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Ground source heat pump systems for energy efficient building retrofitting

Michael Lauermann[a*], Johann Emhofer[a], Karl Ochsner sen.[b]

[a]AIT Austrian Institute of Technology GmbH, Center for Energy,
Giefinggasse 2, 1210 Wien, Austria
[b]Ochsner Wärmepumpen GmbH
Krackowizerstraße 4, 4020 Linz Austria

Abstract

In the case of building retrofitting, the integration of ground source systems with heating/cooling solutions and heat pumps to achieve maximum performance is a great challenge that demands a solution. In order to find a suitable solution for a given building retrofit scenario, two different heat pump configurations are numerically analysed and compared to each other in terms of heating capacity and coefficient of performance (COP). As working fluid, the Low Global Warming Potential (GWP) refrigerant R1234ze(E) with a GWP smaller than 10 will be used to meet with the current F-Gas regulation by reducing the GWP of fluorinated refrigerants. One favourable heat pump configuration is a twin-cycle system. Alternatively, a single-stage configuration which uses a significantly larger condenser for enhanced subcooling in the refrigeration circuit is also analysed. Both systems allow a more efficient operation compared to state-of-the-art heat pump systems in the case of building retrofitting. In that way, the COP increase in relation to a standard heat pump cycle with typical subcooling is in the range of 10-15% depending on the operating point.

Keywords: Geothermal systems; building retrofitting; ground source heat pumps; twin-cycle configuration; enhanced subcooling

1. Introduction

In Europe, the building sector is responsible for 40 % of the total energy consumption and represents about a third of Europe's CO_2 emissions. This is a huge socioeconomic and environmental problem, more if we con-sider that almost half of the EU buildings have boilers installed before 1992, with an efficiency rate of below 60 % [1]. Although energy renovation of existing buildings could help to achieve the EU climate and energy tar-gets, the refurbishment rate is currently below 1 % and renewables are not widely used in the building sector. Within the H2020 project GEOFIT, easy-to-install, economical and enhanced geothermal systems for energy efficient building retrofitting are going to be implemented and demonstrated at five dedicated pilot sites across Europe - a historical building (ITA), a primary school (ESP), an indoor swimming pool (IRL), an office building (FRA) and a single-family house (IRL).

2. Low GWP refrigerants

Component providers and heat pump manufacturers are currently facing new challenges with the so-called F-Gas regulation, which provides for a gradual reduction in emissions of fluorinated greenhouse gases by 2030. Since beginning of 2018, the number of refrigerants that can still be used in the medium term has been drastically reduced, which has led to a significant increase in the price of fluorinated refrigerants.

The GEOFIT heat pump concept is generally foreseen for retrofitting the heating system of existing buildings. The working medium or refrigerant has a major influence on the area of application and the desired temperature levels. The prohibition of chlorofluorocarbon (CFCs) and hydrochlorofluorocarbons (HCFCs) has severely restricted the availability of suitable working media. According to the EU Regulation No. 517/2014 on F-gas reduction (which came into force throughout the EU on 1.1.2015) [2] to reduce greenhouse gas emissions, a drastic multi-stage phase-down of HFCs (hydrofluorocarbons) applies until 2030, with the first significant stage already coming into force at the beginning of 2018. This will exacerbate the shortage of available working media and refrigerants.

For this reason, more and more companies and consumers are looking for alternatives. One option is based on natural refrigerants. Natural refrigerants include hydrocarbons, CO_2, ammonia and water. The most common hydrocarbons are isobutane and propane. However, propane is highly flammable and can form an ignitable and explosive gas mixture with the ambient air. A third generation of synthetic refrigerants, hydrofluoroolefin (HFOs), has recently launched on the market. A candidate would be the low-GWP refrigerant R1234ze(E) with a GWP smaller than 10. However, the core component in a heat pump system – the compressor – lacks approval from the manufacturers for these new refrigerants, e.g. due to technological barriers regarding the long term long-term stability of the seals.

