Challenges and recent developments in applications with large scale heat pumps

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Abstract: Large capacity centrifugal heat pumps are reducing CO_2 emissions for more than 35-years already, increasing thermal efficiency and renewable energy contribution of European district heating networks.

The variety of heat sources and operating conditions of district heating systems is a big challenge in the heat pump design and impose an individual approach to the heat pump design of each project. The key element of a heat pump system is the compressor, with characteristic that should cover all possible operating points, including minimal load conditions.

Several applications with various heat sources will be presented. The 3rd raw sewage water heat pump installed in 2008 in Sandvika (Norway) is a good example for the continuous development of simultaneous district heating and district cooling production, balanced with sewage water as additional heat source. The big challenge was to develop a heat pump with an additional sewage water evaporator, which performs condenser function in a Summer Mode. Due to the flexibility of operating modes the heat pump copes fully automatically with the variable demands for cooling and heating during the whole year.

As a response to the increasingly restrictive environmental regulations of refrigerants, the first heat pump installation with thermal output of 16MW using the ultra-low GWP working fluid HFO-1234ze is in successful operation at Rolfsbukta (Norway) since commissioning in 2012.

Big developments have been done recently in some large capacity heat pump projects exploiting geothermal water from Neocomian and Dogger aquifers in the vicinity of Paris. Different arrangements of high temperature centrifugal heat pumps increasing significantly the heat exploitation from geothermal wells in district heating systems will be explained.

The presented examples will give an overview of recent developments and challenges in large centrifugal heat pumps technology, offering heat upgrades up to 120°C and 20MW heating capacity per unit.

Key Words: High temperature heat pumps, centrifugal compressors, district heating, sewage water, ground water, geothermal water, HFO-1234ze

1 INTRODUCTION

The variety of heat sources and operating conditions of district heating systems is a big challenge in the heat pump design and impose an individual approach to the heat pump design of each project. The key element of a heat pump system is the compressor, with characteristics that should cover all possible operating points, including minimal load conditions. The compressor should be designed to deliver the highest isentropic efficiency possible in all operating points. Heat exchangers design should guarantee very high heat transfer performance and low pressure drop. The chemical composition of heat source is of crucial importance in the material and tubes' internal structure choice.

A big challenge was the design of sewage water heat exchanger and working fluid management inside the 3rd Sandvika heat pump with the heating capacity of 7'700 kW delivered in 2008 to Norway. Roughly filtered sewage water is directly pumped over the evaporator where in Winter Mode heat is recovered and upgraded by the heat pump up to 78°C. In Summer Mode the same heat exchanger performs the function of condenser and heat is evacuated to the sewage water. The special internal structure of tubes and reversible flow operation prevents fouling.
The first two large capacity heat pumps type UNITOP 43/28 using new generation of HFO-1234ze refrigerant have been successfully commissioned 2012 in Rolfsbukta (Norway). The project was very challenging because the working fluid at this time being was classified neither by ASHREA nor European standards. The units with the total cooling capacity of 10'350 kW are producing chilled water at 2.5°C and feeding simultaneously 16'200 kW heat at 80°C into a district heating network of Fornebu Peninsula. If the cooling load is too low to produce the required heating capacity, the rest of heat may be extracted from sea water by means of an intermediate heat exchanger.

A lot of developments have been done recently in some large capacity heat pump projects exploiting geothermal water from Neocomian and Dogger aquifers in the vicinity of Paris. Different arrangements of high temperature centrifugal heat pumps significantly increasing heat exploitation from geothermal wells in district heating systems have been developed.

High heat source temperatures have imposed some important compressors developments.
All above mentioned examples are tailor made heat pumps. The units have been customised to meet requirements of end users and guarantee the highest performance.

2 SEWAGE WATER HEAT PUMPS FOR DISTRICT HEATING IN SANDVIKA (NORWAY)

Sandvika is a suburb of the Norwegian capital Oslo. During the 1980's, Sandvika showed a strong growth rate. A new urban centre was built on 300'000m^2, with offices, housing and recreational facilities. According to a decree of the local parliament, a district heating system had to be provided for the entire area.

Baerum Fjernvarme AS (actually FORTUM Fjernvarme AS) received the order for this project. Starting point for the engineering was a study comparing various possibilities of energy provisions. The most favourable costs finally resulted for the solution with the double use of the heat pumps [Rindisbacher, 2005].

