

Combined Liquid Chiller and Heat Pump Systems for Data Centre Cooling with High-Temperature Heat Recovery

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Abstract

Due to the accelerating use of the Internet, telecom equipment and other network-based services, the number of large-capacity data centres is showing an accelerating growth rate. There are currently more than three million data centres globally, and the electricity consumption of these centres is substantial. Relatively few computer cooling systems are based on free (natural, renewable) cooling or apply high-efficiency heat recovery systems. However, there is a strong trend towards “green data” centres with minimum primary energy use and low greenhouse gas emissions. Since low- and medium-temperature heat recovery systems have rather limited applicability, different cooling technologies with energy efficient high-temperature heat recovery have been developed and utilized the recent years. These include single-stage, two-stage, cascade and compression/-absorption (hybride) liquid chiller and heat pump systems with ammonia (R717), ammonia-water (R717/R718), R134a or HFO-1234ze as working fluids as well as CO₂ (R744) liquid chillers and heat pump water heaters. Examples of some of these eco-friendly state-of-the-art technologies are found in Norway, and include a 800 kW single-stage ammonia (R717) system at the Norwegian University of Science and Technology (NTNU), Trondheim, and a 350 kW CO₂ (R744) system at the University Hospital in North-Norway, Tromsø.

Keywords: computer centres, process cooling, waste heat, liquid chiller, heat pump, high-temperature heat recovery

1. Green Process Cooling Systems for Data Centres

Energy efficient and "green" cooling systems for data centres can be categorized as follows:

1. Free cooling systems utilizing seawater, ground water, bedrock or ambient air (cold climatic zones)
2. Cooling systems with medium-temperature heat recovery (< 50 °C)
3. Cooling systems with high-temperature heat recovery (> 50 °C)

Type 2 systems can be utilized in medium-temperature heating systems in buildings and for preheating of domestic hot water (DHW), whereas Type 3 can be utilized in district heating systems and in high-temperature heating systems in buildings as well for DHW heating in e.g. hotels, hospitals, nursery homes and sport centres.

When free cooling sources are unavailable, cooling systems with high-temperature heat recovery will in most cases be the most relevant approach. Since standard water-cooled liquid chillers have a maximum outlet temperature of approx. 50 °C, technologies especially designed for high supply temperatures have to be used. *Table 1* shows the most important liquid chiller and high-temperature heat pump technologies on the market:

Table 1. State-of-the-art technologies for liquid chillers with high-temperature heat recovery (heat pump) – Type 3.

Heat pump cycle	Compressor type	Pressure rating, PS (bar)	Working fluid	Max. outlet water temperature (°C)
1-stage	Piston, twin-screw, mono-screw	50	NH ₃ (R717)	80
2-stage	Piston and/or twin-screw	40	R134a or HFO-1234ze	75
2-stage	Piston and/or twin-screw	50	NH ₃ (R717)	82
2-stage	Mono-screw	60	R717	90
Cascade	Twin-screw	40	R134a + Öko1	100
Abs.-compr. (hybride)	Piston	28	NH ₃ (R717) + H ₂ O (R718)	110
1-stage supercritical	Piston	120	CO ₂ (R744)	90

The different technologies have their pros and cons with regard to investment costs, seasonal COP (SCOP, SPF), space requirement, operational reliability and maintenance costs. This has to be taken into account when selecting and designing the cooling system. In order to install the most eco-friendly systems, zero or near-zero GWP working fluids should be used, i.e. ammonia, ammonia-water and CO₂. HFO-1234ze represents a possible working fluid in this kind of installations, but the application of the fluid is still at an early stage.

The design and dimensioning of liquid chillers system is mainly determined by the maximum cooling demand, the back-up demand (n+1) and the temperature requirement for cooling. On the other hand, heat recovery systems with *high-temperature* heat pumps should be designed according to the average cooling demand and the temperature requirement for heating. The main high-temperature designs include:

- 3A Liquid chiller / high-temperature heat pumps in the cooling circuit + liquid chillers (peak load)
- 3B High-temperature heat pump in the condenser circuit for the chillers + liquid chillers (peak load)
- 3C Alternative A or B in combination with free cooling (e.g. ambient air)

Figure 1 on the following page shows principle sketches of design A and B for liquid chiller systems with high-temperature heat recovery and utilization of ambient air for free cooling during parts of the year.

