Technology Collaboration Programme
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Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)

Annex 54

Heat Pump Systems with Low-GWP Refrigerants

Country Report Sweden

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Preface

This project was carried out within the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP), which is a Technology Collaboration Programme within the International Energy Agency, IEA.

The IEA

The IEA was established in 1974 within the framework of the Organization for Economic Cooperation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster cooperation among the IEA participating countries to increase energy security through energy conservation, development of alternative energy sources, new energy technology and research and development (R&D). This is achieved, in part, through a programme of energy technology and R&D collaboration, currently within the framework of nearly 40 Technology Collaboration Programmes.

The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)

The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) forms the legal basis for the implementing agreement for a programme of research, development, demonstration and promotion of heat pumping technologies. Signatories of the TCP are either governments or organizations designated by their respective governments to conduct programmes in the field of energy conservation.

Under the TCP, collaborative tasks, or "Annexes", in the field of heat pumps are undertaken. These tasks are conducted on a cost-sharing and/or task-sharing basis by the participating countries. An Annex is in general coordinated by one country which acts as the Operating Agent (manager). Annexes have specific topics and work plans and operate for a specified period, usually several years. The objectives vary from information exchange to the development and implementation of technology. This report presents the results of one Annex.

The Programme is governed by an Executive Committee, which monitors existing projects and identifies new areas where collaborative effort may be beneficial.

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The Heat Pump Centre

A central role within the HPT TCP is played by the Heat Pump Centre (HPC).

Consistent with the overall objective of the HPT TCP, the HPC seeks to accelerate the implementation of heat pump technologies and thereby optimise the use of energy resources for the benefit of the environment. This is achieved by offering a worldwide information service to support all those who can play a part in the implementation of heat pumping technology including researchers, engineers, manufacturers, installers, equipment users, and energy policy makers in utilities, government offices and other organisations. Activities of the HPC include the production of a Magazine with an additional newsletter 3 times per year, the HPT TCP webpage, the organization of workshops, an inquiry service and a promotion programme. The HPC also publishes selected results from other Annexes, and this publication is one result of this activity.

For further information about the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) and for inquiries on heat pump issues in general contact the Heat Pump Centre at the following address:
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Executive Summary

Research on natural refrigerants has been ongoing in Sweden for more than 20 years. Several conclusions have been drawn concerning the use of these refrigerants, and some of the older projects have been summarized in this report, along with the recent studies.

Generally, it is concluded that a low charge of refrigerant should always be an important design goal for any heat pump, independent of the type of refrigerant. Low GWP refrigerants are almost always flammable and low charge then reduces the risks. Synthetic refrigerants with low or high GWP, have environmental concerns, and the charge should be reduced for this reason. It should be clear that low charge can and should be reached without compromising efficiency. This can be reached by carefully selecting the components and the system design.

The new European F-gas regulation (and the international Kigali amendment to the Montreal protocol) will force a phase-out (in Europe) or phase-down (internationally) of HFC refrigerants. Natural refrigerants like hydrocarbons, carbon dioxide, and ammonia can and will take over the largest market share for all types of products, with few exceptions. Synthetic HFO refrigerants may keep some niche markets. These fluids are low-GWP but are flammable and may be restricted as they are, with some exceptions, PFAS substances with possible negative effects on the environment and human health.

Due to climate change, most countries have promised to be climate-neutral by the middle of the century. This means a complete phase-out of fossil fuels. As biofuels will be insufficient as substitutes, the new energy system will be based on renewables and nuclear, all delivering energy in the form of electricity. We will, therefore, head towards an energy system that is more or less totally based on electricity. Electrification of the heating sector will require a transition to heating by heat pumps, directly or indirectly, through district heating. Low GWP natural refrigerants will be required in very large quantities in this transition. The increased demand for cooling will also contribute. Some countries, like Sweden, have already come very far in this transition towards heat pumps, and the change to natural fluids will then happen as heat pumps are being replaced. Other countries will move directly to heat pumps with natural fluids.

The Swedish country report contains the results of a survey where questionnaires were sent to the Swedish refrigeration and heat pump industry asking about the use of refrigerants and the heat pump market now and in the future. Some conclusions are that:

- The hp market demand is expected to be high or very high in the coming three-year period.
- Prices are expected to increase
- Many Swedish customers are now buying their second heat pump (after scrapping the old one)
- The market is still dominated by synthetic refrigerants, with propane having a market share of 2-3%, except in exhaust air heat pumps, where propane's market share is estimated to be 34%.
- HFO-blends are only used for liquid/water heat pumps, and the share is estimated to be 7% of the installations done in 2023.
- High GWP refrigerants (R410A and R40C) are still used to a large extent.

In another study, six heat pump manufacturers and 4 importers were asked to answer a survey concerning their plans for choosing refrigerants for their future products. This study revealed that most respondents were expecting to see flammable refrigerants being used in the future. Training of technicians was considered an obstacle in this transition.

Research projects related to the Annex 54 have continued during 2023. A heat pump prototype using isobutane has been shown to operate well, giving heating capacities up to 12 kW with only 120g of refrigerant. High-temperature heat pumps are another research area, and work was focused on finding suitable oils for such systems. Carbon dioxide systems are now the normal solution for supermarket refrigeration in Sweden. Research focuses on combining these systems with heat recovery for heating buildings and domestic hot water, air conditioning, energy storage etc.

The risks connected to the use of low GWP synthetic fluids and their stability are investigated in another research project. The polymerization of HFOs causing “foaming” has been reported, but the necessary conditions are unknown. Studies of the degradation of the refrigerant and possible change of concentrations in the case of using mixtures have also been initiated. No important findings have been reported yet.

In an effort to decrease the volume of heat exchangers, a study on 3-D printed heat exchangers has been initiated. This technology may have advantages in the future but it is still too expensive for most applications.

2.1 Research work in 2020

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The report starts with a historical review of research on heat pumps with low GWP refrigerants in Sweden. As will be shown, this research goes back to the 1990s and is mainly focused on natural refrigerants as alternatives to synthetic fluids. Only during the last ten years have there been some activities on synthetic low GWP refrigerants.

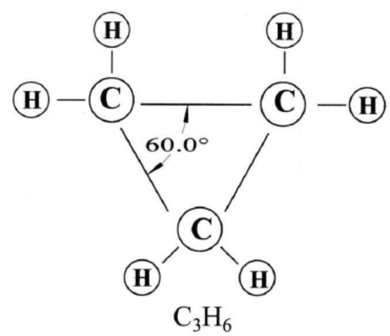

Figure 2-1: Cyclopropane

Sweden is a small country in terms of population, with about 10 million inhabitants, much less than the mega-cities in other parts of the world. As a result, the total number of universities is limited. Most of the university research related to heat pump technology has been performed at KTH Royal Institute of Technology. Another active institution is RISE (Research Institutes of Sweden) and their group in Borås. Representatives for both these organizations are participating in the work for IEA Annex 54.

2.1.1 Introduction to heat pump research in Sweden

Sweden has very good conditions for using heat pumps for heating. First, the climate is cold, with a heating season lasting from Oct 1 to April 30. The potential energy savings by using heat pumps are therefore high. Second, the ratio of the cost of electricity to the cost of fuel is lower than in most countries. There are several reasons for this: Sweden has no fossil fuel resources, but several rivers suitable for hydropower. Also, Sweden is one of the countries in the world with the highest number of nuclear power plants per capita. There has thus never been a shortage of electricity, and the generation has never been based on fossil fuels to a large extent.

During the first and second oil crises in the 1970s, many of the nuclear power plants were set in operation, so while oil prices were going up, the price of electricity was going down. As most single-family houses at the time were heated by oil furnaces, there was a large interest in switching to electric heating. At the time, heat pumps were unknown to the public, and direct or indirect electric heating was installed in many houses. From the government, there was interest to ensure that the electricity was utilized in the best possible way, so research funding was made available already in the first half of the 1980s for developing the heat pump technology, together with other technologies, to decrease the energy use in general. Subsidies were also introduced to support house owners in installing heat pumps, and this also had a positive effect on the industry, with several companies starting production of heat pumps for domestic use. Heat pumps were also introduced in the district heating systems in all major cities where a suitable heat source could be found, typically lake- or sea-water.

During the first years of the 1980s, there was little discussion about the refrigerants used. The effect of CFCs on the ozone layer was proposed by Rowland and Molina in 1974, which resulted in restrictions on the use of CFCs as propellants but had little effect on the refrigeration industry. R12 and R22 were the refrigerants of choice for heat pumps. However, with the Montreal Protocol in 1987, there was a strong focus on new refrigerants with low ODP. At the time, there was no vivid discussion on the contribution of refrigerants to global warming, but there was, amongst researchers and NGOs, a general concern that new synthetic fluids may have unknown environmental effects. For this reason, there was a push for investigating the use of natural refrigerants. Professor Gustav Lorentzen in Trondheim, Norway, was among the first to argue for the use of natural fluids, proposing the use of carbon dioxide as refrigerant.

In a few years, the industry had to switch to low ODP refrigerants, and several research projects related to the new refrigerants were financed by the Swedish Energy Agency, particularly the use of R407C. However, there were also projects related to natural, low-GWP refrigerants.

In 1995, the government agency NUTEK opened a research program called Alternativa Köldmedier (Alternative Refrigerants), financing research on the use of alternatives to the refrigerants used up to then. This was the first in a series of research programs, later financed by the Swedish Energy Agency, each typically lasting three years, with different names but similar focus: Enhancing the performance of heat pumping equipment, while at the same time using refrigerants with low environmental impact. These programs were: *Klimat21, Effsys, Effsys2, Effsys+, Effsys Expand* and *Termo*. The last of these is still running for a couple of years and is the main national funding source for research in the area.

International funding has also been available for research on alternative refrigerants, through the EU research programs. Several such programs that involve Swedish participation are mentioned below.

2.1.2 Previous national projects on low GWP refrigerants

As indicated above, there has been a range of projects related to low GWP refrigerants within national research programs financed by the government through NUTEK and the Swedish Energy Agency. Selections of these projects are mentioned below.

2.1.2.1 Projects within the research program Alternativa Köldmedier (Alternative refrigerants) 1995 - 1997

- **Consequences of changes in composition of mixtures:** The aim of this project was to investigate how changes in composition of non-azeotropic mixtures, due to accumulation of the working fluid in different parts of the system influence the COP and capacity in different applications. It was carried out with an extensive simulation program for vapor compression cycles. It was concluded that the composition of some mixtures which are normally non-flammable, may become flammable due to differences in the solubility of the components in the compressor oil. A result which may still be of interest in a time where new mixtures are designed with the purpose of suggesting fluids which have low GWP but are non-flammable.

- **Evaluation of cyclopropane as a working agent in small refrigeration systems: The stability and health effects of cyclopropane were investigated,** and the performance in a household refrigerator was tested. No negative effects were found, and the refrigerator is still in operation after 25 years in the coffee-room at KTH.

- **Retrofit of refrigeration systems:** In this project, retrofit of non-(H)CFC refrigerants with fluids with less environmental impact was investigated. Experiences from a large number of systems were collected and evaluated regarding performance, chemical stability and life span.

- **Propane in small heat pumps:** The performance of a small heat pump was compared when operated with R22 and with propane. As expected, propane gave lower capacity due to difference in volumetric refrigerating effect. Heatthe pressurer in evaporation and condensation in plate heat exchangers were similar, but pressure drop lower with propane.

- **Propane for heat pump applications using brazed plate heat exchangers:** Heat transfer and pressure drop were measured in plate heat exchangers comparing R22 and propane. The results showed 40-50% lower pressure drop and slightly lower heat transfer. It was concluded that if the heat exchangers were designed for higher pressure drop using propane, the heat transfer performance would be similar. It was also found that theoretical performance was well in line with laboratory tests.

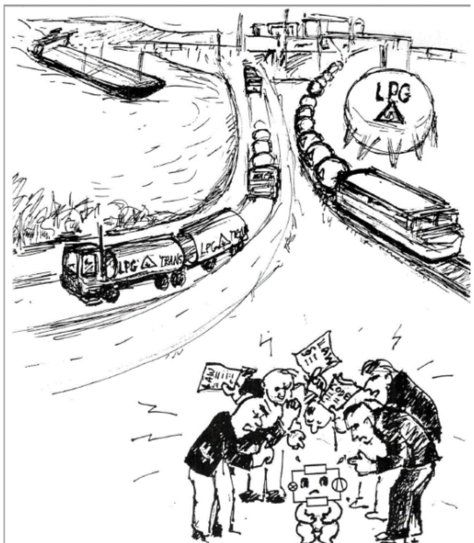

Figure 2-2: Illustration from the report Safety with Flammable Refrigerants

- **Safety with flammable refrigerants**: Risks with HC-refrigerants were discussed. It was concluded that highly flammable refrigerants should not be used for retrofitting, but that new systems with charges up to 5 kg (depending on installation) probably could be designed to be considered safe. Mixtures of fluids with low flammability with non-flammable (quenching) fluids was suggested.

2.1.2.2 Projects within the research program Eff-Sys 2001 – 2004

- Technical possibilities and potential for high temperature refrigerants in public and industrial heat pumps: The project investigated the refrigerant options for heat pumps with condensing temperatures above 80°C. It was concluded that isobutane is a good refrigerant for this application, having good transport properties, low saturation pressure and giving high COP, but with the only drawback that it is highly flammable. Among non-flammable fluids HFC236fa is mentioned, giving lower COP, lower volumetric capacity and having high GWP. Ammonia, CO_2 and water are also mentioned, with the comment that ammonia and water due to low molecular weight give low pressure rise per stage in turbo-compressors.

- CO_2-AC & Bottoming cycle reducing fuel consumption: This project investigated the possibility of using the waste heat from combustion engines as a heat source for bottoming cycles with the intention to decrease energy use of the combustion engine. CO_2 was assumed as the working fluid for this cycle.

2.1.2.3 Projects within the research program Effsys2 2006 – 2010

- CO_2 heat pumps for the Swedish market, Test, and analysis of the SANYO ECO-CUTE heat pump modified for Swedish conditions: CO_2 heat pumps for domestic use have been common in Japan for a long. However, they have not been designed for the Swedish market. In this project, a modified heat pump from Sanyo was tested in the lab. It was concluded that the performance was as expected from the manufacturer's data. It was also concluded that the European test standard EN 14511-1 is not suitable for testing CO_2 heat pumps as the return water temperature to the heat pump is high according to the standard, which is unfavorable for CO_2 heat pumps. Also, lab tests revealed low COP compared to conventional heat pumps for the same reason: The water temperature in the tank acting as the cold sink for the heat pump was relatively high, and stratification of the water in the tank was not achieved. Suggestions for improving the design of the heat pump were given.

- Properties of new low GWP refrigerants: Thermo-physical properties of low GWP refrigerants were obtained and analyzed to compare the performance in comparison to R22 and R134a. The low GWP refrigerants were propane and HFO1234yf. Figures of Merit (FoM) regarding heat transfer for single-phase flow, condensation, and evaporation, as well as for pressure drop, were calculated and tabulated. The results based on fluid properties were compared to experimental results from tests in a small test rig with plate heat exchangers as evaporator and condenser. In the tests, HFO1234yf did not perform as well as expected.

2.1.2.4 Projects within the research program Effsys+ 2010 – 2014

- Refrigerants with low GWP, cost, and energy efficiency optimization of vapor compression systems: As the title tells, this project had two parts, of which the first was related to low GWP refrigerants. This part of the project aimed to provide data, support, and prerequisite information on alternative refrigerants with low GWP at the phasing out of HFC refrigerants for existing and new heating/cooling systems. Within this part, life cycle climate performance was used to compare alternative low GWP refrigerants for heat pumps. The conclusion was that propane was the best option for this application.

- Ammonia as a refrigerant in small refrigeration and heat pump systems: It is well-known in the industry that ammonia is an excellent refrigerant for many applications. It is frequently used in large industrial systems such as breweries and large cold stores. However, it is not used for small systems such as domestic heat pumps. In this project a prototype heat pump was designed, built, and tested, designed for a heating capacity of 8 kW, with a dedicated desuperheater for domestic hot water production at 60°C. It was found to be difficult to find suitable components for the system as copper cannot be used. Hermetic compressors typically have copper windings, and plate heat exchangers are brazed with either copper or nickel. The system was built around an open compressor using fully welded plate heat exchangers as a desuperheater and condenser. The evaporator was a prototype aluminum heat exchanger with flat multichannel tubes. The system could be run with good performance with as little as 120 g of ammonia.

- CO_2 as refrigerant for cooling of milk: Two 5 m^3 milk tanks, normally using R134a for cooling, were redesigned to use CO_2 as refrigerant. Two different solutions were evaluated, one direct and one indirect (using a brine for cooling the tanks). Unfortunately, it was found that the energy used for cooling the milk was almost twice as high with the CO_2 system as with the original R134a system. This was partly because the CO_2 system was not optimized for the current application. A TEWI analysis still indicated that the equivalent CO_2 emissions could be reduced by 35% using a CO_2 system under Swedish conditions.

2.1.2.5 Projects within the research program Effsys Expand 2014 – 2018

- Refrigerants with low global warming potential: The purpose of this project was to provide data, information, and support for the utilization of alternative refrigerants with low GWP for existing and new heating/cooling systems at the phasing out of HFCs. The focus was on thermal properties, requirements for the safety of components and energy efficiency. An important aspect of the project was to supply industry with information about new developments. To this end, articles were presented under a standing heading to the technical journal Kyla & Värme (Cooling & Heating) about 7 times per year.

- Technology for an environmentally friendly ground source heat pump: Within this project, a domestic geothermal heat pump with low environmental impact was developed and tested. The heat pump is designed to use propane as refrigerant and pure water as the secondary fluid in the boreholes. To minimize the charge of propane, a number of special solutions were used: Special plate heat exchangers with low pressing depth were designed and manufactured, and the compressor was a DC scroll compressor normally used for cooling and heating an electric vehicle. This resulted in an extremely compact system with a charge of about 100 g of propane for a capacity of up to 10 kW.

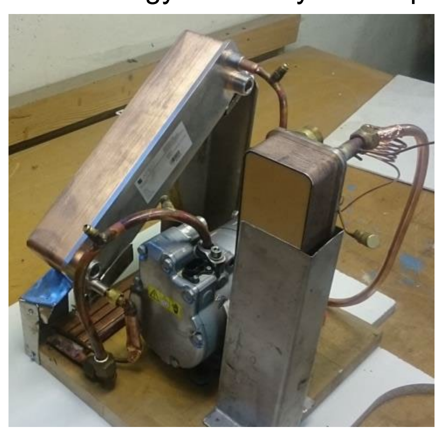

Figure 2-3: Low charge propane heat pump, 2 - 10 kW capacity. Basic components during construction.

The reports from the projects mentioned above can be found through the following website: https://varmtochkallt.se/. Results from many of the projects were also presented at scientific conferences and/or in scientific journal publications. The full references are found in the reports.

2.1.3 Previous international/EU-projects

- SHERHPA, Sustainable Heat and Energy Research for Heat Pump Applications: 3 M€ project running from 2004 to 2007. The Swedish contribution to the project was the design and testing of an ammonia heat pump for domestic applications. This was the initiation of the project mentioned above, which was financed through Effsys+. More information can be found following these links: https://cordis.europa.eu/project/id/500229; https://iifiir.org/en/fridoc/23855;

- GreenHP, Next generation heat pump for retrofitting buildings: 5 M€ project running from 2012 to 2016. A propane heat pump for multifamily buildings was designed and tested. All components of the heat pump were optimized and re-designed to reach good performance and low refrigerant charge. The Swedish contribution was calculation of environmental impact with different refrigerants before arriving at the final choice, design and testing of condenser, calculation of expected charge of the system. More information is found through the following links: https://cordis.europa.eu/project/id/308816; https://cordis.europa.eu/project/id/308816/reporting.

- NXTHPG, Next Generation of Heat Pumps working with Natural fluids: 3.8 M€ project running from 2012 to 2016. The Swedish contribution to the project was testing of two (20 – 40 kW) heat pumps using propane as refrigerant, one air to water and one water to water. The heat pumps were designed for low charge of refrigerant. Both heat pumps are still in operation at KTH. Other groups worked on hydrocarbon heat pumps and CO_2 heat pumps. More information is found here: https://cordis.europa.eu/project/id/307169

- NARECO2, Natural Refrigerant CO_2: The Swedish contribution to this EU-funded project was to support with our experiences from a national perspective. At the time, CO_2 technology for supermarket refrigeration was just introduced and the Nordic countries were first in adapting this technology. Initially the purpose of the project was to compile educational material for students and technicians concerning CO_2 technology. It has however grown to be a 500-page document about CO_2 technology. More information is found in the following links: https://iifiir.org/en/fridoc/3910,www.atmosphere2009.com/files/NaReCO2-handbook-2009.pdf

2.1.4 Ongoing activities in Sweden

2.1.4.1 Overview of ongoing projects

As described above, the Swedish government has supported research related to heat pumps and heat pumping technologies through the Swedish Energy Agency since about 30 years. Since 2018, a new research program has been in operation called Termo. The program supports not only heat pump research, but also other technologies related to heating and cooling of buildings, such as district heating and thermal energy storage of different types. Heat pump research is also supported by other agencies, but to our best knowledge all research projects related to low GWP refrigerants are funded through the Termo-program.

All the major heat pump manufacturers in Sweden (Thermia, IVT/Bosch, NIBE, CTC) are probably also working on new products with low GWP refrigerants, but details of this work are not public.

Below is a description of projects within the research program Termo related to low GWP refrigerants.

2.1.4.2 ECO-Pack, Economizer heat pump with isobutane:

The intention of this project is to investigate the possibility of increasing the energy efficiency and capacity of a multi-apartment building heat pump by adding a second smaller heat pump, using the subcooling of the refrigerant in the larger heat pump as a heat source. As the evaporation temperature of this smaller heat pump will be high, a low-pressure refrigerant needs to be used. The selected refrigerant for the smaller heat pump is isobutane, the same fluid which is already used in almost all refrigerators sold in Europe. To decrease the risks of using a highly flammable refrigerant, measures have been taken to keep the charge of isobutane as low as possible. Two versions of the economizer heat pump have been constructed. The first tested unit has a scroll compressor originally used in the HVAC system of an electric vehicle, allowing a very large capacity range through speed control. It also has specially designed plate heat exchangers with low channel height as evaporator and condenser. The unit has so far been tested as a standalone unit with good results. In the next stage it will be connected to a water-to-water heat pump with propane as refrigerant (see NXTHPG project described above). The second heat pump unit will be a more traditional design with less focus on charge reduction.