To cover basic load of the plant, the world largest sewage water heat pumps with the total heating capacity of 14MW have been designed and commissioned by SULZER-FRIOTHERM already in 1989. The sewage water is pumped from the main channel, cleaned in a two-step process (mechanically and by sedimentation) and finally is passing through the shell and tube heat exchangers of the two heat pump units. After extraction and upgrading of its energy up to 78°C, the waste water returns to the main channel. The heat pumps are equipped with the secondary chilled water evaporators, where chilled water at 4°C is produced in parallel to the heat extraction from the waste water.

The main machine room with the two heat pumps is located next to the waste water channel, inside a subterranean cavern, excavated from bedrocks. Networks, one for district heating and one for district cooling are led in parallel, thus providing the supply required by each customer in Sandvika.

An increasing demand for heating and cooling capacity imposed the installation of the 3rd sewage water heat pump in 2008. The general arrangement of the machine is presented in Figure 1.

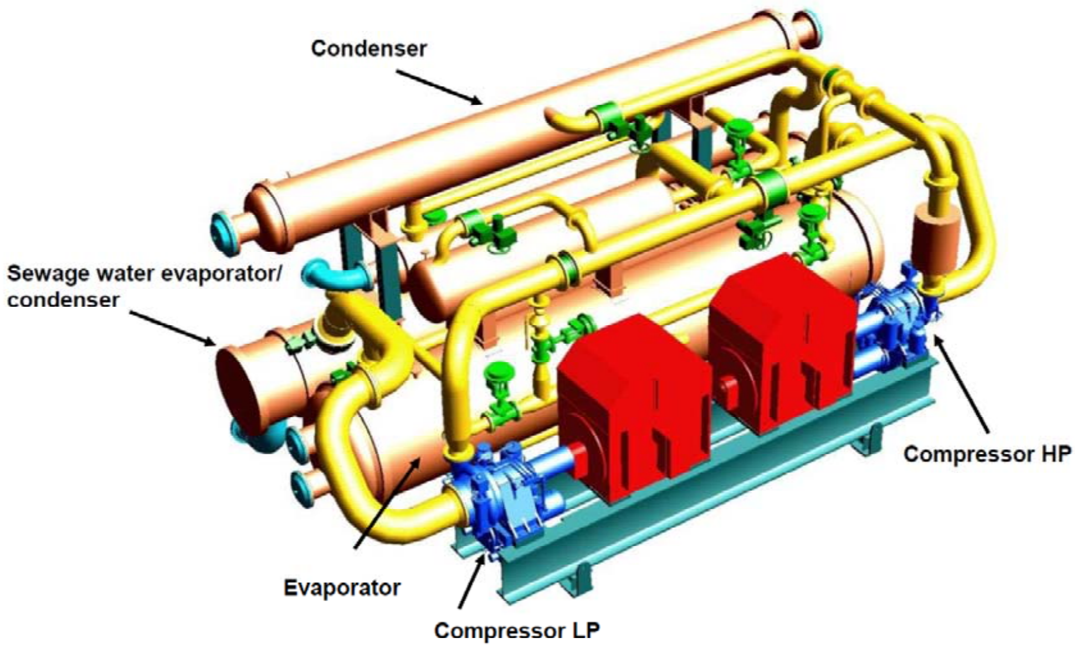

Figure 1: General arrangement of 3rd Sandvika heat pump UNITOP 33/28.

As shown in Figure 1, the unit is equipped with two evaporators for simultaneous heat recovery from waste water and chilled water production. The heat pump may be operated in two different operating modes.

In Winter Mode, hot water production at 78 °C has a priority. Firstly, the heat is extracted from the chilled water, cooling it down to 2°C and then if needed the complementary energy is extracted from the sewage water. For the heat upgrade up to 78°C, high isentropic lift is required and the compressors must be switched in series.

In Summer Mode only chilled water is produced at 2°C. The compressors are connected in parallel and the heat of condensation is rejected to the sewage water increasing its temperature from 14 up to 24°C. The sewage heat exchanger performs now the function of a condenser. The combination of special internal tube's structure and reversible flow operation prevents fouling. The heat exchanger may be operated either as evaporator or as condenser with sewage water without any mechanical cleaning.

The change between both operating modes may be done fully automatically. An additional challenge was the management of working fluid inside the heat pump during the change of operating modes.

