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High efficiency heat pumps for low temperature lift applications

Lukas Gasser[a,b], Stefan Flück[a,c], Mirko Kleingries[a], Christoph Meier[d], Marc Bätschmann[d], Beat Wellig[a*]

[a]Lucerne University of Applied Sciences and Arts, Technikumstrasse 21, CH-6048 Horw, Switzerland
[b]*Alera energies GmbH, Hohenrainstrasse 36, CH-6280 Hochdorf, Switzerland*
[c]*Flimatec AG, Technikumstrasse 21, CH-6048 Horw, Switzerland*
[d]*BS2 AG, Brandstrasse 33, CH-8952 Schlieren, Switzerland*

Abstract

Today heat pump and chiller units are widespread and sophisticated technologies for heating and cooling applications in buildings. Their efficiency as measured by the coefficient of performance (COP) is closely related to the inner temperature lift. In applications with a low external temperature lift, these units have a large potential for saving primary energy and reducing the CO2 emissions of buildings. Unfortunately, this potential is not fully exploited because standard systems are designed for lifts of 30-60 K. The following paper presents practical guidelines for the planning and designing of systems for low temperature lift applications. In order to demonstrate the potential for efficiency improvements, two systems for low temperature lifts were developed, one with a reciprocating compressor and the other with a small-scale turbo compressor. Based on these two systems, detailed experiments were carried out to quantify and confirm the potential of low temperature lift application. Over a relevant temperature lift range of 10 K to 30 K, the low temperature lift heat pump with a turbo compressor achieves an unprecedented high and relatively constant Carnot efficiency of around 60%. By using geothermal heat probes in combination with efficient heat delivery and supply systems, a COP of about 9 for heating mode can be achieved for a temperature lift of 20 K. The use of high temperature space cooling systems in combination with optimized recooling systems leads to a temperature lift of approximately 10 K and a COP of about 15 for cooling mode.

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Keywords: low temperature lift heat pump; small-scale turbo compressor; heat pump design; low-energy buildings; high efficiency

1. Introduction

1.1. Background and objectives

Sustainable use of energy and material resources and the reduction of CO2 emissions are gaining in significance from an ecological and economic point of view. One of the biggest challenges of the 21st century is to develop highly efficient building technology systems.

The heating and cooling of buildings are processes that require a great deal of energy and that cause about 40% of global CO2 emissions. Heat pumps and chillers in particular have a potential for saving primary energy that has hardly been tapped thus far. The only provision is that they can be operated consistently with low temperature lifts in combination with efficient building technology systems. Highly efficient heat pumps also enable buildings to be operated with emission-free heating and cooling as long as they are supplied with

* Corresponding author. Phone: +41 41 349 32 57; fax: +41 41 349 39 60
E-mail address: beat.wellig@hslu.ch

electricity produced by renewable energy. However, previous studies show that the market has not had any heat pumps and chillers available up to now that are capable of utilizing the potential of low-lift applications [1]-[4].

Against this backdrop, Lucerne University of Applied Sciences and Arts (Horw, Switzerland) and BS2 AG (Schlieren, Switzerland) are developing an optimized low-lift heat pump and chiller that achieves unprecedented high and relatively constant Carnot efficiency across the relevant temperature lift range of 10 K to 30 K. New and undiscovered possibilities in building technology are opened up with this development of a highly efficient low-lift heat pump with turbo compressor that exploits a low temperature lift substantially better than today's systems. In combination with efficient building technology systems, the potential of efficient heating and cooling systems with a low temperature lift can be exploited much better and can significantly reduce primary energy consumption and operating costs.

1.2. Temperature lifts of building heating and cooling

The efficiency of heat pumps and chillers is strongly influenced by the temperature lift. In compression heat pumps, the inner temperature lift corresponds (with good approximation) to the temperature difference between the condensation temperature and the evaporation temperature.

Heating: Besides the heat pump technology employed, the temperature lift of a heat pump used for building heating depends substantially on the heat distribution and delivery system as well as the heat source. In geothermal systems, the temperature of the undisturbed soil at a depth of 15 m is approximately 10°C and at 300 m around 19°C (gradient of ca. 0.03 K/m). This permits relatively high evaporation temperatures of up to 10°C when relatively deep geothermal heat probes are combined with properly sized evaporators. Other potential heat sources for low-lift applications include groundwater, river water or lake water. There is also a steady increase in the use of wastewater or the building`s exhaust air as high-temperature heat sources. The heat distribution and delivery system most commonly used in low-energy buildings is underfloor heating.