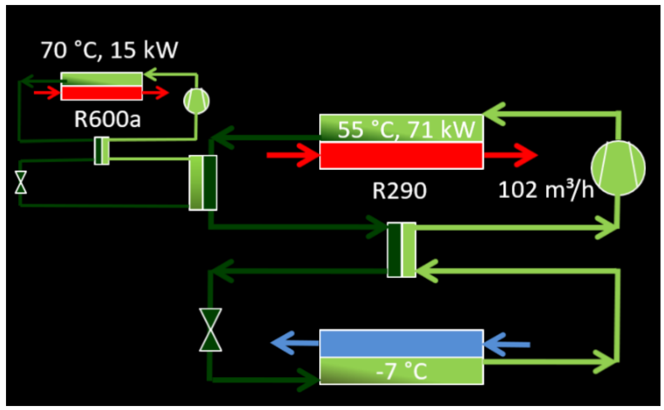

Figure 2-4: Economizer heat pump with isobutane for reaching high temperatures and increasing capacity and efficiency connected to the subcooler of a larger system.

The type of high temperature heat pump developed within the project can easily deliver heating at the temperature levels required for domestic hot water. A second application for this type of high temperature heat pump could be in combination with 4th generation district heating with temperature levels well below 60°C.

Within the project a large effort has been put into developing low charge heat exchangers. This work will continue in a new project specifically focused on heat transfer during evaporation and condensation in flat channels.

2.1.4.3 PROPACK, Air to air propane split system with 150 g of propane:

In previous projects it has been demonstrated that water to water heat pumps for domestic use (up to 10 kW) can be designed to operate with less than 150 g of propane. In this project the intention is to demonstrate that a split AC/HP air/air system can also be designed to function with the same refrigerant charge. The project is led by Klas Andersson Engineering, a small consultancy firm previously working with the demonstration of water-to-water systems and other participants are Electrolux (systems manufacturer), SANHUA (heat exchangers, control), GRÄNGES (aluminum channels), SANDEN (compressors), ebmpapst (fans) AGA/Linde (refrigerants), Lundahl (consulting), and Granryd Consulting and KTH.

2.1.4.4 Low GWP refrigerants for high-temperature heat pumps

Figure 2-5: Schematic of the ideas behind the PROPACK project

High-temperature heat pumps are gaining more and more interest due to the necessity to phase out fossil fuels for heating and the corresponding increase in primary energy supply in the form of electricity from wind and solar. High-temperature heat pumps can be defined as any heat pump delivering heat at or above 70°C. There is no upper boundary for the definition, and heat pumps are sometimes mentioned as a means of converting power to heat in Carnot batteries, where the storage temperature could be several hundred degrees C. The main applications, however, can be expected to be within the temperature range of 70 - 150°C. Applications could be for process heat in the industry, for boosting the temperature from low (or normal) temperature district heating systems, or for thermal energy storage. In the present project, the goal is to demonstrate heat pumps reaching at least 120°C. A test rig is currently under construction at KTH, where different refrigerants can be tested. Both natural fluids and synthetics will be investigated. The system will be a single stage, so the heat source is assumed to be at an elevated level. Experimental work will be done to assess the results of theoretical analyses based on fluid properties.

2.1.4.5 New refrigerants for environmentally friendly heat pump systems:

This project is a continuation of previous projects on low GWP refrigerants. Presently, an evaluation of the comparison between R449A and R404A using artificial neural networks is ongoing. The intention of this study is to investigate the capability of R449A to be used as an alternative to R404A. An article will be published soon.

Another part of the project investigates hydrocarbons as low-GWP alternatives to HFCs. A simulation study was done in which different configurations for the refrigeration cycle, including a single-stage cycle, a cycle with an internal heat exchanger, and a cycle with an economizer when operating with R290, R1270, and R600a, were investigated. An article has been prepared and will be submitted within January.

As a part of this project, a literature review was done concerning the formation of tri-fluoro-acetic acid (TFA) and other decomposition products from synthetic refrigerants. Most sources indicate that the concentrations of TFA will not reach limits, which can be expected to have an environmental impact within the next few decades. However, it is pointed out that TFA is extremely stable and could remain in the environment for several hundred years. TFA is formed during the decomposition of certain HFOs and from some HFCs. As HFOs have short atmospheric lifetimes, the local concentrations close to population centers may be much higher than those in more remote areas.

Recent measurements of halogenated organic acids in the ice cap of Greenland have indicated that the concentration of decomposition products (not only TFA) has increased during the last 15 years. Of course, there is no guarantee that unexpected environmental effects from decomposition products will not appear, as with the effect of the CFCs on the ozone layer.

2.1.4.6 Heat exchangers with low charge:

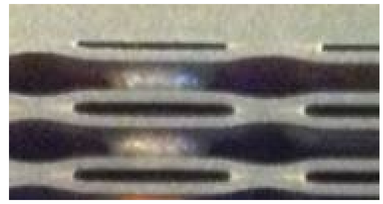

Figure 2-6: Cut view of prototype plate heat exchanger with low

This project is only indirectly related to low GWP refrigerants. As noted in the literature, except for CO_2, there are no low GWP refrigerants (GWP less than about 600) for normal temperature ranges, which are non-flammable. As flammability always constitutes a risk, it is desirable to decrease the charge of flammable refrigerants. Reduction of charge can also be motivated by known or unknown environmental risks related to the release of synthetic refrigerants, e.g. formation of TFA and other decomposition products. Another reason for decreasing the charge is that new refrigerants are complex to manufacture and therefore costly to purchase. There are, thus, several reasons for trying to decrease the charge of refrigerant in heat pump systems. Normally, the largest share of the charge is in the heat exchangers, closely followed by the compressor.

This project focuses on the fundamental problem of determining heat transfer coefficients in boiling and condensation in flat channels. It is hypothesized that in evaporators, most evaporation takes place in a thin film in between the gas bubbles and the heated wall. In flat channels, the areas of these films may be proportionally larger than in standard-size channels, and the heat transfer may therefore be influenced. At higher heat flux or higher vapor fraction, the bubble size may be large enough for the thin film to dry out at the center of the bubble. These effects are expected to be investigated experimentally using high-speed IR thermography and other methods.

2.1.4.7 Refrigerants with low GWP – participation in Annex 54

This project is financing the work within IEA Annex 54, i.e., the collection of information for State-of-the-Art reports/National reports and market surveys to estimate the market for low GWP systems in Sweden. As part of the project, LCCP calculations will be performed on some different designs and refrigerants. Finally, as a special task not yet initiated, the refrigerant will be sampled from commercial systems with refrigerant blends and analyzed with a gas chromatograph to determine if the circulating refrigerant has the composition of the original charge. Reasons for differences could be: 1) that the original concentrations of the components were not according to specifications, 2) that leakage has resulted in a shift in composition, 3) that fluid stored in tanks in the system does not have the same composition as the circulating fluid and 4) that the components have different affinity to the compressor oil. A clear understanding of these phenomena is necessary to correctly evaluate the performance of the system and to make sure that the system is operating safely. A shift in composition may, for example, give the wrong signal concerning the superheat at the outlet of the evaporator. The project will cover both natural and synthetic refrigerants.

2.1.4.8 Trans-critical CO_2 systems for supermarkets

Trans-critical CO_2 systems are becoming the cooling systems of choice in supermarkets in Scandinavia. As refrigeration systems require a large share of the supermarkets' total energy consumption, it is important to design the systems to be as efficient as possible and to utilize the heat released on the hot side of the cycle for useful purposes. This project aims to compare different solutions for designing the refrigeration systems of supermarkets, with the purpose of using the hot side of the cycle for different heating purposes, e.g. for space heating, sanitary hot water production and even selling excess heat to the district heating system. The analysis also includes the possibility of thermal energy storage in boreholes. State-of-the-art solutions using liquid and vapor ejectors, liquid overfeed evaporators and liquid fraction sensors are also included in the analysis. The project is run in close cooperation with some of the most prominent companies delivering systems to the market.

During the spring of 2021, a new CO_2-refrigeration system will be installed to service the climatic chambers of the Department of Energy Technology at KTH. This new system will allow experimentation with different options and different running conditions in a way that is not possible in field tests in actual supermarkets.

2.1.5 Ongoing activities in Sweden

It is quite clear that we will have to accept using flammable refrigerants in the future if we want to get away from high GWP fluids. It has been shown in several scientific publications that there is a clear connection between increasing GWP and decreasing flammability. The simple explanation for this relationship is that fluids that are flammable are reactive and thereby have a short atmospheric lifetime, which in turn means that they will have a short time to contribute to global warming, which is typically measured in a 100-year perspective.

A research need for the future is thus how to mitigate the risks associated with flammable refrigerants. One way, already mentioned several times in this report, is to decrease the charge of refrigerant. However, other methods related to how we design the systems and the safety measures around the systems must also be developed. This could be related to identifying leaks at an early stage and disconnecting any electric devices, which could be potential ignition sources, high-power ventilation of the location of the heat pump, or using inert gas for the volume around the system. Such research is necessary as a basis for new norms and standards concerning flammable refrigerants. Without clear regulations for the design, flammable refrigerants will have difficulty penetrating the market.

Another research area that needs more attention is the effect on the system performance of refrigerant blends. Several such blends are being suggested by the chemical industry. Many of the blends are non-azeotropic and thus have large glides. The systems have to be designed to avoid the disadvantages of the glides, and, if possible, instead benefit from the glides. Using non-azeotropic blends also requires good control of the composition of the refrigerant, both at the first charge and during service or top-up. If the concentrations of the different constituents are different than expected, this may lead to malfunctioning of the system.

Finally, the effect of the release of synthetic low GWP refrigerants requires constant monitoring and research as the decomposition products may have unexpected negative effects on the environment.

2.2 Research work in 2022

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2.2.1 Introduction

This year's national report from Sweden will focus mainly on Task 3 of Annex 54, i.e., Review of design optimization and advancement impacts on LCCP reduction. However, we will also update Task 1, Review of State of the Art Technologies, and Task 2, Case Studies and Design Guidelines.

The research cited and presented is mainly financed by the Swedish government and through the EU. The government finances research in this area through a few different funding agencies:

- **The Swedish Energy Agency** is a government agency with the purpose of leading the transition of the energy system towards sustainable solutions. For many years, the agency has sponsored research related to heat pumps through research programs. The most important program is now called Termo, with the purpose of "contributing to the development of heating and cooling solutions for the future energy system". Another program supporting heat pump research is called E2B2 and is focusing on energy efficient building and living.
- **Formas** is the Swedish research council for sustainable development supporting research related to community building, forestry, and farming.
- **Vinnova** is Sweden's innovation agency, supporting innovation in selected areas through specific calls.
- **SSF** the Swedish Foundation for Strategic Research, supports research in science, technology, and medicine. The focus is to promote the development of strong research environments of high international class.

Heat pump research in Sweden is also funded through the European Union, financing cooperation projects between industry, academia, and institutes. Swedish partners regularly participate in such projects, and notably, the projects SHERHPA, GREEN HP, and NXTHPG were specifically focusing on heat pumps with natural refrigerants.

2.2.2 Review of state-of-the-art technologies

2.2.2.1 Introduction

The Swedish heat pump market is well developed, and more than 60% of all single-family houses are heated by heat pumps. A large share of these is extracting heat from the ground through geothermal wells in the bedrock. More than 500,000 such geothermal heat pumps are installed, in a building stock of about 2 million houses.

The heat pump market is dominated by brands manufactured in Sweden: NIBE, Thermia, CTC, IVT/Bosch. During the last few years, a few foreign brands like Daikin and Mitsubishi have also become common. However, the market for small air-to-air heat pumps is dominated completely by foreign brands. In the following, we will give examples of common designs and common choices of refrigerants, with a focus on units with low-GWP refrigerants.

2.2.2.2 Refrigerants used in heat pumps on the Swedish market.

2.2.2.2.1 Smaller residential units

Air-to-air heat pumps

Theirs is currently no production of air-to-air heat pumps in Sweden in any relevant quantity, however, several manufacturers do import and sell air-to-air heat pumps. Considering the Swedish based manufacturers NIBE, Bosch Thermoteknik, Enertech, Electrolux and Thermia, only Thermia, Electrolux and Bosch officially sell air-to-air heat pumps. As is currently the case for almost all air-to- air heat pumps in Europe, these units all use R32, which still can be considered low-GWP although more stringent regulations may put this in question.

Air-to-water heat pumps

Looking at a European manufacturer's perspective, the air-to-water product group can by far be considered the most important product group for smaller residential units. With approx. 984 thousand units produced in Europe during 2021, eight times as many units compared to brine brine/water-to-water heat pumps; switching to low-GWP for these units is most certainly a priority among manufacturers. Air-to-water heat pumps can be divided into split units and monoblock units, which, in turn, is a factor that can influence the possibility of using certain types and amounts of low-GWP refrigerants. Looking at split-type air-to-water heat pumps, several European manufacturers have followed the same trend as air-to-air heat pumps by using R32, which has the benefit of being a mildly flammable A2L refrigerant although with a substantially higher GWP than A3 refrigerants. Being a split type of unit means that refrigerant normally is passed through the walls of a house to an indoor unit, and as such, a possible leak occurring inside must be considered. Using CO_2 is also an option for split-type air-to-water heat pumps and is commercially available from the manufacturer Mitsubishi Electric, which has a strong presence in the Swedish market, although no manufacturing is done in Sweden.

Considering the major manufacturers, which can be considered Sweden-based, namely NIBE, Bosch Thermoteknik, Enertech, and Thermia, only Thermia offers a split type of air-to-water heat pump using low-GWP refrigerants. Thermias iTec Eco uses 1-2, 2 kg of R32 as refrigerant (Thermia iTec Eco product brochure).

Monoblock type air-to-water uses water (or brine) to transfer heat from the outside unit to an indoor unit. Considering flammable refrigerants, this offers the huge advantage of placing the whole refrigerant circuit outside. This basically means that the unit is not limited regarding refrigerant charge even when using an A3 refrigerant like R290 even though safety related issues still exist like, for example, installer training. It is therefore quite likely that we will see this product group convert to R290, or other A3 refrigerants, in the coming years.

Looking once again at NIBE, Bosch Thermoteknik, Enertech and Thermia, only NIBE has a revealed monoblock type air-to-water heat pump using a low-GWP refrigerant. The S2125-series heat pump is offered in two different sizes, both using 800 g of R290.

Regarding the status of refrigerant use in monoblock air-to-water units one should be careful when making any conclusions in regard to whether or not manufacturers have or have not currently released units with low-GWP refrigerants. Considering the necessity to phase down the use of HFCs combined with the benefits of using A3 refrigerants in monoblock units placed outdoors, it is hard to see any other outcome than that manufacturers will sooner or later release these products with R290 or some other A3 refrigerant. As for split type heat pumps, the future is not as clear, and several pathways are possible including lowered refrigerants charges, use of HFOs and HFO blends. The phase out of the product itself, compared to monoblock technology, is of course also a possible pathway.

Brine/water-to-water heat pumps

Brine-water and water-water heat pumps can, for several reasons, be considered one of the more challenging product groups when developing products with low-GWP refrigerants. This is, of course, mainly due to the fact that most of these products must be constructed in such a way that they can be safely placed indoors at small family houses. In these circumstances, there must be absolutely no risk for leakages, even small, as even a small accident, on top of the actual risk for inhabitants, would constitute a huge negative impact on both the manufacturer of the products as well as the technology itself. In practice, this means that these products currently have limited options for using low-GWP refrigerants, which can be summed up as either using max 4xLFL for A3/A2 refrigerants (152 g for R290, 520 g for R152a) or using HFO-based A2L refrigerants. Even though larger refrigerant charges could be possible with current safety standards it would require manufacturers to set minimum room areas for the products. Considering that these heat pumps are usually installed in small spaces, such an option would only lead to small increases in reasonable refrigerant charge whilst, at the same time, space limits would reduce the attractiveness of the products as well as the practical issue of how the manufacturer can ensure that these limits are followed by installers and end users. Future revisions of the safety standards open up other possibilities by using different technical safety functions and solutions, all with their own different challenges as, for instance, cost increases and installation complexity.

Looking at the Swedish-based manufacturers, as of yet, they have all focused on products using A2L refrigerants as a solution, going over to low-GWP refrigerants for brine-water/water-water heat pumps targeted at small family house installations. The choice is perhaps unsurprising as compared to the option of reducing refrigerant charges to 150 g, it is by far the least technically challenging option.

Refrigerant charges can be held at similar levels as traditional HFCs, which means that the process of dimensioning and construction can remain basically the same and that manufacturers can use the same or similar components.

Looking at the current Swedish market development, we will consider the Swedish-based manufacturers NIBE, Bosch Thermoteknik, Enertech, and Thermia. Other manufacturers do exist but are comparably smaller. One small company (0,5 MSEK turnover) worth mentioning, however, is the company Terrawatt Värmepumpar, which has been producing brine-water/water-water heat pumps since at least 2003, with a small family-house-sized unit containing 600 – 750 g of propane (Terrawatt Villa Komplett, 2015).

Considering the apparent will to phase down, and perhaps phase out, the use of HFC, it is clear that developing products with low-GWP refrigerants is a matter of survival for heat pump manufacturers and that it is only a question of when manufacturers will release low-GWP based products. At the time of writing, however, only two of the mentioned larger Sweden-based manufacturers have released brine-water/water-water heat pumps for the small family house market.

The manufacturer Thermia released its Calibra Eco series in December 2020 (Thermia lanserar Calibra Eco, Press Release, Thermia, 2020-12-11). The Calibra Eco series heat pumps offer three different sizes of inverter-driven heat pumps, 2-8 kW, 3-12 kW, and 4-16 kW, with built-in DHW storage. The heat pump uses R452B as its refrigerant with charge levels of 900g, 1350g, and 1850 g. It can be noted that the maximum charge for R452B according to EN60335-2-40, without any additional measures, is 1854 g. R452B is a mixture of 67% R32, 7% R125, and 26% R1234yf and is marketed as Opteon ™ XL55 by Chemours™ as a low-GWP replacement for R410A. Thermia is transparent with its choice of refrigerant and markets the Calibra Eco series heat pump as "The market's first geothermal heat pump with the future refrigerant R452B".

The manufacturer NIBE revealed its S1256-series brine-water/water-water heat pump at the Swedish building and construction industry fair Nordbygg 25-29 of April 2022. The heat pump is, as of writing, not available for purchase, and as such, publicly available information is scarce. There is, however, a high probability that the S1256 will be inverter driven available in three different sizes similar to the S1255 series sizes of 1.5-6 kW, 3-12 kW, and 4-16 kW. The refrigerant chosen by NIBE for these units is R454B which is a blend of 68,9 % R32 and 31.1 % R1234yf. R454B is marketed as Opteon ™ XL41 by Chemours™ as a low-GWP replacement for R410A.

Exhaust air heat pumps

Exhaust air heat pumps have been an extremely popular choice for newly built family houses in Sweden since the beginning of the 1980s, as they provide a cost-effective solution for well-insulated houses without the need for external units or drilling. Providing mostly DHW in the beginning, these exhaust air heat pumps have become more and more efficient to a level that, for well-insulated houses, is comparable to other types of heat pumps.

R290 has been used in exhaust air heat pumps since at least the 1990's. The combination of low power and that smaller need for a refrigerant charge, as well as the built-in ability for a possible leak to be mechanically ventilated with the exhaust air, is without a doubt a good reason for enabling this.

Considering the Swedish-based manufacturers NIBE, Bosch Thermoteknik, Enertech, Thermia, as well as the exhaust air niched manufacturer ComfortZone, all but Thermia and Enertech currently provide exhaust air heat pumps.

All ComfortZone heat pumps use R32 as refrigerant, which can be considered low-GWP. NIBE, which definitely can be considered as major player when it comes to exhaust air heat pumps has had propane exhaust air heat pumps for decades, however, the well-known inverter-driven exhaust air heat pumps (F750 and F730 series) released in 2013 with the objective of being compliant with the then new and stringent energy requirements for new buildings has been using the HFC R407C (GWP 1,774). At the Swedish building and construction industry fair Nordbygg 25-29 of April 2022, however, NIBE revealed the new exhaust air heat pump S735 using R290 as refrigerants, just as previous NIBE exhaust air heat pumps had used. S735 has a slightly larger capacity and efficiency compared to F750/730 with a modernized control. The charge size is 420 g.

2.2.2.2.2 Larger residential and commercial units

Site built units

When considering low-GWP heat pumps for commercial use, the limiting factors are, in many cases, vastly different from those concerning units for smaller residential units. Whereas the use of, for instance, flammable refrigerants is tightly limited by product standards for residential units, commercial units have more cards to play.

When considering larger place-built units where each component is perhaps chosen by the person and firm the use of type and charge of the refrigerant is up to the customer and is many times a question of cost optimizations. When no longer tied to the “natural incompetents” of a regular house owner, the need to fool-proof safety and costs combined with mass production, several technical solutions can be used to use different amounts and types of low-GWP refrigerants like propane, ammonia, and CO_2. These units can be built while safety is ensured by following standards like EN378 (among others), where options like alarms, detectors, ventilation, special rooms, etc., can increase the use of flammable or toxic refrigerants. However, considering the necessity for increased refrigerant charge with larger capacities, using A3 refrigerant is still complicated even with these technical measures, which means that CO_2 and ammonia are preferred for larger site-built heat pumps. One example of this is heat pump installations provided by Labkyl, a part of Nordic Climate Group, using the so-called DLE-technique. These installations use CO_2 and are offered in capacity ranges from 50 – 1,000 kW (DLE - Delta Lift Energy, Labkyl)

Pre-manufactured units

These units, especially in commercial applications, also have the benefit of being used in settings, which means that safety issues can be handled with external safety solutions, trained staff, adapted placement, etc. Capacity ranges can start around 20 - 30 kW for smaller multifamily houses to several hundreds of kW. Many of these units, however, can be combined to serve even larger heating capacities. Among the previously mentioned manufacturers of smaller heat pumps, NIBE, Bosch Thermoteknik, Enertech, and Thermia all offer larger heat pumps. However, none of these units currently use low- GWP refrigerants.

When looking however to the more professional market a handful of manufacturers, with Swedish manufacturing, appear. One example of this is the company Enrad, which, spurred off the lack of refrigeration and heat pumps using natural refrigerants, started to develop and manufacture heat pumps and chillers using R290. Today Enrad offers heat pumps with capacity of 80 kW- 135 kW using a maximum of 4.3 kg R290 (Enrad modulserie, Enrad). These modular units can be connected in parallel and therefore offer even higher capacities.