The heat recovery potential is to a large extent determined by the average heating demand duration curve for the heat sink (heat distribution system, district heating system, DHW system), the hour by hour available heat from the heat recovery system as well as the temperature requirement. If possible, the temperature level for the heat sink should be reduced in order to maximize the SCOP for the system.

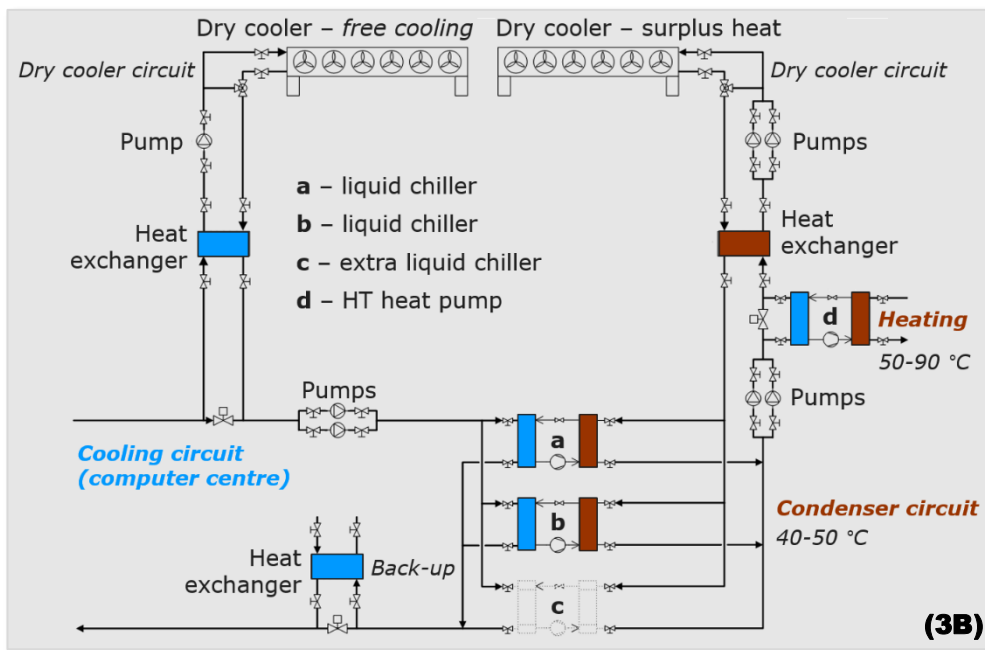
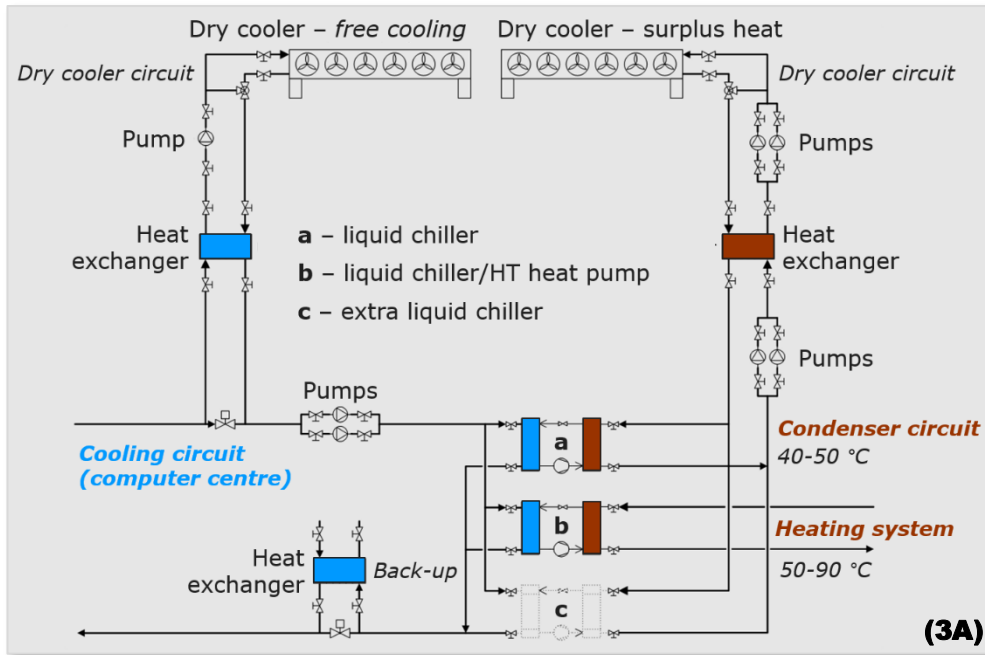


Fig. 1. Principle sketches of possible designs (3A, 3B) for liquid chiller systems with high-temperature heat recovery.