3. Heat pump systems – the different technologies

A technology comparison in Table 1 provides an excerpt and overview of the state of the art for the relevant heat pump technologies, where brine/water and air/water heat pumps are compared with each other. The advantages and disadvantages of brine/water or air/water systems as well as the requirements of the various heat sources are shown. The annual performance factor (SCOP) is the benchmark for the efficiency of a heat pump system over a whole year. It indicates how much heating energy is delivered by the heat pump in relation to the electrical energy used over the course of a whole year. The so-called COP indicates a snapshot of the ratio of heating power to electrical power used. Modern heat pumps achieve COP values of 4 to 5 under standardized test conditions for supply temperature in the range of 35 °C for space heating. For hot water production the COP drops down to values below 3 at a temperature level of 55 °C.

Table 1: Comparison of the relevant technologies and state of the art of ground source and air-based heat pump systems in Austria, adapted from [3].

Heat source	Boreholes	Ambient air
General requirements	• Suitable ground • Required depth: 25 m/kW	• Sufficient distance between supply and exhaust air duct • Split-device: Ensure sound insulation, frost-proof condensate drain
Space requirements (outside the technical room)	• Borehole distance: approx. 10 m • 2.5 m Distance to property boundary • 1.5 m distance to supply and disposal lines (sewer, water, etc.)	• Split device: manufacturer-specific • Indoor installation: none
SCOP	3.5 – 5	2.5 – 3.5
Advantages/Disadvantages	+ high, stable source temperature throughout the year, high efficiency, low space requirement - higher investment costs	+ Low additional installation effort - strongly dependent on temperature level and amount of exhaust air - Sound emissions

The dimensioning of the heat pump in the case of retrofitting depends, among other things, on the previous oil or gas consumption. These values can be used to determine the effective heating energy required. The flow temperature plays an important role in the operation of the heat pump. For well renovated apartments with underfloor heating 35 °C is sufficient. If the heat transfer area of existing radiators is large enough, the temperature should be 50 °C, and in the case of an older building standard 65 °C can be regarded as a guide value. However, the efficiency of the heat pump deteriorates with increasing flow temperature. At this point, the GEOFIT solution comes in.