One other smaller heat pump manufacturer is the company Qvantum Energi AB. Qvantum is specialized in larger units in the range of 32 kW- 165 kW. Although most of their units use traditional HFC, their Qvantum RSe unit uses R-513A (GWP 573) as refrigerant which can be classified as low-GWP. As a side note, it can be mentioned that Qvantum has big ambitions for growth with the aim of specializing in heat pumps for 5th generation district heating and cooling (5GDHC). They have acquired a new factory in Åstorp, Sweden, where they claim they will be able to produce 50,000 heat pumps annually beginning 2023 (Svensk tillverkare: Värmepumpar för VVSForum)

ComfortZone, which specializes in exhaust air heat pumps, offers two models of exhaust air heat pumps for larger residential buildings using R32. Relatively modest in capacity, the RXF120 and RXF180 offer capacities of around 12 – 18 kW. However, by linking several units together higher capacities can be achieved. Four linked units can, as an example, serve a 3,000 square meter residential building with heating.

The very small manufacturer Terrawatt can be mentioned as they have been using propane for many years and do offer brine/water-to-water heat pumps with capacities up to 100 kW. With a turnover of 0.5 MSEK the number of produced large heat pumps cannot be substantial.

2.2.3 Case studies and design guidelines for optimization of components and systems

2.2.3.1 Introduction

In this section we will report on a few interesting case studies with heat pumps with low-GWP refrigerants. We will also discuss some design guidelines for optimum performance of heat pump systems.

2.2.3.2 Case studies

Case 1: EBox a propane heat pump for multifamily buildings

EBox is a system for supplying factory-built complete heating systems consisting of one or several geothermal heat pumps using propane as a refrigerant. The systems are built at the factory into standard 20-foot containers and just need a connection to the electricity grid, the geothermal loop, and the building's heating system. Typically, the container would be placed inside a small building for a better visual appearance (Megawattsolutions, 2022).

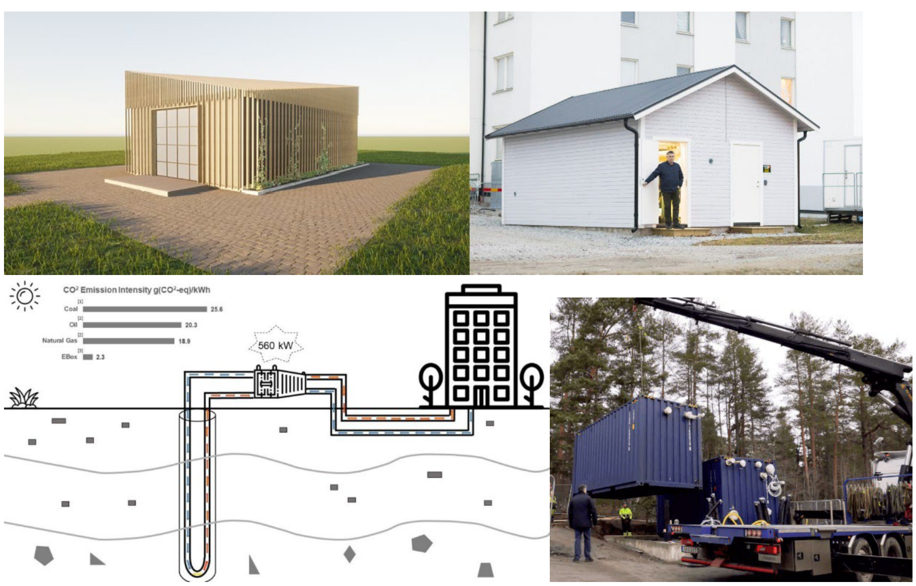


Figure 2-7: a), b) Picture of EBox container hidden in a small building, c) Principle of EBox. d) Delivery of factory-built units. (Source: https://megawattsolutions.se)

The capacity of the systems can be scaled to the needs by selecting the number of heat pump modules in each container (between 4 and 8 in a standard container) as well as the number of containers (see Figure 2-7).

As the system is factory-built and placed outside of the building itself, no additional safety precautions are necessary in the building or at the site, despite using propane as refrigerant. The system can also be used for free cooling, using the boreholes as a cold source and, at the same time, recharging the boreholes for the coming heating season. If necessary, the system can also be used for active cooling by reversing the heat pump cycle. Several such systems have been installed. In the city of Södertälje, just south of Stockholm, two installations have been made. The largest of these is in a residential block called Sjöboden and has a heating capacity of 864 kW. The heated floor area is close to 27,000 square meters and the heat pumps deliver heat both for domestic hot water and heating.

There are several advantages to this type of installation:

- Factory-built systems allow:
  - standardized designs that decrease cost
  - high quality as systems can be tested before delivery
  - high safety levels of the systems even with flammable refrigerants
- Flexible capacity of the systems
- Simple installation, as no refurbishment of the building is necessary, except for the connection of the heating lines
- Short installation time

Case 2: CO_2-system for heating and cooling

At a large block of stores in the city of Uppsala, a complex system for heating, cooling, and energy storage has been installed, using CO_2 as the refrigerant. The prime purpose of the system is to supply cooling for the display cases in the large supermarket in the block. The hot side of this system is then used for heating not only the supermarket but also the neighbouring building. When the heating capacity from the cabinet cooling is not sufficient, additional low-temperature heat from a borehole field is used as a heat source on the cold side. When there is no need for heating, the heat from the hot side of the cooling system can be dumped into the outdoor air or fed into the same ground source loop through a subcooler. By subcooling, the capacity and efficiency of the cooling of the cabinets is increased. The supermarket is large, with about 11,000 m^2 floor area, while the neighbouring building which is heated by the system has an area of 5,000 m^2. The system can be seen as a cooling system with heat recovery, or as a geothermal heat pump with cooling. Figure 2-8 shows a sketch of the system. As shown, there are two de-superheaters connected to the heating system. A gas cooler is provided in case there is no heating needed. The sub-cooler is connected to the geothermal loop. This loop has 20 boreholes, each 225 m long.

The system can also deliver air conditioning to the buildings. This can be done passively by using the cold brine from the boreholes or actively by running the compressor marked PC in the diagram.

CO_2 is becoming the standard choice of refrigerant for refrigeration systems in supermarkets in northern Europe. It is quite common to utilize the hot side of these systems for heating. The system described above, however, is one of few which are connected also to a borehole field and allows delivering higher heating capacities than would be possible using only the cooling cabinets and display cases as the heat source. A theoretical comparison of the energy- and cost-efficiency of the described system compared to other solutions is underway. Preliminary results indicate that the solution is economically feasible under the local technical and economic conditions. More about this, and other similar systems, can be found in the M.Sc. thesis of Almebäck and Magnius (2022).

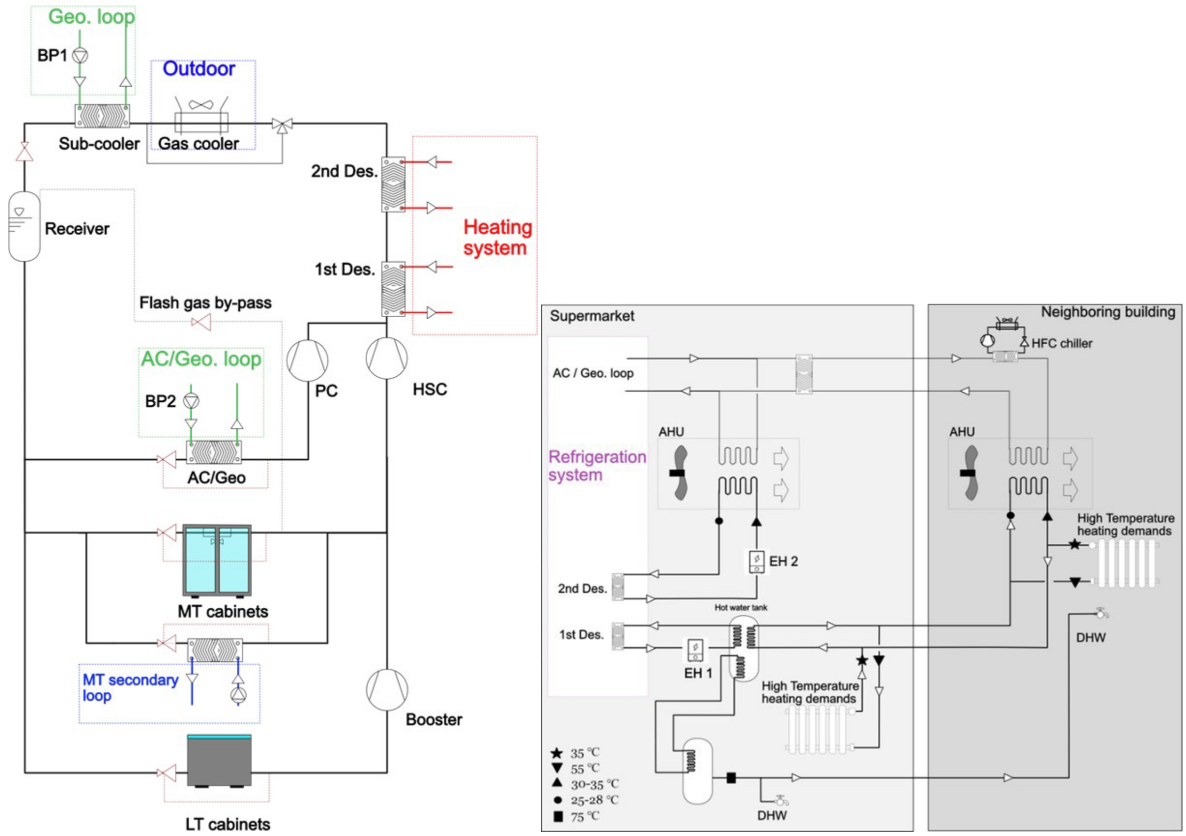


Figure 2-8: Drawing of CO_2-system for heating and cooling, connected to supermarket cabinets, to the heating system and to geothermal loops. (Used with permission of Sotirios Thanasoulas, KTH)

Case 3: R290 Heat pumps and chillers that produce both process cooling and heating

The heat pump manufacturer Enrad AB was a Decarbindustry winner in 2022. Their project involved the world's most environmentally friendly furniture factory called the Plus factory building, which was a great example of the use of heat pumps in an industrial process; it combines energy-efficient Passivhaus strategies with a streamlined, robot-assisted production line, which according to Vestre, reduces its energy consumption by 90 per cent compared to a conventional factory.

Its energy and heating demands are partly met with the help of 900 rooftop solar panels, 17 geothermal wells and heat pumps hidden behind the walls to capture excess heat from the process of drying the components and convert it into heat that is then fed back into the production line and used to warm the building. The Heat pumps and chillers use R290 refrigerant that produces both process cooling and heating for the production line, also comfort cooling and heat to the building by using waste heat, generating 55 per cent lower emissions from energy and materials than a comparable building. Details of the heating and cooling capacities of the system are provided in the schematics see Figure 2-9.

The company claims this also makes the project "Paris-proof", bringing it in line with global targets set out in the Paris Agreement to halve emissions by 2030. The project is reportedly on track to become the first industrial building in the Nordic countries to reach the highest rating in the

BREEAM environmental certification scheme, which is only awarded to the top one per cent of projects.

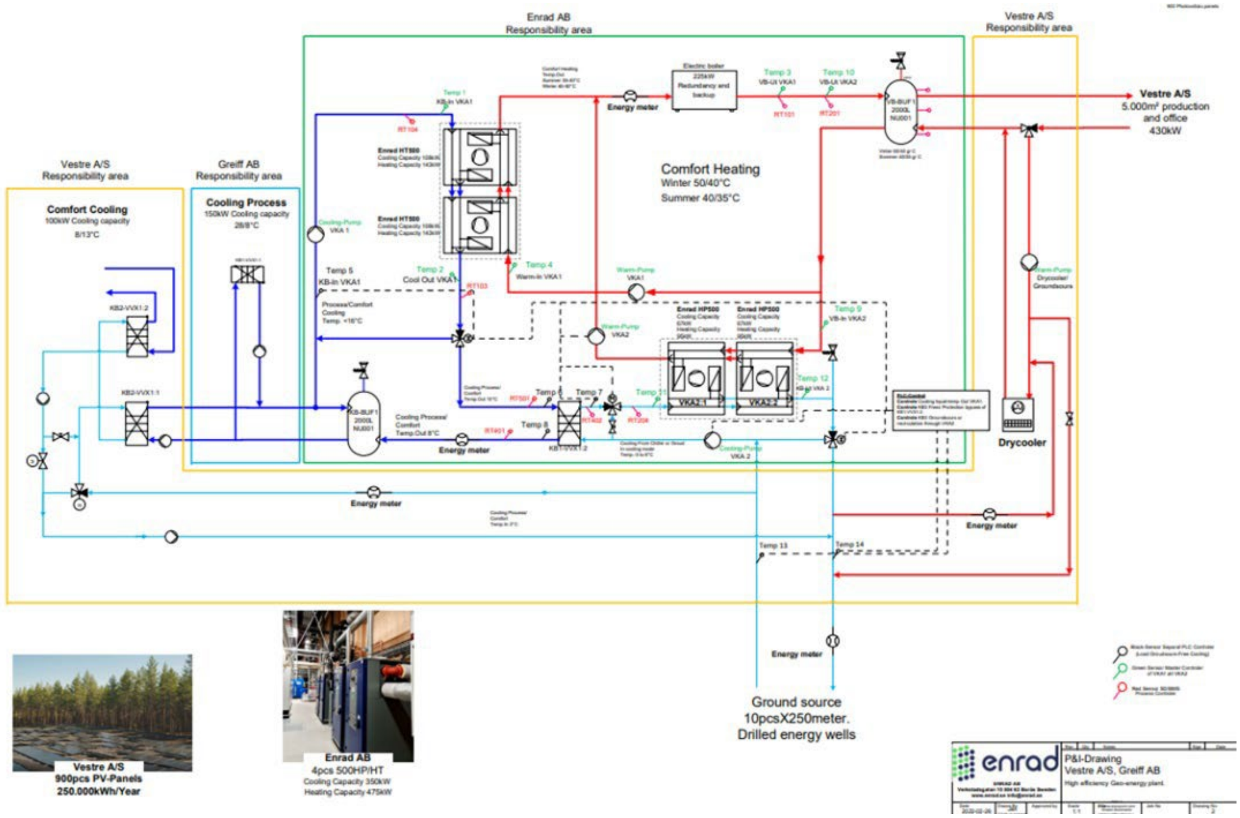


Figure 2-9: Drawing of R290-system for heating and cooling (Used with permission of Enrad AB)

Design guidelines for optimization of components and systems.

During the design of a heat pump, there are several choices to be made related to the size and design of the components as well as the size of the heat pump in relation to the energy demand of the building. The optimum is, in a first approximation, independent of the refrigerant used in the system, but in some cases, the optimum may shift somewhat.

Many of the choices can be considered as searching for an economic optimum rather than technical. For example, increasing the size of evaporators and condensers will decrease the temperature differences and thereby increase the COP of the system, which in turn will decrease the running costs. On the other hand, larger heat exchangers are more costly and, therefore, increase the first cost. An optimum size can only be found by considering factors such as the cost of electricity, the marginal cost of the heat exchanger surface, interest rate, number of running hours per year, and the effect of increased surface area on the COP of the system. Likewise, the capacity of the heat pump in relation to the needs of the building is an economic optimum: A larger heat pump may cover the heating requirements on the coldest day of the year but will be more costly than a smaller heat pump. First costs will be higher, but the running costs will be lower. On the other hand, the volume flow/velocity of the heat source and heat sink fluids can be considered as a technical optimum: Higher flow rates require higher pumping power, which tends to decrease the COP of the system but will also decrease temperature differences which tend to increase the

COP. Similarly, the choice of the number of parallel sections in an evaporator or condenser is a technical optimization. Assuming a constant total tube length, the cost of the unit is more or less the same, but with fewer parallel channels, the pressure drops, and the heat transfer coefficients will be higher than with a larger number of parallel tubes. A certain number of parallel channels will give the highest evaporation temperature (lowest condensing temperature) and, thereby, the highest COP.

The above examples are generally independent of whether the refrigerant has a high GWP or a low GWP. However, there are other factors that should be considered specifically when designing for low GWP refrigerants. Except for carbon dioxide (and water, which is very rarely used as refrigerant), low GWP refrigerants are flammable. For this reason, standards stipulate the maximum allowable charge of refrigerant if the system is to be placed inside a building. This maximum charge is related to the floor area and/or volume of the room where the heat pump is located. To reduce risks related to flammability, or in general related to the release of refrigerant, it is advisable to try to decrease the charge of refrigerant per unit heating capacity. Apart from reducing risks, a small charge could also allow the installation of a higher-capacity heat pump in a given machine room.

To reduce the charge, it is important to understand the following:

- A large share of the charge is in the heat exchangers.
- Depending on the type of heat exchanger, the amount of refrigerant in the condenser may be larger or smaller than in the evaporator.
- Standard hermetic or compressors have an oil sump with considerable amounts of oil. With oils miscible with the refrigerant, the amount of refrigerant in the oil may be substantial.
- The density of the liquid phase is much higher than that of the vapor phase.
- A small receiver may be necessary if the heat pump is operating under varying conditions, but the system should be designed so that the receiver is empty of liquid at the most extreme conditions (typically high heat source temperatures). Alternatively, the system should be designed to allow some liquid to rise into the condenser under certain running conditions.
- It is often the case that the highest COP is reached with several degrees of subcooling of the refrigerant (if no receiver is used). However, the optimum is usually quite flat, so the effect on COP of decreasing the subcooling by reducing the charge is quite small.

Based on the above, the following recommendations can be given for designing systems with flammable refrigerants, if the systems are to be located inside where the charge may be limited due to flammability-related risks:

- To reduce the charge in the heat exchangers, flat channels, e.g., extruded aluminum multichannel tubes or plate heat exchangers with small pressing depth, should be used. Such tubes /channels have much less volume per heat transfer area than circular tubes.
- It is important to note that smaller channels do not necessarily mean a higher pressure drop. For small channels the tube length should be decreased, and the number of parallel channels increased.
- Special care should be taken when designing the headers, as these may otherwise contain more refrigerant than tubes.

- Charge reduction should not be achieved by decreasing the heat transfer areas in the evaporator and condenser as this would lead to lower COP of the system. Instead, use heat exchangers with flat channels.
- All lines should be as short as possible, but in particular, it is important to have a short liquid line. The length of the suction line and the high-pressure line is less crucial.
- The charge of oil in the compressor should be selected based on the volume of the system. Compressor suppliers usually assume that the compressor will be part of a large-volume system and, therefore, add extra oil to the sump as part of the oil will be distributed to the rest of the system during operation. If the system volume is kept low, the necessary charge of oil is usually lower than the original charge from the factory.

2.2.4 Review of design optimization and advancement impacts on LCCP reduction

2.2.4.1 Introduction

In this section, we will describe some ongoing research related to the use of low-GWP refrigerants. Three topics will be covered in some detail: First, some projects related to charge reduction will be presented. Charge reduction can be seen as a means to increase safety, but it may also be considered as a means to decrease the environmental impact and in particular, the LCCP.

Second, a detailed analysis of different oils and their properties will be presented. The study is quite general, but at the end, recommendations for selection of oil for low-GWP refrigerants will be presented.

Third, we will present some ongoing research on high temperature heat pumps with low-GWP refrigerants.

But we will start with a short update on the legislation related to the use of F-gases in Europe, including Sweden,

2.2.4.2 Legislation in Europe, including Sweden

Ever since the implementation of the so-called F-gas directive (EU/517/2014) back in 2015 it has been clear that the intention of the legislator is to gradually phase out the use of high-GWP refrigerants on the European market. The F-gas directive has used a number of tools in order to limit both the amount of F-gases on the market as well as the subsequent release of them to the atmosphere. These have included limiting the amount of substances put on the market through quota systems as well as different direct bans and requirements of leakage checks and training of installers. One can, of course, have different opinions about the effectiveness of these legislative tools. However, the general aim has always been clear. The phase down and eventually phase out of high-GWP substances. It should, therefore, be clear to any manufacturer that, at least in the long run, high-GWP refrigerants will not be an option, whether it will be because of availability and cost issues or outright ban on products. Although it is currently not clear at the moment exactly how it will affect the heat pumps and refrigerants there is also an ongoing process considering including all so-called PFAS substances in the REACH regulation. This could limit, or even make it practically impossible, to use so-called HFO as replacement for the HFC refrigerants. Whatever the outcome of this process, there is an inherent financial risk when it comes to designing products for use with HFO or HFO/HFC blends.

The F-gas directive is currently under revision and the outcome is as of time of writing unclear. One important proposal in the commission proposal 2022/0099 (COD), published on the 5 of April 2022, which can affect how fast the market changes to low-GWP refrigerants for small residential heat pumps is the proposed ban on use of refrigerants with GWP above 150 for brine/water-to-water heat pumps and monoblock air-to-water heat pumps by 2025. This will mean a rapid phase-out of the use of pure HFC for these products in favor of HFO, HFC/HFO-blends, and natural refrigerants and has most certainly increased the stress levels among manufacturers considering that many current products, especially brine/water-to-water heat pumps, will not be possible to sell. Regarding air-to-water monoblock units, the use of flammable natural refrigerants, the switch is relatively easy as the need to limit refrigerant charge is not as important as the unit's places inside. For brine/water-to-water heat pumps the possible ban is more alarming as there is not an easily interchangeable HFO or HFO/HFC- blend available under GWP 150, as well as the drawbacks mentioned above. Regarding the use of flammable natural refrigerants, this is a possible option, and there are commercially available units (Ecoforest). However, it will mean a completely new redesign of the product.

Considering split-type air-to-water and air-to-air heat pumps, the proposal for a GWP threshold is set at 150 in the commission proposal for units with capacities below 12 kW by 2027. This requirement is also challenging for the manufacturers as limiting refrigerant charges for split units is perhaps even more challenging considering the need for refrigerant piping. However, the newly released standard IEC60335-2-40:2022 opens up the possibility of use of even A3 refrigerants in these systems if safety issues can be addressed. As an example, the manufacturer Midea released a R290 air-to-air heat pump on the European market in 2021 (Midea launches R290 split, IIFIIR) with a capacity of 3.53 kW and a refrigerant charge (5 m piping) of 380 g (KlimaWorld).

It must be mentioned that the F-gas revision is not processing without the heat pump and refrigerant business standing idly by. There is a high chance that these specific bans will be relaxed when the legislation is finally decided upon. Prolonging of the time frame as well as increased threshold to allow HFO/HFC-blend is a possibility.

2.2.4.3 Research on charge reduction

2.2.4.3.1 EcoPac

EcoPac is a research project with the goal of investigating the feasibility of using a small heat pump to boost the performance of a larger heat pump by using the subcooling of the liquid after the condenser of the larger heat pump as a heat source for the smaller heat pump. The cycle has been analyzed theoretically (Granryd et al. 2022) and also tested in a prototype propane heat pump at the laboratory of KTH, Royal Institute of Technology using propane, R290, in the main circuit (Forsgren, 2020, Kronström 2021, Ölén et al. 2022). A drawing of the installation is shown in Figure 2-10.