The technical data of the 3rd Sandvika heat pump are presented in Table 1 and Figure 2 depicts the unit after assembling it in the FRIOTHERM workshop.

Table 1: Technical data of the 3rd Sandvika sewage heat pump

	Winter mode	**Summer mode**
Heat source	Sewage water / chilled water	
Cooling capacity	5200 kW	9'500 kW
Evaporator regime	8.7/4.0 °C	10.5/2 °C
Heating capacity	7'700kW	11'460 kW
Condenser regime	70/78°C	14/24 °C
COP cooling	2.0	5.2
COP heating	3.0	--
COP total	5.0	--

Figure 2: The 3rd Sandvika heat pump UNITOP 33/28 in FRIOTHERM workshop.

Due to the flexibility of operating modes the three heat pumps cope fully automatically with the variable demands for cooling and heating during the whole year. Each heat pump is operated more than 8'000 hour per year. It results in overall operating time of about 180'000 hours for the units delivered in 1989 and more than 40'000 operating hours for the 3rd unit, respectively.

3 SEA WATER HEAT PUMP FOR DISTRICT HEATING WITH HFO-1234ze IN FORNEBU/ROLFSBUKTA (NORWAY).

The 340-hectare Fornebu site is situated 10 kilometers from downtown Oslo with its strong commercial and financial community. The development plan for the area includes housing for a population of 5'000 and 15'000 work places in area of 1'350'000 m^2.
The Fornebu development site is equipped with a district heating/cooling system.
Figure 3 shows the annual heat load duration curve for Fornebu development site. The maximum heating power demand has been estimated to 69 MW, and annual heat production to 124 GWh/year. In the energy concept it has been decided that the main heat load will be covered with high capacity heat pumps and the peak load during the coldest period with oil boilers. The first heat pump plants Lysaker (1998) and Fornebu Telenor (2001, 2006) may produce 4'500kW and 13'700 kW heating capacity, respectively.
Further increase of heating and cooling demand in the Fornebu development site resulted in the construction of the Rolfsbukta heat pump plant in 2012. The plant is located in the basement of the SCANDIC Fornebu hotel. As a response to the increasingly restrictive environmental regulations of refrigerants, the use of a new working fluid HFO-1234ze has been decided. At this time being the refrigerant was classified neither by ASHRAE nor European refrigeration standards and its application at this scale unit was very challenging. The classification society Norske Veritas was entrusted by the customer with performing of risk analysis for the heat pump plant using this new slightly flammable working fluid with global warming potential below 1 (Hodnebrog et al. 2013).
The results showed that compared to the refrigerants from safety class A1 some additional safety precautions must be taken. The emergency ventilation in machinery room should be conformed to ATEX 94/9/CE and an automatic power cut-off switch for a case of refrigerant leakage detection is required.
The contract with FRIOTHERM included an option to change fluid to R134a in case of a failure in authorisation obtaining for exploitation of units with HFO-1234ze. Thus, the design took into account higher design pressures for R134a, as well as higher volumetric flow

required for HFO-1234ze. The decision for the final compressor design was taken after the successful release of the hazardous study about 5 months before delivering to site.

