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ABSTRACT

In Swedish district heating systems several large (25 MW) turbo-compressor driven heat pumps using R22 are installed. The only commercially available alternative is R134a, but its use could decrease the heating capacity by 35%. The aim of this work is to find a mixture giving a better "economical performance" than R134a. The heat pump plant investigated uses sea water as heat source fluid, which means a risk of ice formation on the evaporator plates. This paper screens about 2000 mixtures, containing two or more of the components R134a, R32, R143a and R125. The simulation results for the heat pump plant show that there are mixtures that can offer a considerably higher heating capacity than R134a. There is however a decrease in COP.

1. INTRODUCTION

The main part of the work, both internationally and in Sweden, for finding new working fluids in heat pumps and refrigeration plants has been directed towards applications in low and medium temperature level systems (freezing, refrigeration and air conditioning plants, and low-temperature heat pumps, below 60°C). High-temperature heat pumps are of considerable interest in Swedish district heating systems, which utilise several large heat pumps using R22. Since flammable fluids must not be used in such large heat pumps, the only commercially available alternative is R134a. However, if converting from R22 to R134a the decrease in heating capacity can be as large as 35%. This means not just additional cost for alternative heat production, but also increased emissions of greenhouse gases as well as sulphur and nitrogen oxides.

This paper investigates alternative refrigerant mixtures to replace R22 in the above mentioned high-temperature heat pumps. First, a screening is made among almost 2000 mixtures, using criteria such as condenser pressure, Mach number and temperature glide. Simulations of the plant are then made for the accepted mixtures from the screening stage, in order to investigate the change in heating capacity and COP compared to R22 and R134a. Finally, an economical evaluation is made for the most promising mixtures.

2. DESCRIPTION OF THE PLANT

In this paper a method for finding the best working fluid for a specific plant is presented, and applied to a district heating plant in Stockholm. The plant consists of ten heat pumps, having a total heating capacity of 260 MW, and delivering around 1.5 TWh annually. These heat pumps are divided in three groups that are run in series, while the heat pumps in each group are run in parallel. The two first groups (six heat pumps) use R22 and are the ones studied in this paper. In summer, the delivery temperature from heat pump group 2 can be as high as 78°C. The third heat pump group has already been converted from R500 to R134a. Depending on the heat demand, different number of groups, or number of heat pumps in each group, are run. When further heating of the district heating water is necessary, oil, coal, bio fuel and electricity are used. The heat source fluid for all heat pumps is sea water.

A schematic flow chart of one heat pump is shown in *Figure 1*. The evaporator is a plate-type evaporator with vertical channels. This type is often used in large water-source heat pumps, where the water is heavily polluted or has to be cooled close to the freezing point[1]. Since the inlet sea water temperature can be as low as 2°C in wintertime and the temperature decrease through the evaporator is about 1.5°C, there is an obvious risk of ice formation on the evaporator plates.

The automatic control of the heat pumps includes limiting parameters such as maximum motor power, maximum volume flow in to each compressor stage, maximum condensation pressure and minimum evaporator temperature (in order to prevent ice formation).