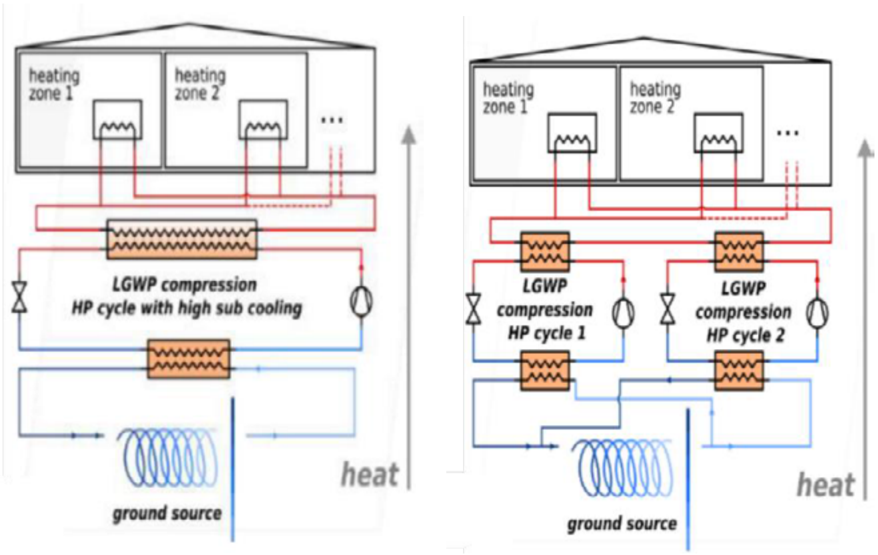
4. Description of the heat pump system

The GEOFIT heat pump system uses a low GWP refrigerant R1234ze(E) with a GWP<10 instead of state-of-the art refrigerants like R134a which has for example a GWP of 1430. The system makes uses of cost effective heat exchangers (e.g. heat exchangers made of Aluminum) that due to the lower raw material costs of Aluminum compared to Copper (about of a third), represent a potential to lower the costs of the heat pumps without performance loss. Since, high temperature differences can be required for retrofit heating systems; we investigate two alternatives to provide them within the project. (1) One solution is based on using two heat pumps with different condensation temperatures but with the same evaporation temperature (see Figure 1 right). (2) The other solution uses a significantly larger condenser compared to a state-of-the art heat pump condenser to make use increase the sensible subcooling of the refrigerant (see Figure 1 left).

The general idea behind the first mentioned configuration is to split up a single refrigeration cycle into two cycles. In that way, one of the two refrigerant cycles does need not to overcome the entire temperature lift. Hydraulically, the two condensers are connected in series, whereas the two evaporators are connected in parallel. Assuming a similar compressor scale on both cycles, roughly half of the total heating capacity can be delivered at a higher COP than the other. This configuration is referred as "Twin-cycle" heat pump configuration depicted in Figure 4. The second configuration is a "Single-Stage" heat pump configuration. In contrary to the Single-Stage heat pump configuration, the Twin-cycle heat pump configuration shows considerable advantages regarding safety, start-up time and legal requirements, as the refrigerant charge for each cycle is only half compared to the Single-Stage configuration. Those advantages and disadvantages are summarized in Table 2.

Table 2: Advantages and disadvantages of the considered heat pump configurations.

Configuration	Advantages	Disadvantages
Single-Stage	• Simplest refrigeration cycle → Low invest costs • Good overall performance in terms of COP and energy cost savings from very low to medium temperature lifts	• Higher refrigerant charge per cycle • Start-up time • Legal requirements due to refrigerant charge • Lower efficiency at high temperature lifts • No part load possible without speed control
Twin-cycle	• Lower refrigerant charge per cycle • Best overall performance from very low to medium temperature lifts • Without speed control, still 50% part load possible	• More complex refrigeration cycle →Higher invest costs



Single-Stage Twin-cycle

Figure 1: GEOFIT concepts for the heat pump systems.

5. Operating modes

When talking about operation of a heat pump, its actual heating capacity in the design point[1] plays a significant role. There is a certain degree of flexibility regarding heat pump sizing. According to that, the following two operating modes will be discussed:

- Monovalent
- Bivalent

5.1 Monovalent operation

A heat pump is usually sized to at least 100% heat demand of the heating season for any given house, meaning that the heat pump should be able to entirely heat the house without electric or other back up system except under the most extreme conditions. In practice, this translates to systems being designed to a target external design temperature[2], depending where the property is located. This type of application should therefore be preferred as far as possible. Brine/water or water/water heat pumps in a state of the art building standard are usually operated monovalently. Monovalent operation of air/water heat pumps is also possible, but not always feasible.

5.2 Bivalent operation

The heat pump covers most of the heat demand on its own. At very low outside temperatures, the heat pump and the supplemental heat generator, work together. This temperature is known as the bivalent point (BP). This operating mode is used when renovating existing buildings while retaining the installed gas boiler. If the heat pump could not cover all the heat load and is also restricted to its maximum supply temperature at extreme outdoor conditions, the additional heating system will pick up the shortfall in terms of increased capacity and increased supply temperature. In the case of building retrofitting, it is usually the existing gas boiler. Figure 2 shows an overview of the different operating modes.

