HIGH CONDENSING TEMPERATURES

In selecting a NARM, the most essential characteristics relate to the *chemical stability* of the refrigerant, and *health and safety* characteristics.

In the search for an ideal NARM, it follows that mixtures that do not adhere to the abovementioned characteristics, or that form azeotropes or near-azeotropes, should be eliminated from the candidate list. Morrison and McLinden (1993) investigated azeotropy in 300 binary mixtures by using experimental values which were correlated with numerical predictions.

After application of the abovementioned criteria, 25 pure compounds remain that have been used as refrigerants or that have been proposed as alternatives. Of these, only 220 NARM candidates remain.

With industrial heat pumps, especially the compressor and type of refrigerant determine the possible condensing temperature and the heating capacity. Figure 1 provides an example of the application limits of a reciprocating compressor concerning evaporation and condensing temperatures and the volumetric heating capacity for three widely used hydrocarbons in larger systems of the past.

In the search for a fluid capable of producing high water temperatures, it follows that the requirements for high heating capacity and high water temperatures are mutually exclusive (i.e. *high capacity fluids tend to produce a low maximum water temperature, whereas fluids capable of producing high temperature water tend to be low capacity fluids*).

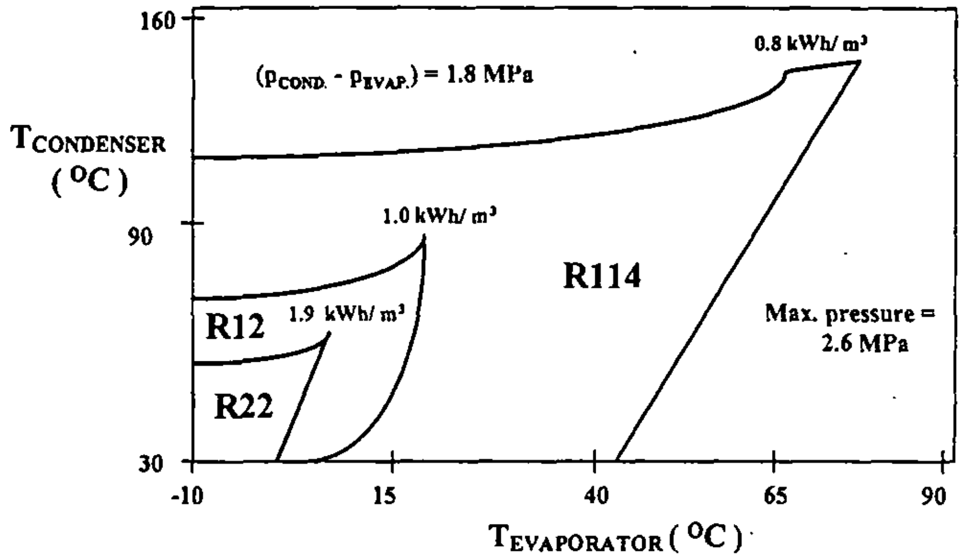

FIGURE 1: Compressor application fields with different refrigerants, indicating the benefits of capacity control by mixing suitable refrigerants (adapted from Kruse, 1984). ***Boiling temperatures: R-22 (-40.76 °C), R-12 (-29.79 °C), R-114(3.61 °C).***

After consideration of temperature glides and differences in normal boiling points, vapour heat capacities, and critical temperatures, only the 15 NARMs shown in Table 1 remain as candidate working fluids. (The current existing range of HCFC-based *ternaries* (i.e. the R-40x range), is not considered in this paper.)

TABLE 1
Possible binary NARMs for high temperature HPWHs requiring capacity control.
Criteria: Temperature glide > 10 °C, condensing temperature: 100 °C, lowest ambient temperature: 10 °C

REFRIGERANTS	R-124	R-142b	RC-318	R-143
R-32	✓	✓	-	✓
R-125	✓	✓	✓	✓
R-143a	✓	✓	-	✓
R-22	✓	✓	-	✓
R-218	-	-	✓	-
R-134a	-	-	-	✓

EFFICIENCY IMPROVEMENT OF HEAT PUMP OPERATING WITH NARM

Coefficient of performance

Due to the isothermal heat exchange processes with a *single-component working fluid* heat pump water heater, the Carnot cycle (Fig. 2a) represents an appropriate cycle approximation:

$$COP_{\substack{CARNOT,\\HEATING}} = \frac{Q_{OUT}}{W_{IN}} = \frac{T_{SINK}}{T_{SINK} - T_{SOURCE}} \tag{1}$$

