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Liquid Ice District Cooling Systems

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SUMMARY

District cooling systems using chilled water extract heat cheaply at a central point due to economy of scale and more favourable sinks for heat rejection than those available for individual buildings. However, they have relatively expensive distribution systems due to the small temperature difference between delivery water and return water, which results in large pipe diameters.

The system described in this article uses "liquid ice", namely, a solution of a suitable substance such as a salt or sugar in water to form crystallization cores for ice formation at temperatures somewhat below 0°C (32°F). The mixture of ice crystals and liquid behaves like a liquid and can flow along pipes. It can therefore be used both as a cold transport medium and cold storage medium, with an energy capacity per unit volume which is a factor of 5 greater than that for chilled water. Therefore piping dimensions are much reduced and cold storage becomes economically feasible, allowing the cutting of daily and sometimes even seasonal cooling peaks by such stores and, to a large extent, concentration of heat pump operation to periods when lower off-peak electricity rates apply.

Additional advantages can often be obtained by integrating district heating and cooling systems, using common trenches for the pipes of the two types of system, heat pumps to deliver heat extracted by the cooling system to the heating system, and cheap types of storage to balance the time differences between the demands for cold and heat.

The concept was first described by Peter Margen in a paper to the International District Heating and Cooling Association, USA, June 1985, but has since been developed into a practical system by Studsvik Energy.

WHY SLUSH ICE?

It is well known that chilled water systems for district cooling have to use much larger pipes than those used for similar transported powers in district heating systems. The reason is that the overall temperature difference available between the freezing point of water and the building air temperature - is strictly limited to about 22°C (40°F) and some of it has to be reserved for a temperature margin against freezing in the chillers, some for the temperature rise in the delivery pipes and some for the temperature difference in the building heat exchangers. This leaves typically only about 11°C (20°F) for the temperature change of the water - or about 1/5th to 1/6th of the amount available in typical district heating systems (Fig. 1). Hence, chilled water distribution systems tend to be expensive, even allowing for some simplifications in technology permitted by the lower temperatures. The difference in pipe diameters for comparable transported powers is illustrated by Fig. 2.

In some cases the cost of the chilled water system is reduced by using a one-way system, rejecting the return water to local drainage systems. On the other hand, this results in increased costs of water

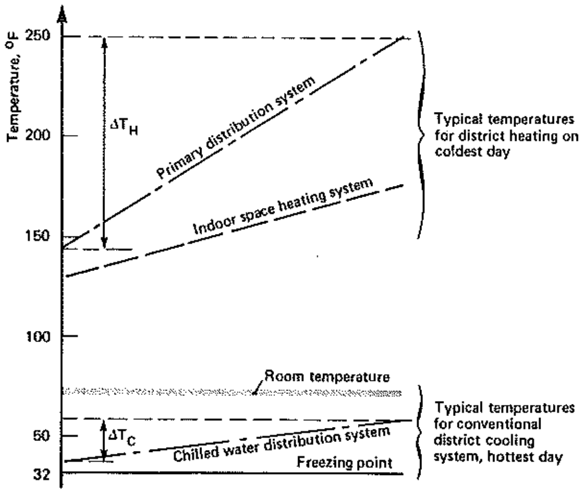


Fig. 1. Temperature range, ΔT_H for district heating, and ΔT_C for chilled water district heating respectively.

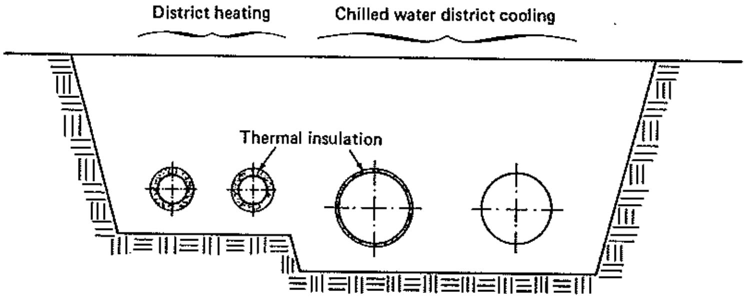


Fig. 2. Relative pipe sizes for district heating and chilled water district cooling systems.

supply and sometimes drains, so that this can be justified only where very cheap water is available.