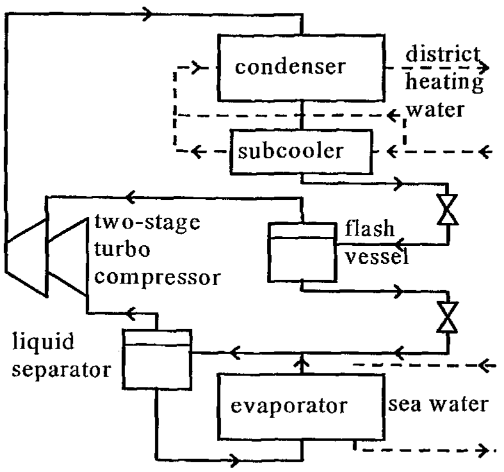

Figure 1: Schematic flow chart of one heat pump

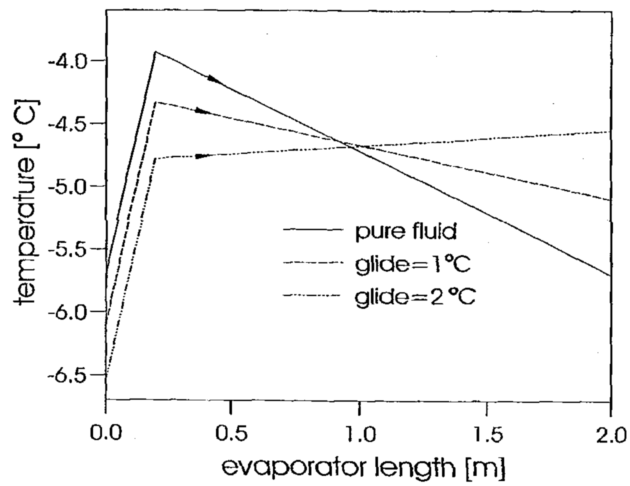

Figure 2: Principal difference in the evaporator temperature profile between a pure fluid and non-azeotropic mixtures

3. CONSEQUENCES OF USING ANOTHER WORKING FLUID

3.1 Risk of ice formation

Since the mixtures for replacing R22 studied in this paper are all non-azeotropic mixtures, there will be a change in the evaporator temperature profile due to the non-isothermal evaporation of non-azeotropic mixtures. In *Figure 2*, this difference in temperature profile is shown. The comparison is made at equal evaporator area and evaporator heat duty, as well as assuming equal heat transfer coefficients and inlet subcooling. This also means an equal mean temperature difference for the evaporation process, and therefore the evaporator inlet temperature is lower for the non-azeotropic mixtures, resulting in a larger risk of ice formation on the plates. Further, according to Haukås[2], when there is a risk of ice formation the maximal duty is achieved at operating conditions giving the most uniform outside wall temperature profile. For the same liquid level in the system, the outside wall temperature becomes less uniform when using a non-azeotropic mixture compared to a pure fluid.

3.2 Compressor

The possibility for replacement of the working fluid in an existing turbo compressor mainly depends on the molar mass and normal boiling temperature of the new and original working fluid[3]. For example, there is an upper limit on the Mach number in order to prevent transonic flow phenomena.

3.3 Change in composition

As seen in *Figure 1*, the two-stage system uses a flash vessel, not a heat exchanger, and there is a liquid separator after the evaporator. Hence, there will be different compositions in different parts of the system when a non-azeotropic mixture is used. Note that all compositions denoted in this paper are referred to as the composition in mole% after the condenser.

4. CALCULATIONS

4.1 STEP 1 - screening stage

Based on, for example, critical properties and vapour pressure curve the following substances were included in this study; R134a, R32, R143a and R125. The screening covers almost 2000 mixtures of two or more of these four substances. The "accepted" mixtures from this screening are the ones fulfilling the conditions stated below.

Flammability:	Non-flammable [4]
Molar mass:	Mach number < 1.8
Condenser pressure:	$P_{cond} = P_{bubble}(T_{cond}) < P_{max} = 43\text{bar}$
	Case A: $T_{cond} = 80°C$
	Case B: $T_{cond} = 70°C$
Critical properties:	$0.99\ T_{crit} > T_{cond}$
	$0.95\ P_{crit} > P_{cond}$
Evaporator pressure:	$P_{evap} = P_{dew}(-5°C) > 1\text{bar}$
Glide:	$\text{glide} = T_{dew}(P_{evap}) - T_{bubble}(P_{evap})$
	Case A: glide < 4°C [a]
	Case B: glide < 2°C

[a] In Case A, the glide limit is 5°C for mixtures containing R32, while for other mixtures the glide limit is 4°C.