The temperature lift in most applications is typically around 15 K to about 75 K depending on the heat source and the heating system (Fig. 1). For an efficiently heated low-energy building, the desired temperature lift is in the range of 15 K to 30 K. This would entail, for example, a geothermal heat probe at a depth of 300 m and a modern low-temperature heating system. Fig. 2 shows the $COP_{HP, ideal}$ of an ideal heat pump (*i.e.* Carnot heat pump between the evaporation and condensation temperature) as a function of the temperature lift for a constant evaporation temperature of 10°C. For a temperature lift of 20 K, a COP_{ideal} of 15.2 is possible. If a system with a Carnot efficiency of 60% were used, a COP_{HP} of 9.1 would result (the Carnot efficiency is the effective COP_{HP} divided by the $COP_{HP, ideal}$ operating between the corresponding cycle temperature levels).

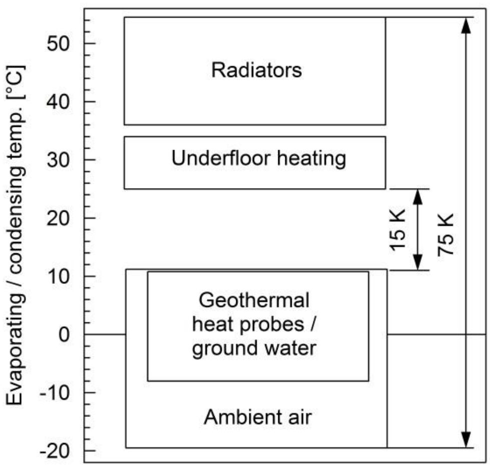

Figure 1: Typical evaporation and condensation temperatures and temperature lifts of different heat pump systems.

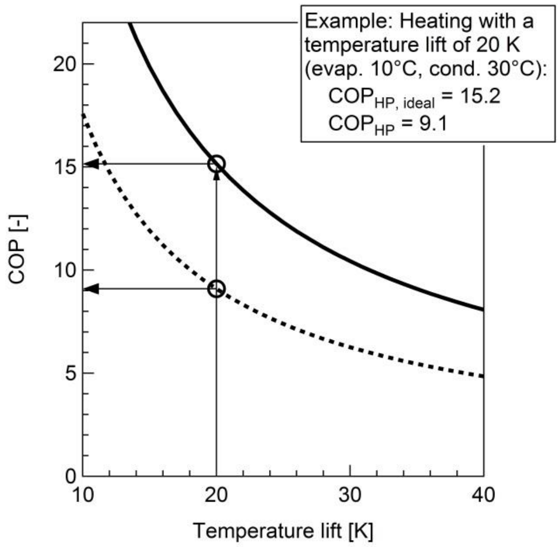

Figure 2: COP of an ideal heat pump and a real heat pump with a Carnot efficiency of 60% as a function of the temperature lift for a constant evaporation temperature of 10°C.

Cooling: Fig. 3 shows typical temperature lifts for various building cooling systems. Depending on the system, the lift varies between 10 K and 55 K as extreme examples. For the cooling of buildings, *e.g.* with a chilled ceiling, concrete core activation or highly efficient fan coil units combined with efficient hybrid re-cooling systems, a lift of between 10 K and 20 K is considered possible for the central European climate. However, even though the temperature difference between the heat source and the heat sink is small, the potential for highly efficient cooling processes is hardly used. The reasons are that i. conventional cooling systems require low chilled water temperatures to be provided by the cooling system and ii. inefficient dry coolers are used. Typically, the chilled water temperatures range from 8°C to 14°C resulting in a low evaporation temperature. In addition, due to the head pressure control, the condensation temperature is often maintained at a high level (*e.g.* 35°C to 45°C). Consequently, conventional building cooling systems often work with an unnecessarily high temperature lift.

Fig. 4 shows the $COP_{Ch,ideal}$ of an ideal chiller (Carnot chiller between the evaporation and condensation temperatures) as a function of temperature lift for a constant evaporation temperature of 14°C. For space cooling with a lift of 12 K, which is sufficient for numerous applications in the central European climate, a Carnot COP of 24 is theoretically possible. Under these conditions a COP of 14.4 can be achieved using a chiller with a Carnot efficiency of about 60% (*i.e.* ratio of the actual COP_{Ch} to the $COP_{Ch, ideal}$). However, practical experience shows that the Carnot efficiency of standard chillers, which are designed for high temperature lifts between 30 K and 60 K, is often considerably lower than 50% or in some cases below 40% for these given climate conditions.

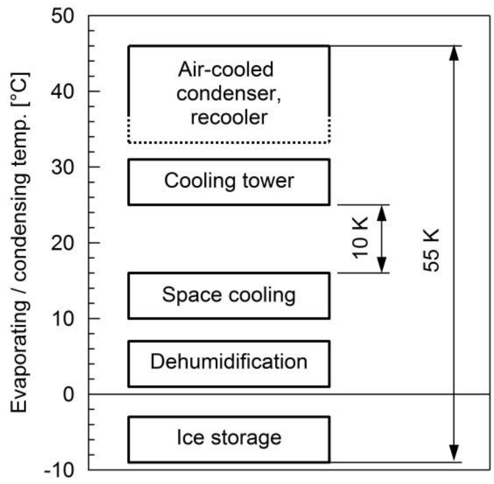

Figure 3: Typical evaporation and condensation temperatures and temperature lifts of different building cooling systems.