The system described in this paper removes the disadvantage of large pipe diameters (and some others) of conventional chilled water systems, by using not only the sensible heat of water, but in addition the phase transition heat of ice formation for heat transport and cold storage. It makes use of the well-known fact that water to which soluble substances such as salt or sugar have been added will form small ice crystals around crystallization cores and form a mixture "liquid ice". This "feels" like a liquid to the touch (as can be checked by adding water to snow crystals), and can therefore be pumped along pipes or stored in tanks.

Figure 3 illustrates the typical process of liquid ice formation as described in the literature. The liquid at point A at the return line temperature is cooled until the phase change line is reached at B. On further heat extraction the state moves along the curved phase change line BC whilst crystals of pure H_2O ice are formed, increasing the concentration of the residual liquid. The final mass ratio of ice to liquid is given by the ratio CD to DE.

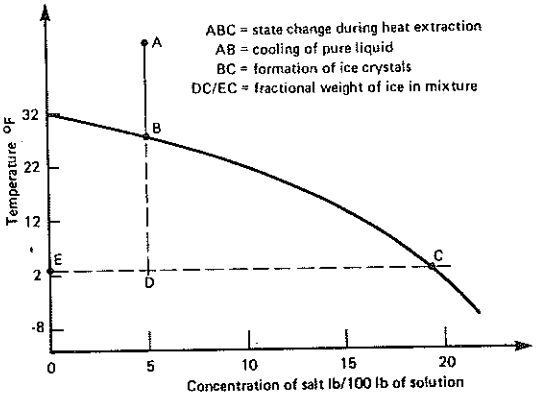


Fig. 3. Example of change of state of salt solution during heat extraction.

At Studsvik Energy work has been in progress for a number of years on devices for liquid ice formation, and units with very satisfactory performances have been developed.

DISTRIBUTION OF "COLD" BY LIQUID ICE

Figure 4 shows the principle of the circuit proposed when applied to district cooling. A special chiller (i.e. heat pump) cools the return liquid and forms liquid ice. As the special chiller cannot produce the high ice concentration desired for transport, i.e. 40 to 45 % ice, a tank is used to increase the concentration of ice. Liquid is extracted from the bottom of the tank and liquid ice, at the concentration the chiller can achieve, is delivered to a higher point in the tank. In the top part of the vessel the ice concentration builds up to the value desired for transport. It is then pumped to the distribution system and distributed to the individual building heat exchangers which produce cooled air, melting the ice crystals in the process and heating the liquid some degrees above the phase change temperature. This pure liquid is returned to the circulating pump which pumps it to the chiller.

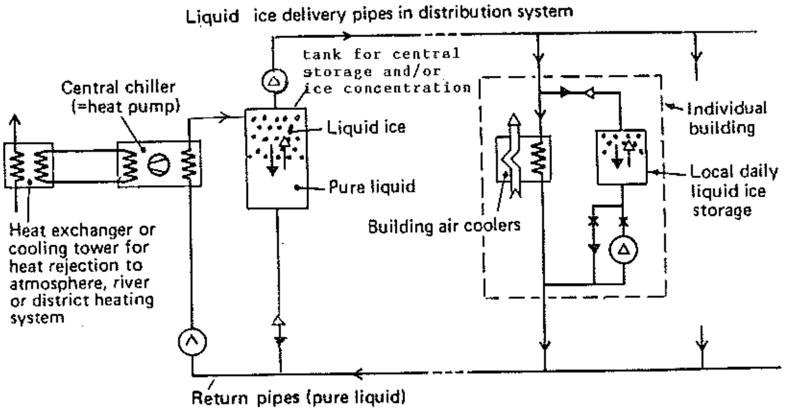


Fig. 4. Simplified schematic diagram for liquid ice district cooling system.

By suitable choices of delivery and return water temperature, the combined heat extraction due to sensible heat and phase change heat can be increased to about 55 kWh/m^3 (5,300 Btu/ft^3) of the delivered fluid, which is about 5 times the value practical for chilled water systems. Allowing for the use of somewhat lower flow velocities for the smaller pipe dimensions which can be used, the volume of the pipes in the distribution system can be reduced by a factor of about 4, on this account alone. Often cheap flexible plastic pipes can be used at least for the smaller dimensions, which simplifies laying. No insulation is needed for the return pipe. The solution used has to be compatible with circuit materials so as to avoid corrosion.