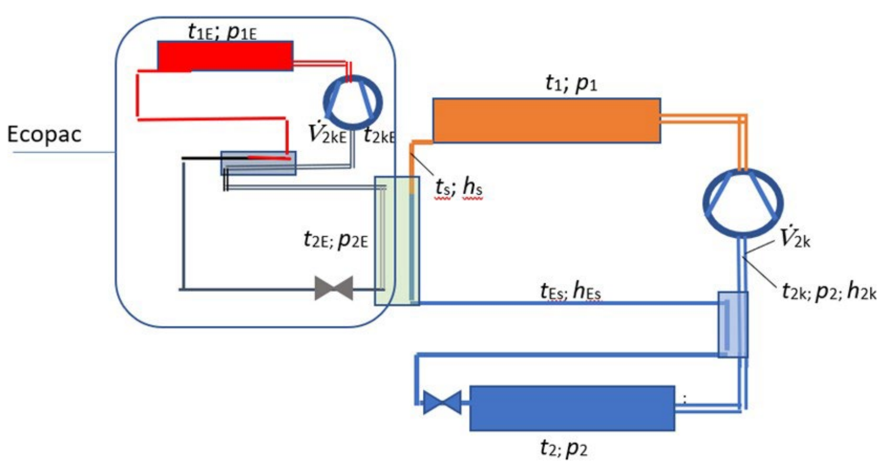


Figure 2-10: Drawing of the EcoPac heat pump unit connected to a larger heat pump. (From Granryd et al. 2022)

As the evaporation temperature of the EcoPac unit is higher than for the larger heat pump, isobutane R600a, was selected as the refrigerant. This would allow reaching high condensing temperatures without excessive pressure levels. The investigation showed, both theoretically and experimentally, that a combined system of this type can reach higher COPs and higher capacities compared to the larger heat pump alone. The total performance depends on the selected condensing temperature levels in the two cycles. One possible solution would be to use the large heat pump for heating of the building, and for pre-heating of domestic hot water, while the EcoPac unit could be used to increase the temperature of the preheated domestic hot water to the 60°C required in order to avoid legionella. In this way, the condensing temperature in the main loop could be decreased, which will of course increase the COP of this system.

During tests, the EcoPac unit was operated with the evaporation temperature in the range 15 - 35°C, while the condensing temperature was in the range 50 - 70°C. Two different versions of the EcoPac unit were built. In the first, standard components (semi-hermetic compressor, standard plate heat exchangers) were used. In the second version, measures were taken to reduce the charge of refrigerant to a minimum. To this end, prototype plate heat exchangers with small pressing depths were used, as well as a DC compressor of the type normally used in AC systems of electric cars, SHS33 from Sanden. This type of compressor has a very small internal volume and requires very small amounts of oil. It also has a very broad speed range. In the tests, the compressor was run at 2000, 4000, and 6000 rpm, giving a heating capacity at 25°C evaporation temperature from about 3 to 9 kW. However, the allowable speed of the compressor is up to 8000 rpm according to the manufacturer, thus allowing even higher capacities. More importantly, it was demonstrated that this system could be run with a charge of about 120 g of isobutane only. A special challenge to reach this low charge was the design of the internal heat exchanger. As no commercial heat exchanger with a low enough charge was found, a prototype was designed, see

Figure **2-11**, based on multichannel aluminum tubes. The EcoPac project continues, and new

designs of the internal heat exchanger have been developed and will be tested in a coming prototype system.

Figure 2-11: Scroll compressor, Sanden SHS33, used in the EcoPac system (from https://sanden.wpengine.com/).

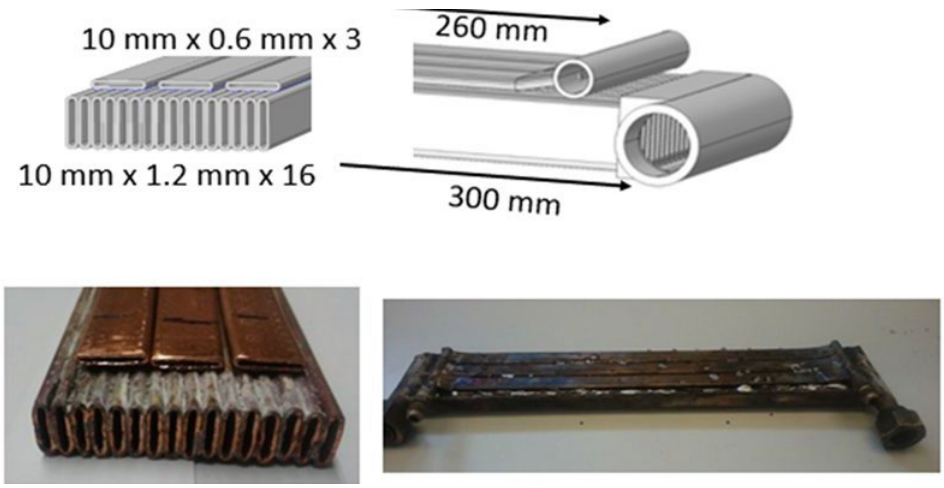


Figure 2-12: Drawing and photo of prototype internal heat exchanger of the EcoPac unit. (From Ölén, V., et al. 2022)

2.2.4.3.2 ProPac

In the ProPac project, a prototype split AC system was designed using propane as a refrigerant. The goal of the project was to use less than 150 g propane for a system giving a capacity of 3,5 kW. The system is described in some detail in a report to the Swedish Energy Agency (Andersson K., 2022). Some of the solutions are similar to those in the EcoPac project.

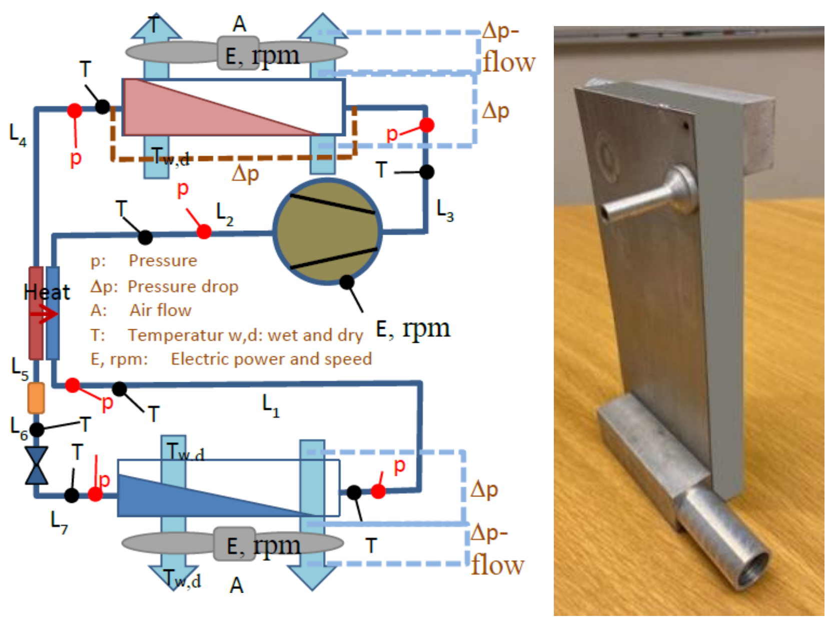


Figure 2-13: a) Sketch of the ProPac system. b) internal heat exchanger (From Andersson, K., 2022)

To reach the low charge, several uncommon design options were used for the components: The condenser was made from extruded flat microchannel tubes with small rectangular channels and fins on the outside. This was perhaps the most standard component of the system. However, special measures were taken to reduce the accumulation of liquid refrigerant in the headers. In spite of this, the charge in the headers was estimated to be almost three times the charge in the tubes (35.6 g as compared to 13.6 g). For the evaporator, different versions of microchannel heat exchangers were tested. It was concluded that even distribution of refrigerant to the 1,000 parallel channels in the evaporator is a key factor in achieving low charge while maintaining low-pressure drop and high heat transfer. Tests were done with horizontal flow as well as with vertical upflow and vertical downflow. In the end, a solution with vertical downflow was found to give the best results, with low charge and reasonable performance. In order to avoid liquid pools in the top header, part of the tubes inserted into the headers were removed, see Figure 2-15. The baffle plate originally installed in the evaporator was also removed. Finally, spray nozzles were used to distribute the refrigerant evenly among the top headers.

For the internal heat exchanger, a new type was designed together with the participating industrial partners, see Figure 2-13 b.

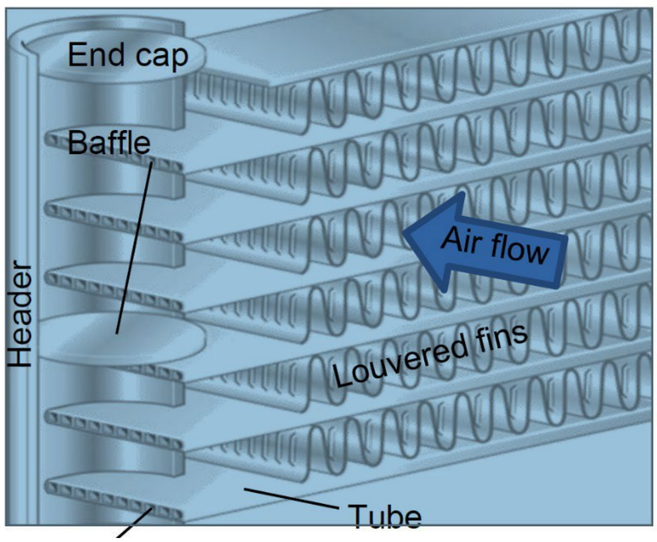


Figure 2-14: Design of condenser (From Andersson, K., 2022)

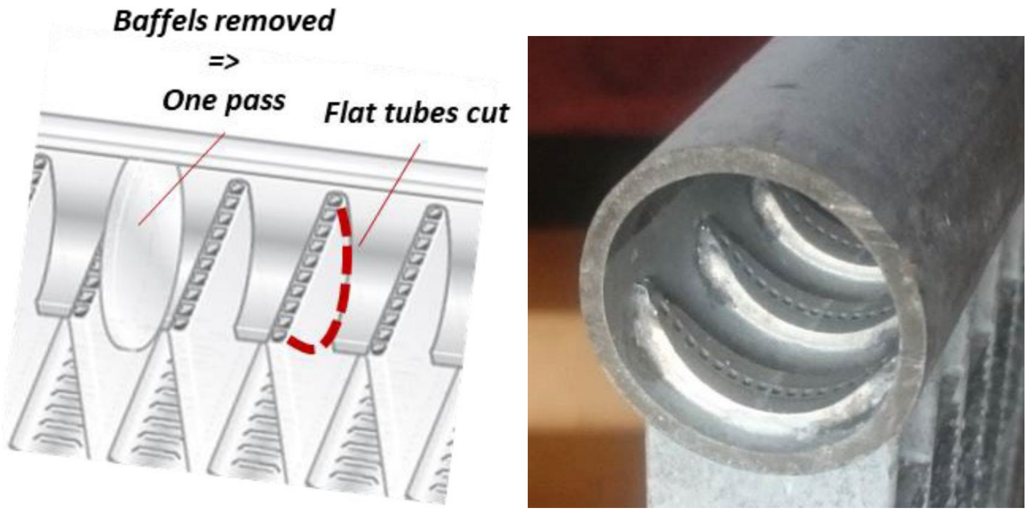


Figure 2-15: Original top header and modified header (From Andersson, K., 2022)

The system used a DC compressor developed for AC systems in electric vehicles and originally designed for R1234yf (Sanden SHS33, same as for the EcoPac project). According to the report, this compressor has a speed range from 800 to 8,500 rpm. The expansion device was a standard electronic valve from Sanhua.

The project goal was reached, with a final charge of 147 g of propane when the connecting lines between the indoor and outdoor units were 6 m long. It should be noted that the expansion device is located close to the condenser (in the outdoor unit) and that the connecting line to the indoor unit is a two-phase line. The charge in this two-phase line (6 m) was about 10 g, and in the suction line, the charge was 7 – 8 g. The COP (cooling), including the fans, was 3,5.

2.2.4.4 Selection of oil

2.2.4.4.1 <u>Lubricant/oil refrigerant mixtures.</u>

In this report, the relationship between lubricant/oil as a substance and refrigerants should be cleared and defined. The term Lubricant-Refrigerant Mixture (LRM) states the effect of the refrigerant on the lubricant in the compressor sump only, while Refrigerant-Oil Mixture (ROM) investigates the effect of the dissolved oil within a circulating refrigerant on the refrigeration system and its effect on the refrigerant thermophysical properties.

Lubricants, in general, have many roles to play in many machines that have moving parts. It acts as a coolant, transferring the heat from bearings and mechanism elements to a heat sink, which, in turn, dissipates this heat to the biggest sink reservoir, the environment. It also helps reduce noise generated by moving parts. Compressors, for example, used in HVAC and refrigeration systems require a lubricant to separate the gas on the discharge side from the gas on the suction side. Hermetic compressors, in which the electrical motor is always exposed to the lubricant, require lubricant with electrical insulating properties, too. As the lubricant is charged only once in a hermetic system, the chemical stability required of the lubricant is the most important characteristic in the presence of refrigerants. Lubricants used in refrigeration compressors are selected based on their viscosity and miscibility/solubility with refrigerants primarily. Figure 2-16 shows the relationship between the total efficiency of a compressor and the lubricant's viscosity. It is clear from the figure that low viscosity values lead to poor lubricant film and low volumetric efficiency, whereas high viscosity values lead to good film thickness but high frictional losses or low mechanical efficiency within the compressor.

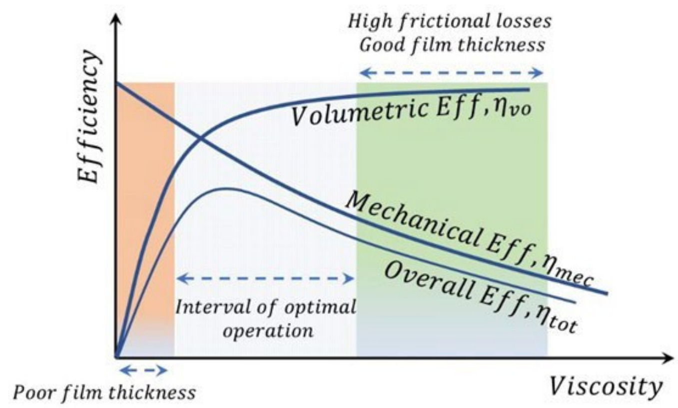


Figure 2-16. Relationship between compressor's efficiency and viscosity.

Other relevant properties are lubricity, chemical and thermal stability, low hygroscopicity, low-temperature properties (low pour point, low wax), thermal conductivity, electrical resistivity, non--deposit forming, and environmentally acceptable. Generally, the higher the lubricant's viscosity, the better the sealing and noise reduction capabilities.

The behavior of the oil in the refrigeration systems and its physical interaction with refrigerants are of great importance to the design of the whole system parts. The viscosity of the ROM solution, for example, is crucial for the flow of the mixture within the components of the refrigeration system and their lifetime. Oil can be soluble in refrigerant, and the refrigerant gas phase carries some oil to different parts of the refrigeration cycle. It flows through the condenser, expansion valve or control devices, and evaporator, returns to the compressor in a reasonable time, and must have adequate fluidity at low temperatures. It must be free from suspended matter or components such as wax that might clog equipment in the refrigeration system or deposit it on the evaporator or condenser surfaces and adversely affect the heat transfer coefficient and the heat transfer process.

2.2.4.4.2 Lubricant/Oil Types

Lubricants/oils that are frequently used with low Global Warning Potential (low-GWP) refrigerants, whether they are synthetic or natural are mineral oils (MOs), alkyl-benzenes (ABs); Poly-alpha-olefins (PAOs), poly-alkylene-glycols (PAGs); poly-vinyl-ethers (PVEs); and poly-ol-esters (POEs).

Rudnick (Rudnick 2013) put together an excellent introduction to all types of synthetic lubricants, including polyglycols and esters.

Mineral Oils (MOs)

Mineral oils, also called petroleum oils, are the lubricant of choice for the vast majority of refrigerants before 1990 and they remain the least expensive oils in the market up to date. They are used with CFCs, and some of the HCFCs as well as HCs. They are not miscible with most HFC or HFO refrigerants due to their high polarity, which was the primary reason for the major shift to oxygenated synthetic lubricants. HFC refrigerants are forbidden to use mineral oil because of their poor miscibility in lower temperature conditions in general. The primary limiting property for this oil is its “pour point” which can vary greatly depending on the exact hydrocarbon mix of the lubricant. Inadequate pour point properties make mineral oils unacceptable for applications requiring very low evaporator temperatures (less than –40°C); this problem led to the first use of synthetic lubricants in refrigeration systems (Rudnick 2013). Mineral oils’ properties vary depending on their molecular weight and the process by which they are refined. They are supplied in a liquid form and made from carbon and hydrogen molecules only. They are light yellow in color and slightly hygroscopic. MOs are blends of linear and branched alkanes, cyclic alkanes (naphthene), and aromatic compounds.

Alkyl-benzenes (ABs)

The chemical structure of ABs of unsaturated double-bond carbon ring results in a stable molecule. Made to replace MOs. The viscosity of ABs is controlled by the size of the hydrocarbon chain, the degree of branching of the chains, and the number of chains attached to the aromatic ring. ABs have improved solubility and miscibility in HCFCs (Takigawa 2002), better oxidation stability with respect to MOs, and lower Pour Point, which makes them suitable for very low-temperature applications (less than –50°C) using CFC and HCFC refrigerants than MOs.

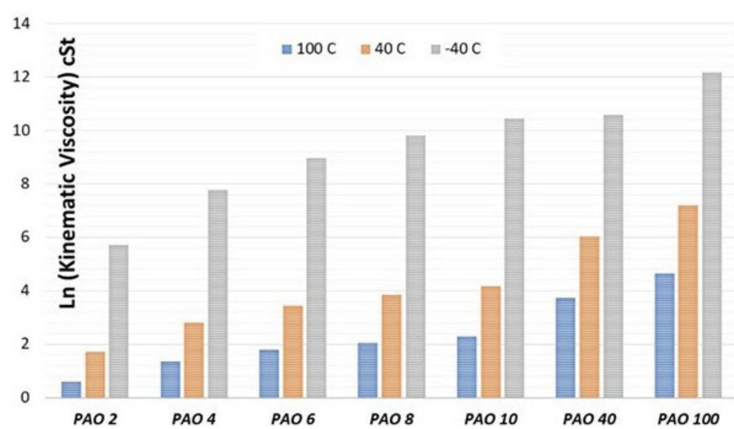


Figure 2-17: KV values of PAOs for different test temperatures.

Poly-alpha-olefins (PAOs)

PAOs are derived by controlled oligomerization of linear alpha-olefins derived from ethylene, and they are 100% synthetic hydrocarbons. PAOs are classified according to their approximate kinematic viscosity (KV) at 40C. Kinematic viscosity is controlled by the degree of polymerization of the olefin and by the amount of rearrangement of the reactants and products to produce branched isomers. The commercial name of PAO comes with a number, the higher the number, the higher the viscosity of the lubricant/oil. For example, PAO-10 has 9.87 cSt, 64.50 cSt, and

34600 cSt values based on ASTM D 445 test at 100°C, 40°C, and -40°C, respectively, while PAO-40 has 41 cSt, 410 cSt, 40000 cSt, for the same temperatures.

Figure 2-17 indicates the increasing trend of kinematic viscosity values of PAOs. PAOs have improved properties compared to mineral oils with higher viscosity index (VI), decreasing the pour point to the range of -75°C suitable for cold weather, improving thermal stability, and increasing the flash point to the range of 290°C. Table 2-1 compares POA-4 synthetic oil with several mineral oils: 100 Neutral (100N), 100 Neutral with low pour point (100NLP), and hydrotreated high viscosity index (VHVI). It shows the improved properties of PAOs over several mineral lubricants. PAOs have also been used in ammonia and fluorocarbon refrigeration compressors because of their low pour points.

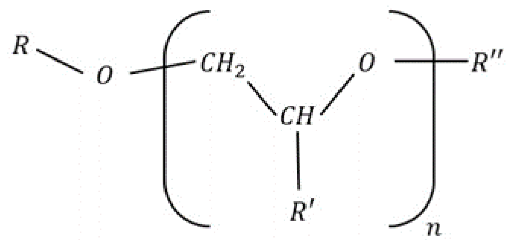
Table 2-1: PAOs compared to Mineral Oils (Rudnick 2013).

Oil/Properties	PAO-4	100N	100NLP	VHVI
KV @ 100°C	3.84	3.81	4.02	3.75
KV @ 40°C	16.7	18.6	20.1	16.2
KV @ -40°C	2390	Solid	Solid	Solid
Viscosity Index	124	89	94	121
Pour Point	-72	-15	-15	-27
Flash Point	213	200	197	206

Poly-alkylene-glycols (PAGs)

PAGs derive from the controlled polymerization of propylene oxide (PO), or a mixture of PO and ethylene oxide (EO). The viscosity of PAGs is determined by the average molecular weight of the polymer chain. The properties can be easily tailored to control viscosity while also optimizing compatibility (miscibility/solubility) with a particular refrigerant as seen in Figure 2-18. Polymerization is usually initiated either with alcohol or by water. Initiation by mono-alcohol results in a “monol” (mono-end-capped); initiation by water or a di-alcohol results in a “diol” (uncapped). Another type is the double-end-capped PAG, a mono-capped PAG that is further reacted with alkylating agents.

Double-end-capped PAGs are common lubricants in automotive air-conditioning systems using R-134a, because of their benefits in boundary lubrication and refrigerant miscibility. PAGs have a very high viscosity index, excellent lubricity, low pour point, and good compatibility with most elastomers. However, they are susceptible to depolymerization in the presence of trace amounts of strong acids, bases, and free radicals. Developed for R134a, color light blue, viscosity has three types 46 cSt, 100 cSt, 150 cSt, highly hygroscopic, mixed well with HFC, could not be used in hermetic compressors for its low electrical resistivity.



$R' = H, alkyl\ or\ both$

$Mono\ end\ Capped, R = alkyl\ and\ R'' = H$

$Double\ end\ Capped, R + R'' = alkyl$

$Uncapped, R = R'' = H$

Figure 2-18: PAGs chemical formulation

Poly-vinyl-ethers (PVEs)

PVEs belong to a special class of PAOs where the side chains contain oxygen atoms and make it more miscible with HFC refrigerants than traditional PAOs. Similar characteristic to MOs. The chemical structure's side chain has characteristics of PAG oils with good solubility and no hydrolysis.