For *NARMs*, the appropriate cycle approximation would be the Lorentz cycle (Fig. 2b), due to the gliding characteristic of the working fluid which is catered for:

$$COP_{\substack{LORENTZ,\\HEATING}} = \frac{Q_{OUT}}{W_{IN}} = \frac{T_{CM}}{T_{CM} - T_{EM}} \tag{2}$$

where

T_{CM} = mean condensing temperature = $\dfrac{T_{CU} - T_{CL}}{\ln(T_{CU} / T_{CL})}$

T_{EM} = mean evaporating temperature = $\dfrac{T_{EU} - T_{EL}}{\ln(T_{EU} / T_{EL})}$

The above logarithmic mean temperature difference (LMTD) method has been shown to be rather accurate (Högberg et al, 1993), despite the fact that the use of LMTDs assume constant specific heats and constant convection heat transfer coefficients, both of which do not apply to NARMs.

By comparing the work done in both cycles, it is apparent that the heat pump cycle employing a NARM (i.e. the Lorentz Cycle) requires less work to accomplish the same amount of heat transfer (i.e. $W_{1'2'3'4'} < W_{1234}$), thus ensuring a higher COP for the NARM-operated heat pump. This is due to the inherent gliding temperature characteristic of NARMs, which could be closely matched with the sink and/ or source's temperature profile.

It also follows from Fig. 2 that the possibilities of increasing the COP are greatest for

- the types of heat pumps in which the temperature decrease of the heat source and the temperature increase of the heat sink are comparable, and
- where the heat exchangers are arranged to be counter-current.

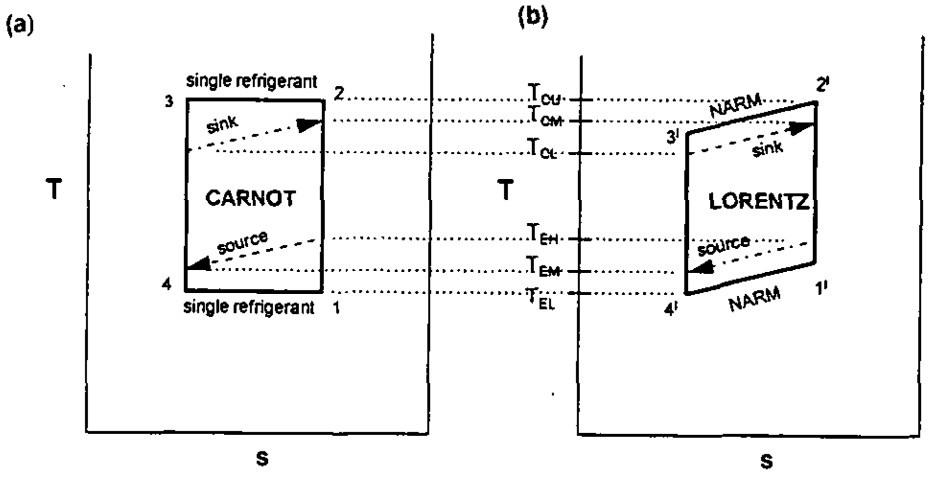

FIGURE 2: Lorentz cycle versus Carnot cycle

HEATING CAPACITY CONTROL USING NARMs

It is possible to find mixtures with higher heating capacities than their pure working fluid counterparts, due to the fact that the upper limit of the condensing temperature of a normally-used fluid can be increased when a proper second fluid is introduced to it.

The biggest factor affecting the range of capacity modulation is the effect of composition change on the NARM vapour pressure (in the evaporator). Consequently, a larger difference in component vapour pressure generally results in a greater capacity range as well as a larger spread between the dewpoint and bubble-point temperatures.

It has been found that as the critical temperature of refrigerants are increased the volumetric heating capacities *decrease* (McLinden and Didion, 1987). This is due to the lower vapour pressure, and thus lower vapour densities, for refrigerants with higher critical temperatures. Conversely, the COP drops as the condensing temperature approaches the critical refrigerant temperature, due to excessive compressor superheat and flash gas losses (McLinden and Didion, 1987). There is therefore a *fundamental trade-off between high capacity and high efficiency*.

The use of a NARM (such as R-22/ R-142b) therefore offers an additional possibility of modulating the capacity by controlling the molar density at the compressor inlet through changes in the composition of the circulating refrigerant mixture, and hence, in the evaporator pressure.