COLD STORAGE

Its high energy content per unit volume makes liquid ice also very suitable for cold storage. For a given duty, the volume of a cold storage with liquid ice is only about 1/5th of that of the volume of cold storage using chilled water. Cold storage can take the form of a central tank close to the central chiller - in fact simply an enlarged version of the "ice concentration tank" mentioned above, or the form of one tank in each major building, i.e. "distributed storage", see Fig. 4. Further information on these two types of storage is presented as follows:

Central Storage

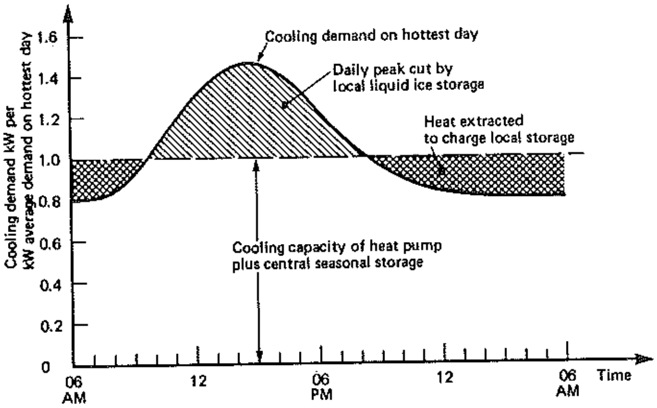
A central tank has low specific costs because of its large size, and because an inexpensive site can often be chosen. Its functions are :

1) It cuts daily demand peaks. As indicated by Fig. 5(A), day time demands are much higher than night time demands, especially for down town areas with commercial buildings which usually shut off their ventilation systems at night. This reduces both the capacity of the central chillers needed and hence their cost, and the peak electricity demands for chiller driving power, and thus the electricity demand charges.
2) On days which are not critical for the electricity demand charges one can go further than levelling the 24 hour cooling demand, i.e. produce most or all cooling energy at night when electricity energy rates are low and little or none during the day, when these rates are high.
3) In certain cases when the central tanks can be built very cheaply, even seasonal cold storage can be justified, see Fig. 5(B), or "several day storage" to cover a heat wave, so as to further reduce the peak electricity demand charges and required chiller capacity and cost.

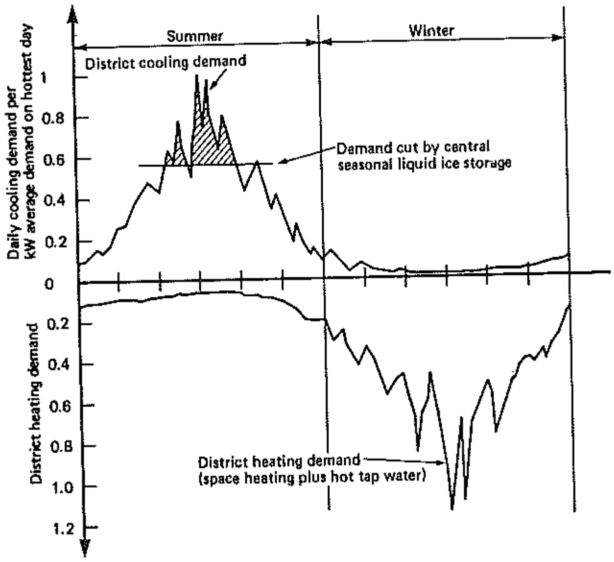
A cheap way of building such a tank when readily excavated ground is available is to excavate a pit in earth, line it with a rubber membrane and then fill with the storage solution. A floating lid of cellular plastic blocks can be provided as thermal insulation against the atmosphere, as has been done for the 650m^3 (23,000 ft^3) earth pit storage vessel at Studsvik, which has been used as a seasonal heat store for the last six years.