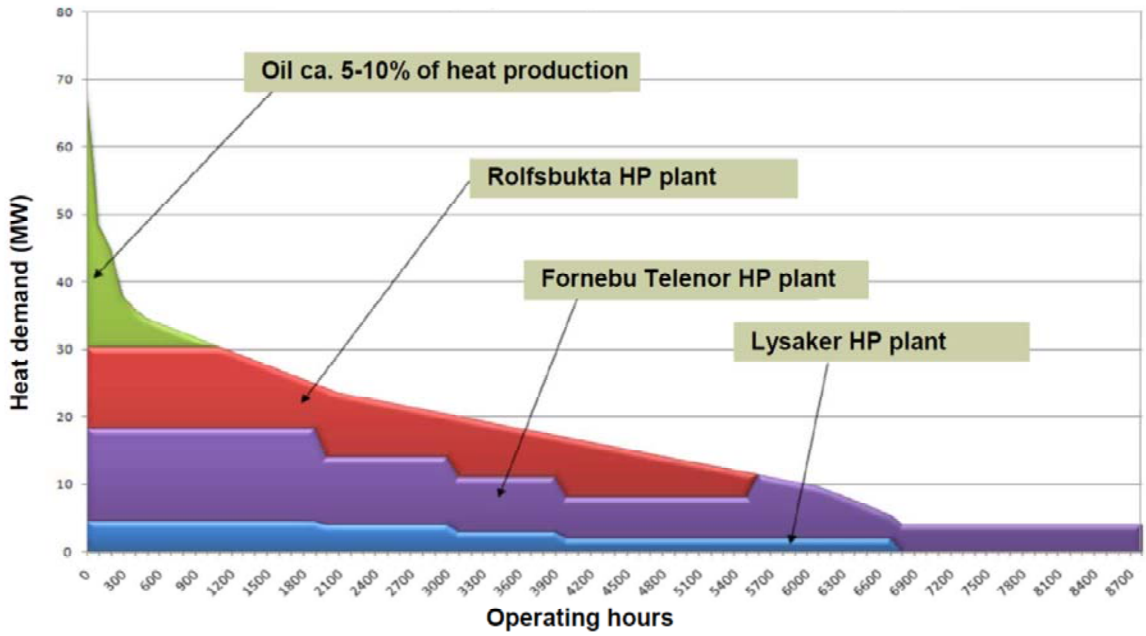

Figure 3: Annual heat load duration curve for Fornebu development site - [FORTUM, 2009].

The total heating capacity of both heat pumps is Winter Mode is 16MW. The heat pumps producing simultaneously chilled water at 2.5°C for district cooling with heat recovery at 80°C for district heating. If the cooling demand is too low, the additional low temperature heat is extracted from sea water by the means of intermediate heat exchangers. Figure 4a shows one of the heat pumps installed in the Rolfsbukta plant and Figure 4b depicts intermediate heat exchangers used between clean and sea water.

b)

Figure 4: a) UNITOP 43/28 installed in the Rolfsbukta heat pump plant, b) Intermediate heat exchangers between sea and clean water.

In Summer Mode compressors of each heat pump are switched in parallel. With reduced isentropic lift and cooling indirectly by sea water, both units are producing up to 20'000kW of cooling capacity with chilled water at 2.5°C.

The Rolfsbukta plant is the first and largest heat pump plant worldwide, using HFO-1234ze and is an important development in the use of new ultra-low GWP working fluids.

4 LARGE CAPACITY HEAT PUMPS IN GEOTHERMAL APPLICATIONS

Heat pumps in geothermal applications require very different arrangements and designs depending on temperatures and volumetric flows of heat sources.
Ground water may be used as a heat source in winter as well as a cooling medium in summer time. The heat upgrade in winter requires high isentropic lift. In contrary in summer operation a moderate isentropic lift with large modulation range is needed.
The geothermal water from Neocomien aquifer with a temperature of around 39°C is a very valuable heat source and due to effectively low investments cost may be an alternative for heating of smaller cities with high COP values. Depending on its volumetric flow and district heating requirements an optimisation of heat pumps arrangement has to be performed and compressors have to cope with high operating pressures.
Waters from the Dogger aquifers of the Paris basin utilized for heating, have a chlorinity in the range 0.07-0.6 mole/litre and a temperature in the range 48-80°C (Michard G. et all 1988). Water from the Dogger aquifer may be used as a heat source; however its

exploitation may be significantly increased by cooling of district heating water return before the geothermal heat exchanger. Due to very low required isentropic lifts, heat pumps offer an excellent performance.

4.1 GROUND WATER – PROJECT IN THE ILE-DE-FRANCE REGION

Ground water with the mean temperature of 14°C is the most cost-effective heat source from the investment point of view. In contrary to river or lake water the temperature of ground water is almost constant even in the winter period. In summer, ground water can be used for cooling of heat pumps in chiller-mode and rejected heat may be stored underground for reuse during the heating season. With 2-stage units heat may be lifted up to 90°C.
Direct use of ground water as a heat source requires a special design of evaporator. However, installations with an intermediate heat exchanger between ground water and clean chilled water are also widely used. Even if there is an additional water loop and pump required, this solution offers a very good flexibility. Figure 5a shows a simplified schema of two-stage heat pump with the heating capacity of 5'000kW designed for a project in the region Ile-de-France. During winter and intermediate season the heat pump produces hot water at 80°C and chilled water at 5°C simultaneously. As the cooling demand especially in winter is reduced, the required heat source capacity may be completed from the ground water by means of an intermediate heat exchanger. As shown in Figure 5a, the compressors are connected in series producing very high isentropic lift. The coefficient of performance (COP) for heating is 3.0 and if the complete cooling capacity of 3'350kW may be used, the total COP for heating and cooling rises up to 5.0.