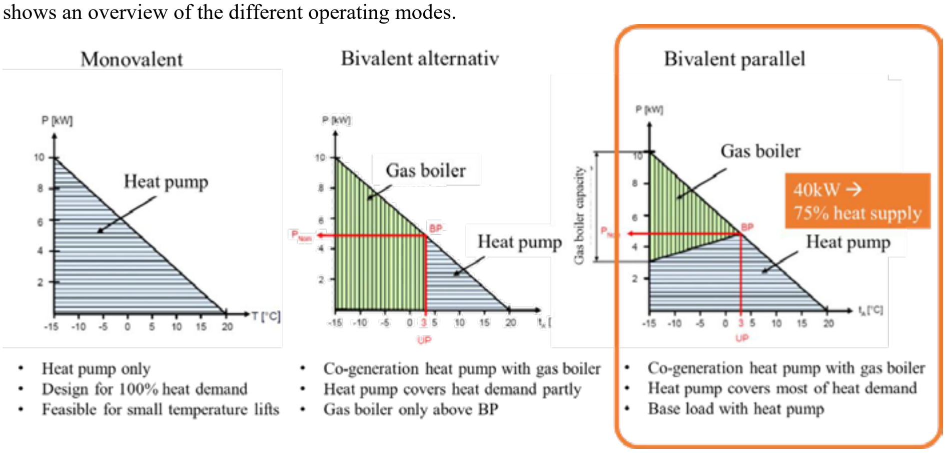


Figure 2: Heat pump operating modes. Monovalent, Bivalent alternative and Bivalent parallel. For the GEOFIT case, a heat pump with 40kW heating capacity is able to deliver 75% heat demand.

If gas boilers are already installed, the bivalent parallel is a favorable option, where the heat pump acts as base load system and the existing gas boilers are switched on below the bivalent point as discussed in [4]. With such operating control, the maximum operating hours of the heat pump can be achieved, having the most economical solution for retrofitting. However, this operating mode poses a great challenge regarding the hydraulic integration and the control of the two coupled systems in order to avoid derogating the heat pump efficiency when the gas boiler turns on. Though, the hydraulic integration is not part of this work as we address the refrigeration circuit layout assuming a correct integration and operating control.

[1] The design point for a heat pump system is usually given by the most extreme operating condition, i.e. coldest day of the year.
[2] This is the target minimum low external temperature as established according to National Building Codes or based upon statistical or historical meteorological data available for each location.

6. Simulation environment

The numerical simulations are performed in Dymola. Dymola is a commercially available simulation environment to solve actual problems written in the modelling language Modelica. It is suited for multi-domain modelling, (e.g. thermal, mechanical, electrical and hydraulic). Modelica is an equation-based object-oriented modelling language, which allows reproducing complex physical systems and solving time-dependent problems in mechanical, electrical, hydraulic, thermal, fluid and control fields, with the help of algebraic, differential and discrete equations [5].

The heat pump modelling in general takes place in the thermo-hydraulic domain. A heat pump system is built up by standard components, such as heat exchangers, compressors, expansion valves, control systems, sensors, etc. These components can be custom written or selected from either free or commercial libraries written in Modelica. Within the GEOFIT project, we use the TIL-Library [6] for the thermal component modelling as it is widely used and proven by the refrigeration industry. The specific modelling approach allows for a detailed representation of the physics and parameterization of each heat pump component from the compressor to the heat exchangers up to the entire piping of the refrigerant cycle, if necessary. Furthermore, an extensive database of refrigerants is available in TIL libraries. Figure 3, Figure 4 show the different heat pump configurations as simple schematic view and model representations in Dymola.

Schematic view of a Single-Stage cycle | Graphical view of the Modelica model in Dymola