Esters or poly-ol-esters (POEs)

The POEs have four general structures, neo-pentyl glycol (NPG), tri-methylol-propane (TMP), penta- erythritol (PE), and Di-penta-erythritol (DiPE) (NIH 2022). They are manufactured by the reaction of a carboxylic acid with an alcohol as per Figure 2-19.

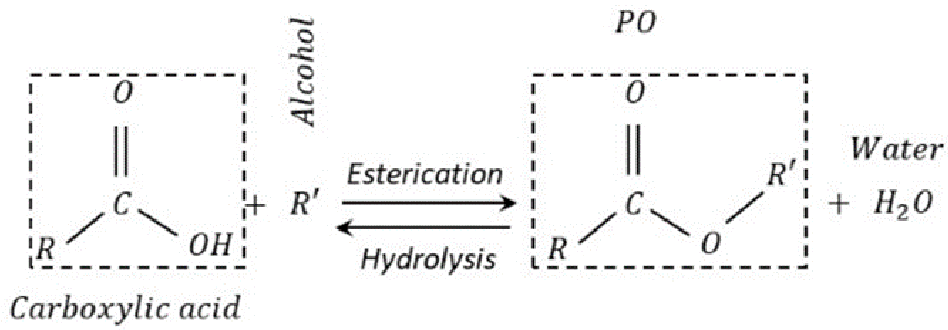


Figure 2-19: POEs chemical process.

POEs are used in HFC refrigerants where their cohesive properties (miscibility and solubility) can be designed to optimize their compatibility with a given working fluid. Within the temperature and pressure operating envelope, the oil-refrigerant mixture should remain as a single phase. Too much compatibility between the two could lead to undesirable viscosity dilution of the lubricant by the refrigerant, leading to poor lubrication of the moving parts within the compressor. The objective is to be sufficiently miscible to ensure proper oil return to the compressor while limiting solubility to avoid excessive viscosity reduction in the compressor. In general, the miscibility decreases with increasing molecular weight and linear acid content because more refrigerant molecules must organize around each ester molecule to achieve solubility. POEs lose miscibility with HFC when linear carbon chain lengths exceed six carbons, so using branched-chain acids will improve the miscibility. They are universal oil, clear color, not used for R134a, slightly hygroscopic, polar mix better with HFCs, biodegradable, and miscible with MOs.

Pentaerythritol esters (PECs), which are linear, branched, and/or cyclic-chained esters, are the main precursors and components of POE lubricants, and it is an excellent solvent for impurities such as moisture, compressor wax, and mineral oils (Herbe and Lundqvist 1997). It also prevents clogging in the fluid line components such as filters, vanes, and valves. Many experimental studies regarding PECs with R-1234yf and R-134a, as well as other fluorinated refrigerants including R-1234ze(E), R-32, R- 152a, R-143a and R-125 have been recently published (Sun et al., 2017, Sun et al., 2020, Wahlström and Vamling 1999, Wahlström and Vamling 2000, and Wang et al., 2016).

The Polyethylene Glycol Dimethyl Ethers (PEGDMEs) family has also been promoted as alternative lubricants to be an excellent solvent for HFC and HFO. There is numerous vapor-liquid equilibrium (VLE) data available for mixtures of PEGDMEs with R-134a (Chaudhari et al., 2008, Coronas et al., 2002, López et al., 2009, López et al., 2004, Marchi et al., 2006, Tseregounis and Riley, 1994, and Zehioua et al., 2010), while data for R-1234yf is not enough (Fang et al., 2018).

2.2.4.4.3 Lubricant/Oil Classifications

According to DIN 51503 Part 1, refrigeration oils are classified alphabetically into the following groups:

Class KAA

Refrigeration oils are immiscible with ammonia–mineral oils and/or synthetic oils based on poly-alpha-olefin (PAO), alkyl-benzene (AB), or hydrogenated mineral oils. Highly refined, naphthenic refrigeration oils are mostly used as KAA oils. Hydrogenated refrigeration oils and PAOs are becoming increasingly popular in practice.

Class KAB

Refrigeration oils miscible with ammonia–poly-alkylene-glycol (PAG). The PAG lubricants normally used should not exceed a maximum water content of 350 ppm (fresh oil).

Class KB

Refrigeration oils for carbon dioxide (CO_2) – synthetic polyol esters (POE), poly-alkylene-glycols (PAG) or poly-alpha-olefins (PAO). POE oils generally have good CO_2 miscibility. PAG oils are significantly less miscible with CO_2 (larger miscibility gap with CO_2). Synthetic refrigeration oils based on poly-alpha-olefins are referred to as refrigeration oils that are immiscible with CO_2.

Class KC

Refrigeration oils for fully and partially halogenated chlorofluorocarbons (CFC, HCFC) – usually mineral oils and alkyl benzenes (ester oils are also possible in individual cases) Mostly highly refined, naphthenic mineral oils and specially treated alkyl benzenes (alkylates) are used. The water content of the KC oils (fresh oils) should be less than 30 ppm. If the water content is higher, it can be assumed that undesirable reactions with the refrigerant will occur, leading to the decomposition of the oil- refrigerant mixture.

Class KD

Refrigeration oils for fully and partially fluorinated Fluorocarbons (FC, HFC) – polyol ester oils (POE) or poly-alkylene-glycols (PAG) The refrigeration machine oils described in group KD are polar products with highly hygroscopic properties. A maximum permissible water content of

100ppm in fresh oil applies to polyol esters (POE). Poly-alkylene-glycols are preferably used in A/C systems. They should not exceed a maximum water content of 350 ppm (fresh oil).

Class KE

Refrigeration oils for hydrocarbons (e.g., propane, isobutane) – mineral oils or synthetic oils based on alkylbenzenes, PAO, POE or PAG Depending on the substance group, the maximum permissible water content is 30ppm for mineral oils/ Alkylbenzenes, 50ppm for PAO, 100ppm for POE, and 350 ppm for PAG (fresh oil parameters).

2.2.4.4.4 Mixtures' Properties.

To understand the core relationship between oil and refrigerant in any refrigeration or heat pump system, we should though focus and differentiate between the relationship of ORMs, which represent the effect of the presence of the oil within the refrigerant charge in the refrigeration cycle components, and RLMs, which shows the effect of refrigerant within lubricant in the compressor sump on the other hand. ORMs have many important properties for which boiling point of the mixture, heat load for vaporization and condensation, densities of the liquid and gas phases, blockage, and materials compatibility are the most crucial properties that we should investigate, whereas RLMs have different properties for which viscosity, solubility, viscosity index (VI), lubricity, and hydrolytic stability are the most important properties that we need to understand to prevent the compressor from failure.

Several factors should be investigated when using ORMs in a refrigeration system. The amount of the oil dissolved should also be known where increasing the mass fraction of the oil within the refrigerant can affect the thermos-physical properties of the mixture, such as mixture viscosity, vapor pressure, vapor density, and the performance of the system. The compatibility issues between the oil and the refrigerant's chemical structure are also important where the new low GWP refrigerants use only certain types of oils.

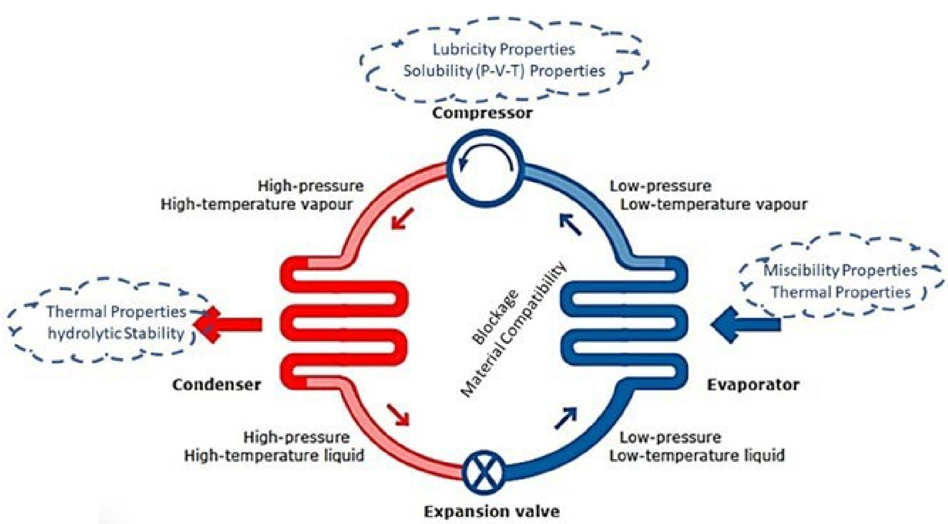


Figure 2-20: Oil/Refrigerant issues in heat pump equipment.

Figure 2-20 illustrates the ORM factors that should be addressed and solved. In the condenser, hydrolytic stability as well as thermal properties should be examined. In the evaporator, miscibility, as well as thermal properties, should be understood carefully where the boiling point could be altered if the amount of the oil varies, oil holdup within the evaporator and the condenser can decrease the heat transfer coefficient, reduce the design cooling capacity, and decrease the coefficient of performance of the system. A study was done on the distribution of R-134a with different pressure ratios, compressor strokes, and refrigerant charges, indicating that the condenser holds the maximum charge (Chen 2019).

Figure 2-21 shows the refrigerant mass ratio holdup within different parts of one specific system. It proves that in this case 70% of the total charge is within the condenser, 10% within the evaporator, 15% within the liquid line, and 5% within other components. The distribution trend can be seen with different strokes and pressure ratios.

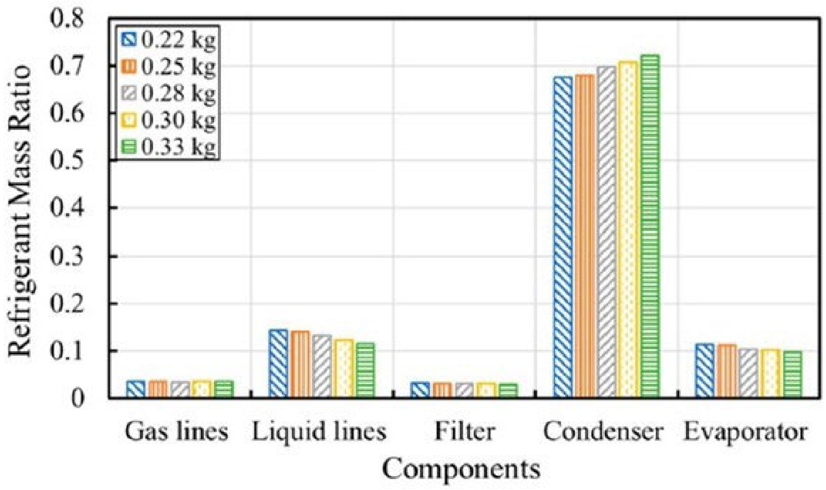


Figure 2-21: Refrigerant R-134a distribution in a refrigeration system.

2.2.4.4.5 Refrigerant-lubricant mixture (RLM) Properties

The effect of the vapor or liquid refrigerant within the lubrication fluid in the compressor sump will be highlighted and studied. Lubricant properties vary with its chemical family. These properties are viscosity, solubility, viscosity index (VI), lubricity, pour point, thermal and hydrolytic properties, and oxidation stabilities.

Viscosity

Dynamic viscosity selection depends upon the minimum film thickness required to avoid wear surfaces, maximum allowable viscous drag, minimum sealing, minimum flow rate, and minimum variation within the operating envelope (temperature, pressure, and refrigerant floodback). The viscosity of the lubricant in the presence of any refrigerant may decrease as much as an order of magnitude since the refrigerant viscosity is typically 2 to 3 orders of magnitude smaller than that of oil (A. M. Yokozeki 1994). Figure 2-22 shows the variation of viscosity for POE with R-32, R-134a, R-410A, and R-22 at 40C. The curvature of the lines depends on the molecular weight of the refrigerant. The lighter values, the faster the decrease in the viscosity (Toumas and Jonsson 1999).

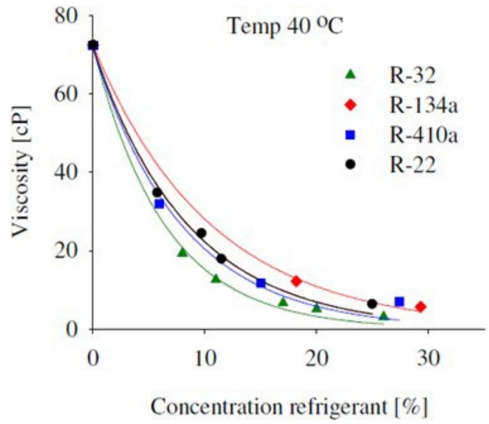


Figure 2-22: Viscosity vs. concentration.

The viscosity of RLMs can be given analytically by relating the viscosity of the lubricant and the refrigerant as in equation (1) (Schroeder 1986). The density of the mixture also can be given in equation (2):

$$ln\,\vartheta_{RLM} = \left(1-\gamma_{ref}\right) * ln\,\vartheta_{lubricant} + \gamma_{ref} * ln\,\vartheta_{ref} \qquad (1)$$

$$\rho_{RLM} = \frac{1}{1-k} * \frac{\rho_{lubricant}}{1+\gamma_{ref}\left(\frac{\rho_{lubricant}}{\rho_{ref}}-1\right)} \qquad (2)$$

where γ_{ref} is a refrigerant mass fraction and (k) can be computed by interpolation from the data published by Jaeger (Jaeger 1972).

Figure 2-23 shows how the viscosity and density of the sample lubricants vary with temperature. The sample of three lubricants (SL-22, SL-68, SL-220) have different viscosities and are used in an open drive reciprocating compressor, Coldex-Frigor type. The figure shows that the viscosity and the density decrease with the increase in the temperature of the mixture for all lubricants. It also indicated that SL-220 sample with the highest viscosity demonstrates maximum power consumption (Afsharia, et al. 2017). Viscosity can also be obtained from PVxT chart. The parameters used to construct the chart are pressure, temperature, solubility, and kinematic viscosity. The combined PVxT data that includes isobaric curves is called Daniel Plot. The Plot of any mixture is derived from refrigerant solubility data (x), density data (ρ), and viscosity data versus temperatures (μ). To get the dynamic viscosity of a specific RLM:

- pressure and temperature are selected first.
- pressure versus temperature is used to measure solubility parameter.
- solubility versus temperature is used to measure kinematic viscosity (KV or $\vartheta\vartheta$ = $\mu\mu/\rho\rho$, cSt) and density parameters.

- dynamic viscosity ($\mu\mu$, cP) is obtained by the product of KV and density.

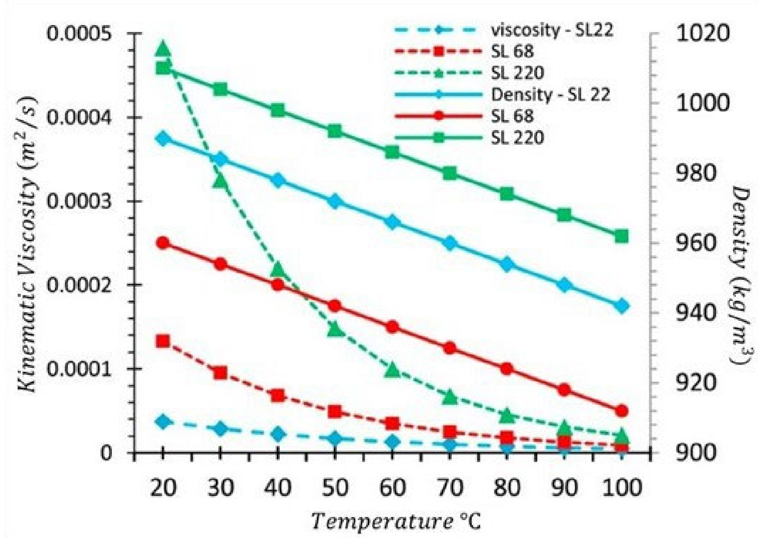


Figure 2-23: Viscosity and density of RLM with respect to temperature.

Figure 2-24 gives the kinematic viscosity parameter from Daniel Chart for Fuchs' SEZ 32 lubricants with R-1234yf a low GWP refrigerant (FUCHS 2014). In Daniel Chart, constant pressure (isobaric) curves are incorporated to show the effect of pressure on the viscosity. The pressure curves are typically 10, 15, 25, and 35 bar.

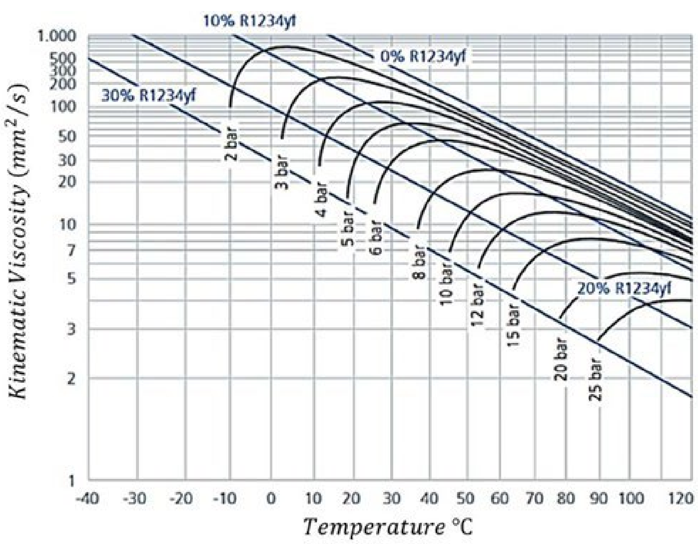


Figure 2-24: Daniel Chart for R-1234yf and Fuchs' SEZ 32 lubricant mixtures.

Figure 2-25 and Figure 2-26 give the relationship between kinematic viscosity (cSt), pressure (MPa), and temperature (°C) for refrigerants R-1234yf and R-1234ze(E) as refrigerants with International ISO VG 32 lubricant (Morais 2020). ISO VG stands for "International Standards Organization Viscosity Grade" and is reported in numbers ranging from 2 all the way up to 1500. The ISO VG 32 gives the flow speed of this lubricant in meter per second under the effect of gravity forces inside a Capillary U-Tube Viscometer Test controlled at (40°C or 104°F). In industry practice, the liquid composition often only ranges from pure lubricant 100% down to about 70% as seen in the figures. To find the viscosity range of the lubricant containing the refrigerant in ($mmmm$2/$ssssss$=1 centistokes or cSt) and the concentration of the refrigerant within the lubricant, we need to specify the range of the operating temperatures (horizontal axis) plus the superheated temperatures values and the corresponding evaporation pressures in (MPa). The blue curved lines toward the horizontal axis are the pressure lines of the mixture. It is obvious from the figure that the increase in the compressor suction temperature and the evaporation pressure for a certain concentration will ultimately lead to the decrease in the lubricant viscosity of the compressor.

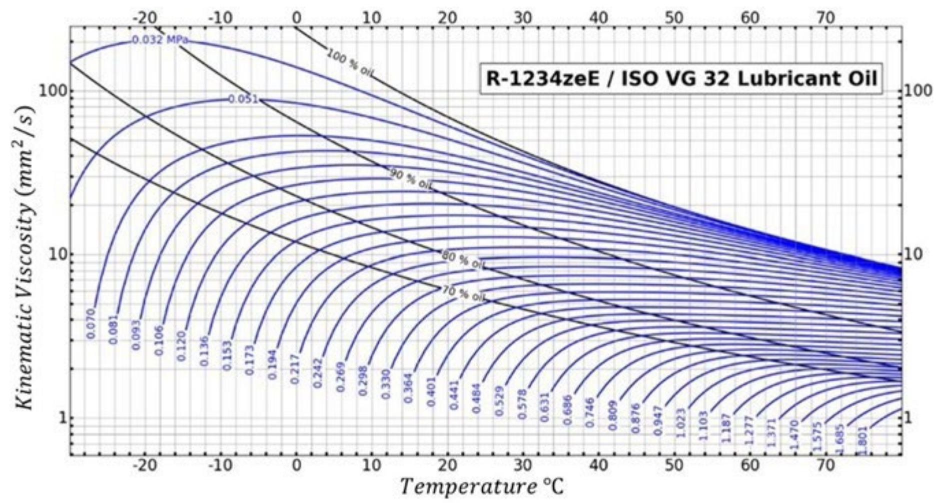


Figure 2-25: Daniel Chart for R-1234ze (E) with ISO VG 32 lubricant.

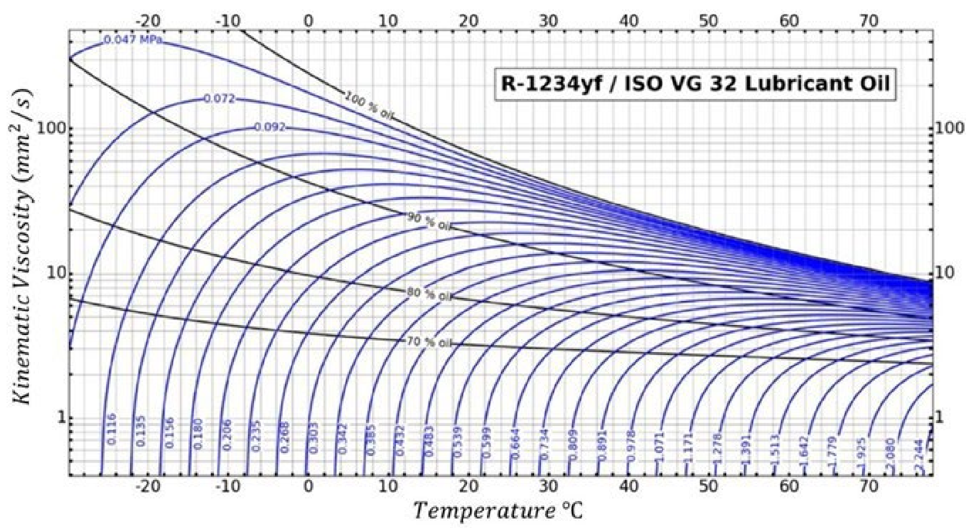


Figure 2-26: Daniel Chart for R-1234yf with ISO VG 32 lubricant.