Distributed Storage

An alternative or complement to central storage is to provide one cold storage tank for each major building, as illustrated in Fig. 4. These tanks can perform the functions (1) and (2) of the central tanks, but in addition reduce the capacity of the distribution piping system needed, as they cut the daily peaks at the consumption point. Typically this can reduce the required cross-sectional areas of the distribution pipes by a further factor of 4 x 1.5 = 6 smaller than for a conventional chilled water system



A: Daily variation in cooling demand.



B: Seasonal variations in cooling and heating demand (including hot tap water)

Fig. 5. Daily and seasonal variations in demand, illustrating use of liquid ice storage.

without distributed storage.

Such tanks can be located in the cellars of buildings or placed outside buildings. Because of their small size and the high cost of building space or site space in commercial areas they are more expensive per unit volume than the central tanks, but the extra cost is often justified by the savings achieved in the distribution system, especially in locations where piping costs are high. In contrast, individual chilled water storage tanks are rarely justified on district cooling systems, as their large volume results in excessive costs compared to the benefit of reduced piping costs.

PIPES AND EQUIPMENT INSIDE NEW BUILDINGS

When new buildings are being built at the same time as the district cooling scheme or after the cooling scheme has been built, the diameter of the cooling system pipes within the buildings can be reduced when liquid ice is being used. Moreover, a larger temperature difference between the liquid ice and the air in the air coolers is available compared to a conventional chilled water scheme, thus allowing the size of these coolers to be reduced. Care has to be exercised to avoid freezing of condensate on the air side under these conditions, but several ways of avoiding this are available.

SUMMARY OF MERITS OF SYSTEM

From the preceding discussion we can summarize the advantages of the system compared to conventional (two-pipe) chilled water systems:

1) The volume of the distribution pipes can be reduced by about a factor of 6, using the combined effects of greater heat capacity for transport and the merit of cheap daily heat storage.
2) The capacity (in kW heat extraction) of the central chiller can be reduced by 50% to 60% by cutting the daily and seasonal peaks.
3) The capacity of the electrical connections to the heat pump and kW charge for electricity can be reduced on account of 2) above.
4) Often electricity costs can be reduced further during the times of the year when the chiller has excess capacity by using the heat storages to increase night electricity consumption and reduce day-time consumption when different on-peak/off-peak electricity rates apply.
5) For new buildings, the dimensions of the indoor pipes and air coolers can be reduced substantially due to the use of liquid ice.

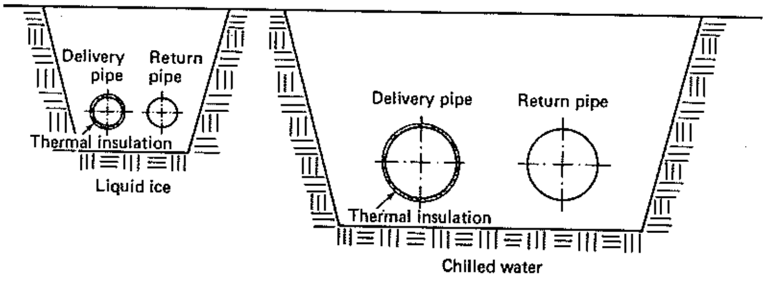


Fig. 6. Comparison of pipe sizes for chilled water and liquid ice.

Some price has to be paid for these advantages in the form of the cost of the liquid ice storage tanks (which however is a small item), the increased cost of the chiller per kW cooling capacity, due to the lower average temperature of the source from which heat is extracted, and a reduction in the coefficient of performance of the chiller for the same reason. However, this price is small compared to the sum of the advantages outlined above. The magnitude of these advantages is illustrated by Fig. 7.