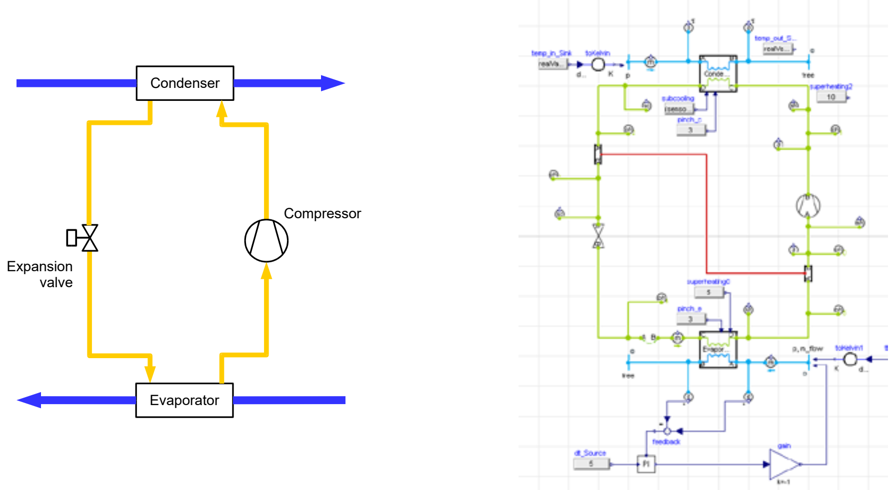


Figure 3: Schematic view (left) and Modelica model in Dymola (right) of a single-stage heat pump.

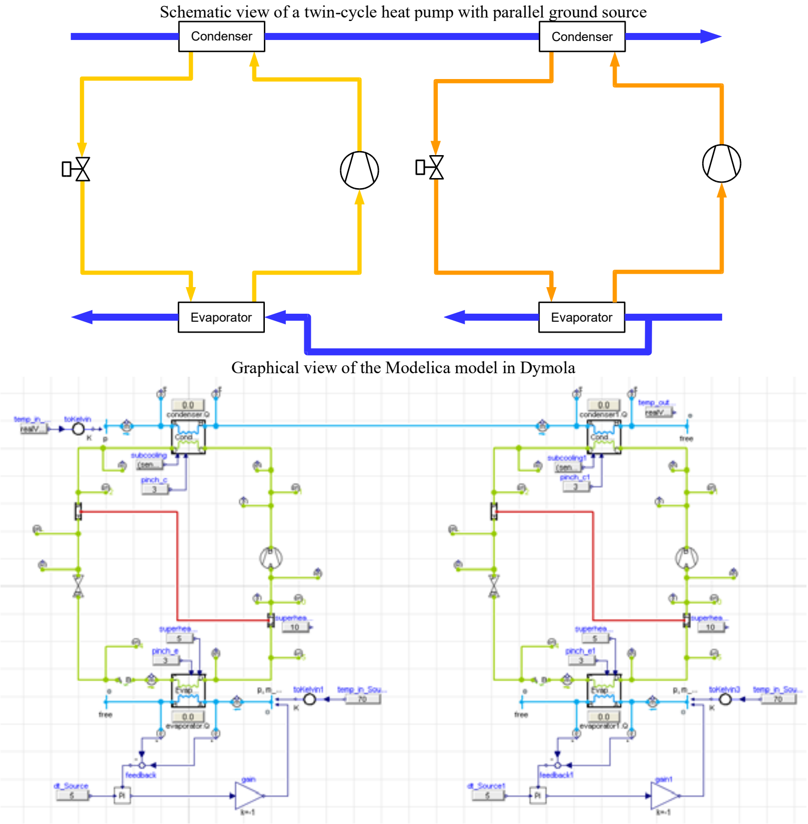


Figure 4: Schematic view (top) and Modelica model in Dymola (bottom) of a twin-cycle heat pump cycle with parallel source.

7. Methodology

The methodology for the layout and design of heat pump system is roughly depicted in Figure 5. After the implementation and model setup phase, the model parameters are set to manufacturer data. A critical role is played by the compressor characteristics, which are usually given for a standard refrigerant with high-GWP values (e.g. R134a). At present, efficiency data for low-GWP refrigerants, such as R1234ze(E) is not yet available for the chosen compressor type. The Bitzer refrigerant report states [7], that operating experiences gained from laboratory and field trials to date allow a positive performance assessment on the efficiency behavior compared to R134a. For the usual operation range, the COP is within a range of 5 %. Therefore, it is expected that simple system modifications will provide the same efficiency as with R134a. However, R1234ze(E) is sometimes called an R134a substitute, the resulting heating capacity is the range of 20 % below that of R134a. With this information and the proper heat pump configuration, we changed the refrigerant from R134a to R1234ze(E) in our models keeping the efficiency values from R134a. We are aware that an accurate quantitative assessment is not possible with this methodology but a qualitative comparison of different heat pump configurations.