Capacity modulation

The difference in liquid composition at the exit of the condenser and evaporator can be exploited by a system employing two accumulators to provide composition (and capacity) modulation. A schematic of such a system is shown in Fig. 3. By controlling the accumulation and depletion in the two accumulators, a steady-state can be reached when the amount and composition of the withdrawn vapour and the returned liquid are equal. Assume that the system is charged with a NARM with a composition of z and that the charge hold-up outside the accumulators is negligible:

- ***Low heating capacity system:*** When the high pressure accumulator is full of liquid (i.e. *low boiler*) and the low pressure accumulator is empty, the circulating NARM composition is the same as that of the total charge as can be deduced from Fig. 1b (i.e. $x_L = z$). This is the lowest capacity operation of the system.
- ***High heating capacity system:*** As more liquid is allowed to flow out of the high pressure accumulator and collects in the low pressure accumulator, the circulating mixture becomes richer in the more volatile compound (or *low boiler*, A) and the capacity increases (c.f. Fig. 1b). When the low pressure accumulator becomes full, its liquid would have a composition richer in (A) by one equilibrium stage (i.e. the evaporator stage) and the system operates with maximum capacity. Referring to Fig. 3b, the uncondensed vapour at (7) is significantly richer in component (A) than the circulating NARM, resulting in the stored liquid to be of composition x_H.

The extremes of operation are now represented by a maximum capacity when $z = x_H$ and a minimum capacity when $z = x_L$ (Gromoll and Gutbier, 1985; Vakil, 1983).

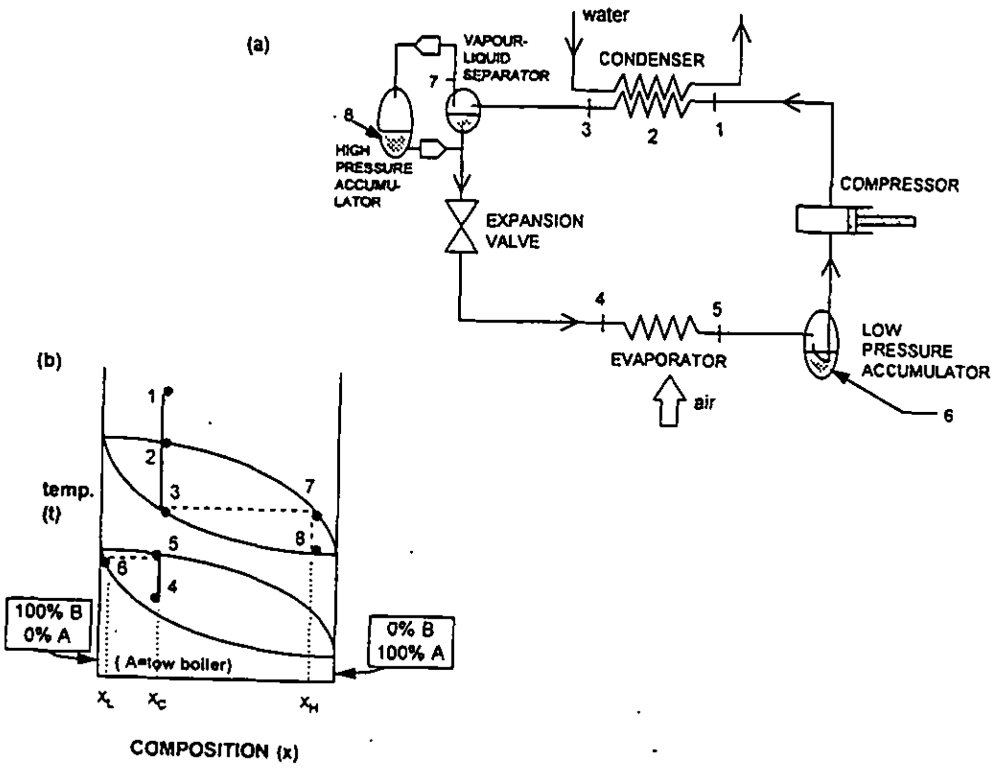

FIGURE 3: Two-accumulator heat pump water heater with NARM.

SIMULATION

Selection of a NARM

For the purpose of this paper, a NARM was sought which would have *a wide capacity range*, the possibility of producing *condensing temperatures of 100 °C, with good COP characteristics*.