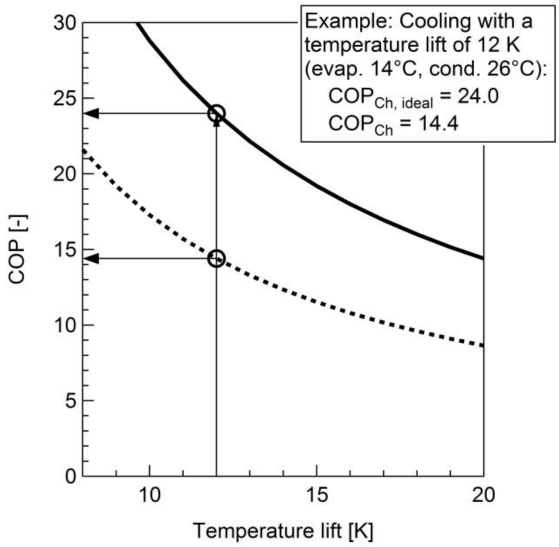

Figure 4: COP of an ideal chiller and a real chiller with a Carnot efficiency of 60% as a function of the temperature lift for a constant evaporation temperature of 14°C.

1.3. Objectives

Heating and cooling systems with a temperature level around room temperature are indispensable requirements for low inner temperature lifts. Heat pumps and chillers with low temperature lifts only achieve a high efficiency if designed specifically for the relevant operating conditions (*i.e.* high evaporation temperatures and simultaneously low temperature lifts). Therefore, the paper's main objective is to provide advice concerning the design and application of optimized heat pumps and chillers for operation at low temperature lifts. Furthermore, results from detailed experiments are presented and discussed.

2. Design of optimized low temperature lift heat pumps and chillers

Standard heat pumps and chillers are typically designed for inner temperature lifts of about 30 K to 60 K. This leads to relatively poor efficiencies if they are operated at low temperature lifts. It has been shown in various lab and field measurements that the Carnot efficiency sometimes drops considerably below 40% [1]. The full potential can only be exploited with systems that are specially designed for small lifts. In order to demonstrate the potential for efficiency improvement, two types of heat pumps for low temperature lifts were developed and tested.

2.1. Low temperature lift heat pump with reciprocating compressor

In an earlier research project, a low temperature lift heat pump with reciprocating compressor was built and tested. In the process, important findings were made on the design and operation of heat pumps of this kind. The heat pump and the experimental results were presented in detail at the Clima Conference 2010 [3] and the IEA Heat Pump Conference 2011 [4].

Achieving efficient heat pumps for low temperature lifts requires a new approach to the design and selection of the components. Therefore, all components of the heat pump were specifically selected for this application. For example, the selection criterion for the electronic expansion valve described by Wyssen *et al.* [3] [4] leads to greatly oversized expansion valves with respect to the evaporation capacity indicated by the manufacturers. The main selection criterion is to have the maximum permissible pressure drop at the expansion valve when it is fully opened (Fig. 5). The decisive operating condition is a heat pump with the highest evaporation temperature and the lowest temperature lift (*i.e.* lowest pressure ratio and highest refrigerant mass flow). If the pressure loss in the fully opened expansion valve is greater than the difference between the condensation and evaporation pressure, the desired operating condition cannot be reached. The resulting temperature lift will be higher than the one striven for.

In summary, these research efforts show that it is fundamentally possible to build and operate heat pumps and chillers based on standard components and designed especially to run at low temperature lifts. However, even with an optimum design, these systems do only a poor job of exploiting the potential for efficiency increases when operating at temperature lifts of less than 20 K (see Sec. 3). This can be attributed in particular to the unfavorable operating characteristics of standard positive-displacement compressors. For this reason, the next generation of low-lift heat pumps was equipped with a small-scale turbo compressor.