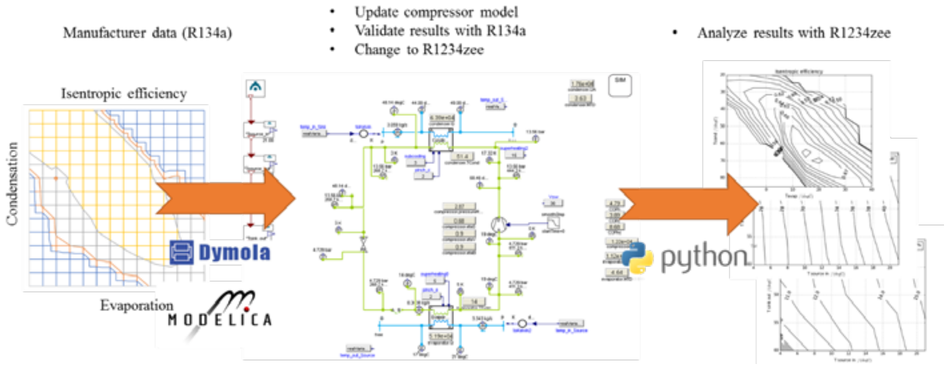


Figure 5: Methodology for the evaluation of the heat pump system.

Six typical operating states were simulated and the parameters such as heating capacity of the heat pump ($\dot{Q}_{heat}$), electricity consumption of the compressor (P_{el}) and COP were used to compare to each other. Those operating states are given in the Table 3. The temperature conditions on the source and on the sink – assuming a proper control strategy and hydraulic integration for the retrofit case - are the inputs for the numerical models.

Table 3: Temperature boundary conditions for the typical reftofit case.

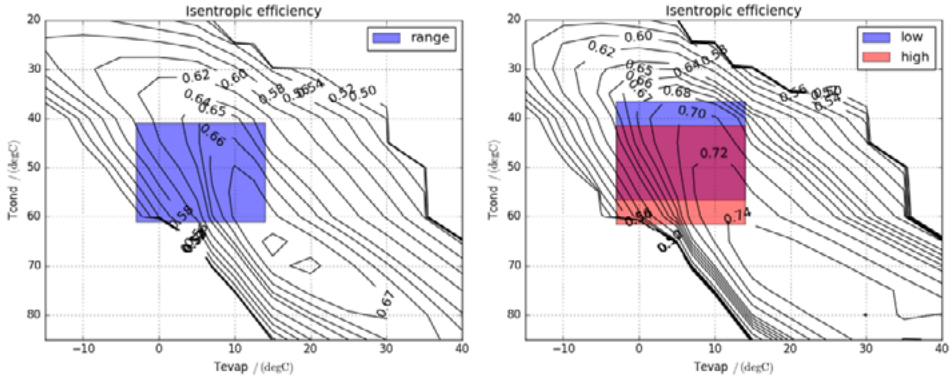
Operating point	T_{source_in}	T_{source_out}	T_{sink_in}	T_{sink_out}
-		degC		
1	4	2	35	40
2	4	2	45	50
3	11	7	35	40
4	11	7	45	50
5	21	17	35	40
6	21	17	45	50

In GEOFIT, the compressor type of the electrical driven heat pump system is chosen to be a scroll compressor. This specific compressor type is a positive displacement compressor. We chose to follow the efficiency-based modeling approach. In order to describe the compression cycle, the isentropic and the volumetric efficiency are prescribed. They are usually given as a function of pressure ratio and condensing or evaporating temperature. An ideal isentropic compression is complemented by different physical effects:

- pressure drop suction side
- pressure drop discharge side
- internal leakage
- re-expansion of the compressed fluid
- mechanical friction
- heat losses

The volumetric efficiency gives the relation between the geometrical mass flow and the actual mass flow over the compressor. The geometrical mass flow can be calculated with the known refrigerant properties on the suction side and the swept volume. For the specific scroll compressor in GEOFIT, the manufacturer provides efficiency curves for R134a. While the isentropic efficiency is used to calculate the discharge enthalpy of the refrigerant, the effective isentropic efficiency represents the electric power consumption of the motor. Usually, it's the effective isentropic efficiency which is experimentally identified, as the measurement of electric power is more accurate, than the measurement of the discharge temperature. However, for the sake of simplicity, both efficiencies are considered equal for the considerations in this work.

Figure 6 shows the compressor characteristics based on manufacturer data for the two heat pump configurations. The blue region for the Single Stage system (left) show the resulting operating window based on the values in Table 3 for a single compressor. For the Twin-cycle system (right), the blue region reflects the lower cycle and the red region the higher cycle. Both compressor types are from the same compressor series, but only differ in displacement. The compressor for the Single-stage system has approx. twice the displacement than one of the two compressors for the Twin-cycle system. Even though the compressors belong to the same compressor series, when comparing the isentropic efficiencies in Figure 6, it can be seen, that the qualitative behavior is similar but the peak value for the Twin-cycle compressors is at 0.74 while for the Single-stage compressor it is at 0.67. This difference is directly affecting the resulting COP as it can be seen in the next section.



Single Stage　　Twin-cycle

Figure 6: Compressor characteristics for the Single-stage system (left) and the Twin-cycle system (right).

8. Results

Before comparing the two heat pump configurations, a general remark on operating a heat pump in building retrofitting. The lower the return flow temperature, the higher the efficiency of the heat pump. Together with an existing gas boiler, the interaction between those two heating elements must be even more carefully considered in order to avoid high return flow temperatures when operating in bivalent parallel mode. In GEOFIT a top-level control for the two heating systems will be implemented to ensure an energy efficient operation.

Figure 7 shows the results for the Single-stage system and Figure 8 the results for the Twin-cycle system. The contour plots with the isolines allow for a quick assessment of the characteristics at different operating points. For both systems, the heating capacity depends almost only on the source temperature. The sink temperature has a minor impact where the heating capacity slightly decreases with increasing sink temperature. Comparing the different configurations, the Twin-cycle shows the best results in terms of COP. Due to reduced temperature lift on the low cycle, less electricity is consumed by the compressors compared to the Single-Stage configuration. For both configurations, the overall heating capacity varies from roughly 42 kW down to 26 kW depending on the source temperature level with slightly higher values for the Twin-cycle configuration. The COP values are in the range of 2.2 to 5.8 for the Single-stage system and 2.5 to 6.5 for the Twin-cycle system. Therefore, the COP increase for the Twin-Cycle is approx. 5 to 15% according to the operating point, which is a significant improvement considering long term operation and energy costs. In Figure 9, the increase is depicted for all operating points.

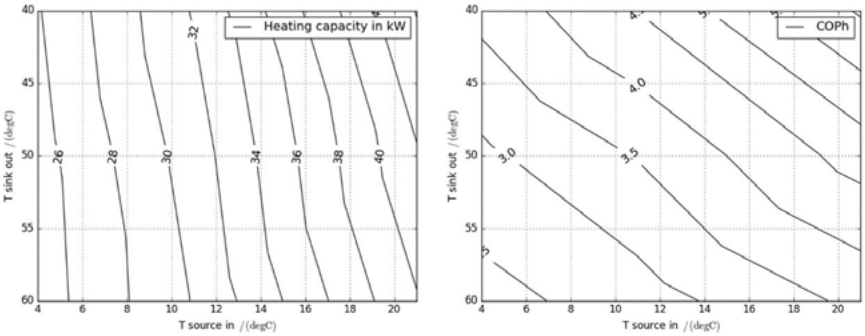


Figure 7: Results for the Single-Stage system.