The cooling demand rises in summer and at the same time the need of heat recovery for sanitary water production is limited. As shown in Figure 5b, the compressors may be connected during the summer period in parallel to increase the cooling capacity of the heat pump up to 6'200kW. Both compressors may be operated simultaneously or individually, what offers very effective partial load regulation. The condenser is cooled indirectly by the geothermal water pumped back to the geothermal well at 30°C. The switching from 2-stage (compressors in series) to 1-stage operation (compressors in parallel) is performed fully automatically by the combination of valves.

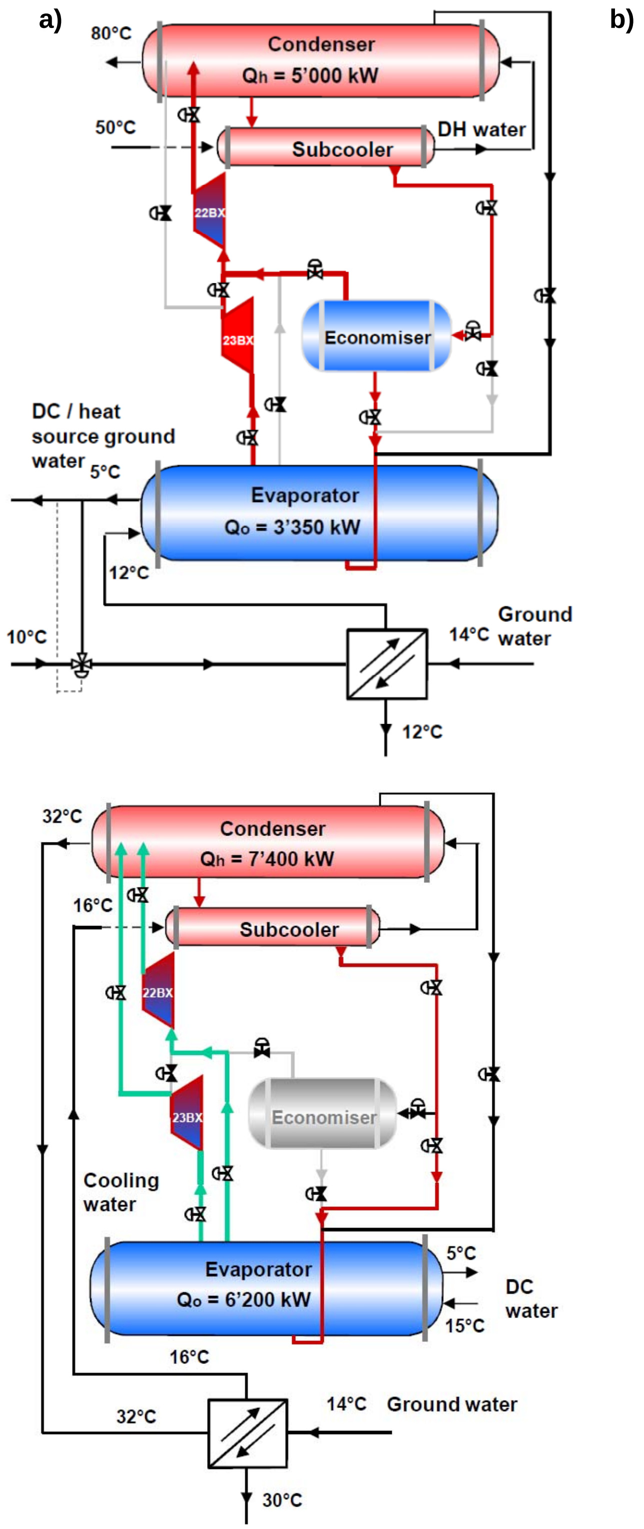

Figure 5: a) Simplified schema of heat pump UNITOP 23/22 in two-stage operation for hot water production at 80°C, b) Simplified schema of heat pump UNITOP 23/22 in summer mode - 1-stage operation. Compressors in parallel.

The performance data of the heat pump for both operating modes are shown in Table 2. It may be seen that in Summer Mode, the value of COP in 1-stage operation rises up to 5.1.