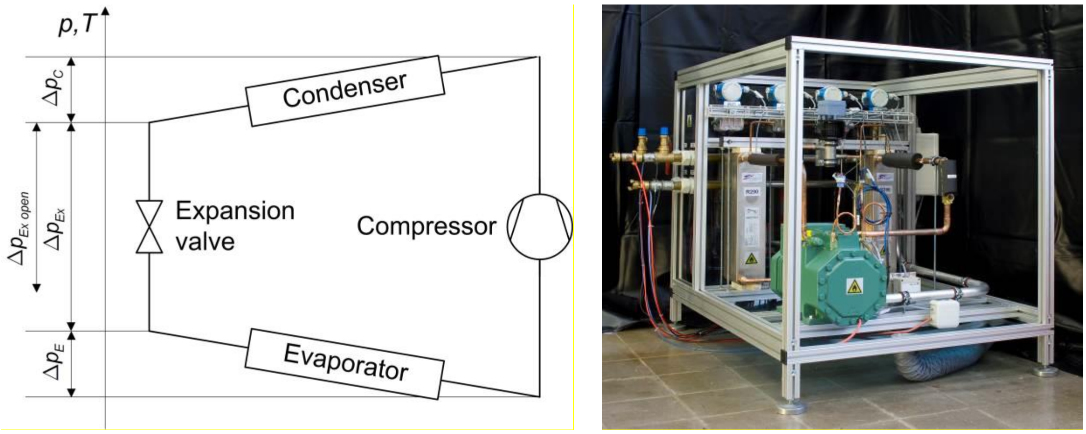

Figure 5 (adapted from Wyssen et al. [3] [4]): *Left*: Schematic diagram of the refrigerant circuit of the heat pump with pressure losses in the evaporator and condenser. Also shown is the required drop in pressure of the expansion valve as well as the resulting pressure loss in the fully opened expansion valve (see text). *Right*: Heat pump prototype with reciprocating compressor. This heat pump uses propane (R290) as refrigerant.

2.2. Low temperature lift heat pump with turbo compressor

There are currently no compressors available on the market that are suitable for operating at low temperature lifts (or small pressure ratios). Turbo compressors are the only exception. Besides being suitable for low temperature lifts, they have additional advantages for use in heat pumps. Most of today's heat pumps and chillers are operated with scroll or reciprocating compressors. Problems with oil lubrication can arise when compressors of this type are run at low temperature lifts and the low heating gas temperatures associated with them. Turbo compressors, for their part, can be built to be oil-free. Furthermore, turbo compressors pack high capacity in minimal space so they can be built smaller than conventional compressors. Heat pumps and chillers with turbo compressors are state-of-the-art for large heating and cooling capacities (above approximately 100-150 kW). Until recently there was no suitable turbo compressor technology available for smaller thermal capacities. In recent years, however, a small-scale radial turbo compressor geared and tailored specifically to this application was developed in Switzerland (Celeroton AG, Volketswil, Switzerland).

To help bring about the breakthrough of highly efficient low-lift systems, the Lucerne University of Applied Sciences and Arts together with BS2 AG developed an optimized low-lift heat pump with a turbo compressor for thermal capacities ranging from 9 kW to 20 kW [5] (Fig. 6). It achieves an unprecedented high and relatively constant Carnot efficiency across the relevant temperature lift range of 10 K to 30 K (see Sec. 3).

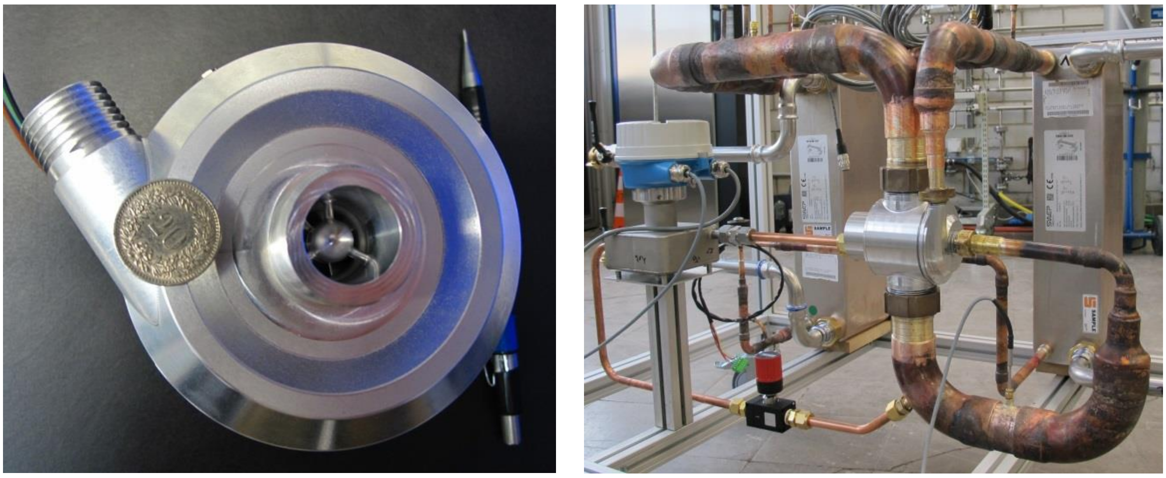

Figure 6: *Left*: Turbo compressor for low temperature lift applications with thermal capacities ranging from 9 kW to approximately 20 kW. *Right*: Heat pump prototype with turbo compressor in the laboratory of the Lucerne University of Applied Sciences and Arts.