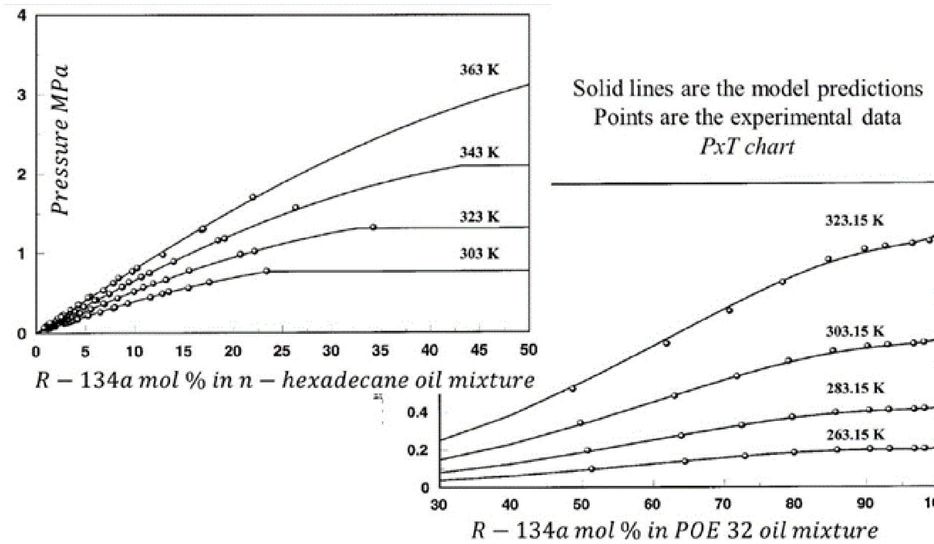


Figure 2-27: SRK analytical model results for an RLM solution.

An analytical model was developed to predict the PVxT parameters for any nonconventional mixing rules between RLM using cubic equations of state (EOS), namely the modified Soave-Redlich-Kwong (SRK) equation. The matching between the model and experimental vapor-liquid-liquid equilibrium (VLLE) or vapor-liquid equilibrium (VLE) data for several mixtures was validated. Figure 2-27 shows the pressure in MPa versus refrigerant molar concentration in a specific lubricant. The solid lines are representing the model fitting the experimental vapor-liquid-liquid equilibrium (VLLE) data for certain RLM.

Another analytical model used to define the correlation between RLM concentration and pressure is the soft-SAFT equation of state (Albà, Llovell and Vega 2021). They have obtained the PVxT chart for R-134a in POE lubricant, PEC5 type lubricant (Wahlström, et al. 1999), and R-1234yf in POE lubricant, TrEGDME type lubricant (Fang, et al. 2018) at different temperatures as seen in Figure 2-28. Both models need to be verified for new low GWP refrigerants.

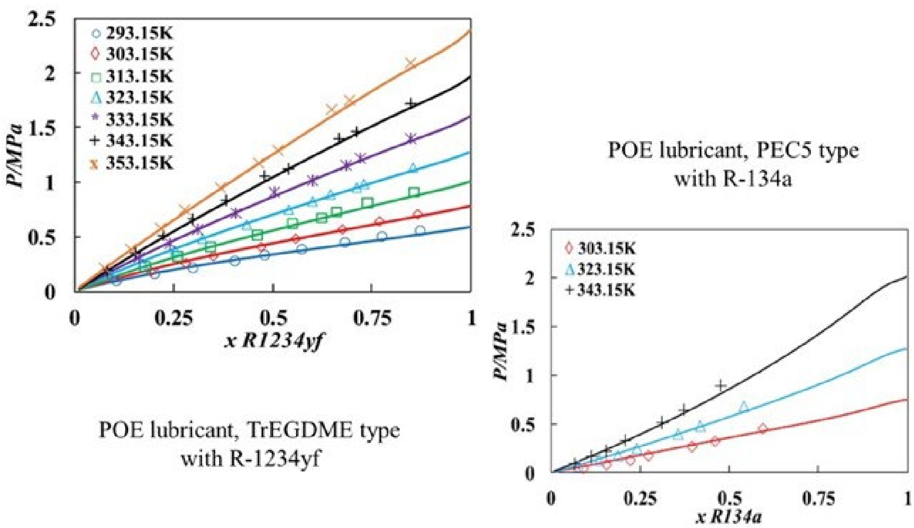


Figure 2-28: Soft-SAFT analytical model results for an oil refrigerant mixture.

Viscosity Index (VI)

The viscosity index is used as a method of measuring a fluid's change of viscosity in relation to temperature. This index is used to characterize the viscosity-temperature behavior of lubricants. The higher the VI, the smaller the relative change in viscosity with temperature, and the lower the VI, the more the viscosity is affected by changes in temperature. VI improvers, also known as viscosity modifiers, are additives that increase the viscosity of the fluid throughout its useful temperature range. These modifiers are polymeric molecules that are sensitive to temperature. At low temperatures, the molecule chain contracts and does not impact the fluid viscosity, and at high temperatures, the chain relaxes and an increase in viscosity occurs.

Hydrolytic Stability

Lubricant's ability to resist chemical decomposition in the presence of water is known as the lubricant's hydrolytic stability (DIN 51777). Some lubricants are, by nature, hygroscopic fluids, which absorb vapor water from the air. Polyol esters (POEs) and phosphate esters fluid are an example of such lubricants. The existence of water in the POE lubricant can change the structure of the lubricant when metal catalysis exists. Over time, these impurities break down the chemical structure of the lubricant and produce carboxylic acids. By measuring the acid number (AN), we can determine the by-product of oxidation or lubricant depletion rate. Acids can erode the copper piping and heat exchanger plates and can lead to component damage. The interaction between HFO refrigerants, pure or blend, with PVEs has been studied. Figure 2-29 indicates that the AN value increases in the presence of metal catalysis and when the water content increases. Figure 2-30 shows the moisture absorption (hygroscopicity) of different lubricants. Nonpolar lubricants such as MOs and PAOs, which normally have water contents of less than 30 ppm, show no significant increase in water content. POEs which are described as polar, hygroscopic lubricants, display a marked increase in water content. The diagram also shows the increase in water content in relation to viscosity. Low-viscosity ester oils absorb moisture more rapidly than high-viscosity ester oils. PAGs which are mostly used in aircon systems with R134a, are even more hygroscopic. PAGs absorb large quantities of moisture in relatively little time and thus rapidly exceed permissible thresholds of about 800 ppm.

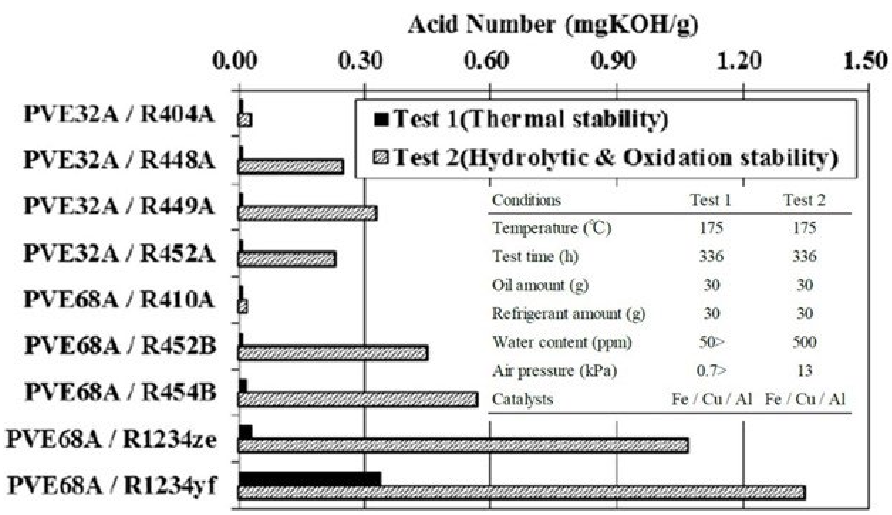


Figure 2-29: Hydrolysis test for several HFO refrigerants

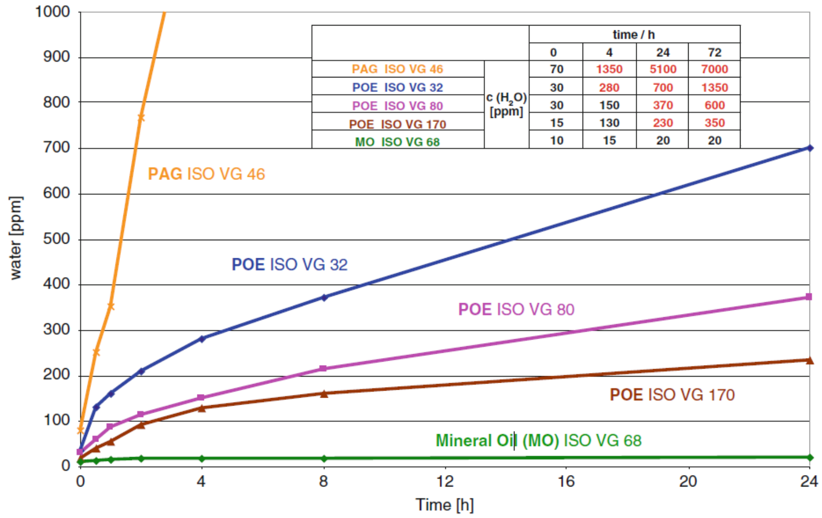


Figure 2-30: Water absorption (hygroscopicity) of lubricants.

Pour Point

The pour point is defined as the lowest temperature at which a lubricant is observed to flow by gravity in a specified lab test (ASTM D97-17b). Specifically, the pour point is 3 degrees C (5 degrees F) above the temperature at which the lubricant shows no movement when a lab sample container is held horizontally for 5 seconds. Pour point depressants are polymers that allow lubricants to flow at low temperatures. They are typically used in paraffinic base oils.

Oxidation Stability

Oxidation stability is a chemical reaction that occurs with a combination of lubricant and oxygen. The rate of oxidation is a time function, and it will be accelerated by high temperatures, water content, acids, and catalysts such as copper and other materials. Oxidation will lead to an increase in the oil's viscosity and deposits of varnish and sludge that could harm the compressor on startup.

Lubricity

Lubricity is the ability of a fluid to minimize the degree of friction between surfaces in relative motion under load conditions. When the lubricity is not at a satisfactory level, excessive wear and metal damage can occur, which leads to inefficient performance, shortened service life, and high replacement costs. The refrigerant introduction into the lubricant would decrease its viscosity, which leads to better lubricity. Inserting additives to the oil, such as phosphate-based additives, improves the lubricity with refrigerant R134a (Tuomas 2006). The chlorine in HCFC refrigerants acts as an additive and delays early compressor failure. Refrigerants with two or more chlorine atoms in the chemical structure of the refrigerant showed improved lubrication properties (Murray, S. F.; Johnson, R. L.; Swikert, M. A.1956). It is reported that the wear rate of the bearing surfaces typically requires 50% higher viscosity when lubricated with a POE/R134a mixture than for a bearing lubricated with MO/R-22 (Jacobson 1994). Refrigerant HFC, HFO, and HC with no chlorine particles mixed with POEs have shown poor lubricating properties. There are different additives based on their functionality: Anti Wear (AW), Extreme Pressure (EP), and Friction Modifier (FM) (Urrego 2012).

2.2.4.4.6 Oil-refrigerant mixture (ORM) Properties

The ORM properties do not differ from RLM properties, but miscibility-solubility properties and the thermo-physical properties are the most important issues that need to be evaluated to understand the effect of the mixture on the energy efficiency of the systems and its performance.

Miscibility - Solubility

Miscibility is the property of two substances that completely mix in all proportions or concentrations to form a homogeneous clear solution, whereas solubility is the ability of one component (the solute) to dissolve in the other component (the solvent) till saturation point or phase separation occurs. An example of miscible solutions are water and alcohol. The chemical miscibility of the oil-refrigerant mixture is a good indicator of how well the refrigerant will help move the oil around the system. We must indicate that the amount of oil circulated with the refrigerant is small, but its effect is crucial.

Miscibility is typically studied by mixing known concentrations of refrigerant and lubricant and lowering the temperature until a phase separation is observed (DIN 51514). The results are used to plot a curve of concentration versus temperature which indicates the miscibility boundaries before causing separation of an oil-rich phase. The curve shows the amount of refrigerant mixed with the oil-rich phase (solubility of refrigerant in oil). Knowing where the separation phase will form and how much refrigerant is needed to dilute an oil-rich phase will help us determine which types of lubricants are acceptable for use with a given refrigerant.

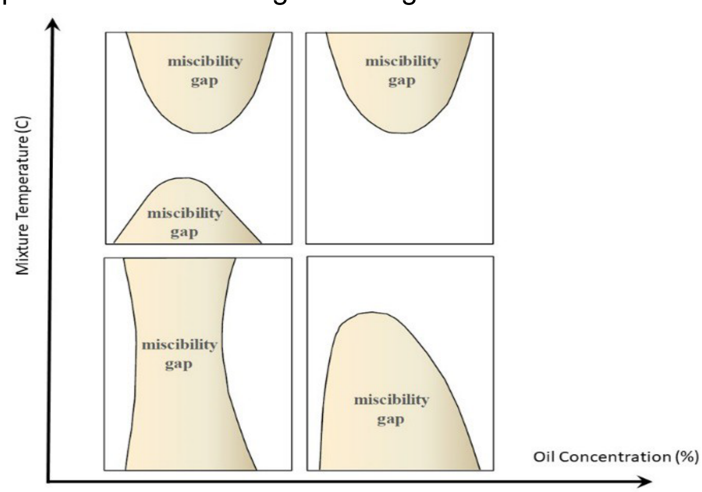


Figure 2-31: Possible miscibility gaps.

Figure 2-31 states all the possibilities of miscibility gaps between refrigerants and oils. The miscibility curves of Fuchs' POE SEZ 32 oil with refrigerant R-134a and low GWP refrigerant R-1234yf are seen in the figure. The horizontal axis represents the concentration of the oil mass in a corresponding refrigerant. For R-134a, the target area of full miscibility is between -15C and 90C for all oil concentrations, and the area(s) of phase separation is located at the bottom and the top of the figure. In the case of refrigerant R-1234yf and Fuchs' SEZ 170 oil mixture, the whole miscibility area has completely changed where the phase separation is between oil concentration of 5% till 48% for all temperatures range of -60°C and 120°C. The amount of oil in R-1234yf is less than 5%, which will not affect the thermal properties of the heat pump cycle, or more between 48% and 57%, as seen in the figure. Increasing the concentration of the oil within the refrigerant is not recommended due to its effects on the thermal properties of the refrigeration cycle and performance.

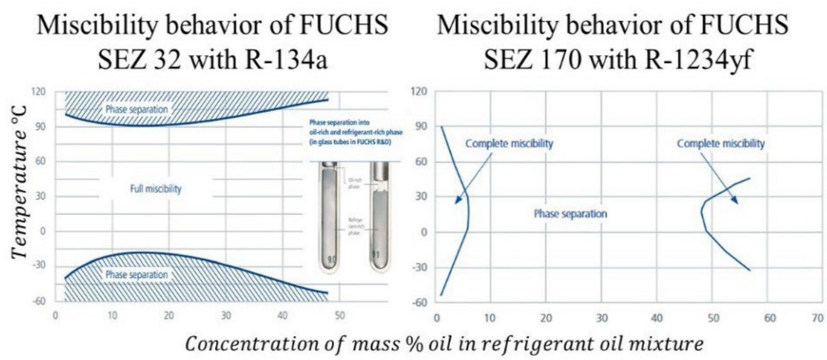


Figure 2-32: Fuchs' miscibility charts with R-134a & R-1234yf.

The miscibility property is crucial to prevent phase separation between the lubricant and refrigerant mixture, especially in the evaporator. When the refrigerant vapor migrates from the evaporator to the compressor's crankcase, it is absorbed, condensed, and precipitated as a refrigerant liquid at the bottom of the crankcase because it is heavier than the oil. The refrigerant, either in the form of liquid or vapor, travels to places where pressure is the lowest. These places are the compressor's suction line or the compressor's crankcase. Manufacturers will incorporate a crankcase heater on the compressor to prevent this phenomenon. The resulting vapor will be forced back into the suction line and may condense, causing slugging in the compressor's cylinders on the next start-up; blockage thus happens during the compressor's long shutdown period.

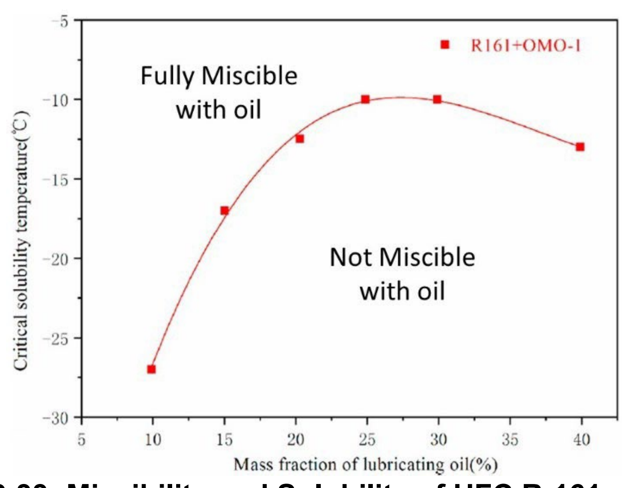


Figure 2-33: Miscibility and Solubility of HFC R-161 with mineral oil.

Experimental results on the miscibility of POE and PVE oils with the low GWP refrigerant R-1234ze(E) showed that the non-miscible area of R-1234ze(E) and PVE 68 oil mixture is 13% larger than that of R-1234ze(E)/POE 68 mixture (Lee et al., 2016). Other experiments have been performed on R-152a (HFC)/OMO (mineral oil) mixture with different concentrations indicating that oil cannot be dissolved completely, but refrigerant R-161 (HFC) was totally miscible with the same oil as seen in Figure 2-33.

The figure also shows the relationship between miscibility and solubility of the same mixture where solubility is another indicator of the mixtures' compatibility (Zhai et al., 2019).

2.2.4.4.7 Thermo-physical properties

The existence of the oil dissolved in the refrigerant has some effects on the energy efficiency of the system. The changes in the working fluid from a pure refrigerant with well-known properties to a poorly understood mixture, with properties that depend on the oil type and concentration, can affect the heat transfer processes in the evaporator and condenser. This effect can either improve or impair heat transfer, depending on oil concentration. The boiling point of the mixture is elevated above that of the pure refrigerant, according to Raoult's Law, and the heat-carrying capacity of the mixture is reduced during evaporation because the oil holds a proportion of the refrigerant in the liquid phase, thereby reducing the latent heat pick-up. As will be shown later, this effect implies a reduction in the COP. Heat pumps using reciprocating compressors normally have very low oil circulation (typically less than 5%), so the effects on COP are not serious (Huges et al., 1980). However, if a higher oil circulation ratio, possibly more than 10%, the effect on COP can then become quite significant with a 30% reduction, and some thoughts need to be given to ways of reducing the problem. Figure 2-34 illustrates the deviation between ORM and pure refrigerant in a heat pump system.

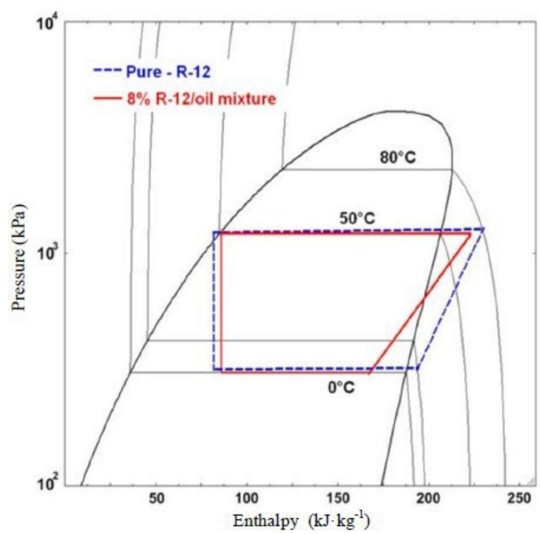


Figure 2-34: Pressure-enthalpy chart deviation of pure and ORM.

We can see that an oil concentration of 8% in the refrigerant R-12 could reduce the COP by as much as 30% due to the change in vapor mass velocity and its effect on the flow in heat exchangers, boiling point of ORM, and saturation pressures and temperatures.

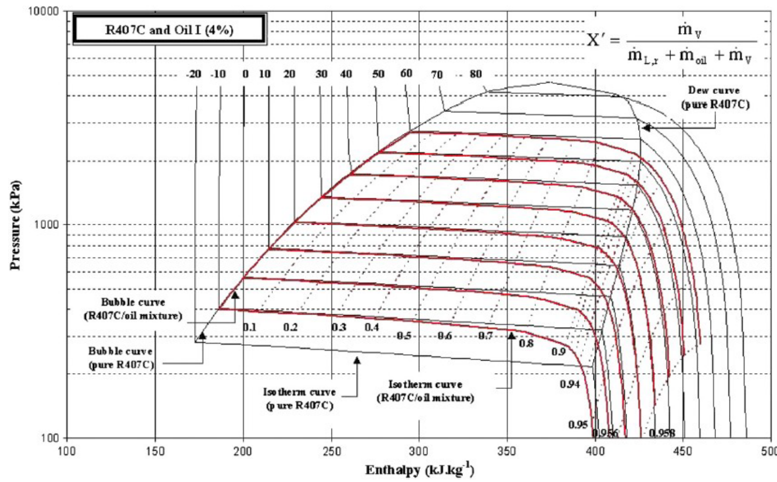


Figure 2-35: Log(P)-h diagram of R-407C and 4% of POE oil .

Figure 2-35 shows the log(P)-h diagram for R-407C with 4% of POE oil in a refrigeration cycle and Figure 2-36 shows the same diagram for R-290 and 5% of POE 68. It clearly proves that the vapor line in the vapor-liquid mixture zone is not as obvious as in pure refrigerant, as the oil is considered to remain in the liquid state. Two regions during evaporation appear to take place. ORM behaves as the pure refrigerant in the beginning and part of the evaporator (isothermal lines) and sensible heat region closer to the vapor line of pure refrigerant where the amount of the oil within the refrigerant increases.

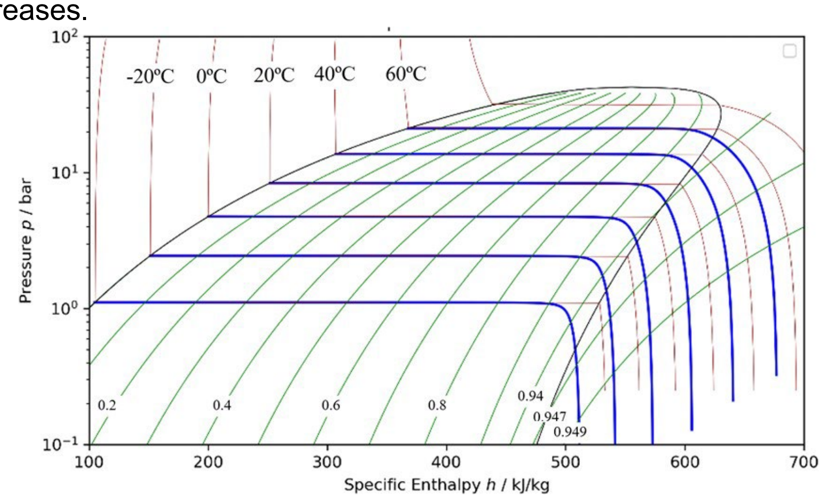


Figure 2-36: Log(P)-h diagram of R290 and 5% of POE 68.

