DISTRICT HEATING AND COOLING WITH HEAT PUMPS AND REFRIGERANT NETWORKS: UTOPIA OR POSSIBILITY?

D. Favrat, T. Grivel
(Laboratoire d'énergétique industrielle, Ecole Polytechnique Fédérale de Lausanne, Switzerland)

Abstract

Growing concern for environmental changes like the global warming effect should contribute to boost the use of heat pumps. Water from lakes or sea has an enormous potential of low grade energy to satisfy both heating and cooling needs.Distribution through urban areas is best achieved via District heating networks. A feasibility study of a concept of 3 pipe refrigerant network for heating and cooling from a central heat pump at the lakeshore is presented. The paper shows potential gains of 6 to 30% on the heating coefficient of performance alone compared to a heat pump fed conventional water network. Compared to the high excavation costs, additional costs associated with the refrigerant inventory and safety measures are within reasonable limits for R22 and NH3.

District Heating and Cooling, Heat Pump, Refrigerant Network

1. Introduction

Today combustion of fossil fuels still satisfies around 80 % of the worldwide energy needs. Energy conservation linked to the growing concern for the environmental impacts from combustion gases like acid rain, greenhouse effect and superficial ozone is likely to boost the use of more efficient technologies to satisfy basic heating and air-conditioning duties. It is useful to remember in this context that heat pumps are the only technology which allow us to obtain more useful heating energy than consumed in the form of primary energy. This advantage is however closely dependant on the proximity of a convenient low temperature heat source and can only be economically exploited if the temperature lift requirements are low. The former is not obvious in urban areas where noise and space restrict the use of individual air source heat pumps. The latter is more and more possible in view of the improved design of modern buildings with better thermal insulation and large window areas to the south which can usually be heated with low temperature heating systems. However, even in Europa, these new buildings also have increasing needs for air conditioning in the summer especially in urban areas with a high density of shops and office buildings.

Various District heating schemes with heat pumps have been proposed and are mainly based on the upgrading of energy from water ressources (lake, sea, river, sewage water). The earliest plant of this kind (ETH-Z) was installed in Zurich in 1939 and consisted in a water network heated by two ammonia heat pumps with the river Limmat as the evaporator heat source. While the development of this technology stagnated during the cheap oil after war period, interest picked up from 1973 and a fast growth of large heat pumps was noticeable from 1980 in the scandinavian countries and in Japan in particular [1]. The most popular networks in Europe are dual pipe medium temperature water networks, the water being heated in average from 60 to 80 °C by central heat pumps supplemented by peak boilers. Air source heat pumps with storage are the favoured systems in Japan with both heating and cooling through double dual pipe water networks (one for heating, one for cooling). Delivery temperatures of the heating networks are generally lower than in Europe with 47 to 50 °C [2,3].

Lower temperature dual pipe networks distributing water at a temperature of 25 °C or less have also been proposed and implemented, for example in Higariga-Oka Park near Tokyo [3]. This water is either cooled in the evaporators of decentralized heat pumps in heating mode or heated by the condenser heat of cooling units. Similar low temperature networks including schemes with a single pipe distribution and return through the sewage network have been proposed by Lorentzen [4] and others [5].

As mentionned above, heat pumps are most effective if the temperature lift is low. Unfortunately, the temperature requirements of the hydronic systems in European buildings tend to vary depending on the age of the buildings, on the level of insulation retrofitting and on the conservatism used in the design of the room convectors. A common attitude has been to adapt the delivery temperature of the District heating networks to the most exigent customer which usually results in excessively high delivery temperatures. This is economically acceptable as long as combustion of fossil fuels represents the major source of energy and efficient cogeneration is not a major ambition. The introduction of large centralized heat pumps however, gives a strong incentive to adjust the delivery temperature levels towards lower values. Hence, the importance of reducing the number of heat exchangers cascading heat from the central plant to the customer heating system. Among the various attempts to reduce the temperature lifts in the centralized heat pumps let us cite the Oslo network [6] where the District heating water was directly circulated in the buildings without intermediate heat exchangers. This attempt unfortunately failed for what was apparently legal responsability problems and individual building heat exchangers had to be introduced. The situation is easier when the heated buildings and the network are run by the same owner. Such a situation exists on the site of the Swiss Federal Institute of Technology of Lausanne (EPFL) where buildings are directly fed with the network water without the need for individual heat exchangers.

When faced with urban areas including buildings with diversified heating level requirements an approach would be to adjust the network water temperature to the majority of users and use additional boosting heat pumps for the few customers having higher temperature requirements. However, these additional heat pumps are expensive and result in high cumulated temperature lifts which are fairly inefficient. Moreover, the water network temperature would still be too high to be of any use in connection with air-conditioning duties.