The components for the low-lift system were designed and built on the basis of findings from the system featuring a reciprocating compressor ([3] [4], Sec. 2.1). To achieve high energy efficiency and low suction gas superheating, an electronic expansion valve is also used. The evaporator and condenser are designed as commercially available plate heat exchangers. The objective of the design was to keep the temperature differences for heat exchange as small as possible leading to "thermally long" plate heat exchangers, *i.e.* ones that are narrow and high. The developed oil-free low temperature lift heat pump uses butane (R600) as refrigerant. Butane does not have any ozone depletion potential (ODP) and a negligible direct global warming potential (GWP). It exhibits favorable thermodynamic and fluid-dynamic properties for use with the small-scale turbo compressors. Finally, the use of butane as a refrigerant poses no particular material problems.

3. Results and discussion

3.1. Experiments

Both heat pumps were integrated into a testing facility that provides fluid flows with exact and adjustable temperature level and mass flow control to simulate the heat source and the heat sink. This testing facility is versatile and can be employed in many ways for examining different heat pump systems. It is described elsewhere in detail (Gasser *et al.* [6]).

The heat pumps were equipped with very precise measuring devices for electric power, temperature, pressure and volume flow to retrieve all relevant process data. This process data enables a detailed and reliable energetic and exergetic analysis to be conducted at different operating conditions. The heat flows in the evaporator and the condenser can be calculated by the energy balances on the side of the heat source and the heat sink. The next section discusses and compares some important results from the experiments on the low-lift heat pump with reciprocating compressor and the low-lift heat pump with turbo compressor.

3.2. Energetic analysis

Fig. 7 presents the Coefficient of Performance without auxiliary equipment for the low-lift heat pump with reciprocating compressor as a function of the temperature lift at a constant evaporation temperature of 10°C when in heating mode operation. The COP_{HP} increases from 6.4 at a temperature lift of 30 K to 11.1 at about 15 K. With the 15 K reduction of the temperature lift, the COP_{HP} can be increased by approximately 73%. Analogously, the cooling COP (*i.e.* COP_{Ch}) for the low-lift system with reciprocating compressor is 5.7 at a temperature lift of 30 K and rises to 10.3 at 15 K (Fig. 9). The Carnot efficiency is an important key figure for assessing heat pumps and chillers as it expresses the internal behavior of the process. The Carnot efficiency of the low-lift heat pump with reciprocating compressor amounts to about 60% for operation in heating mode and in cooling mode if the temperature lift is 20 K to 30 K. For lower temperature lifts, it decreases to around 50% as a result of the unfavorable operating characteristics of the positive-displacement compressor. The Carnot efficiency (heating and cooling) of the low-lift system with reciprocating compressor is already considerably above the values of the standard heat pump represented in Fig. 7 and 9 (market available standard heat pump with a reciprocating compressor, refrigerant R134a, not optimized for low-lift applications). In the latter systems, the Carnot efficiency can fall to 40% if the temperature lifts are small. As developed, the low-lift system with turbo compressor enables yet another major increase in efficiency values.

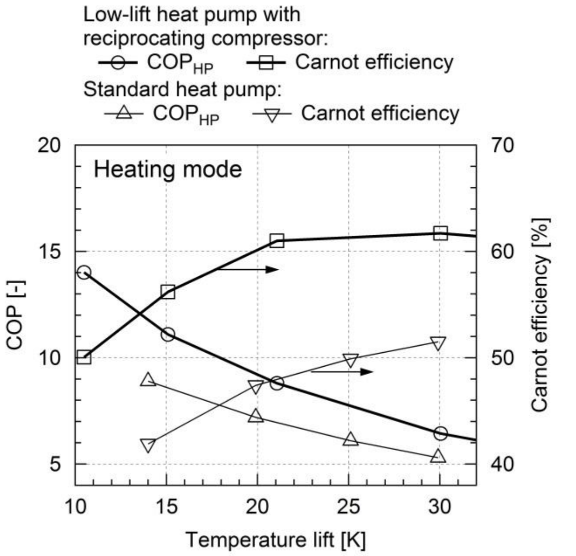

Figure 7: COP und Carnot efficiency for operation in heating mode as a function of the temperature lift for the *low temperature lift heat pump with reciprocating compressor* and for a standard heat pump with reciprocating compressor at a constant evaporation temperature of 10°C.