In Scandinavia there are a number of interesting recent examples of data centres with high-temperature heat recovery to district heating systems from large-capacity tailor-made liquid chiller systems (Type 3A):

- At “The Falun Eco Data Centre”, Sweden (2015), the surplus heat from the liquid chillers is rejected to a district heating system. Due to the high-temperature heat recovery and the application of hydro and solar electricity generation, they claim to be the worlds greenest high-performance data centre.

- One of the largest Apple computer centres in the world is now being constructed outside Viborg in Denmark. The surplus heat from the liquid chillers will be rejected to a district heating system, and the electricity will be generated from local wind power stations.
- In 2014 a combined liquid chiller and high-temperature heat pump system was installed at the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway. The plant cools supercomputers and other server stations via a district cooling network. The excess heat is rejected to the district heating network at the campus. In Norway the electricity is generated by hydro power. This innovative cooling and heat recovery system is presented in the following section.



Fig. 2. The supercomputer installation at NTNU, Trondheim/Norway (Photo: Bjørn Lindi, NTNU).

2. Example 1 – Liquid Chiller and High-Temperature Heat Pump Plant at NTNU (Type 3A)

2.1. Plant Presentation – Cooling/Heating demands and Temperature Levels

The liquid chiller plant with high-temperature heat recovery at NTNU, Norway, comprises two ammonia (NH₃, R717) units from GEA Refrigeration Techn. GmbH, each having 400 kW cooling capacity at 7/12 °C. The total heating capacity is approx. 1100-1200 kW, and the maximum supply temperature is 80 °C. This is about 30 °C higher than that of standard liquid chillers, and enhances the application range considerably. At the design outdoor temperature (-20 °C) the supply/return temperature in the district heating system is 90/65 °C. The excess heat from the liquid chiller plant is rejected to the return pipeline in the district heating system in order to minimize the supply temperature and enable full operation even during the coldest days of the year. At design conditions the chiller plant heats the water from 65 to 80 °C. The max. heating demand at the campus is about 14 MW, while the minimum demand during the summer is less than 1 MW, Figure 3. During summer operation the heating capacity for the chiller plant exceeds the heating demand, and surplus heat is rejected to the ambient by means of a dry cooler system. Since the heating capacity of the chiller plant is much smaller than the max. heating demand for the district heating system, more than 90 % of the excess heat is recovered.

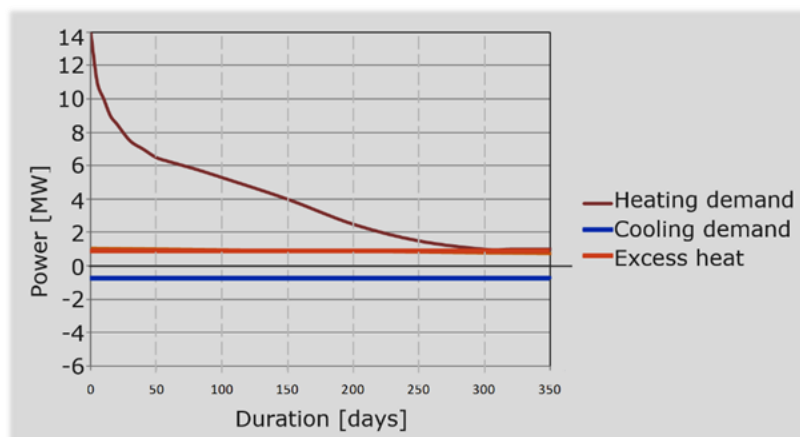


Fig. 3. The power duration curve, cooling demand and excess heat from the liquid chiller plant at NTNU, Trondheim/Norway [1].

The chiller plant is located in a long and very narrow machinery room in the transportation zone in the basement of a building at the campus, *Figure 4*. The plant comprises tailor-made single-stage units since there was insufficient space for a two-stage plant or other space consuming plant designs in the machinery room. Despite the single-stage design, the plant achieves a relatively high COP even at high supply temperatures due to the use of ammonia as the working fluid, high-efficiency components and heat rejection from as many as 7 heat exchangers, all connected in series. *Figure 5* on the following page shows a principle sketch of the liquid chiller plant connected to a district cooling system, a district heating system and a dry-cooler system for rejection of excess heat during summer operation.