To some extent, similar problems are also found in tall buildings requiring both heating and cooling and where water distribution networks are generally used. It is worth mentionning in this context an interesting concept based on the distribution of the refrigerant itself which has been applied in a 157m high building commissioned last year in Osaka [6]. In this particular case, two dual pipe loops distribute the refrigerant (R22) throughout the entire building to the individual room condensers or evaporators.

Recognizing the importance of the factors mentionned above, the present paper deals with a feasibility study of a concept of District heating and cooling network in which the energy carrier is the refrigerant itself instead of the pressurized water traditionnally used.

2. Description of the basic concept

The basic concept introduced here consists in a 3 pipes network with one pressurized vapour delivery line, one intermediate pressure condensate return line and one low pressure vapour return line for the air-conditioning duties (fig.1). For safety and legal reasons individual heat exchangers (condensers in this case) are assumed to be maintained in each building to separate the District heating network from the local hydronic systems. A centralized multi-stage heat pump installed near the cold water source (lake, sewage plant, etc) feeds the network with vapour at a pressure adapted to the temperature requirements of the majority of the buildings of the deserved area.

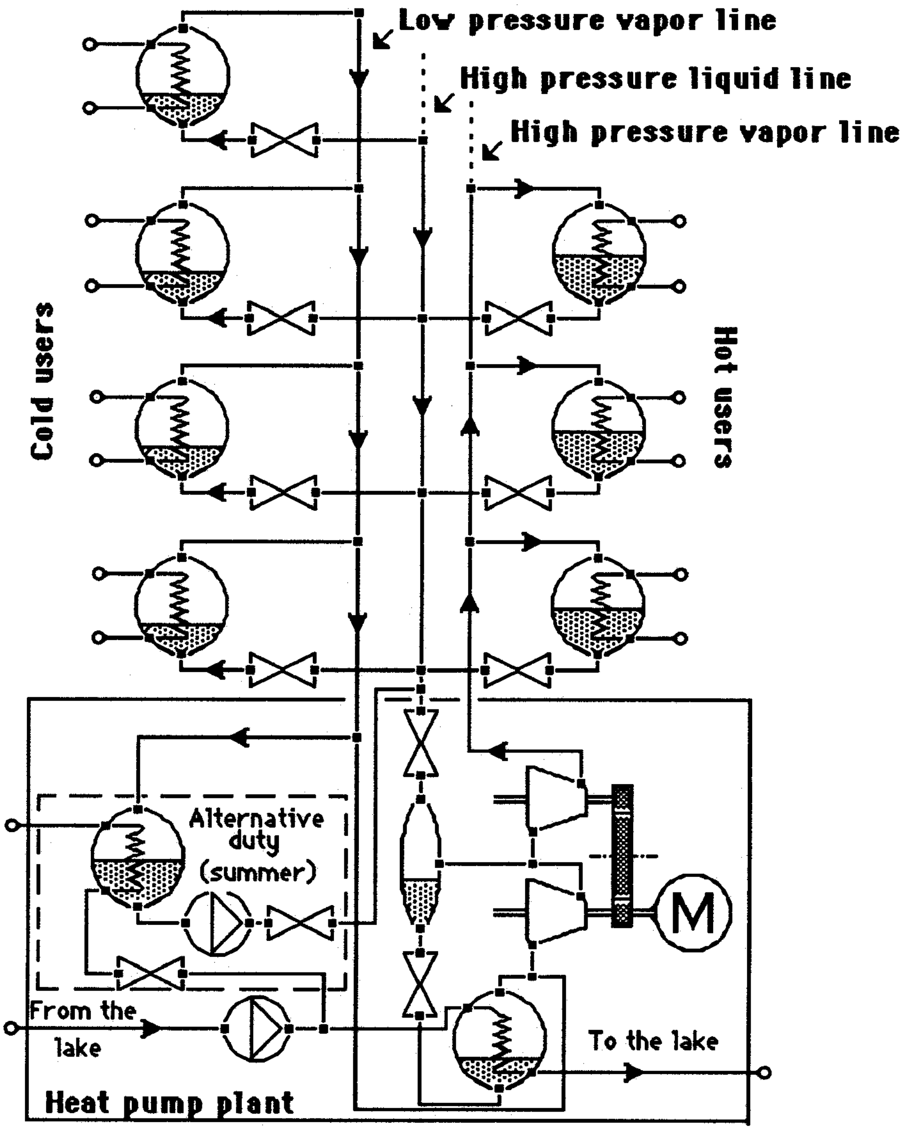


Figure 1 : District heating & cooling with refrigerant network, fed by heat pump.

In **heating mode**, the flow of refrigerant vapour is adjusted in each building by a thermostatic expansion valve located downstream of the condenser and the condensate is returned to the heat pump via the main liquid return line. The regulation parameter is the refrigerant subcooling upstream of the valve which must be sufficient to avoid two-phase flow into the return liquid line. The pressure differential between the high pressure vapor and the liquid lines should at every point of the network be sufficient to permit a satisfactory behaviour of the valves and adequate automatic purging of the occasional condensates of the vapour line. For buildings requiring a higher temperature than directly provided by the network, a local vapour compression stage can be added between the high pressure vapour line and the condenser. This is one of the interesting features of this concept as open cycle booster heat pumps are known to be much more efficient than close cycle heat pumps for the same duty.