From Table 1, and based on the above requirements, the most ideal NARM *is R-22/ R-142b*, considering its 11 °C temperature glide and very low value of mixture parameter (according to McLinden and Didion, 1987). The high capacity fluid (i.e. R-22, with its high vapour pressure; boiling point = - 40.76 °C) is therefore mixed with a fluid suitable for high water temperature (i.e. R-142b, with its low vapour pressure; boiling point = - 9.78 °C), to obtain a NARM with improved characteristics that can be adjusted by varying the mixture composition (NIST, 1996). This is confirmed by the simulation and experimental work of Johannsen (1992). The R-22/ R-142b NARM is also only flammable at mass fractions of R-22 below 38% (Bivens, 1989), so that it should be ensured that the heat pump water heater operates at greater R-22 mass fractions, say 45%. Both R-22 and R-142b also have low ozone-depleting potentials (when compared with R-11).

As a basis for comparison of the energy saving potential of a capacity-controlled R-22/ R-142b heat pump when compared with a conventional pure fluid heat pump, the monthly water heating requirement for the production of 10 000 litres hot water per day (at 60 °C water exit temperature, $\overline{T}_{EXIT}$), was considered. The heat pump was sized to heat the specified total volume of water in a storage tank (i.e. 10 000 l), during the coldest part of the day (during the coldest month of the year) within a period *(T)* of 16 hours.

The nominal size of the heat pump could therefore be determined from

$$Q_{HEATING} = \frac{\dot{m}\, C_P(\overline{T}_{EXIT} - \overline{T}_{FEED})}{3600T} \qquad (3)$$

The winter month of July, being the coldest on average, was therefore used in the calculation, revealing a 35 kW heat pump capacity to adhere to set specifications.

Assumed *COP* and *capacity* characteristics of NARM R-22/ R-142b

COP and heating capacity data as functions of ambient air wet-bulb temperatures, were obtained from manufacturer's catalogues, for a 35 kW air-source heat pump operating with R-22. As a first assumption, these values were superimposed on the R-22/ R-142b versus composition (x) characteristics obtained from the extensive research work of Högberg and Berntsson (1994); Högberg, Vamling and Berntsson (1993); Greyvenstein and Meyer (1993); and Kruse (1984).

Climatological statistics for Johannesburg (South Africa) were used to obtain average monthly wet-bulb temperatures (to determine monthly heating COPs); Average monthly (municipal) feedwater temperatures were also obtained, and used to determine monthly heat pump heating load requirements (cf. Table 2). The simulated characteristics are shown in Fig. 4.

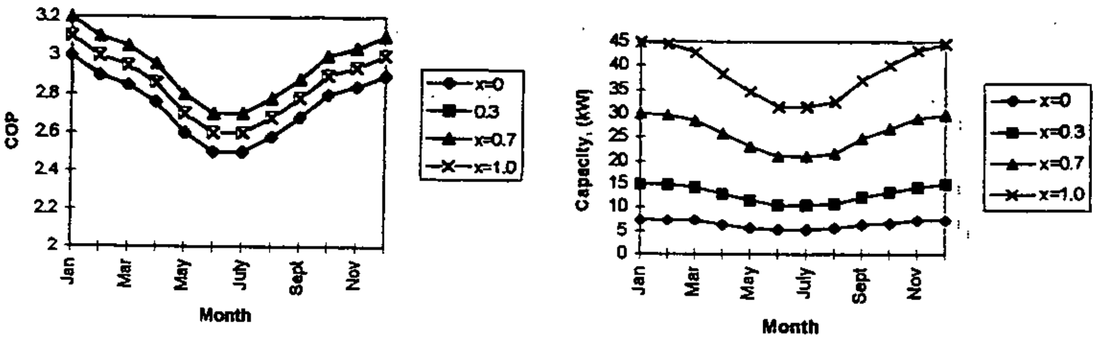

FIGURE 4: Assumed COP and heating capacity characteristics for an R-22/ R-142b NARM. (Geographical location: Johannesburg, South Africa, 40 kW heat pump; 'x' denotes the mass fraction of R-22).