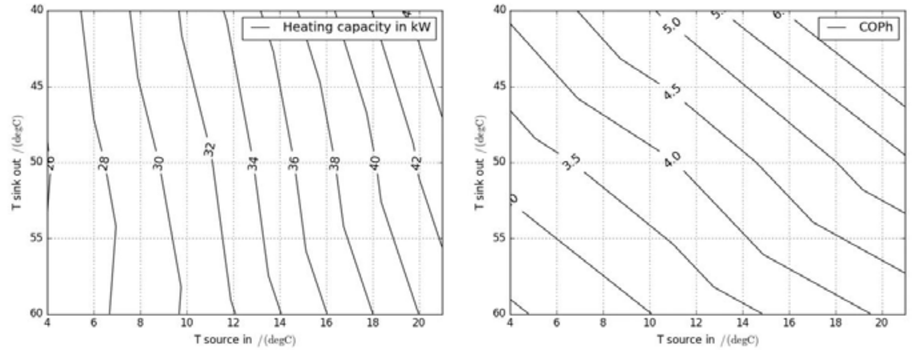


Figure 8: Results for the Twin-cycle system.

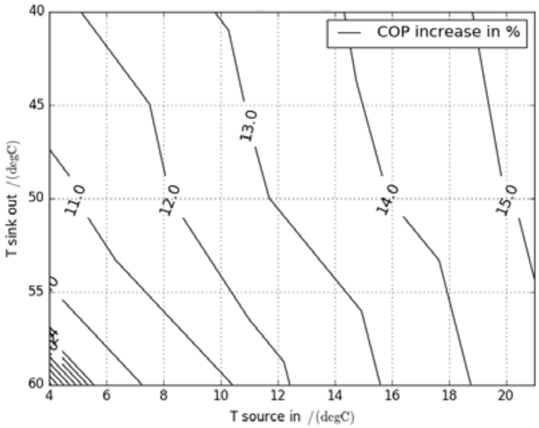


Figure 9: COP increase of the Twin-cycle system compared to a Single-stage system.

9. Conclusion

This paper presents a numerical comparison of two different heat pump configurations for a specific building retrofitting case in the framework of the H2020 project GEOFIT. The compressor characteristics were taken from manufacturer data for R134a and transferred for the use of the low-GWP refrigerant R1234ze(E). The results show a significant COP increase in the range of up to 15% for a Twin-cycle configuration compared to a Single-stage heat pump with enhanced subcooling.

The results are based on a given temperature spread on the supply side of 5K by preserving the installed radiators in the building. Increasing the heat transfer area of the heat distribution system in the building by either changing the radiators or upgrading them with a ventilation system, can lower return temperatures significantly. This has a positive effect on the heat pump efficiency by lowering the mean supply temperature between flow and return side.

In this work we outline a possible way to increase the heat pump efficiency by a twin-cycle system. There are also other ways for an improved heat pump cycle, e.g. a two-stage with EVI-injection. But all those enhancements come along with increased investment costs compared to a Single-Stage system. These additional costs need to be contrasted with the efficiency gain and is part of the future work within the GEOFIT project. In the case of building retrofitting, a parallel operation with an existing gas boiler is the most economical solution. A great challenge is the hydraulic integration and the control of the coupled systems in order to avoid derogating the heat pump efficiency when the gas boiler turns on.

A successful integration of ground source heat pumps systems in existing buildings needs an integral approach where the ground source, the heat pump and the hydraulics in the building receive equal attention. In that way it is possible to increase the commercial attractiveness of geothermal energy in combination with ground source heat pumps and therefore increase the penetration of this renewable source in building retrofitting.

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