All conditions are evaluated assuming no difference in mixture composition between different parts of the system, since it is difficult to estimate this change in composition before doing system simulations (STEP 2). The composition after the condenser is used because the most important requirement is the supply temperature at the condenser. After having done the system simulations (STEP 2) the other conditions are, however, checked again at the actual mixture composition.

The demand on condensation temperature is 80°C for heat pump group 2 and around 70°C for heat pump group 1. For flexibility reasons it is of course best to use the same working fluid in both heat pump groups. However, if there was a large gain in performance by using different working fluids in the two groups, this could also be considered as an alternative. Therefore, the screening was performed at these two different levels of condensation temperature (Case A and B).

As already mentioned, there is a lower limit on the evaporator temperature due to the risk of ice formation. If the glide is "too large", the evaporator temperature becomes the limiting parameter and the maximum volume flow into the compressor cannot be used, giving a drop in capacity. An even larger glide would further decrease the volume flow and, thus, also the capacity. Therefore, to find mixtures giving an increase in capacity compared to R134a, the glide has to be limited. Furthermore, the glide has to be limited due to the possible decrease in condensation and evaporation heat transfer when using a non-azeotropic mixture instead of a pure fluid. However, this is not considered in the present study.

It is difficult to set a glide limit equal for all mixtures, due to possible differences between the mixtures in terms of parameters affecting the evaporator temperature, such as evaporator heat duty, pressure drop, outlet vapour fraction and inlet subcooling. Further, since there is a change in composition between different parts of the heat pump, the actual glide in the evaporator might, depending on the mixture composition, be both larger and smaller than the glide calculated in the screening stage. Therefore, the screening was performed at a number of glide limits. Based on the results from some system simulations (STEP 2) the glide limits given above are the most relevant ones.

<u>4.2 STEP 2 - system simulations</u>

For the mixtures that are "accepted" from STEP 1, simulations of the plant are made with a comprehensive computer program, developed in the Department. The aim is to study the change in performance, i.e. heating capacity and COP, compared to R22 and R134a, for five reference cases during the year. The main differences between the cases are seen in *Table 1*. For the three cases where the district heating water flow is fixed, a high capacity is most important. However, for the two other cases, where the outlet district heating water temperature is fixed instead, a high COP is more important. The reason is that during this part of the year, all heat pumps are not running due to a lower heat demand. In the simulations, changes in, for instance, heat transfer, compressor efficiency, evaporator outlet vapor fraction, and lower limit on evaporator temperature, when using different working fluids are neglected.

Table 1: Main differences between the reference cases

Reference case	Inlet sea water temperature (°C)	Inlet district heating water temperature (to group 1) (°C)	Outlet district heating water temperature (from group 2) (°C)	District heating water flow (to each group) (kg/s)
Extreme winter	2	50	is calculated	1650
Normal winter	3	50	is calculated	1920
Early summer	6	40	78	is calculated
Early autumn	12	46	78	is calculated
Late autumn	8	42	is calculated	1670

A sensitivity analysis was however made in order to investigate the influence of these assumptions.

4.3 STEP 3 – economical evaluation

Since most part of the year it is important to have a working fluid that can offer as high capacity as possible, while during the rest of the year it is more important with a high COP, an economical evaluation was needed to be able to decide which mixture is the best alternative on an annual basis. With an estimation of the annual operating time for each reference case and with costs given for alternative heat production as well as for purchase of electricity (cost taken as 40% higher for electricity than for heat), an approximate change in annual income can be calculated.

5. RESULTS AND DISCUSSION

5.1 STEP 1 - screening stage

The number of accepted mixtures mainly depends on the glide limit and the demand on condensation temperature. Additionally, a lot of mixtures are not accepted because they are flammable. In *Figures 3a* and *b* the results, in form of accepted mixture compositions, are shown from the screening made at the two different levels of condensation temperature (Case A and B) and for the most relevant glide limit for each case. The accepted mixtures that can be used in both groups (Case A) contain quite a large amount of R134a (at least 40%), since otherwise the mixture will have critical properties that are too low. However, if the mixture should be used only in heat pump group 1 (Case B) the content of R134a can be smaller (10%), which means a larger potential for an increase in capacity compared to pure R134a.