Comparison of energy saving between a capacity-controlled NARM-heat pump and a conventional single-fluid heat pump

Figure 5 shows the simulated heating load curve for the selected heat pump as a function of feedwater temperature. The heat pump characteristics are shown when operating with pure R-22 (e.g. a high heating capacity system), as well as when operating on a lower capacity NARM (e.g. 70% R-22, 30% R-142b). At feedwater temperatures below the balance point temperature, the heat pump will not have adequate capacity and its output would therefore have to be supplemented from an external source. At feedwater temperatures above the balance point temperature, point A, the R-22 operated heat pump will have excess capacity. There is thus a capacity mismatch between the heating load and heat pump.

With a capacity-modulated NARM-system however, the heat pump characteristic can be altered to follow the load line from point A to point B (which is here assumed to be the low capacity limit). This capacity modulation may be brought about by systems such as that described in Fig. 3. With feedwater temperatures above the minimum capacity point B, the heat pump will have an excess capacity, and if possible, the composition should be adjusted to include more low boiling fluid (such as 60% R-22 and 40% R-142b). With this particular NARM, care should be taken so as not to operate at R-22 mass fractions lower than 38% (say 45%), due to mild flammability of the NARM.

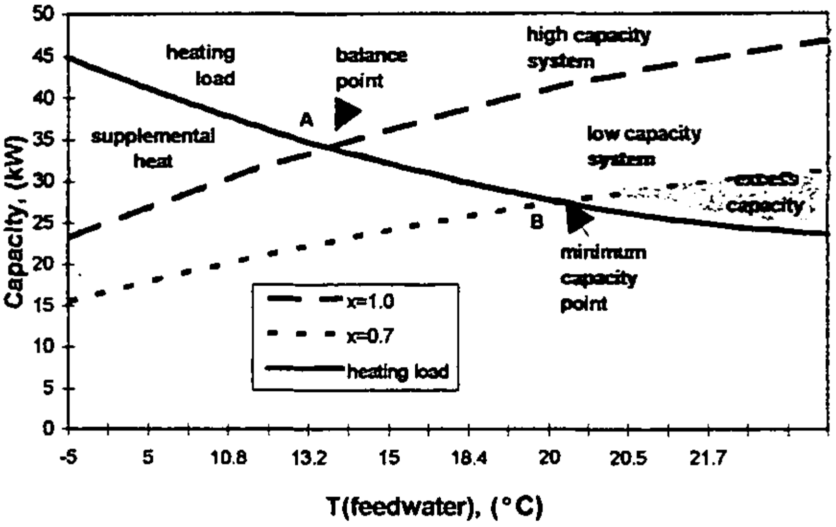

FIGURE 5: NARM-operated air-source heat pump water heater characteristics superimposed on water heating load characteristic. Required water to be heated = 10 000 l/day; Heating period: 16 h/day; Required water exit temperature: 60°C.

Table 2 reproduces the numerical values of available heating capacities and COPs, as well as the heating load energy requirements, based on a 16 hour daily runtime of the heat pump.

The energy consumptions for three different systems were calculated:

- x = 1.0 (pure R22)
- x = 0.7 (70% R-22)
- capacity-controlled-heat pump (which would ensure movement on the load line between points A and B in Fig. 5):
  - ◊ At feedwater temperatures below 13.5°C, the capacity-controlled system follows the R-22 system line (and supplemental heat is required to cope with the heating load);
  - ◊ At feedwater temperatures between 13.5°C and 20.1°C, the load line between points A and B is exactly followed;
  - ◊ At feedwater temperatures higher than 20.1°C, the 70% R-22 system line is followed, and the system has excess capacity.

To satisfy an annual energy demand of 173 670 kWh, a conventional R-22 heat pump would consume 81 258 kWh_e (and require supplemental heat below 14°C) ; and one operating with a 70% R-22/ 30% R-142b mixture, 52 140 kWh_e (but one which cannot cope with the heating load at temperatures below 20°C). A capacity-controlled heat pump would consume 62 718 kWh$_e$/ year and provide the best fit to the load curve possible. A seasonal COP of 2.77 is therefore established by the latter, and represents a 29.6% improvement in energy conversion when compared with the traditional R-22 system.

TABLE 2
Energy requirements and consumption of the NARM capacity-controlled and the conventional heat pumps, based on 16 hour heat pump runtimes; production of 10 000 litres of hot water (@ 60° C) per day.