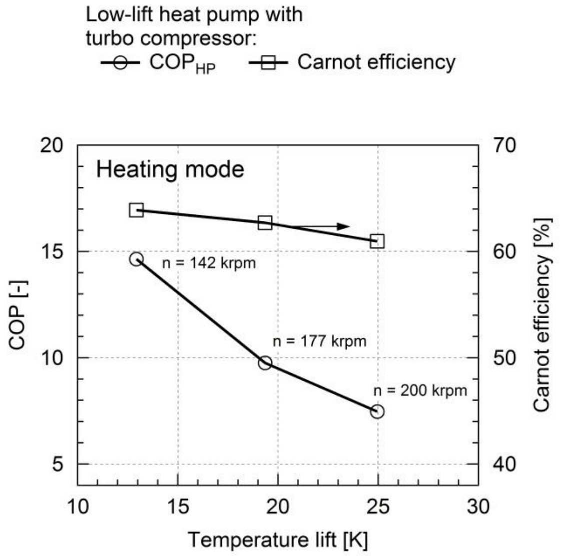

Figure 8: COP und Carnot efficiency for operation in heating mode as a function of the temperature lift for the *low temperature lift heat pump with turbo compressor* at a constant evaporation temperature of 10°C. Also shown are the rotational speeds of the turbo compressor.

Fig. 8 and 10 present the Coefficient of Performance and the Carnot efficiency of the low-lift system with small-scale turbo compressor as a function of the temperature lift at a constant evaporation temperature of 10°C for operation in heating mode or in cooling mode. At a temperature lift of 13 K, for example, the low-lift system with turbo compressor has a COP_{HP} of 14.6 and a COP_{Ch} of 13.8. The Carnot efficiency at this operating point is 63.9% for operation in heating mode and 63.0% for operation in cooling mode. In the range of examined temperature lifts of around 14 K to 26 K, the Carnot efficiency of the low-lift system with turbo compressor for operation in heating mode remained constantly above 60% despite a slight decrease as the temperature lift increased. For temperature lifts of less than about 25 K, the attainable coefficients of performance for the low-lift system with turbo compressor are therefore considerably higher than the values for the low-lift system with reciprocating compressor.

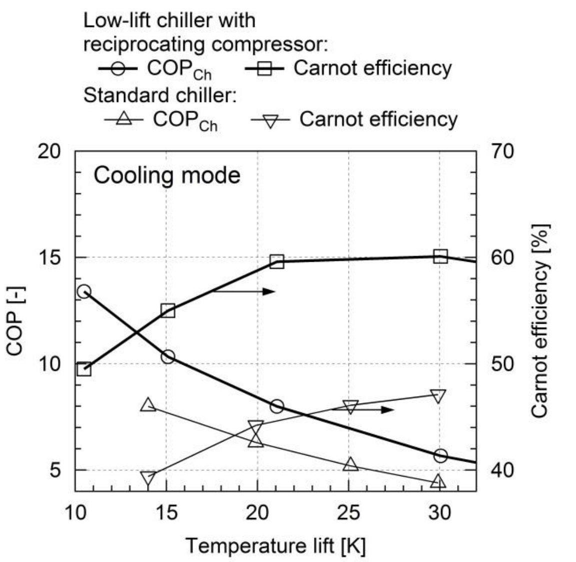

Figure 9: COP und Carnot efficiency for operation in cooling mode as a function of the temperature lift for the *low temperature lift chiller with reciprocating compressor* and for a standard chiller with reciprocating compressor at a constant evaporation temperature of 10°C.

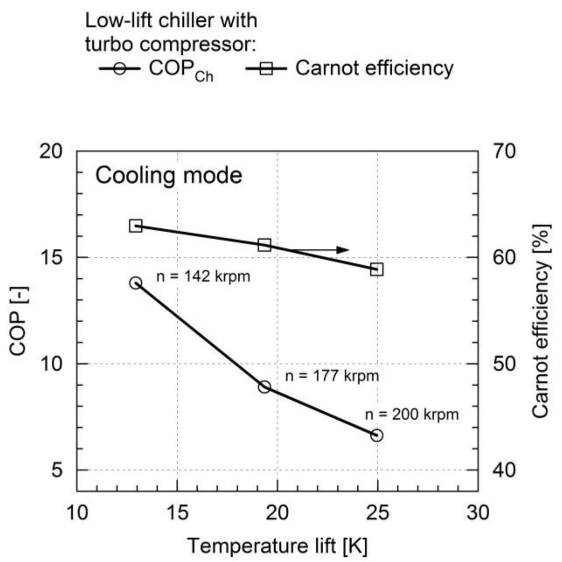

Figure 10: COP und Carnot efficiency for operation in cooling mode as a function of the temperature lift for the *low temperature lift chiller with turbo compressor* at a constant evaporation temperature of 10°C. Also shown are the rotational speeds of the turbo compressor.

A comparison with today's standard systems (designed for temperature lifts considerably higher than 30 K) shows that a marked improvement can be made in the efficiency of heat pumps and chillers by using the design specifically executed for low temperature lifts and by using turbo compressors, especially when operated at very low temperature lifts. The potential of efficient heating and cooling systems with a low temperature lift can be best exploited in combination with efficient building technology systems. This approach also enables primary energy consumption and operating costs to be reduced substantially. The following variations in the use of a low-lift system as a low temperature lift heat pump and as a low temperature lift chiller are discussed exclusively on the basis of the newly developed low-lift system with turbo compressor.