Table 2: Performance data of UNITOP 23/22

	Winter mode	Summer mode
Cooling capacity	3'350kW	6'200kW
Evaporator regime	12/5°C	15/5°C
Heating capacity	5'000kW	7'400kW
Condenser regime	50/80°C	16/32°C
COP cooling	2.0	5.1
COP heating	3.0	--
COP total	5.0	--

Figure 6 shows a general arrangement of UNITOP 23/22. The unit with the dimensions 3'800 x 9'000 x 3'200 may be delivered as a complete package ready for the installation on site. Thanks to the possibility of operation in different modes, very effective partial load conditions and the heat source balancing with geothermal water in winter, the heat pump copes with various operating conditions and can be operated all-the-year with the highest efficiency.

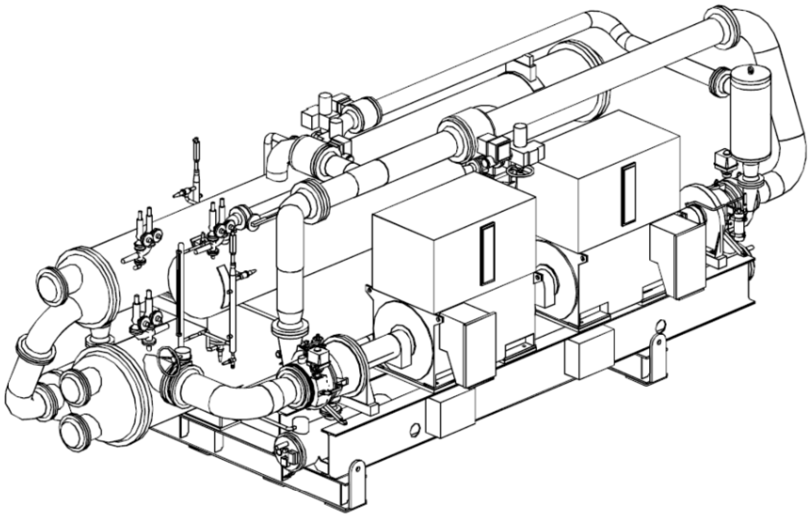

Figure 6: General arrangement of two-stage heat pump UNITOP 23/22 for hot water production at 80°C (Ile-de-France).

4.2 WATER FROM NEOCOMIEN ACQUIFER – PROJECT LE PLESSIS-ROBINSON

In February 2013 DALKIA FRANCE commissioned the first geothermal installation using water from the Neocomian aquifer, which provides heat to 3'500 accommodations and two large public buildings. The heat source is water at 39°C with the volumetric flow of 200m^3/h exploited from a 900m deep geothermal well. The geothermal water is cooled down to 15°C in the evaporators of heat pumps and injected into a geothermal well. Figure 7 shows borehole drilling of injection well.

Figure 7: Borehole drilling of injection well (Le Plessis-Robinson).

The heat is then upgraded to 70°C by means of heat pumps. After a long study phase the solution with two FRIOTHERM's 1-stage heat pumps type UNITOP 22 has been chosen. As shown in Figure 8a, the evaporators and condensers are connected counter-currently in series. This arrangement allows equalising of compressors isentropic lifts and increases significantly the COP value. Between geothermal water and evaporator water an intermediate heat exchanger with a temperature gap of 1°C has been installed. The return temperature from district heating network varies between 40 and 50°C. The technical data of heat pumps are shown in Table 3.