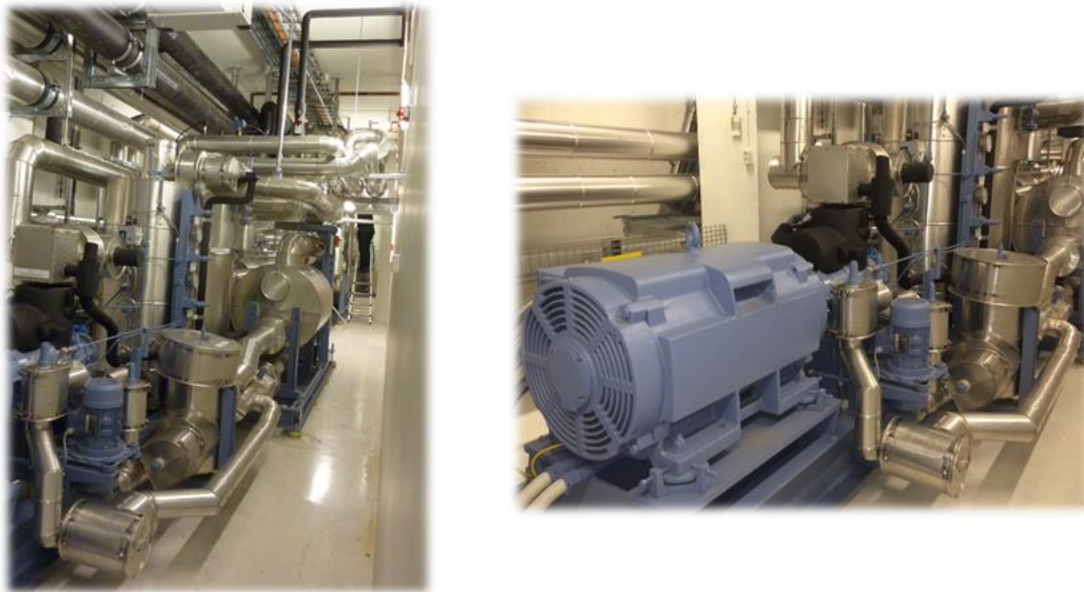


Fig. 4. The ammonia liquid chiller and high-temperature heat pump plant at NTNU (Photo: Eptec Energy AS).

Liquid chiller Unit 1 is equipped with a condenser, an oil-cooler and a desuperheater while Unit 2 has a sub-cooler, an oil-cooler, a condenser and a desuperheater. The high-efficiency oil-coolers maximize heat recovery and lower the discharge temperature to a very low level (< 90 °C), the desuperheaters lower the condensation temperature for both units while the subcooler increases both the cooling and heating capacity of Unit 2.

Since the two liquid chiller units reject heat at different temperature levels, the high-pressure sides are designed for 40 bar and 52 bar pressure rating, respectively. Unit 1 comprises a recirculation evaporator (plate heat exchanger, PHE), an open high-efficiency twin-screw compressor with combined variable speed drive (50 to 100 %) and slide valve control (12-50 %), a condenser (shell-and-plate heat exchanger, SPHE), an oil-cooler (SPHE), and a desuperheater (tube-and-shell heat exchanger). Unit 2 has the same main components, but in addition it's equipped with a sub-cooler (SPHE). Due to the compact design and the application of PHE and SPHE, the total ammonia charge is only 220 kg, i.e. approx. 0.28/0.20 kg per kW cooling/heating capacity.