In **cooling mode**, liquid refrigerant is taken from the liquid line, expanded to the required evaporator pressure and the resulting vapour downstream of the local evaporator is injected into the low pressure vapour line. Here again the pressure of this return vapour line is adjusted to the cooling requirements of the majority of users. Lower cooling temperatures could still be achieved locally by adding a compressor stage between the evaporator and the main low pressure vapour line.

If cooling requirements exceed the heating requirements, in summer time for example, when only domestic hot water is heated, the returning low pressure vapour is condensed in an additional central condenser using the same water supply than the heat pump (lake, etc.) and pumped backwards into the liquid line. Energy requirements for cooling will therefore be reduced to a minimum compared to conventional cooling systems. Moreover investment expensive load leveling systems like ice storage tanks could be avoided considering the relatively low electric consumption of refrigerant liquid pumps compared to compressors.

3. Duties and refrigerants

In view of the concern for the greenhouse and ozone depletion effects the refrigerant issue is of course of primary importance and particularly critical for the concept under consideration.

New HCFCs or HFCs will be more expensive [8] and still have a global warming effect which is not negligeable (fig.2). One critical parameter with these fluids will be the inventory cost which, in spite of the high relative cost of excavation, can become significant.

Alternative fluids like butane and ammonia are usually considered as environmentally safe but pose stringent safety problems linked to their flammability and explosion factors. The latter also causes major health considerations in view of its toxicity. Special attention would therefore have to be put on piping solutions to circumvene these drawbacks.

3.1 Comparison test case

For the sake of comparing the relative qualities of the refrigerants considered and the concept of 3 pipes refrigerant network with regards to more traditional networks, a District heating network with the following features has been chosen :

Peak heating power: 9MWth

Piping length: 3 x 2 km.

Typical users include condominiums, office buildings and department stores. The Swiss situation is chosen as a basis for the evaluation of the building needs. Although most existing buildings have hydronic systems with a 70 to 90 °C design temperature range, real requirements are usually some 15 °C lower than these design values [7]. This means that the water delivery temperature requirements are indeed of 71 to 75 °C for an atmospheric temperature of -8 °C.