2.2.4.4.8 Suitability of oils and refrigerants

The suitability of oils and refrigerants is a grey area where we still have much to learn about. Table 2-2 summarizes the possibilities of using lubricant/oil with refrigerants in general. The (√√) sign means that there are supported facts to possibly use the refrigerant category with the mentioned oil. The (NR) sign means “Not Recommended,” which states that there are no facts to account for the suitability of the oils and refrigerants. The (Res) indicates that there is still ongoing research on the compatibility in ORM. R-717 (Ammonia), R-718 (Water), and R-744 (Carbon Dioxide) are not included here in this report.

Table 2-2: Summary of oil/lubricant refrigerant compatibilities issues.

Refrigerant/Oil	MO	AB	PAO	PAG	PVE	POE
HCFC	√√	√√	√√	NR	NR	Res.
HFC	NR	√√	NR	√√	Res.	√√
HFO	NR	NR	NR	√√	Res.	Res.
HC	√√	Res.	Res.	Res.	NR	Res.

2.2.4.4.9 Conclusions

In refrigeration or heat pump systems, many variables and factors must be considered before choosing the right refrigerant. Data from compressor manufacturers is always taken as given, and we never question or even ask if the lubricant they supply is appropriate because we lack knowledge or expertise on these matters. A number of these factors can be related to compressor performance or to refrigerants themselves. Several studies focus on RLM issues and how to calculate the necessary dynamic viscosity of the oil in the compressor but neglect the importance of the oil concentration within the ORM. When oil is present in the refrigerant, refrigeration, and heat pump systems can suffer performance losses of 25% in COP values.

There has been extensive research on the compatibility issues of RLM and concrete methods of choosing the right lubricant for the compressor. For several lubricants, the effect of the refrigerant on the dynamic viscosity has been studied and measured. Not all low GWP refrigerants were researched. Only R-1234yf and R-1234ze(E) were investigated thoroughly to replace R-134a. Other potential synthetic refrigerants such as R-1336mzz (Z), R-1233zd (E), and natural ones such as R-601 with high critical temperatures need to be evaluated. On the side of ORM, scarce research has been done to study the effect of oil concentration on the performance of the system and its energy efficiency with low GWP refrigerants.

2.2.4.5 High-temperature heat pumps

The definition for a high-temperature heat pump is when the temperature of the sink reservoir can reach above 100°C and the source temperature for the heat pump should be above 40°C. Synthetic Refrigerants with good thermo-physical properties to cover these ranges are scarce in the market. If they are found, they might have some environmental issues, such as the formation of TFA upon decomposition. Natural refrigerants such as R-600 or R-601 are more appealing but dangerous with their flammability issues. The transition to the new refrigerant must be smooth and without any drawbacks. We should not fall into the same problems that we faced during the move from CFC to HCFC and HFC refrigerants, where the market was stormed with the news of the ban on the use of CFC. The industry at that time was not ready for that transition. This move led to many compressor failures due to many factors such as unsuitable lubricants, undersized and oversized heat exchangers, and problems such as higher power consumption and lower values of coefficient of performance (COP). The new move against PFAS that covers several F-gases in the EU countries, including certain HFCs and HFOs and the hidden danger of TFA, which is an atmospheric degradation product of R- 1234yf and R-134a should help us out in stirring our research in developing better and safe machines using better synthetic, safe HC, and natural refrigerants in the coming years.

Various criteria should be considered to identify the right refrigerant with the best thermophysical and thermodynamic properties, which maximizes the system's performance and minimizes the environmental impact. Figure 2-37 shows the families of synthetic refrigerants obtained from natural ones and how the chemical processes would be done to obtain the required synthetic refrigerant.

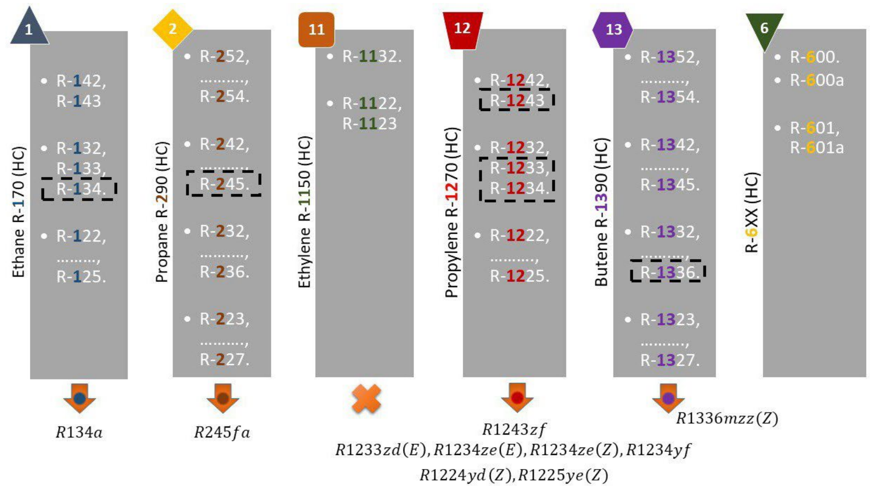


Figure 2-37: Synthetic refrigerants' families.

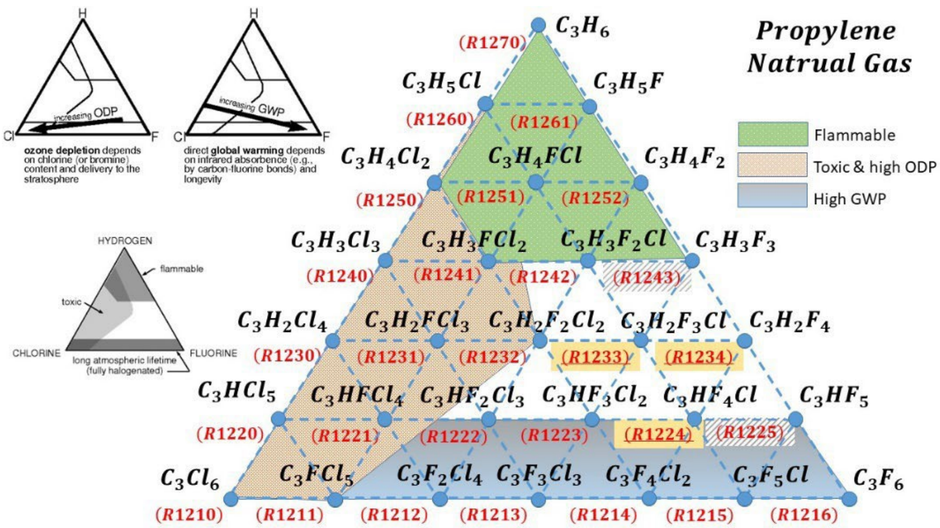


Figure 2-38: Synthetic refrigerants from natural ones.

Figure 2-38 represents the triangle of elements, Hydrogen on the top, Chlorine on the bottom left, and Fluorine on the bottom right, where we can locate flammable, toxic, and long atmospheric lifetime (fully halogenated) areas. We can also find areas where refrigerants have high GWP values and high ozone depletion potential (ODP) rates. Figure 2-38 indicates how we can make R-1234, not its isomers, from Propylene gas R-1270. Many advertised refrigerants such as R-1243zf, R-1233zd (E), R- 1234ze(E), R-1234ze(Z), R-1234yf, R-1224yd(Z), and R-1225e(Z) can be obtained from Propylene. Most of these gases are in the safe area of low flammability, no toxicity, and low GWP values. It is worth mentioning here that the isomers of R-1336, which are R-1336mzz(Z) and R-1336mzz(E), are produced from Butene gas R-1390.

Royal Institute of Technology (KTH) / Energy Technology lab (EGI) has developed a high-temperature heat pump to test several available refrigerants in the market. Figure 2-39 shows the schematic of the test rig already built in the EGI lab and an actual setup at the KTH laboratory. This project will help support the Swedish industry in its endeavor to save energy and reduce GHG emissions. It will also strengthen KTH, a well-known research place, and maintain an advanced position among prestigious international universities and institutes.

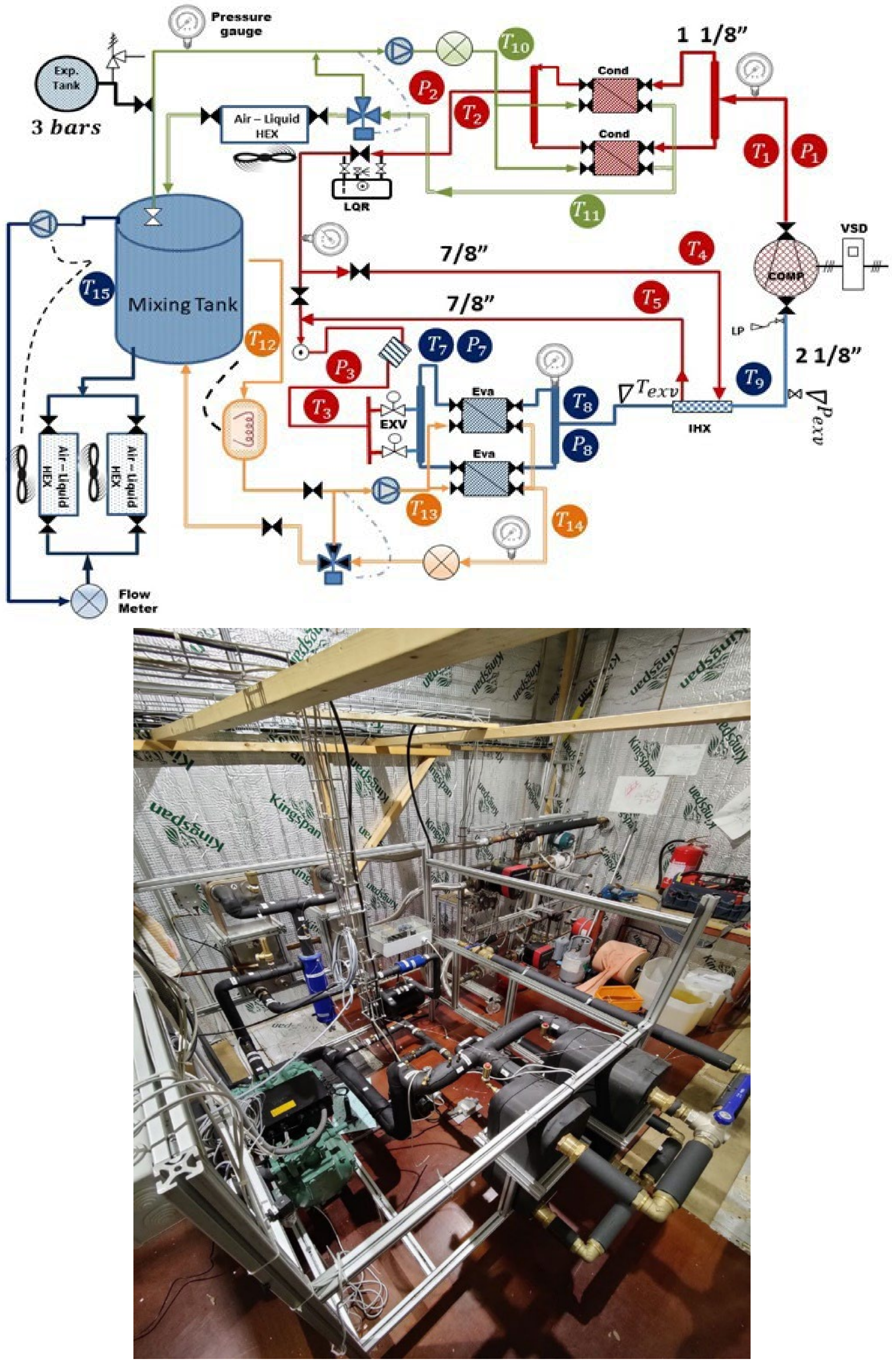


Figure 2-39: HTHP test rig schematic layout.

Research Institute of Sweden (RISE) has been granted a project from the Swedish Energy Agency (SWEA) to work on heat pumps for drying processes. The project aims to build international knowledge on resource-efficient drying with heat-pumping technology. The proposed project will be used as a Swedish national project to contribute to the overall aim of the new IEA HPT Annex 59 in the form of a joint project with RISE, CIT and KTH as the executive team. The project will collect Swedish case studies focused on industrial drying, mainly in forests, pulp/paper, agriculture/food. Both state of the art and innovative solutions will be investigated and described, including needs surveys, analyses, and in-depth case studies will be analyzed from a technical, practical and financial perspective to achieve a shift towards electrified resource-efficient drying. The successful implementation of these drying processes will address complex multidimensional challenges. This proposed project will explore opportunities to significantly increase the efficiency, flexibility and cost-effectiveness of drying applications using heat pumps. The IEA Heat Pumping Technologies (HPT) Technology Collaboration Platform (TCP) has initiated a new Annex 59 focusing on structure and describing the numerous possibilities and advantages of heat pump integration in dryers. The Annex is led by Austria and is believed to attract many countries. Sweden has long experience and extensive expertise in heat pump technology and has the potential to contribute to Annex 59 in a fruitful way and to learn from the other participating countries and their experience of drying with heat pumps.

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2.3 Research work in 2023

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This is the final country report from Sweden within the IEA HPT Annex 54. In this report, we will cover research and development related to heat pumps with low GWP refrigerants done in Sweden during the year 2023 and also give some highlights from the previous years. Naturally, most research projects last more than one year, so some of the projects discussed have also been mentioned in previous country reports. In these cases, we will give a short introduction with reference to these earlier reports.

As this is the final report in the Annex, we will also present what we consider to be the most important developments in Sweden during the entire duration of the Annex. It should be noted that what is reported is an overview of several research projects related to the topic of the Annex. This means that the intention is not to go into detail in each of these projects but rather to give an overview and, where possible, to reference other reports where the results are described in more detail.

The projects covered are mostly related to the use of natural refrigerants, primarily hydrocarbons, but projects on low-GWP synthetic refrigerants are also included.

Even though this is a country report from Sweden, some projects and development trends are common to other countries in the EU. Also, sales statistics from the EU countries are included in some cases as these are, in some cases, more reliable than the national statistics from Sweden.

The content of the report is structured as agreed with the Operating Agent in order to facilitate the compilation of the country reports into one comprehensive final report of the Annex.

The editor of this report has been Björn Palm, a professor at KTH Royal Institute of Technology, who has also written chapters 1 – 2 and 4 – 5. Chapter 3 is written by Dr. Metkel Yebio at RISE, Research Institutes of Sweden, with the support of colleagues. Of course, many people have been involved in the projects and in the development of the products presented in the report.

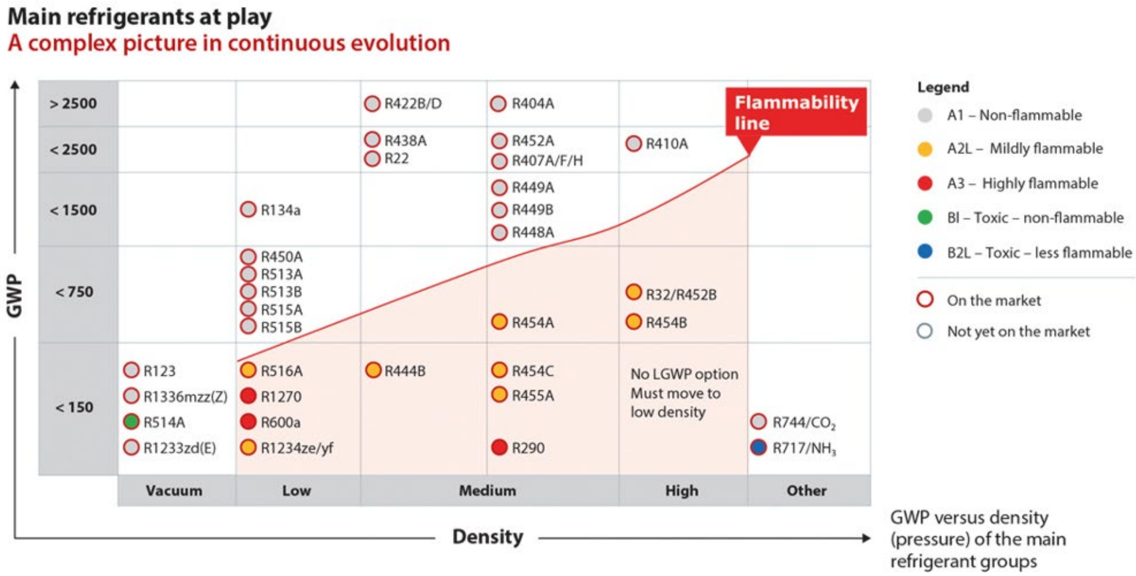


Figure 2-40: Relation between GWP, density, and flammability. (From [1])

2.3.1 Summary of Tasks 3 – 5

2.3.1.1 Task 3: Review of design optimization and advancement impacts on LCCP reduction (Year 3-5: 2021-2023)

As has been shown in several reports, e.g. [1], [2], there are no refrigerants with low GWP with normal pressures that are non-flammable, except for CO_2. As flammability is always a risk, the charge of refrigerant in a system should be as low as possible without affecting the energy efficiency of the system. Even with non-flammable, high GWP refrigerants, charge reduction should be considered due to an environmental concern, as the risk of large leakages is greater if the charge is large. However, until recently, heat pump and refrigeration systems have not been designed with low internal volume or low charge in mind. There have also been statements claiming that low charge/low volume systems should be less energy efficient than systems with larger charges. An interesting graph (Figure 2-41) of the specific charge vs the seasonal coefficient of performance (SCOP) was presented in [3]. The graph to the left is for Air-to-Water (ATW) heat pumps with a heating capacity of less than 20 kW, and the one to the right is for Liquid-to-Water (LTW) heat pumps with capacities of less than 30 kW. The data comes from a database of products on the European market. It is interesting to see the large deviations between the specific charge (kg/kW) even when comparing heat pumps with the same refrigerant, propane. It is also interesting to note that there is no clear correlation between the specific charge and the SCOP. For the LTW heat pumps, the three heat pump models with the lowest specific charge also have the highest SCOP! These graphs clearly demonstrate the possibility of substantially decreasing the charge of refrigerant compared to what is common by adjusting the designs wisely, thereby decreasing the risks connected to flammability.

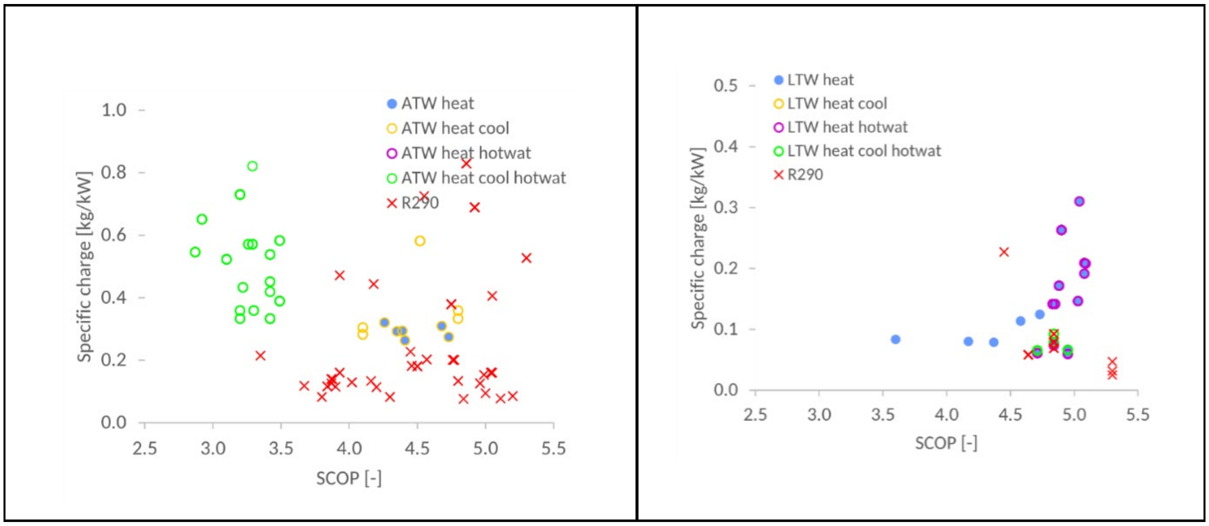


Figure 2-41: Specific charge for small to medium size heat pumps. Left: Air-to-Water, < 20 kW. Right: Liquid-to-Water < 30 kW. From [3]

To achieve low charges, heat exchangers with small internal charges must be selected. Preferably, the cross-sectional area of the channels should be small. This can be achieved in plate heat exchangers by using smaller pressing depths and by reducing the inlet and outlet headers. It is also possible to substitute conventional circular copper tubes with flat multiport tubes. When moving from HFCs to hydrocarbons, it is also important to consider the lower pressure drops and design the distributors to get an even distribution of refrigerants between the parallel channels of the heat exchangers.

Other design changes possible besides charge reduction to limit the risks connected to flammability are already included in the new IEC 60335-2-40:2022. According to this standard, heat pumps with flammable refrigerants can be installed indoors without any particular safety precautions if the charge is lower than four times the lower flammability limit (LFL). For propane, this corresponds to 150g. Larger charges are also allowed if any of the following methods of limiting the risks is implemented:

- If the releasable charge is limited, e.g. by sectionizing the system by quick closing valves in case of leakage.
- If the heat pump unit is in a large room
- If the heat pump has a tight ventilated enclosure connected to the ambient

Other methods may also be used if these are tested and proven to be safe.

2.3.1.2 Task 4: Outlook for 2030 (Year 5: 2022 – 2023)

In Europe, new legislation is affecting the heat pump market in an important way. The new F-gas regulation was finally adopted in Jan 2024. This regulation includes a phase-out scheme for HFC refrigerants, which is much faster than the one in the previous version of the regulation. It should be noted that HFO is not considered as HFC according to the definition used in the regulation. However, HFOs are considered as F-gases. As seen in Figure 2-42The decrease will occur very fast in the next six years, with a reduction to less than one-fourth of the 2024 level in 2030, expressed in CO2 equivalents put on the market. In 2050, no HFCs will be allowed to be put on the market.