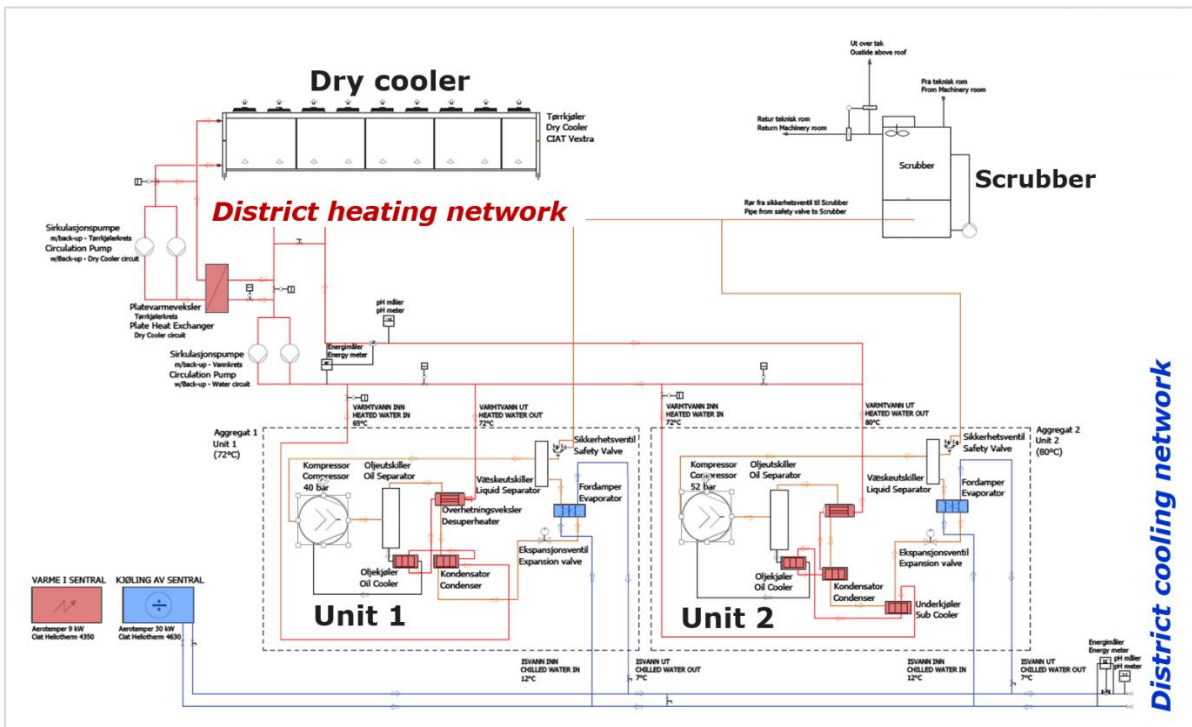


Fig. 5. Piping diagram for the ammonia liquid chiller and high-temperature heat pump plant at NTNU (Photo: Eptec Energy AS).

2.2. Ammonia as Working Fluid – Mandatory and Extra Safety Measures

Ammonia (R717, NH₃) is a natural working fluid with a global warming potential of zero (GWP_{R717=0}), and the fluid is not controlled by the F-gas Directive. R717 has excellent thermophysical properties that leads to high cycle COP, efficient heat transfer and high compressor efficiency. Other beneficial properties are the very small mass flow rate and the high critical temperature/pressure that enables high-temperature heat supply. Due to the low vapour density, R717 reaches high discharge gas temperatures even at moderate pressure ratios, and it's therefore very important to implement measures to keep the discharge temperature at an acceptable level.

In the European refrigeration and heat pump standard EN378, R717 is classified in group B2, i.e. higher toxicity (IDLH 500 ppm) but lower flammability (LEL 15 %, AIT 650 °C). R717 has a pungent odour that eases the detection of leakage, but it may also cause panic and dangerous situations if R717 is released in public areas where people are not accustomed with the properties of the fluid. Due to the toxicity and the pungent odour of R717, NTNU wanted the most extensive safety measures to be implemented since the plant is situated in a building located at the campus.

The R717 liquid chiller units, the machinery room and the safety equipment have been designed according to EN378, which require a leakage-proof machinery room, a separate fail-safe ventilation system, leak detectors for low/high/critical alarm, and an automatic alarm system. The liquid chiller units have also sectioning valves that are activated in case of a leakage. As an additional safety measure a scrubber system, that comprises a large water tank with a water spray system, has been installed in the machinery room. In the event of an R717 leakage, the ventilation air is passed through the water spray for efficient absorption of the R717 vapour. The air in the machinery room is recirculated through the scrubber several times, and the scrubber absorbs up to 98 % of the R717. The remaining air with a low R717 concentration is rejected to the ambient. After a leakage the ammonium water in the tank has to be treated as waste water, and the tank is recharged with fresh water.