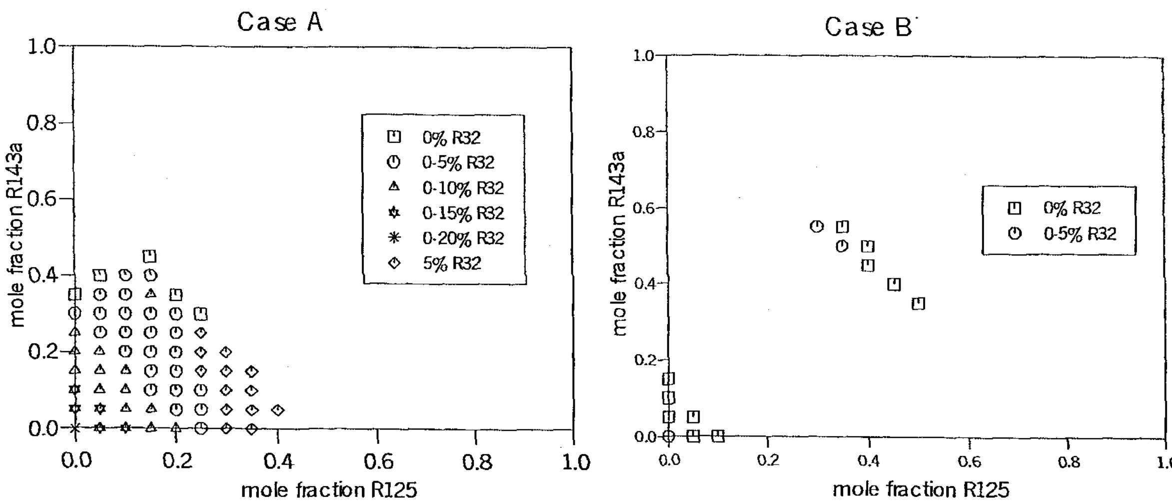

Figure 3a and b: Accepted mixture compositions from STEP 1 for Case A and for Case B. All mixtures also contain R134a, making the total composition equal to 100%.

5.2 STEP 2 - system simulations

In *Figure 4a* and *b* below, the change in capacity and COP, compared to R134a, are shown for the four most promising mixtures. These four mixtures are referred to as follows.

Mix1: 20% R32 + 80%R134a

Mix1_mod: 25% R32 + 75% R134a

Mix2: 30% R143a + 25% R125 + 45% R134a

Mix3: 55% R143a + 30% R125 + 15% R134a (can only be used in group 1)

The composition is given in mole% and corresponds to the composition after the condenser.

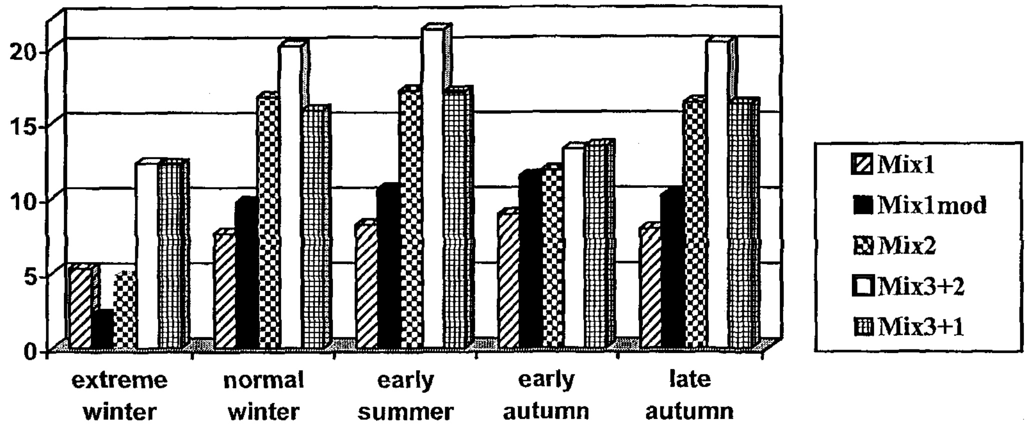

Figure 4a: Change in capacity compared to R134a (%)