3.3. Use as low temperature lift heat pump

When the newly developed turbo heat pump is used in combination with modern low-temperature heating systems and deep geothermal heat probes, very high efficiency values can be achieved in the heating of buildings. One example is the building B35 in Zurich that aims at reducing the CO2 emissions of a building`s operation to zero [7]-[9] (see Fig. 11). In this example, the building technology was optimized for low temperature lifts. Through the application of two geothermal heat probes with depths of 300 m and 380 m, respectively, regeneration of the soil during the summer months and an efficient heat distribution and delivery system low external temperature lifts are to be expected.

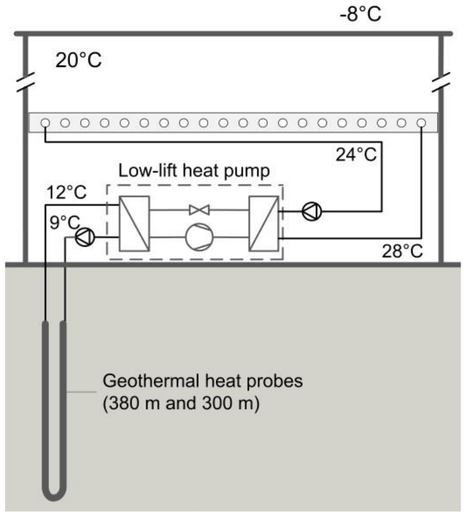

Figure 11: Building heating system in an apartment building in Zurich using a low temperature lift heat pump with geothermal heat probes (see text).

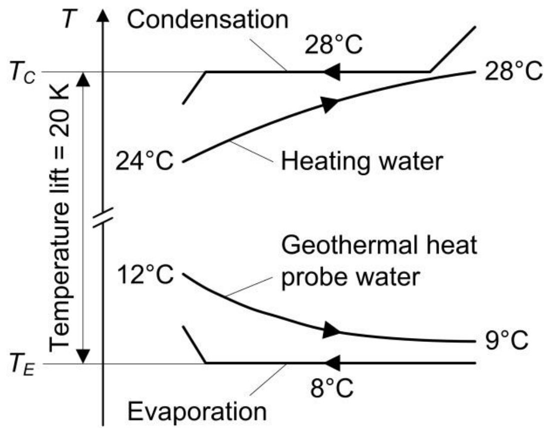

Figure 12: Qualitative temperature profiles in the evaporator and condenser of the low-lift heat pump with turbo compressor (de-superheating, subcooling in the condenser and the superheating in the evaporator are not drawn to scale).

At an ambient temperature of -8°C (*i.e.* design temperature for Zurich), efficient underfloor heating systems in low-energy buildings require a heating water supply temperature of about 28°C (Fig. 11 and 12). The resulting condensation temperature of the low-lift heat pump with turbo compressor is thus about 28°C (or even lower in the case of a thermally long condenser). Using deep geothermal heat probes, the attainable evaporation temperature is about 8°C (water at 12/9°C) and the resulting temperature lift of the low-lift heat pump with turbo compressor is about 20 K. This operating state of the low-lift heat pump with turbo compressor produces a COP_{HP} of 9.7 and a Carnot efficiency of 62.7%. During the seasonal transition period, considerably lower temperature lifts are to be expected. In these periods, the efficiency advantages of the low-lift heat pump with turbo compressor are even greater since the Carnot efficiency remains relatively constant at around 60% if the temperature lift drops to lower values.

These COP values and Carnot efficiencies are much higher than that of commercially available heat pumps. However, not only the heat pump has to be highly efficient, but the entire system including all hydraulic circuits, controls etc. must be designed to function efficiently in order to achieve high system overall efficiency. If both circulation pumps (geothermal heat probe and heating system) are taken into account, the coefficient of system performance (COSP) is approximately 8.8, which is also markedly higher than the typical COSP values of standard heat pump systems. In summary, the consistent use of the low external temperature lift can considerably reduce exergy losses and opens the way to very high efficiency values for building heating.

3.4. Use as low temperature lift chiller

The use of a low temperature lift heat pump for building cooling also has great potential for efficiency improvements. This can be clearly illustrated by a comparison based on a building cooling system in an office building in Zurich (Fig. 13, adapted from Wyssen *et al.* [3]). The cooling system used in the building is highly efficient and features high chilled water temperatures (CWTs), low recooling temperatures and a very high percentage of free cooling. The cold supply in the rooms is generated by highly efficient fan coil units with CWTs of 16°C to 20°C. The recooling loop is equipped with a wet cooling tower where the wet bulb temperature is 1 K to 2 K. In principle, free cooling is the primary method of cooling. Once the wet bulb temperature or the required cooling capacity makes free-cooling impossible, the chiller is put into operation. It is worth mentioning that in such optimized cooling systems the external temperature lift is *never* above 10 K in central European regions.