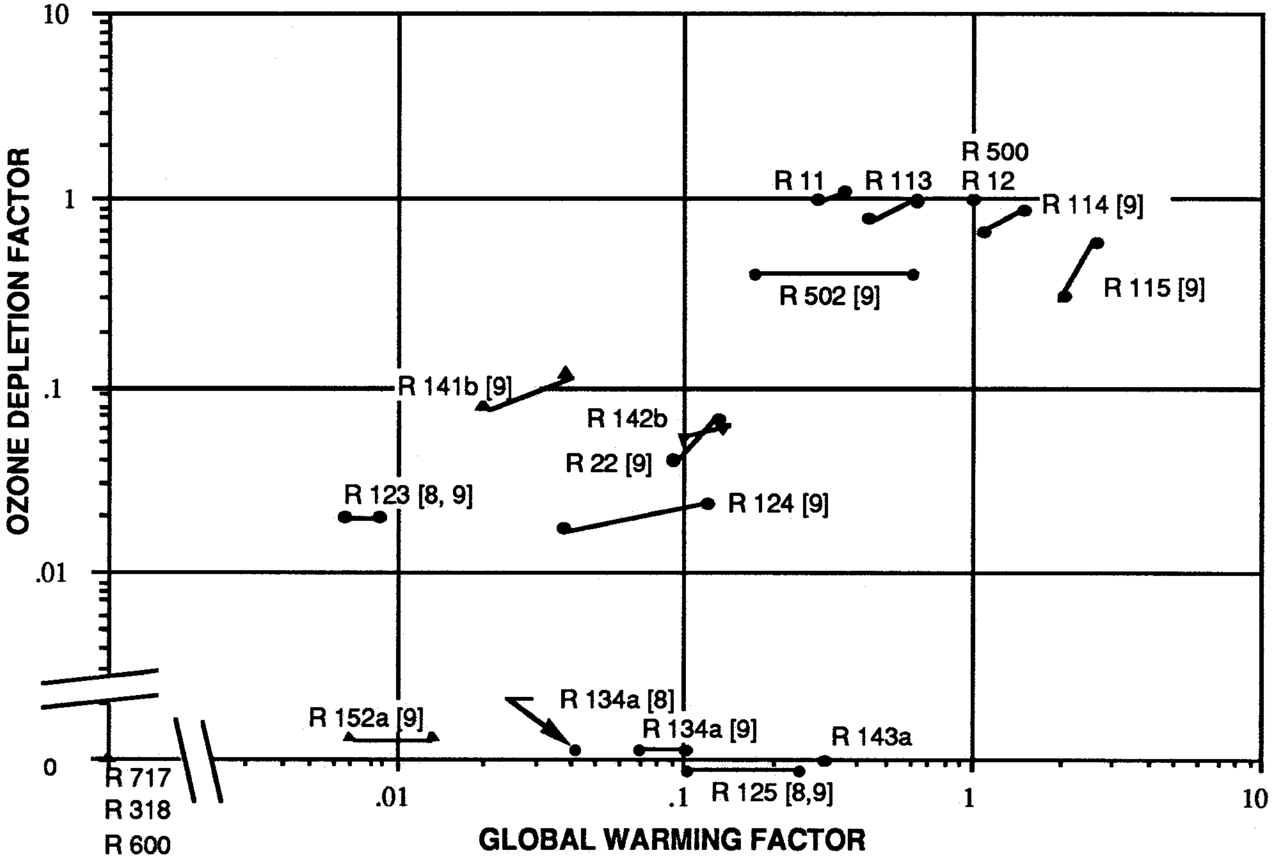


Figure 2 : Ozone depletion & greenhouse effects of some refrigerants.

In view of its particular piping requirements, the network would have to be a new network not branched to any other older network.

The following refrigerants have been considered for comparison:

HCFC and HFC family: R22, R134a, R123

Others: R600 (nbutane), R717 (ammonia).

A computer program allows us to compute the main cycle and network design variables accounting for pressure and heat transfer losses, heat exchanger pinches, inlet evaporator water temperature and outlet condenser water. In a first approach, the following assumptions are made concerning the results illustrated in Figures 3 to 5 :

Single user at the opposite end of the network.

Evaporator pinch $\partial e=3$ °C

Condenser and subcooler pinches $\partial sc=\partial c=4$ °C

First stage and economizer superheat $\partial se=\partial s=4$ °C for R600,0.1 °C for the other fluids

Difference between delivery and return water temperature in the hydronic system of the user is 10 °C.

Pressure drop in the high pressure vapor line corresponding to a drop of 2 °C of the condensation temperature.

Minimum pressure drop in the customer expansion valve = 100 kPa

Pressure drop in the non insulated liquid line limited to avoid flashing in the line assuming that the heat pump plant is always at the lowest altitude (case of lake sources).

Central multi-stage compressor isentropic efficiency of 78 %.