Month	Average feed water temperature, $\overline{T}_{FEED}$, (°C)	Average wet-bulb temperature, (°C)	Available heating capacity, (kW)		COP		Heating load energy requirements, (kWh/ month)	Energy consumption, (kWh$_e$/ month)		
			R22	*x=0.7*	*x=0.7*	*R22*		*R22*	*x=0.7*	capacity-control
Jan	21.7	15.3	45	30	3.2	3.1	12 152	7 200	4 650	4 724
Feb	21.8	15.1	44.5	29.7	3.1	3.0	11 110	7 357	4 747	4 825
Mar	20.5	14	43	28.7	3.05	2.95	12 400	7 229	4 662	4 740
Apr	18.4	11.4	38.5	25.7	2.96	2.86	13 440	6 979	4 301	4 619
May	14.4	8.1	34.5	23	2.8	2.7	15872	6 337	4 074	5 772
June	10.8	5.1	31.5	21	2.7	2.6	17 280	6 009	3 858	5 896
July	10.9	5.1	31.5	21	2.7	2.6	17 608	6 009	3 858	6 645
Aug	13.2	6.6	32.5	21.7	2.78	2.68	16 800	6 015	3 866	5 905
Sept	16.6	9.4	37.1	24.7	2.88	2.78	15 376	6 619	4 259	5 433
Oct	18.6	11.9	40.1	26.7	3	2.9	13 344	6 859	4419	4 523
Nov	20.1	13.5	43.2	28.8	3.04	2.94	14 384	7 288	4 699	4 811
Dec	21.5	14.7	44.5	29.7	3.1	3.0	11 904	7 357	4 747	4 825
						Total/ year (kWh):	173 670	81 258	52 140	62 718
						Seasonal COP:		2.14	3.33	2.77

Capacity modulation and volume of water

The benefits of capacity modulation in a water heating function are illustrated in Fig. 6, which shows the maximum attainable water volume in a 10 hour/day heat pump operation. When a low volume of water is to be heated, the NARM circulating mixture should be changed to larger amounts of the high boiler (R-142b in this case, e.g. $x = 0$; $x = 0.3$); When larger volumes are to be heated, more low boiler (R-22 in this case) would be required (e.g. $x = 0.7$; $x = 1.0$).

ECONOMIC ANALYSIS

The viability to operate a capacity-modulated heat pump from an efficiency viewpoint, is undeniable. A study of the reduced operating costs of capacity-modulated systems due to increased efficiency, is required to determine whether the additional purchasing expense of such systems is justified.

Economic parameters

Payback period (PP)

$$PP = \Delta\ Capital\ cost / S \qquad (4)$$

where Δ *Capital cost* = (Cost of NARM heat pump) - (Cost of conventional R-22 heat pump)

S = Energy cost saving during coldest month ($) = (Energy saving during coldest month, kWh) • (Unit electricity tariff, $/ kWh)

Energy saving during coldest month, kWh = (Energy consumption, R-22) - (Energy consumption, Capacity-controlled NARM-heat pump)

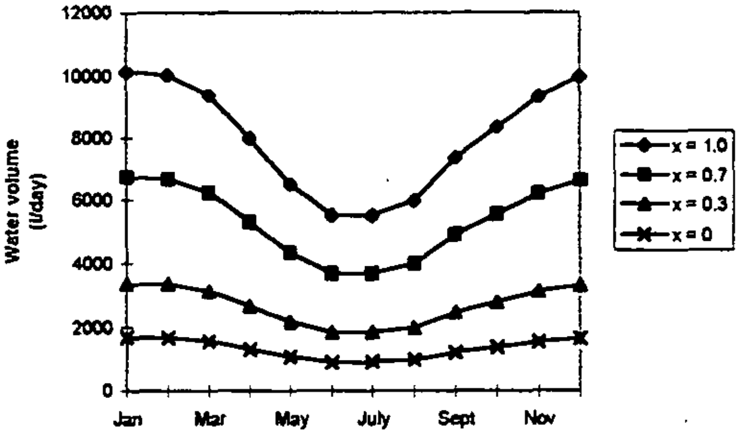

FIGURE 6: Maximum attainable water volume, to be heated in 10 hours heat pump operation per day; (40 kW heat pump, operating in Johannesburg, South Africa)

From Table 2, the savings for the coldest month (July) may be calculated and the payback periods determined as a function of the electricity tariff, the results being summarized in Fig. 7. Considering an electricity tariff of $0.10/ kWh, an acceptable payback period of 3 years is attained, when the additional purchase cost of the capacity-controlled heat pump water heater does not exceed $5 000. It is also apparent that the cost-effectiveness increases with electricity tariff.