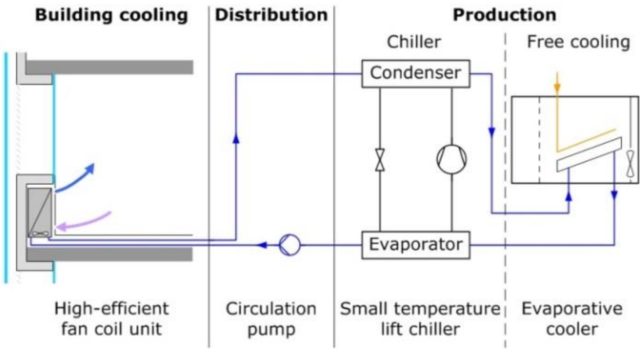

Figure 13: Building cooling system in an office building in Zurich using a low temperature lift chiller [4].

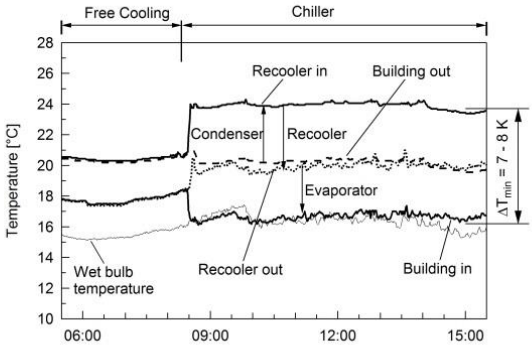

Figure 14: Typical temperature profiles for a summer day [4]. The external temperature lift in this system is never higher than 10 K.

The cooling Coefficient of Performance of a standard chiller is 7.2 and its Carnot efficiency is 47.7% at a typical operating point for this system [4]. To provide the CWT at the same temperature level with the low temperature lift chiller with turbo compressor, the resulting COP_{Ch} amounts to 13.8 and the Carnot efficiency to 63.0%. The low temperature lift chiller with turbo compressor that is specifically designed for low temperature lifts achieves a COP value that is better by a factor of nearly 1.9. The substantial difference can be attributed to the much lower temperature lift resulting from the optimized heat exchangers and the much higher Carnot efficiency of the low-lift system. For standard systems, unnecessarily low evaporation temperatures and unnecessarily high condensation temperatures are required, which leads to poor efficiencies (see for example Wellig *et al.* [1] [2]).

Also in the case of building cooling, not only the chiller but the entire system including hydraulic circuits, recooling system, controls etc. have to be specifically designed and optimized for low temperature lifts. If all auxiliary equipment (circulation pump, fan of recooler, fan coil units for space cooling, control) are taken into account the COSP is 8.1 (calculation based on field measurements [3]). For standard cooling systems, unnecessarily low evaporation temperatures and high condensation temperatures are required. It is well known that COSP values of standard building cooling systems are mostly below 3 (Wellig *et al.* [1] [2]). As a result, optimized building cooling systems and chillers that are specifically designed for low temperature lifts exhibit considerably higher energy efficiency.

4. Conclusions

Our research projects show that the consistent use of a low external temperature lift in heating and cooling can save valuable primary energy while at the same time creating the prerequisite for emission-free building operations. A mandatory requirement for doing so is that the heat pump or chiller used must be specifically designed for these operating conditions and thus enable a high Carnot efficiency in connection with low temperature lifts. What is also needed is a suitable low-lift building technology that provides the optimum boundary conditions for the heat pump or chiller in operation (*i.e.* high source temperatures and low sink temperatures). These projects have laid the necessary scientific and technical groundwork for a marketable, highly efficient, and operationally reliable low-lift heat pump with small-scale turbo compressor.

If modern low-temperature heating systems are used in combination with deep geothermal heat probes and a temperature lift of about 20 K, COP values of more than 9 can be achieved using a low-lift heat pump with a turbo compressor (used for the building heating). In efficient building cooling systems featuring high temperature cooling systems and optimized recooling systems, COP values of about 15 can be achieved for the expected temperature lift of approximately 10 K. The best possible way of exploiting the potential of a low available temperature lift is with optimized low-lift systems featuring small-scale turbo compressors.

Although, the approach of using low temperature lifts is, on the face of it, quite straightforward, it poses many obstacles. In order to achieve high system efficiency, not only the heat pump or the chiller must be efficient, but the entire system must be designed to function efficiently. That includes hydraulic circuits, heat exchange on the source and sink side, building dynamics, controls etc. Suitable approaches are being developed, for example, by the Alliance 2SOL [9]. The implementation of all these measures will lead to a significant reduction in exergy consumption and on-going operating costs for the heating and cooling of buildings.

Acknowledgements

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