3.2 Overall coefficients of performance (heating mode only)

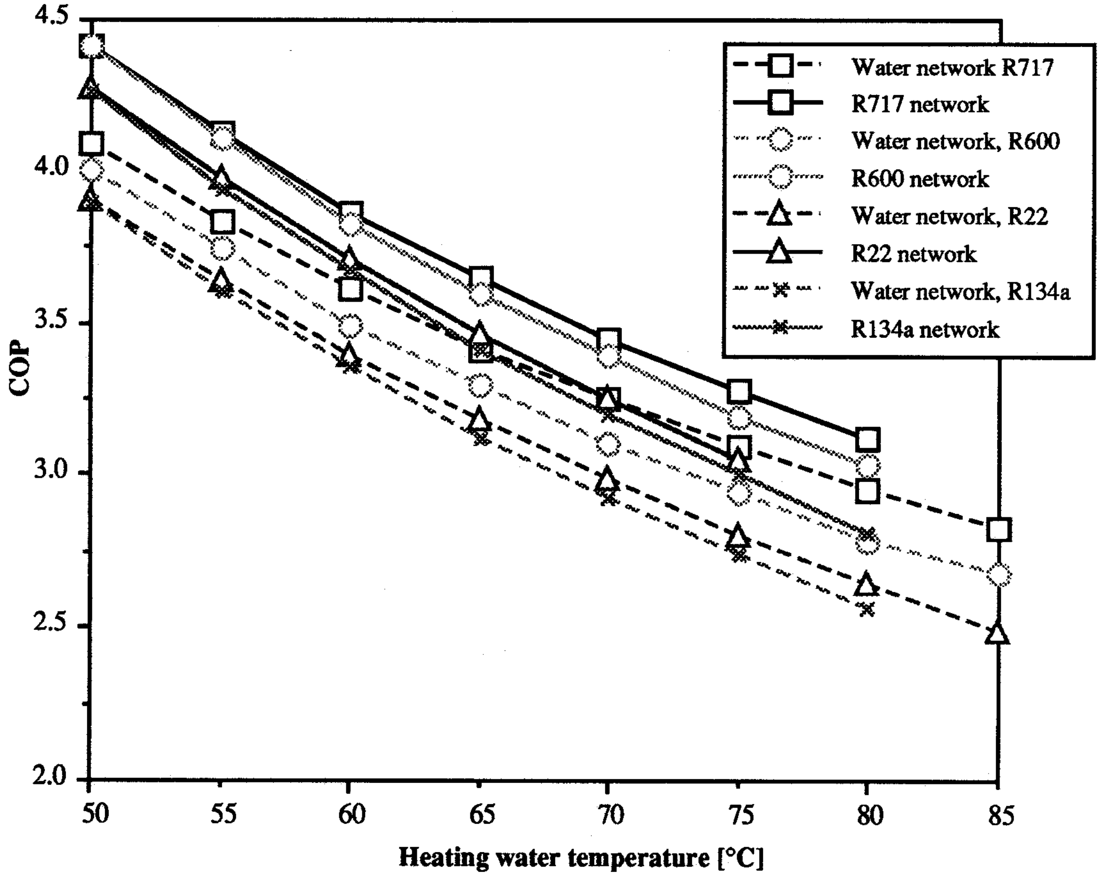


Figure 3 : Variation of overall COP for various refrigerant networks.

Figure 3 shows the variation of overall COP for various refrigerant networks (solid lines) in comparison with the corresponding performances of the more traditional concepts (dotted lines) based on a central heat pump and a hot water distribution network. In the latter case, the difference of temperature at each user is also assumed to be 10 °C. Note that a higher temperature difference on the network side even if often observed in real networks tends to give lower average COPs which would increase the performance difference in favor of the refrigerant network concept. A pinch corresponding to the log mean temperature difference of the refrigerant-water local heaters of the refrigerant networks was adopted for the corresponding counter-current water to water local heaters of water networks.

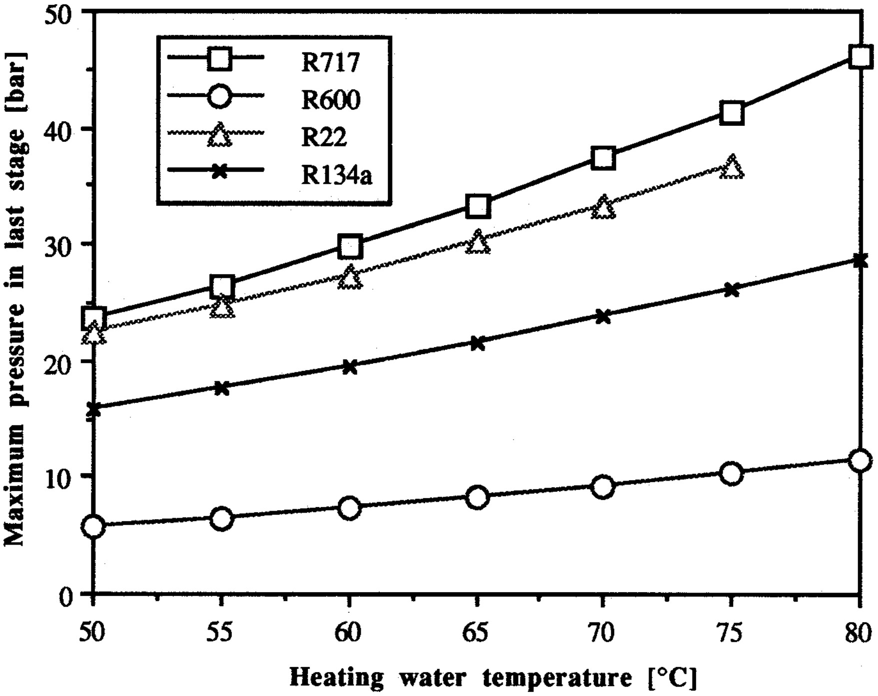


Figure 4 : Pressure in the last stage for different refrigerant.

The analysis is based on a centrifugal compressor heat pump with two-stage compression for all refrigerants except for ammonia for which a 3-stage cycle was considered over the entire range of delivery water temperatures. For these duties, ammonia and nButane give the best performances followed by R22 and R134a. The corresponding pressures are fairly high for ammonia and R22 as shown in Figure 4. As could be expected considering the heating mode only, the performance improvement with refrigerant networks is more significant if the required water temperature of the building hydronic systems is low. This performance improvement corresponds to a decrease in mechanical power of the order of 6 to 8 % for ammonia and of 9.5 to 10 % for R134a in the range of delivery temperatures from 80 °C to 50 °C. In the absence of cooling needs this is a rather small margin to pay for the extra expenses and risks associated with refrigerant networks. However, as pointed out earlier, the temperature requirements of users in a given district usually vary and the following alternatives can be considered to satisfy all users :

a) heat pump with a water network temperature boosted to the requirements of the most exigent user.

b) heat pump with a water network temperature adapted to the majority of users and completed by individual closed cycle heat pumps used for boosting the temperature of the more exigent users. In this case the network water provides heat to the evaporator of the local heat pump.