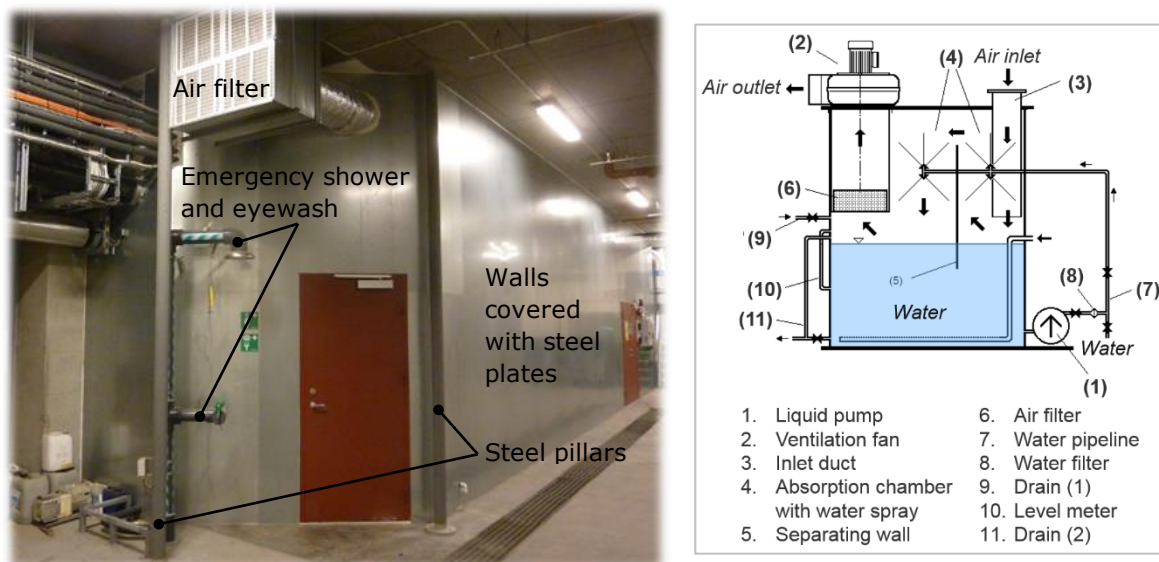


Fig. 6. The machinery room and the scrubber system for the liquid chiller plant at NTNU (Photo: Eptec Energy AS, Norway).

2.3. Measurement Results and Profitability

Master students at technological universities who study heat pump and refrigeration engineering need access to high-quality demonstration plants. The liquid chiller and high-temperature heat pump installation at NTNU represents one of the most energy efficient and environmentally benign technologies on the market. The plant is equipped with a large number of pressure and temperature sensors as well as thermal and electric energy meters in order to make possible detailed monitoring and analysis of the plant. Some of the measurement results from the first years of operation can be summarized as follows [2]:

- At 65 °C outlet water temperature from the plant, about 60 % of the total heat supply comes from the condensers, 28 % from the oil coolers, 9 % from the sub-cooler and 3 % from the desuperheaters.
- The compressor efficiency is very high and more or less constant when using VSD control. The additional slide valve control leads to poor efficiency at part loads below 50 % and very low COP, and is therefore never used.
- The discharge gas temperature is as low as 70 to 90 °C due to very efficient oil cooling
- The average heating COP is about 3.0 at 7/65 °C, which corresponds to a Carnot-efficiency of 52 %

- The average drop in cooling capacity and heating COP is about 1.5 % and 2.5 %, respectively, per °C rise in the return water temperature in the district heating network

The cooling demand for the supercomputer centre varies moderately during the day and night with an average of about 700 kW. This corresponds to an average heating capacity of approx. 1 000 kW for the liquid chiller. During the Summer the minimum heating demand in the district heating network at the campus is 600 to 800 kW, which means that most of the rejected heat from the chiller plant is useful heat. The measured annual heat supply is about 7 to 8 GWh/year, and the annual energy saving is about 5 GWh/year.

Despite the relatively high total investment costs for the liquid chiller plant installation, the pay-off time is only 4 years due to the long equivalent operating time.

3. Example 2 – Liquid Chiller and High-Temperature Heat Pump Plant at UNN (Type 3A)

3.1. Introduction – CO₂ Heat Pump Water Heaters in Hospitals

Hospitals are very complex buildings with considerable process cooling demands due to in-house telecom systems, centralized data centres for digital imaging (PAC – MRIs, x-rays, CAT-scans), pharmacy, clinical communication systems and medical records as well as cooling of all kinds of technical equipment and biological products at different temperature levels. In Norway the average specific energy use in hospital is around 280 kWh/(m²year) [4], while the requirement according to the new Norwegian building code is 225 kWh/m²year) [5]. In order to minimise the energy use in hospitals free (natural) cooling should be utilized if possible as well as efficient heat recovery from the cooling systems.