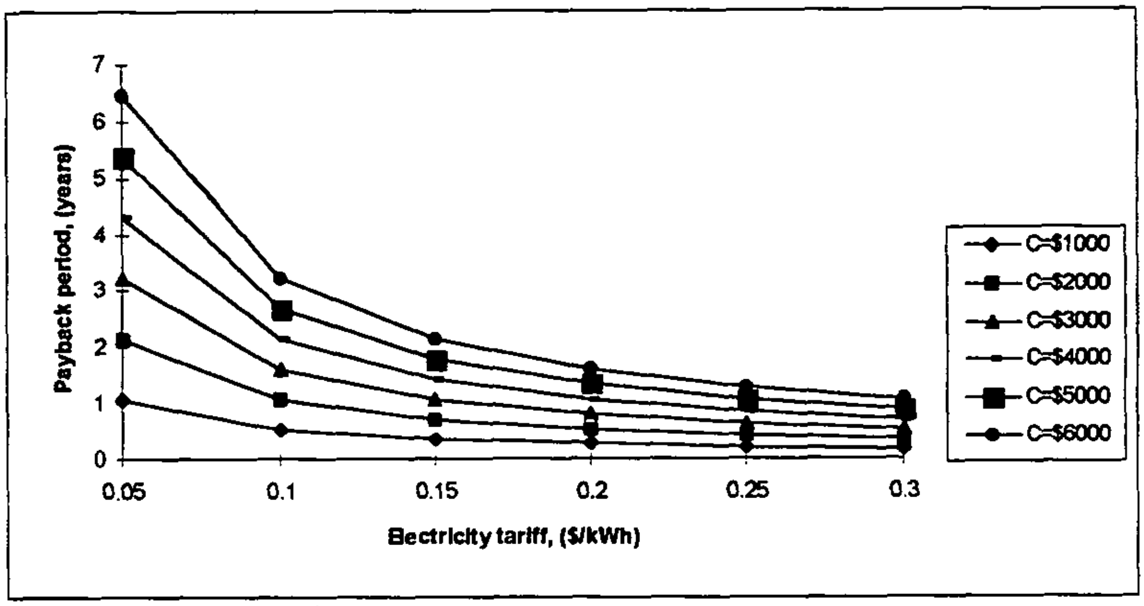

FIGURE 7: Payback period versus electricity tariff to heat 10 000 litres of water per day during the coldest month (July). The heat pump is sized in such a way that the volume of water is heated in 16 hours during the coldest month.
('C' is the excess purchasing cost of a capacity-controlled heat pump water heater).

Although the simulations were based on a limited number of cases, it should also be mentioned that an electrically-operated heat pump has superior performance for typical industrial applications with long, uninterrupted periods of operation throughout the most favourable hours of the day, and where there exists a simultaneous and balanced need for both heating and cooling (Greyvenstein and Meyer, 1993).

CONCLUSIONS

This paper investigates the viability of capacity control of high temperature heat pump water heaters operating non-azeotropic refrigerant mixtures. It is shown that:

- The use of NARMs offers the possibility of modulating the system heating capacity by controlling the molar density at the compressor inlet through changes in the composition of the circulating refrigerant mixture;
- A NARM of R-22 and R-142b was chosen for the purpose of the study, and due to its suitability for high temperature (i.e. 100°C) water heating, with a good COP characteristic and wide capacity range.
- COPs of NARMs vary with circulating fluid composition (and gliding temperature characteristic), and may be higher than those of the pure refrigerants;
- Typical heating load curves do not match typical heat pump system curves. A capacity-modulated system however best follows the load line, thus optimizing energy consumption.
- A capacity-controlled heat pump, employing accumulators, servovalves and electronic controller, shows a seasonal COP of 2.77, representing a 29.6% improvement in energy conversion when compared with the traditional R-22 system.
- The described 45 kW heat pump capacity-controlled system, would have an acceptable payback period of three years if the additional cost of this system (relative to an R-22 system) would be less than $5 000 (assuming an electricity tariff of $0.10/ kWh).
- The NARM R-22/ R-142b was selected to suit the predetermined system operating characteristics, and to demonstrate the viability of a NARM-driven capacity-controlled system. Although HCFCs are to be phased out by the year 2020, most current alternative HCFCs are mixtures using R-22. The importance of capacity-controlled HPWHs using an R-22-based NARM, is therefore undisputed and corroborated by the positive results presented in this paper.

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