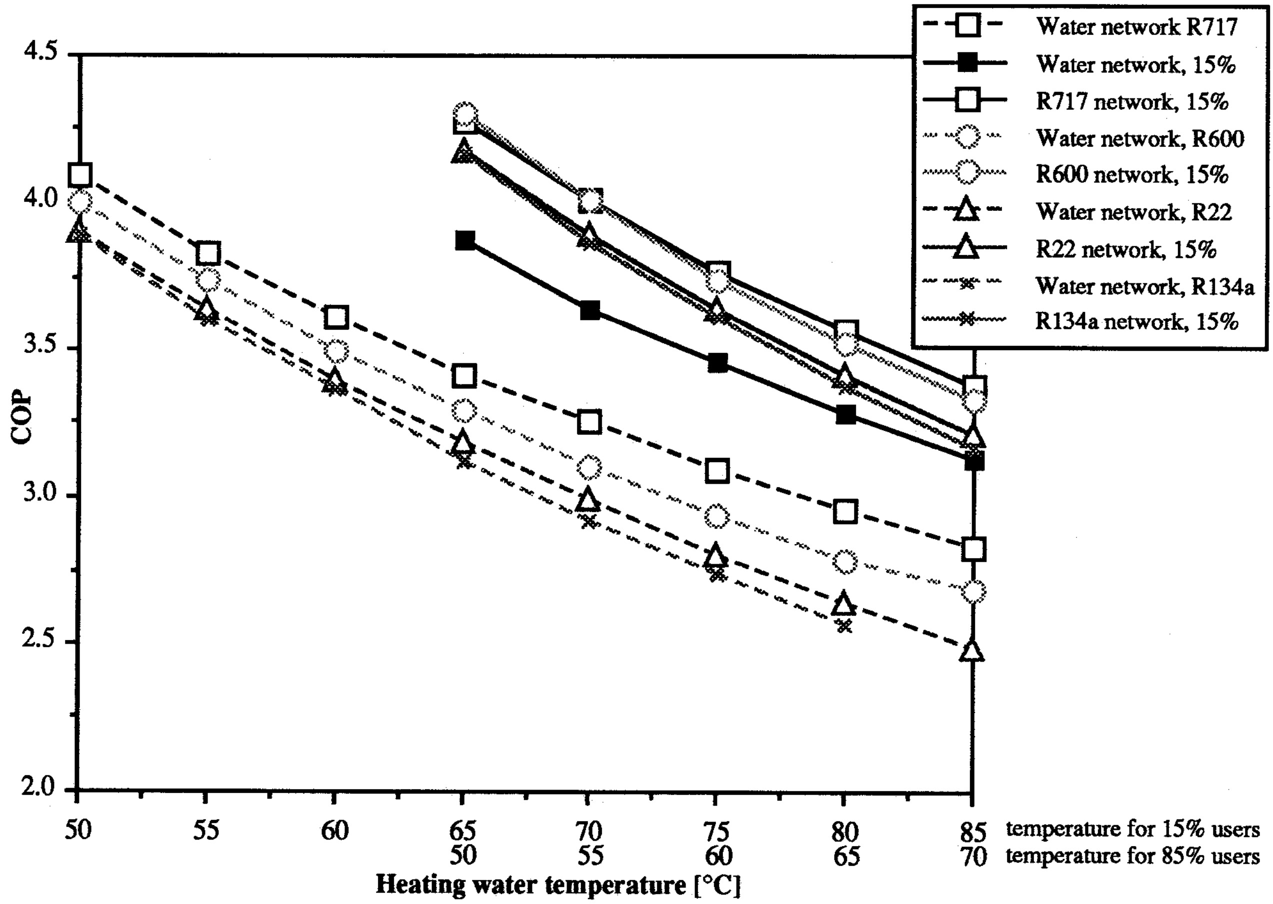
c) heat pump with a refrigerant network temperature adapted to the majority of users and completed by individual booster compressors.

Nowadays experience tends to show that the temperature difference between the return and delivery temperatures of local hydronic systems is generally reduced to 10 to 15 °C. We have, therefore, not considered in our comparison the case of a central heat pump with a boosting boiler which is more adapted to networks with large temperature differences.

Figure 5 shows the comparison of performance for a case where 85 % of users require a given temperature while the remaining 15 % require a temperature boost of 15 °C. For the concepts with either open or closed cycle boosters we consider the following average COP :

$$\overline{COP}=\frac{\dot{Q}_{cond}}{\sum \dot{E}_{compr}}$$

and the isentropic efficiency of the booster compressors is assumed to be 70 % heat pump).



<u>Figure 5</u> : Water network & boosted refrigerant network.

Comparison between the upper curves of figure 5 which correspond to refrigerant networks according to case *c* above and the lower curves which correspond to case *a* show an increased benefit for the refrigerant networks over the water networks. As an example, if 85 % of users require only 60 °C and the remaining 15 % require 75 °C, the overall mechanical power reduction varies between 22 % for ammonia and 32 % for R22.