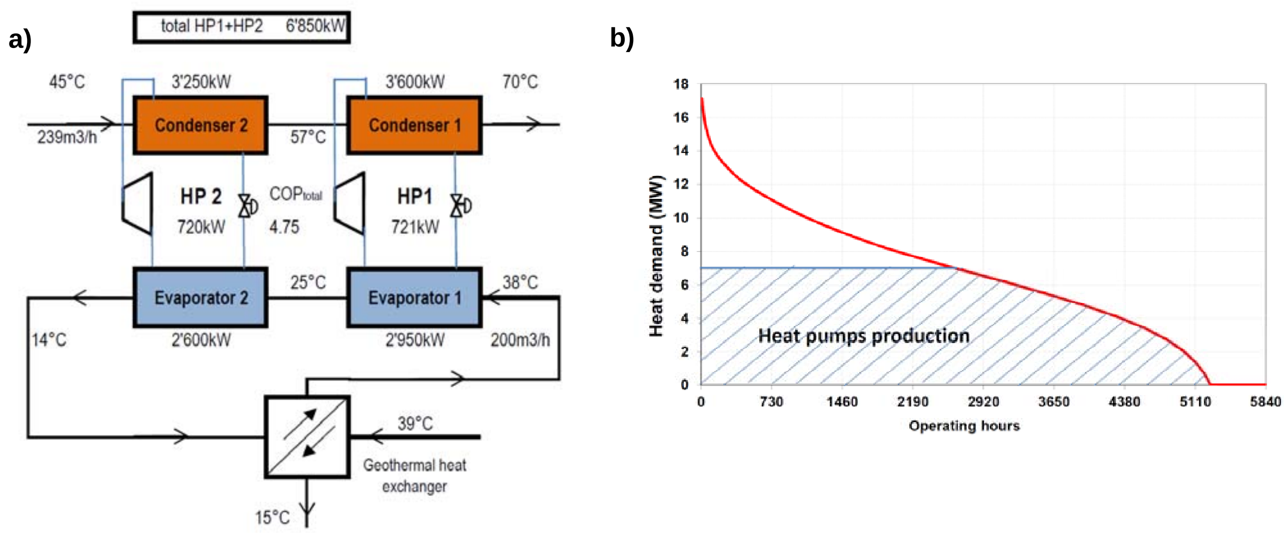

Figure 8: a) Heat pumps arrangement (Le Plessis-Robinson), b) Annual heat load duration curve for Le Plessis-Robinson (DALKIA).

Table 3: Performance data of UNITOPs 22

	HP2	HP1
Cooling capacity	2'600kW	2'950kW
Evaporator regime	25/14°C	38/25°C
Heating capacity	3'250kW	3'600kW
Condenser regime	45/57°C	57/70°C
COP heating	4.50	5.00
COP total	4.75	

Figure 8b shows the annual heat duration curve for the district heating network of Plessis-Robinson. The total heat production by heat pumps covers more than 78% of the annual heat demand. During the coldest days the complementary heat is produced by means of gas boilers. It is very important to design the heat pumps for the basic load of district heating, what maintain the maximal number of operating hours with the highest heat pump/-s performance.

The project Le Plessis-Robinson is the first one exploiting heat from Neocomien acquifer worldwide and has been awarded for its innovation and quality during the trade show and conference *Les Journées de la Géothermie 2014* in Paris with *The Geothermal Trophy*.

4.3 WATER FROM DOGGER ACQUIFER – PROJECT CRETEIL

Waters from Dogger aquifers of the Paris basin utilized for heating, have a chlorinity in the range 0.07-0.6 mole/litre and a temperature in the range 48-80°C (Michard G. et all 1988). However, most of the Dogger geothermal wells provide water at temperatures around 70°C, what allows a direct use of geothermal heat transferred into a district heating network in the intermediate heat exchangers. The flows of geothermal water from Dogger aquifers of the Paris basin are in the range of 250 m^3/h.
Figure 9 shows titanium heat exchangers of a geothermal installation with water from Dogger aquifer in Créteil. The volumetric flow of Dogger water is 280 m^3/h and the temperature oscillates around 76°C. Depending on the network return temperatures, the thermal power transferred into a district heating varies between 6'300 and 11'000kW.

Figure 9: Titanium heat exchangers of a geothermal installation with Dogger water.

The utilisation of geothermal heat in the most of district heating systems is limited by the high return temperature from the network. This effect is magnified especially during the winter time, when the return temperatures in some installations may increase even up to 60°C. As a consequence, geothermal water with a relatively high temperature has to be injected into a geothermal well.

The most efficient way to boost the geothermal wells' exploitation is the installation of heat pump for cooling of district heating water before entering into a geothermal heat exchanger. This temperature reduction of district heating water increases heat extraction from geothermal water.

Figure 10 depicts such type of arrangement for the installation Créteil. The district heating water is cooled in the heat pump's evaporator from 55 to 37.5°C, then is reheated in two stages firstly by the geothermal water up to 67.2°C and finally in the condenser up to 89°C. In this case, the use of heat pump increases the exploitation of heat from geothermal water by 5'550kW.