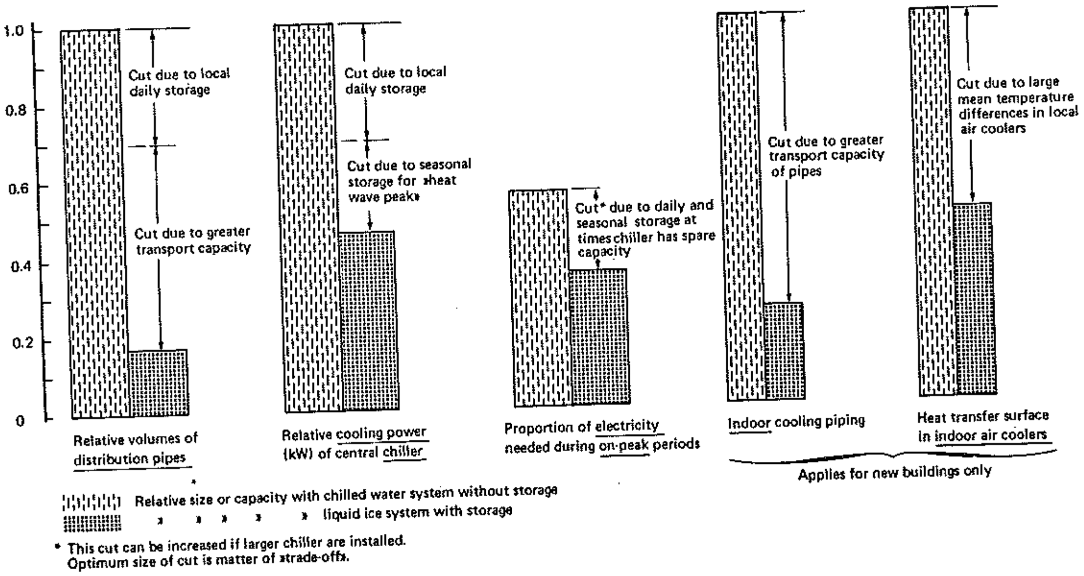


Fig. 7. Relative size or capacities of components in chilled water systems without storage and liquid ice system with storage.

FURTHER POSSIBILITIES OF COST REDUCTIONS

Whereas individual cooling schemes for buildings mostly have to reject the surplus heat to the atmosphere using cooling towers on the building roofs, large central cooling schemes can often use heat recipients at lower temperatures, for instance a nearby river or lake, or ground water when this is plentiful. The use of such low temperature heat recipients reduces the cost of chillers and the required driving electricity and benefits district cooling schemes of both the chilled water and liquid ice type. By reducing this cost component, the percentage advantage of the liquid ice system which has much cheaper distribution systems is, however, further increased.

When district heating and cooling systems are built simultaneously, both types of pipe can be laid in the same trenches. The saving achieved by this is particularly large in the liquid ice case, as the pipes are more similar in dimensions to the heating pipes than is the case with chilled water pipes.

Moreover, in combined district heating and cooling systems, the heat extracted from the cooling system can often be used for district heating, though at the expense of an increase in the rejection temperature and therefore the amount of electricity needed to drive the heat pump. As the seasonal demands for heat and cold are out of phase (see Fig. 5b), this transfer of heat is practicable only to a limited extent without using seasonal energy storage. For this more limited use, without seasonal storage, a special small heat pump suited for heat rejection at a higher temperature can be used, while leaving the main heat pump for heat rejection to the atmosphere, a river or any other recipient.

A possible arrangement involving seasonal storage is shown by Fig. 8. Only a cheap type of seasonal storage can be justified, e.g. drilled rock stores (Fig. 9) which have already been used in Sweden for seasonal storage in some related applications.

Figure 11 illustrates such an application for storing excess summer waste heat from the freeze boxes and air-conditioning system of a supermarket at Finspång, Sweden, in a drilled rock store, for recovery during winter for space heating. Figure 12 illustrates the use of the piping system of a 7,400

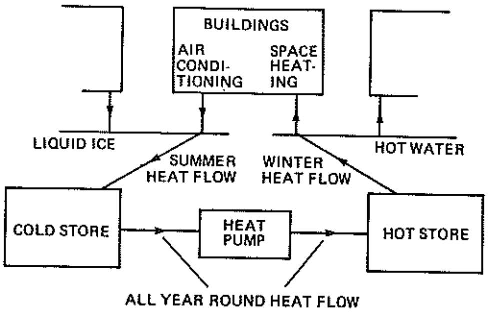


Fig. 8. Combined district heating and cooling system with seasonal heat storage (each line represents two pipes).