This difference is lower for case *b* with still a significant advantage for the refrigerant network, because the closed cycle booster heat pumps have to upgrade the refrigerant energy over a higher temperature difference. Average temperature upgrades are 15 °C for the open cycle heat pump (*c*) and 29 °C for the closed cycle case (*b*).

It is clear that the above remarks are part of a conceptual analysis with the futur in mind and are not restricted to the actual constraints of the present market for compressors in particular. New developments would have to be initiated to bring adequate booster compressors in a power range broad enough to cover major types of building needs.

3.3 Pipe dimensions and refrigerant inventory

Keeping the same assumptions as described in § 3.1 above, the table 1 shows the order of magnitude of the pipe diameters for the different heating duties considered and for a single user at the end of the lines. The diameter of the liquid return line is sized on the basis of the maximum heating duty. In central European climates, it is reasonable to assume that such a design will be sufficient for the air-conditioning needs which in any case are likely to greatly vary from district to district. These values are intended to show the relative advantages or disadvantages of the different refrigerants for an estimation of the costs associated with piping and refrigerant inventory. At this stage no attempt has been made to design according to standard pipe dimensions available on the present market.

Because of its high latent heat and its high vapour pressures, ammonia requires the smallest pipe diameters which also results in the smallest inventory and associated costs. In spite of the large pipes nbutane requires, its low specific cost per unit of mass compensates and the inventory price per unit of District heating length is of the same order of magnitude than for ammonia (10 to 13 Swiss Frs/m). As expected, the issue is more critical for the HCFC refrigerants. In view of the high excavation costs the relative price of R22 could still be considered while R134a with more than 1300 CHFrs/m has be disregarded for economic reasons.

3.4 Safety

Further selection among refrigerants cannot be pursued without considering the important safety issues associated with the use of ammonia or nbutane in an urban environment.

Nbutane is highly explosive and its heating value is high so that risks of fires are critical.

Ammonia is the object of a lot of controversy with many recent advocating papers [9,10,11,12]. Ammonia explosive range is narrow and several order of magnitudes away from the easy detectable concentration range. Its heating value is too low to maintain a fire without additional fuels. It is toxic but risks are considerably limited because of its easy detection. Examples of large inventories are common in industrial refrigeration. Even in this city we have a history case of the heat pump plant of the former EPFL building in Lausanne with ammonia underground lines over 400 meters from an evaporator at the lakeshore to the condenser located in the building itself. This heat pump operated from 1946 to the early sixties and was stopped after a major leak from the unprotected pipes buried in the ground. The major consequence mentionned was apparently the noticeable fertilizer action on the lawn!

Nevertheless, considering the potential major drawbacks of these two fluids it is imperative to take into consideration in our evaluation the appropriate technical measures which could to be enforced to greatly reduce risks. One of these is to systematically use double pipes with a buffer medium between the refrigerant line and the ground. Fortunately such steel pipes, presinsulated, are already available on the market for the higher temperature water district heating lines. Gaz detectors could be installed in the buffer annular pipe to prevent damages resulting from leaks. Two fluids are known inhibitors for ammonia, carbon dioxyde and water. The former should preferably be chosen around the high pressure vapour line as it would act as an insulator as well as a neutralizer of minor leaks of ammonia. On the other hand the liquid and low pressure vapour lines which have no significant insulation needs could be surrounded by water which also neutralizes ammonia. These water lines could also be used to transport industrial water or to build a closed loop water source for a traditional heat pump located further away from the network extreme point.In this latter case the water would be warmed up while ensuring the refrigerant subcooling.

For both ammonia and nbutane the surrounding safety envelop would have to be continued in the network branches driving to the individual buildings with a leak tight canopy around the local heat exchanger and the compressor if needed. A relief valve in the condenser unit could download the refrigerant towards the low pressure vapour line in case of fire or other emergency.

Among side advantages related to nbutane, let us note a possibility of taking part of this fluid for other combustion duties in the buildings. The heat pump network would then be used as a thermal energy network as well as a fuel distribution network.

In any event, those above mentionned opportunities should be considered as potential complementary benefits but the viability of the idea of refrigerant network should first be demonstrated on the basis of the heating and cooling duties only. Therefore piping costs for both ammonia and nbutane have to account for the double envelop. Similar requirements are not made for the HCFCs or HFC in view of their nonflammability and very low toxicity.

Table 2 summarizes the approximate costs per unit length of refrigerant network including both refrigerant and piping costs. Provided the pressure levels can be dealt with, R22 and ammonia require, compared to a single pipe water network of equivalent heat rate, an overinvestment of 350 and resp. 440 CHFrs/m. These costs include only the two main lines for the heating mode.