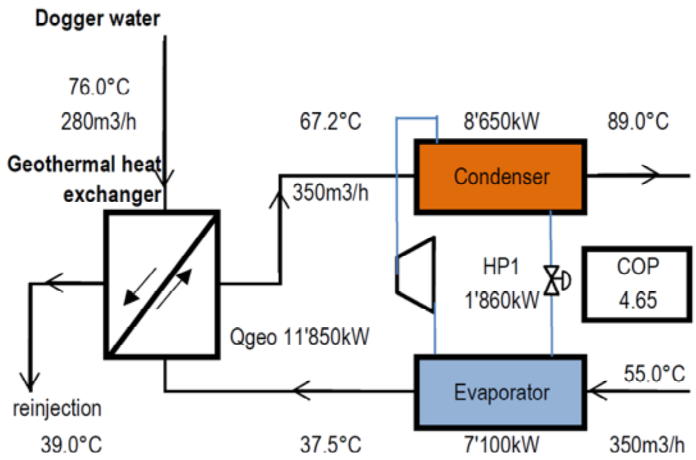

Figure 10: Heat pump arrangement for boosting of geothermal well exploitation.

Depending on the customer's needs, different heat pumps arrangement may be proposed. Figure 11 presents a very effective use of heat pump for boosting of a geothermal well exploitation in a district heating network with higher volumetric flow. The return flow is split into two streams. The evaporator gets the same volumetric flow as the flow of geothermal water and the rest of district heating water flows through the condenser. The evaporator water is cooled down by 10.3Kelvin to 31.7°C and then is reheated by the Dogger water up to 71°C. The extracted heat in the evaporator is rejected by the heat pump into the condenser water, lifting its temperature up to 61.6°C. After that, both hot water streams flow together producing hot water at 67.5°C. The use of heat pump in this application increases the thermal power extracted from geothermal water by 3'000kW. As the required temperature lift is not high, the COP of the heat pump gives very high value of 6.3.

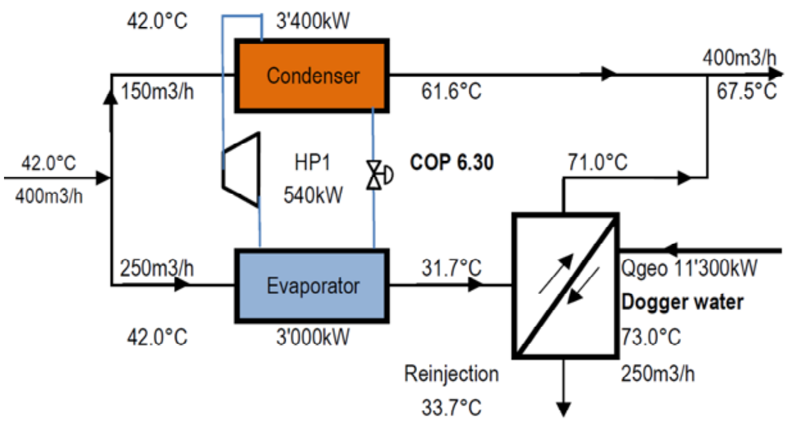

Figure 11: Heat pump arrangement for boosting of geothermal well exploitation for district heating network with higher volumetric flow.

It is obvious that volumetric flow and return temperature in district heating networks vary continuously. Thus, it is of crucial importance to take into account all possible operating conditions during the heat pump design.

Figure 12 shows the picture of the FRIOTHERM's heat pump type UNITOP 33C widely used in the high temperature geothermal applications.

Figure 12: Heat pump type UNITOP 33C designed for boosting of geothermal well exploitation.

5 CONCLUSIONS

The presented high temperature centrifugal heat pump technology has been continuously developed over the last 35 years and offers mature solutions for various heat sources. Important developments have been done in heat pumps operating in winter and summer in different modes. The change from heating (compressors in series) to cooling mode (compressors in parallel) and vice-versa, as well as the management of working fluid inside the heat pump may be performed fully automatically by the combination of valves. Due to the flexibility of operating modes the heat pumps cope with the variable demands for cooling and heating during the whole year.
Furthermore, recent developments have been done to use the ultra-low GWP working fluid HFO-1234ze in large capacity heat pumps. First large scale heat pump plant with 2 units is in successful operation since commissioning in 2012.
New developments in geothermal heat pump technology enable heat exploitation from large range of heat sources with temperatures up to 65°C. Each large geothermal project is a new challenge requiring an individual study to optimise the heat pump design and its hydraulic implementation for the operation in all possible district heating conditions with the highest possible COP values.
The large capacity heat pump technology is in continuous development increasing its performance and extending its application range for new challenging heat sources.

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