There is a considerable demand for domestic hot water (DHW) in hospitals. According to the prevailing Norwegian building code, the annual energy demand for DHW heating constitutes about 60 % of the total annual heating demand [5]. CO₂ (R744) heat pump water heaters (HPWH), where heat is rejected at a gliding CO₂ temperature at supercritical pressure, is the most energy efficient heat pump technology for DHW heating [6]. Moreover, combined CO₂ liquid chillers and HPWH represents a high-efficiency and flexible solution for hospitals since they can be designed for base load process cooling and simultaneously supply high-temperature DHW (70-80 °C) without any reheating.

After the fundamental research and development at NTNU-SINTEF in Norway during the 1990'ies and the commercialization in Japan in 2001, CO₂ HPWH have eventually reached a high technological level. Many large-capacity air-source and water/brine-source systems have been installed in Asia, Europe and the USA the recent years. In 2014, a combined CO₂ liquid chiller and HPWH was installed at *the University Hospital of North-Norway (UNN) in Tromsø, Norway*. The installation was designed to cover the base load for process cooling at the hospital as well as the entire DHW demand.

3.2. Plant Presentation

Prior to the installation of the 350 kW CO₂ HPWH, the existing DHW tanks were connected in series in order to achieve the lowest possible inlet water temperature for the gas cooler and with that maximize the COP of the heat pump. Figure 7 shows a principle sketch of the DHW heating and storage system with three large-capacity storage tanks (1.2, 1.3 and 1.4) that are connected to the CO₂ liquid chiller (LC) and HPWH. The process cooling system (heat source) is not shown in the figure. District heating, that was formerly used to cover the entire DHW heating demand via two heat exchanger stations, is now mainly used for maintaining the 75 °C DHW temperature in the DHW storage tanks 2.2, 2.3 and 2.4 that are used as a back-up.

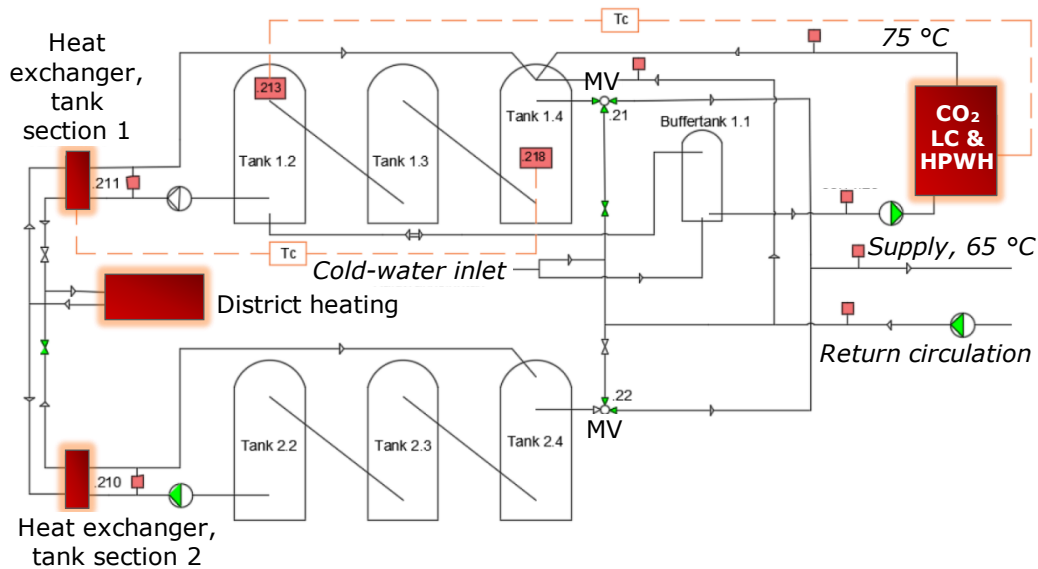


Fig. 7. The DHW heating and storage system at UNN, Tromsø/Norway. LC = liquid chiller, MV = mixing valve [3].