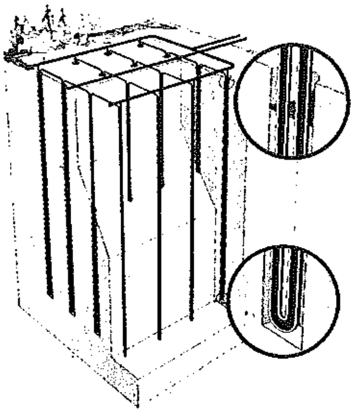


Fig. 9. Drilled rock store (Sunstore method patents, subsidiary of Studsvik).

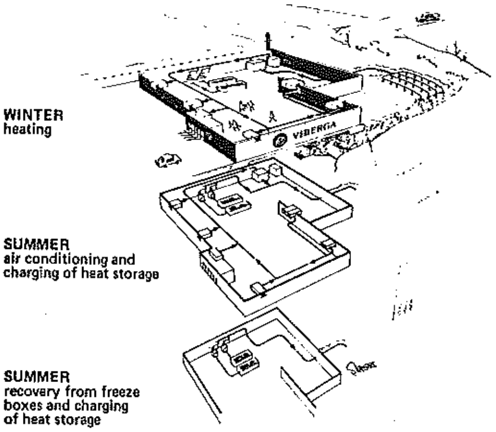


Fig. 10. Seasonal drilled rock heat store used for heating Swedish supermarket with waste heat from existing freeze boxes (Scandenergy system, commissioned in 1984).

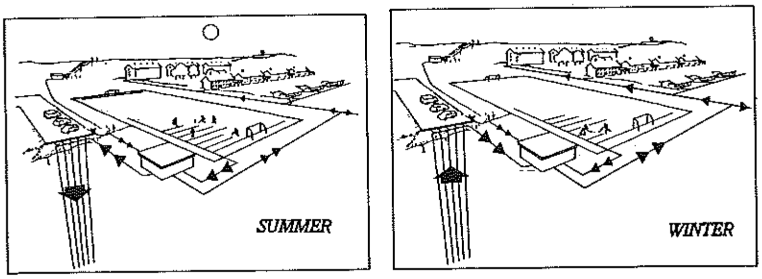


Fig. 11. Seasonal drilled rock heat store for district heating system using large skating rink as energy collector (Scandenergy system under construction).

m^2 (80,000 ft^2) skating rink (used for the Scandinavian game of "bandy" now gaining popularity also in the U.S.) to charge another much larger (14 million m^3 or 500 million ft^3) drilled rock store during the summer season when the pipes act as a solar collector, whilst heat is recovered from the store using a heat pump in winter. The first of these schemes went operational in 1984, the second will come into operation this year. Both are delivered on a turn key basis by Scandenergy (a subsidiary of Studsvik Energy). They show that seasonal storage of heat can also be economic when the conditions are suitable.

In future applications, a liquid ice store may be used to reduce the heat pump capacity required for meeting the peak freezing load for the ice rink in the fall, at the start of the skating season.

DEVELOPMENT STATUS

The critical component of liquid ice systems is the chiller evaporator. Conventional evaporators cannot be used as ice coatings tend to build up on the tube walls if the chilled water is cooled to freezing point. These ice coatings gradually block the tubes and prevent flow. Studsvik Energy has developed an evaporator which avoids this problem completely. Small and medium size units can now be tendered.

In a laboratory loop at Studsvik, liquid ice has been pumped at various concentrations without problems. Friction pressure drops have been found to be close to those for water at the same velocities, until ice fractions begin to exceed about 40 to 45%. Similarly, various ice storage arrangements have been tested. The liquid ice system is now close to commercial introduction.

CONCLUDING REMARKS

The high specific energy per unit volume makes the liquid ice an excellent substance for the transport and storage of cold, reducing the dimensions of the distribution systems by spectacular amounts, and making central storage of cold and often also local daily storage highly economic. These properties can be used to improve the economics of district cooling by very significant amounts, which should result in an increase in market penetration for district cooling systems.

Integration with district heating systems can often improve the economics of both district heating and district cooling, by reducing the total costs of piping when pipes are laid simultaneously in common trenches and by offering opportunities to use heat extracted by the cooling system for district heating with the assistance of seasonal storage.