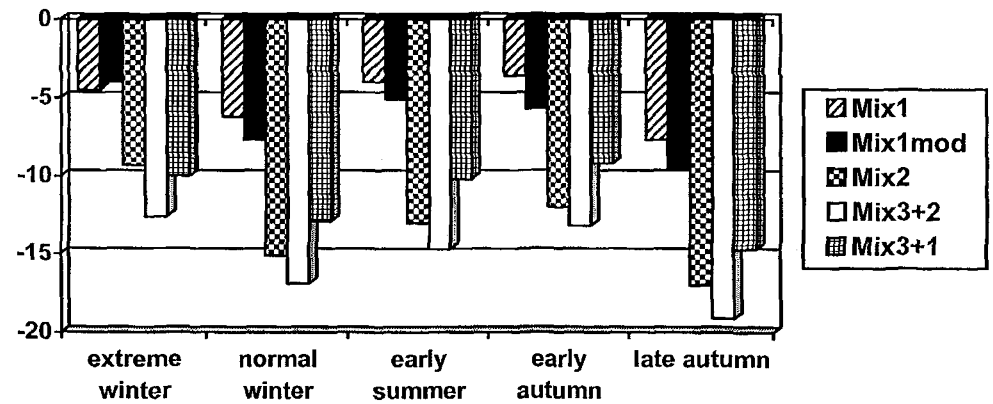

Figure 4b: Change in COP compared to R134a (%)

As seen if comparing *Figure 4a* and *b*, the mixtures that can offer the largest increase in capacity compared to R134a, however, also give the largest decrease in COP. For example, the alternative of using different mixtures in the two groups gives the highest capacity, but also the largest decrease in COP. The limiting parameters for each working fluid are represented in *Table 2*. These differences in limiting parameters are important to consider when discussing the result. For example, the volume flow is always limiting for R134a. Thus, if a larger compressor could be used, the decrease in capacity for R134a compared to R22 would not be that large. Furthermore, the relatively low capacity increase for Mix2, Mix3+2 and Mix3+1 in early autumn can be explained by the limiting parameters. In early autumn, the operating conditions result in a relatively large volume flow to compressor stage 2. For Mix2, and especially for Mix3, this volume flow is limiting already in some other cases. As also seen in *Figure 4a*, a raise in inlet sea water temperature from 2 to 3°C, which is the difference between extreme winter and normal winter, means a large increase in capacity for the mixtures compared to R134a. The reason is that at 3°C inlet sea water temperature the evaporator temperature is no longer limiting and, thus, the maximum volume flows can be used. If comparing Mix1 with Mix1_mod, with the latter one having a larger glide, it is seen that the capacity is higher for the mixture with the largest glide for every set of condition except in the extreme winter case. The reason is the increased risk of ice formation when using a mixture with a larger glide.