The single-stage CO₂ liquid chiller and HPWH unit from Green & Cool has the following main components:

- Compressors – 3 semi-hermetic reciprocating (piston) units in parallel
- Gas cooler – 3 plate heat exchangers (PHE) in frame, serial connection on the water/CO₂ side
- Evaporator – 1 flooded plate-and-shell heat exchanger
- Suction gas (internal) heat exchanger – 1 plate heat exchanger (PHE) in frame

Figure 8 shows a principle piping diagram of the CO₂ liquid chiller and HPWH, while Figure 9 shows the installation in the machinery room including the connecting pipelines to the DHW system. The compressor capacity is controlled according to the set-point temperature in the process cooling system (5 °C), and the heat pump heats the DHW to the set-point temperature (75 °C) as long as there is a heating demand. Two compressors have intermittent operation (on/off) whereas one unit uses variable speed drive (VSD) for maximum part load efficiency at varying process cooling demand. When the DHW tanks are fully charged the compressors are stopped, and the entire process cooling demand is covered by the back-up cooling system. The excess heat is given off to the ambient by means of a dry cooling system.

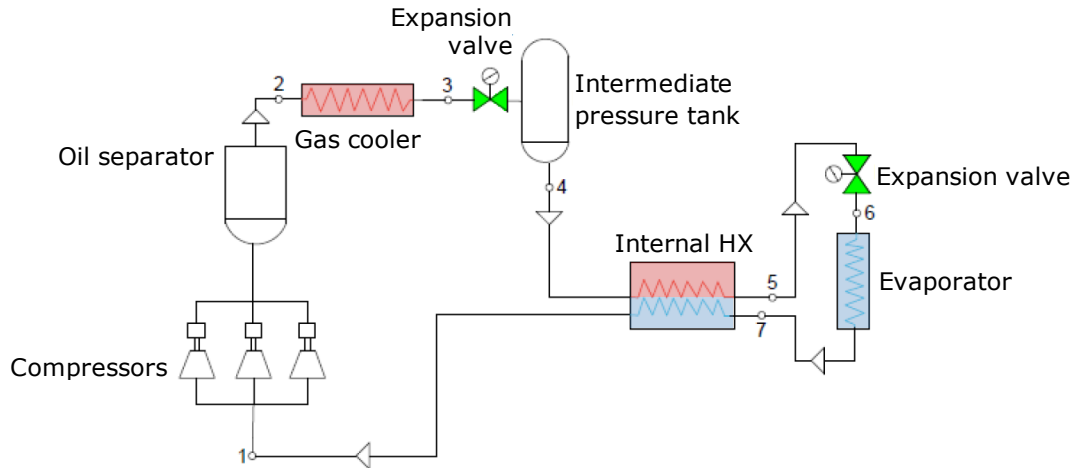


Fig. 8. Principle piping diagram of the CO₂ liquid chiller and HPWH installation at UNN, Tromsø [3].



Fig. 9. The CO₂ liquid chiller (LC) and HPWH installation at UNN, Tromsø (Photo: Kuldteknisk AS, Norway).

The installation at UNN is the largest CO₂ liquid chiller and HPWH in Norway and maybe the largest in Europe. The COP is 3.7 at nominal operating conditions, i.e. at 10/5 °C inlet/outlet water temperature from the evaporator and 5/75 °C inlet/outlet water temperature for the gas cooler. This corresponds to a Lorentz-efficiency of approx. 0.45. The COP can be improved by upgrading the insulation standard for the existing DHW pipelines and further optimization of the DHW system design and control strategy. Since the CO₂ liquid chiller and HPWH provides simultaneous cooling and heating, the current total SCOP is about 7, i.e. approx. 3 kWh cooling and 4 kWh heating for 1 kWh electricity. The combined operation is an excellent example on how to minimize primary energy use in thermal energy plants in buildings with both heating and cooling demands.

Summary and Conclusion

Most liquid chiller systems for computer and process cooling apply standard HFC technology with low- to medium-temperature heat recovery with rather limited applicability or no heat recovery at all. In recent years there has been a growing interest for high-temperature heat recovery (> 50 °C) from various process cooling systems incl. computer cooling. Typical application areas include heat supply to district heating systems, heating of buildings with high-temperature heating system and domestic hot water (DHW) heating. A number of different cooling technologies for energy efficient, high-temperature heat recovery have been developed and utilized in recent years. These include advanced single-stage, two-stage, cascade and compression/absorption (hybride) liquid chiller and heat pump systems with ammonia (R717), ammonia-water (R717/R718), R134a or HFO-1234ze as working fluids as well as CO₂ (R744) liquid chiller and heat pump water heaters (HPWH). This paper presents, among other things, two Norwegian examples of the next generation high-efficiency large-capacity systems using 100 % eco-friendly, natural working fluids (ammonia, CO₂). Despite the rather high installation costs the profitability is good due to high average COP and considerable annual heat supply,

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