3.5 Influence of the geographic distribution of users

The progressive reduction of the pipe diameters as we get away from the central plant is shown for ammonia in figure 7. A uniform distribution of 100 users requiring 90 kWth each was assumed for illustration purposes. This progressive area reduction will positively affect piping and inventory costs.

3.6 Other consideration

For hilly cities side benefits like snow clearing on sidewalks as proposed by Lorentzen [4] could be obtained with minimum losses from the subcooling the liquid refrigerant in the intermediate pressure liquid line.The lack of insulation around both the liquid and low pressure vapour lines would be positive in this regard.

The present concept eliminates the possibility of a central booster boiler for the most chilly days or the possibility to efficiently benefit from a thermal drive for the compressors. The concept has to include a complementary compressor stage for the coldest periods provided the pipe strength margin is suffisant.The avoidance of a central stack could however be an advantage when countryside is to be preserved as often is the case in lakeshore areas.

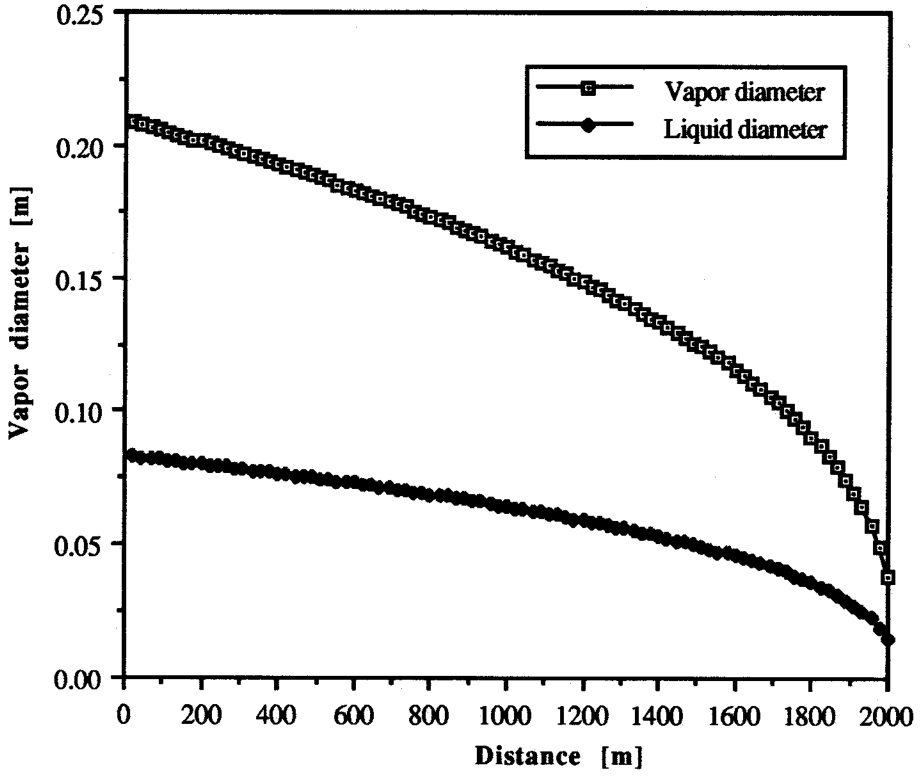


Figure 7 : Variation of pipes diameter for a R 717 network.

4. Conclusions

Considering the present trends towards low temperature heating systems and the increased cooling needs for buildings, refrigerant District and cooling networks could represent one way of increasing the efficiency of the systems based on heat pumps. The proposed 3 pipes system has performance advantages for urban areas with a significant cooling load in the summer and a majority of users having low temperature heating systems in winter.In the crowded substreet space of modern urban areas, ammonia with its excellent refrigerant characteristics, low cost and small pipe diameter requirements would be a potential candidate. Concentric pipes with a safety envelop could alleviate some of the perceived risks. R22 is also conceivable. Further studies considering controls, unsteady phenomena, pressure modulation throughout the seasons, the development of decentralized compressor units and including a detailed risk analysis are still required to validate this concept.

Figures must be included in text:

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Fig. 1 Concept of 3 pipe District heating and cooling refrigerant network

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Fig. 2 Global warming + ozone depletion for refr.

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Fig. 3 Comparison of the coefficient of performance of district heating and cooling networks with heat pumps and either hot water or refrigerant distribution. Case with 100 % of customers directly satisfied with the delivery water temperature level considered.

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Fig. 4 refrigerant maximum pressure levels for case of Fig.3

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Fig. 5 Comparison of the coefficient of performance of district heating and cooling networks with heat pumps and either hot water or refrigerant distribution. Case with 85 % of customers directly satisfied with the delivery water temperature level considered and 15 % requiring a level of temperature 15 °C higher.

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Fig. 6 Pipe diameters and inventory

Fig 7 Pipe diameter and inventory reduction for a case with 90 users of 100 KWth each regularly distributed along the network

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