Table 2: Limiting parameters (T=minimum evaporator temperature, V=volume flow to compressor, 1=first stage, 2=second stage, E=motor power)

Working fluid	Extreme winter	Normal winter	Early summer	Early autumn	Late autumn
R22	T,T	V_{12}, E	V_1,E	E,E	V_{12},E
R134a	V_1,V_1	V_1,V_1	V_1,V_1	V_1,V_1	V_1,V_1
Mix1	T,T	V_1,V_1	V_1,V_1	V_1,V_1	V_1,V_1
Mix1_mod	T,T	V_1,V_1	V_1,V_1	V_1,V_1	V_1,V_1
Mix2	T,T	V_{12},V_{12}	V_1,E	V_2, E	V_{12},V_{12}
Mix3	T	V_2	V_2	V_2	V_2

In a sensitivity analysis the influence of the assumptions made in the system simulations was investigated. The most important result is that for mixtures where the evaporator temperature is the only limiting parameter, a decrease in evaporation heat transfer has a crucial influence on the capacity for the extreme winter case. Note that this result was obtained by keeping the limit on the minimum evaporator temperature constant. However, a decrease in heat transfer (on the refrigerant side) also decreases the limit on the minimum evaporator temperature since the wall temperature increases. This indicates the need for theoretical and experimental studies concerning the evaporation heat transfer and ice formation.

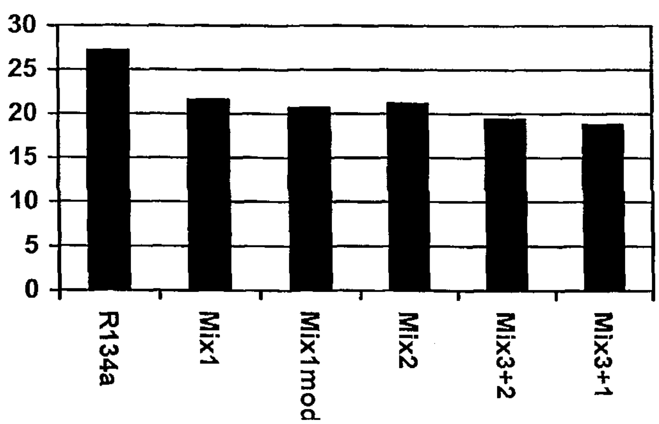

Figure 5: Change in annual income compared to R22 (%)

5.3 Economical evaluation

The result, in form of decrease in annual income compared to R22, is given in *Figure 5*. As seen, if converting to R134a, the decrease in annual income is around 27%. The mixtures can offer an increase in annual income of 6-9% compared to R134a. Thus, despite the rather large differences in capacity and COP between the mixtures and between the five reference cases, the difference in economic performance is quite small if looking over a whole year. These results led to a more detailed economical evaluation, carried out by Birka Energi, Stockholm, using a production-planning program for a future scenario which assumes a somewhat higher electricity price. Costs for fuel and electricity, environmental taxes and fees, operating and maintenance costs, sales and purchase of heat, as well as income from the power production were considered as net production cost. The result shows that there will be no decrease in production cost when using a mixture instead of pure R134a. The explanation is mainly that in the district heating system considered, there are two combined heat and power plants (oil- and coal-fired, respectively) that can replace the decreased heat production from the heat pumps. This gives an increase in electricity production that more than compensates for the increased cost for heat production. This shows that the simplified economical model discussed above should not be used for a system including combined heat and power units. It is however relevant for a plant producing heat-only. Thus, in the actual plant there would be no economical gain in using a HFC mixture instead of R134a. There would however be some relatively large environmental gains, for example a decrease in CO_2 emissions of 3% compared to R134a.

6. CONCLUDING REMARKS

A screening was made covering almost 2000 mixtures, containing two or more of the substances R134a, R32, R143a and R125. The number of accepted mixtures mainly depends on the condition concerning the glide limit, the demand on condensation temperature, and flammability.

The results from simulations of the heat pump plant show that there are a number of mixtures that can offer an increase in capacity, compared to R134a, of up to 12% for extreme winter conditions and up to 20% for summer conditions. However, these mixtures give a large decrease in COP compared to R134a. The economical evaluation shows that in a heat producing net, the increase in annual income if using the mixtures compared to R134a would be 6-9%. However, if using a mixture instead of R134a in the actual heat and power producing net, calculations show no economical gain. Still, there would be environmental gains.

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