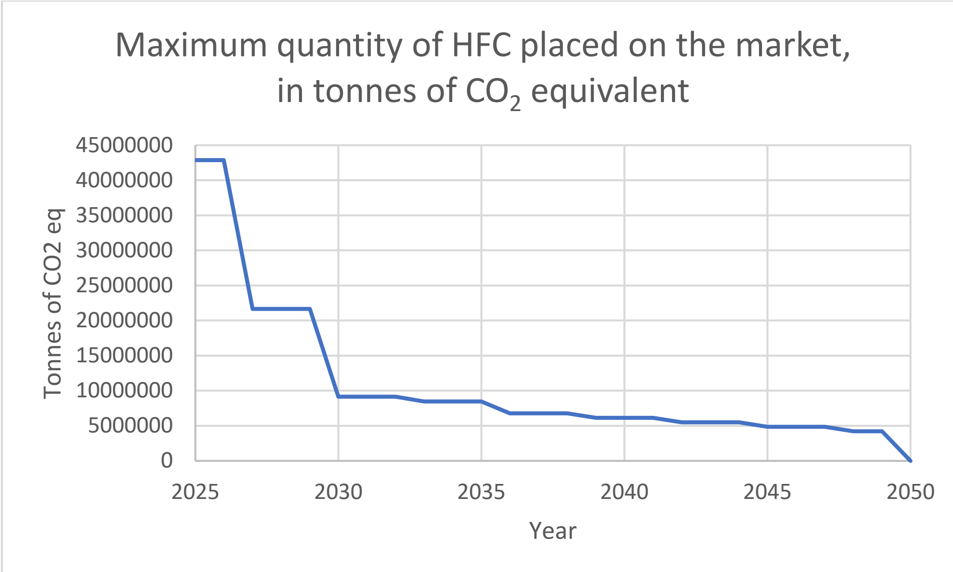


Figure 2-42: Maximum allowed amounts of HFC to be put on the market in EU according to the F-gas regulation, expressed in CO2 equivalents. (Based on legal text of F-gas regulation)

In addition to the phase-out of HFCs, there are product bans in the F-gas directive dictating the maximum GWP of the refrigerants from certain years, depending on the type of system. For systems <12kW, no F-gases (including HFO) will be allowed from 2035. This regulation is forcing the heat pump industry in Europe to adopt natural fluids.

Another factor related to the choice of refrigerants in the future is a proposal to the EU to ban all PFAS substances. PFAS is a group of more than 10,000 substances characterized by having fully fluorinated carbon atoms in the molecule, i.e., $–CF_3$ or $–CF_2–$ groups. This means that almost all synthetic refrigerants belong to this group. If this proposal is adopted, the possibility of using HFOs in systems larger than 12 kW (i.e. not covered by the F-gas regulation) will be very limited.

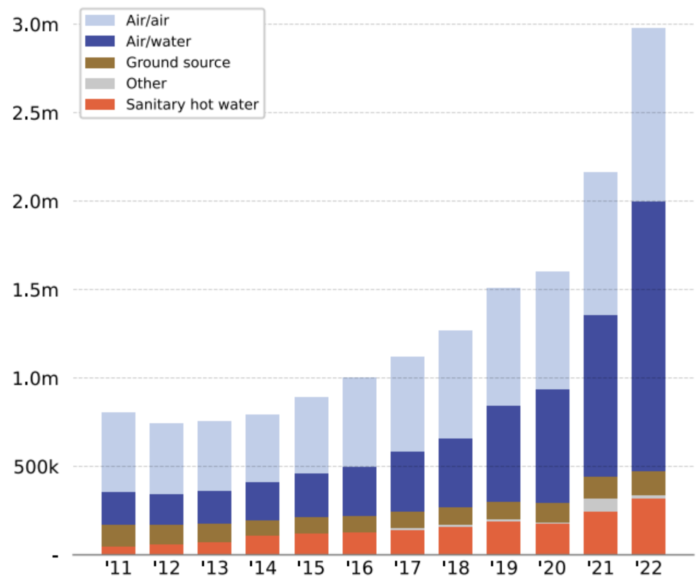


Figure 2-43: Heat pump sales on the European market 1990 - 2022. [4]

At the same time, as the use of synthetic refrigerants is prohibited for low-capacity applications, the EU has made decisions about electrifying the heating sector. The main reason is to make it possible to reach the commitments according to the Paris Agreement and to reach the goals of the RePowerEU plan, which aims to decrease dependence on fossil fuels, mainly gas, from Russia. Several countries have also restricted the installation of gas burners, and some have also subsidized the installation of heat pumps. Together, this resulted in a boom in heat pump sales in Europe during 2022 and the first half of 2023, Figure 2-43. During the second half of 2023, the gas prices were much lower than a year before, and the sales of heat pumps decreased substantially. However, the industry expects this to be a temporary dip and that the sales of heat pumps will continue to increase in the coming years. Now (at the beginning of 2024), the EU Commission and Parliament are negotiating a Heat Pump Action Plan, which is designed to accelerate the roll-out of heat pumps on the European market through new legislation and by ensuring accessible financing. Heat pumps are already the most selected heating technology in northern Europe, but the difference between countries is large. This is clearly seen in Figure 2-44, where the market share of heat pumps and the total sales of heat pumps and boilers are shown for the European countries. The Scandinavian countries are at the top, with a market share for heat pumps of more than 90%, while the UK is at the bottom with only 3%.

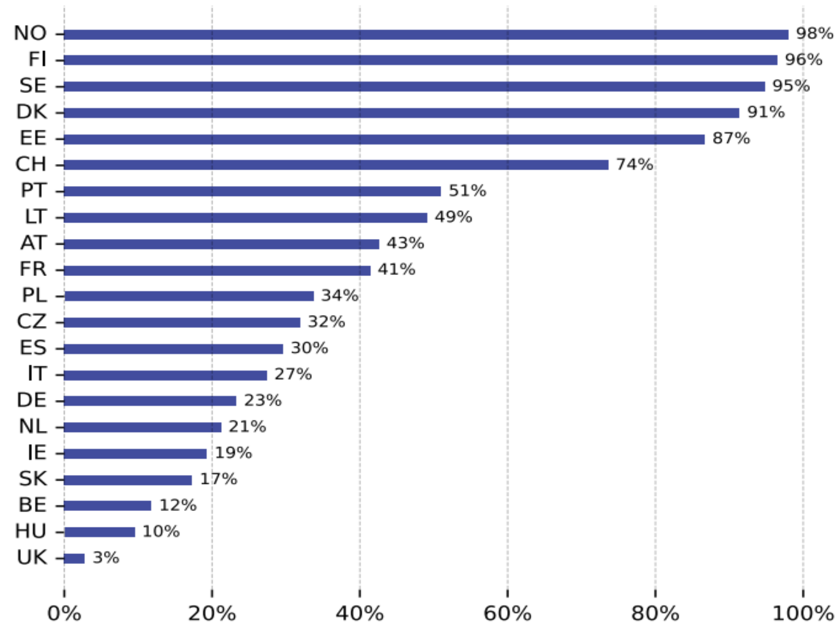


Figure 2-44: Heat pump market shares in % of combined sales of boilers and heat pumps, for different countries in Europe. [4]

A Swedish heat pump market survey is included as a separate chapter, Ch. 4, in this report.

2.3.1.3 Task 5: Report and information dissemination (Year 5: 2023)

The major dissemination event in 2023 for research related to heat-pumping technologies in general was the IIR International Congress of Refrigeration (ICR) in August in Paris. The following are activities and presentations in conjunction with the ICR:

- A seminar was arranged jointly by KTH and the University of Valencia in remembrance of Professor Eric Granryd and Professor José Miguel Corberan, who were both pioneers in the field of research related to using hydrocarbons as refrigerants in heat pumps and refrigeration systems. During the seminar, their work was summarized, and presentations were given by international experts on the state of the art of hydrocarbons as refrigerants.
- A keynote lecture was given by Professor Björn Palm, entitled Importance of heat pumps in the future energy system [5]. The presentation covered the necessity of electrification of the heating sector to make the phase-out of fossil fuels possible. It was also pointed out that going from gas and oil heating, with efficiencies in the range of 70 – 90%, to modern heat pumps with COPs of 4 – 5 will reduce the need for energy input to the energy system considerably. The talk also pointed to the need to move to flammable refrigerants as HFCs will be phased down according to international agreements like the Kigali amendment to the Montreal protocol and, in Europe, the F-gas regulation. There are also good reasons to move to natural refrigerants, like hydrocarbon, ammonia, and carbon dioxide, as there are discussions worldwide about the use of PFAS fluids and the formation of TFA in the decomposition of HFC, including HFO [6], [7].
- A paper was presented by Ph.D. candidate Monika Ignatowicz with the title Environmentally friendly lubricants for high-temperature heat pumps with low GWP refrigerants [8], co-authored by Professor Rahmat Khodabandeh, KTH.

- A paper was presented by Dr Saman Gunasekara with the title Analysis of Refrigerant R452B in Use-phase versus Pristine Conditions using Gas Chromatography [9]. Co-authors were Professor Björn Palm, Ph.D. candidate Monika Ignatowicz and M. Sc. Peter Hill. The paper describes the analysis of the low GWP refrigerant blend R452B taken from a heat pump after about 7,800 hours of operation and compared to pristine R452B. The analysis was done with a gas chromatograph equipped with TCD and FID sensors. The refrigerant used revealed traces of R134a, moisture, possibly CO2, and small amounts of other light gases that could not be identified.

Other publications related to the Annex 54 work:

- A journal article was written based on the work on the isobutane heat pump with low charge, which was described in a previous annual report. The title of the article was Experimental Evaluation of the Effect of Mechanical Subcooling on a Hydrocarbon Heat Pump System, and it was published in Energy [10].
- A research area at KTH is the use of CO_2 as a refrigerant in supermarket refrigeration systems. In one article, the possibility of using the hot side of such systems for heating buildings by direct connection or through the district heating network was analyzed. The article was published in Applied Thermal Engineering [11]. The first author, S Thanasoulas, is a Ph.D. student with Associate Professor S. Sawalha as main supervisor.
- A Master's thesis entitled Status Mapping of Tank to Grave Management of Low-GWP Refrigerants was presented. [12]. The thesis uses LCA to analyze the complete life of refrigerants, covering both natural fluids and low-GWP synthetic fluids. Interviews with stakeholders in different positions are conducted, and conclusions about the expected development regarding the choice of refrigerant are presented. The student's name is S. Parra Gimeno and the supervisor was assistant professor S. Gunasekara.
- Another master's thesis was defended concerning the selection of refrigerants in large-scale heat pumps of district heating systems [13]. The background is that some of the world's largest seawater and wastewater heat pumps are in Stockholm. Several other cities in Sweden also have large heat pumps supplying heat to district heating networks. These heat pumps all use HFC refrigerants, and according to the new F-gas regulation, they will not be allowed to service these heat pumps within the coming ten years. It is, therefore, necessary to find low-GWP alternatives if the systems should be used in the future. In particular, the thesis focuses on systems with heating capacities larger than 10 MW that are now using R134a as working fluid. The conclusion is that ammonia would be the best alternative if the heat pumps are substituted. However, considering the poisonous nature of ammonia, it is recommended that R600a or R152b be used in the future. The student's name is G. Balyaligil, and the supervisor was Associate Professor S. Sawalha.

2.3.1.4 Swedish heat pump market

The Swedish refrigeration and heat pump industry each year sends out questionnaires to their members to take the temperature of the market and to identify market trends. The results are found on the organization's website [14]. Some of these trends will be presented in this section. Some of the questions have been asked annually for several years, making it possible to see the development over time.

The first question was: How do you think the demand for heat pumps will be during the coming three-year period? As shown in Figure 2-45, the expectations of more than 90% of the respondents have been on the high side for the last six years. However, the trend is declining slightly, and the share answering Very high decreased considerably, most probably because the market is close to saturation in Sweden.

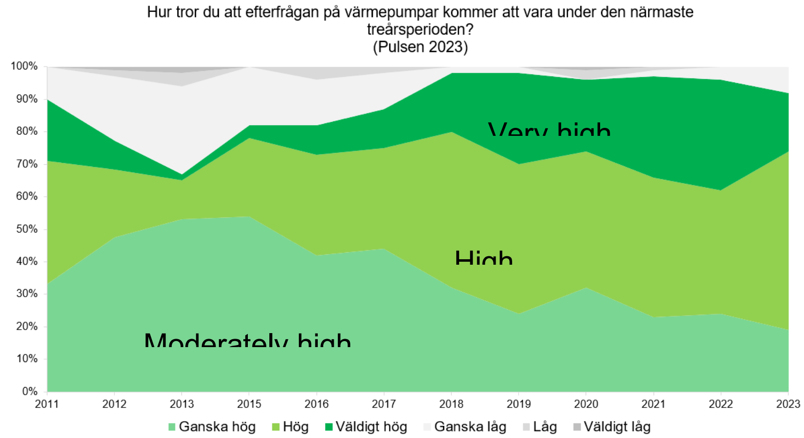


Figure 2-45: Expectations about the demand on the heat pump market in Sweden in the coming 3-year period [14].

During 2022 and the first part of 2023, the demand for heat pumps in Europe was so high that the customers had to wait to get a unit delivered. As it was the seller's market, this influenced the price of the heat pump installations. Also, the inflation rate peaked at about 10%, which should be kept in mind when prices are compared. The second question, related to this, was: What would you estimate to be the total cost of a heat pump installation in a house requiring a total of 20,000 kWh per year in your area, for different types of heat pumps? The responses are shown in Figure 2-46, where the vertical axis shows the cost in Swedish krona (1 US$=10,5 sek). As shown, the expected costs rose quite sharply from 2022 to 2023 for all types except air-to-air, for which the cost increase was low. Geothermal heat pumps, extracting heat from a borehole, typically 200m deep, are the most expensive, followed by heat pumps using shallow ground heat exchangers or groundwater. It should be noted that geothermal heat pumps are often the only alternative to these three in urban areas as there is no space for digging and no ground water is easily available. Air-to-water heat pumps are expected to be about 25% less costly than geothermal. In the cold climate of Sweden, geothermal heat pumps are considered more reliable, especially during very cold weather. Exhaust air heat pumps cannot cover the complete power demand of the house and are typically used for producing sanitary hot water and/or heating the incoming ventilation air. Almost all buildings have a hydronic system, connected to conventional radiators or, less commonly, to underfloor heating systems. The least expensive solution is the air/air heat pumps, typically single-split units. One unit will only be sufficient if the house has an open floor plan. Also, as the heating capacity is highly dependent on the outdoor temperature, these systems are usually combined with direct or indirect electric heating.

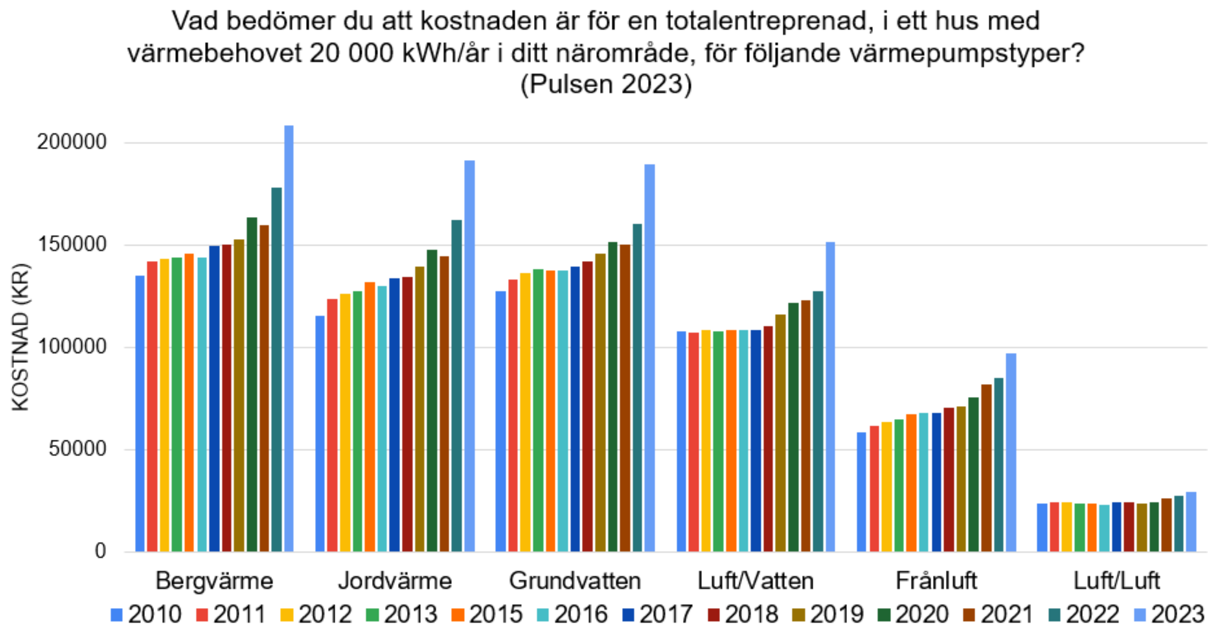


Figure 2-46: Expected total cost of a heat pump installation in a house with an energy need of 20 000 kWh/year [14].

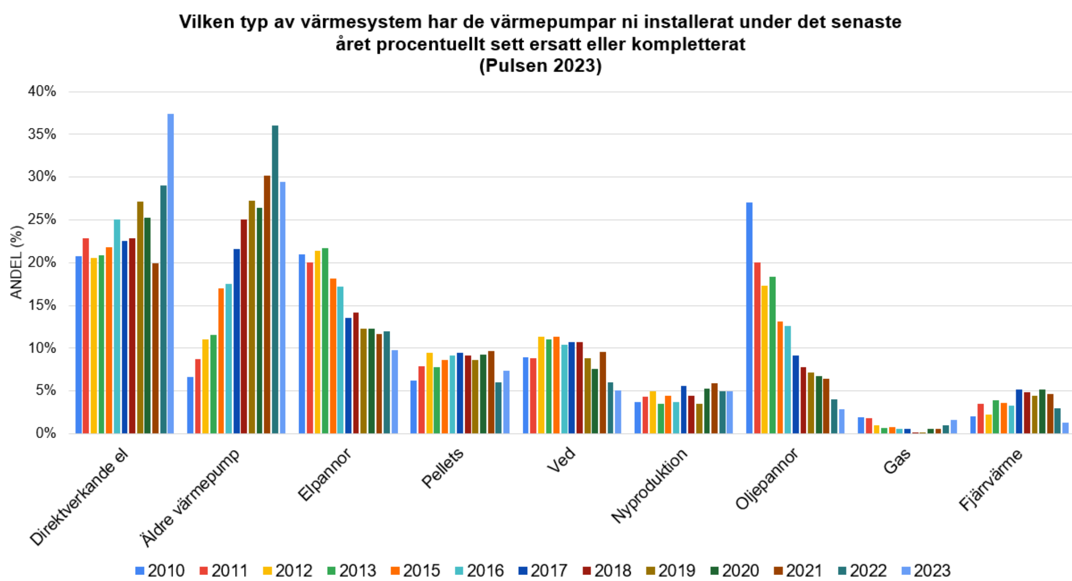


Figure 2-47: What heating system heat pumps installed 2023 replaced [14].

The next question was: What type of heating system have the heat pumps installed last year replaced or complemented, in %? The responses are shown in Figure 2-47. Several interesting conclusions can be drawn from this figure. Looking at the development over time, it is clear that less and less oil boilers are replaced, simply because they have already been replaced and now very few remain. Second, the trend is increasing for new heat pumps replacing old ones. The expected lifetime of a heat pump is 15 – 20 years, and the trend is just a result of more and more heat pumps being installed during the last decades. Third, the share of heat pumps replacing direct electric heating has increased considerably during 2023. The reason is most probably the extremely high price of electricity during the summer of 2022 and the following winter. It is also interesting to note the low share of gas boilers being replaced. This is totally different from what would be the case in continental Europe, where gas heaters are the most common method of heating. In Sweden, only some areas along the southwest coast have access to fossil gas through pipelines, so conversion from gas to heat pumps is a very small share.

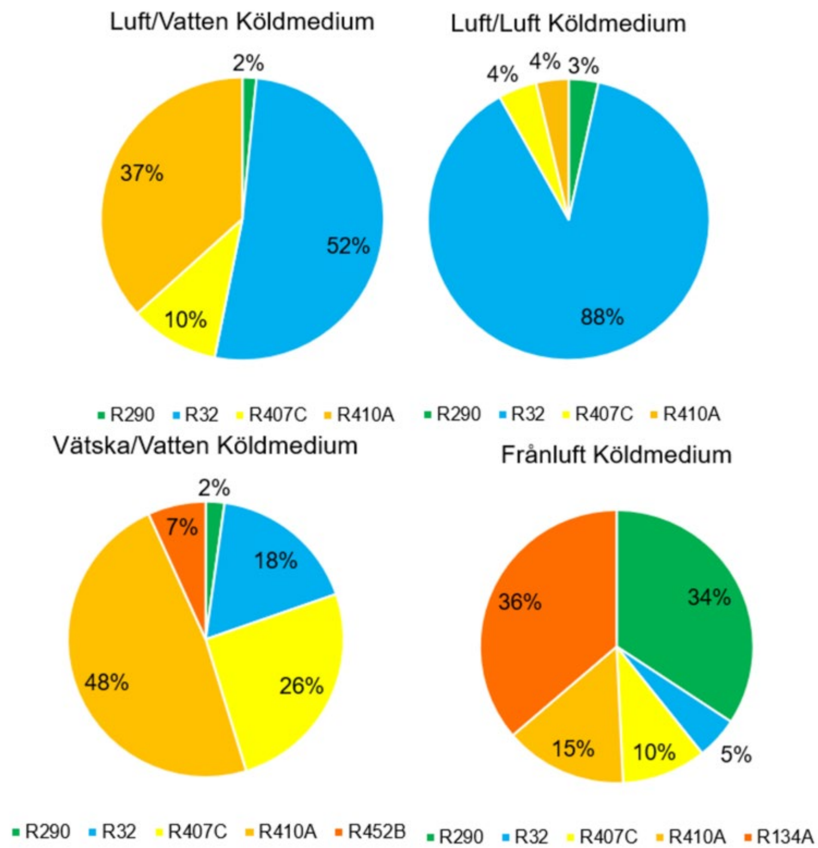


Figure 2-48: Estimate of refrigerants used in different types of heat pumps installed in 2023 [14].

Finally, the questionnaire asked about what refrigerants were used in the heat pumps installed during 2023. It should be noted that the numbers are estimates by a limited number of people taking the survey and not true sales statistics. The results are shown in Figure 2-48. As shown, the distribution depends very much on the type of heat pump. For Air-to-Air, R32 totally dominates, with 88% of the installations being installed. Perhaps it is interesting to note that a few percent were using propane as a refrigerant. For Air-to-Water heat pumps, R32 is also dominating, with 52% of the installations. Second largest is R410A with 37%, followed by R407C with 10%. A couple of percent use propane as refrigerant.

For Liquid/Water heat pumps, the picture is different. In this case, R410A dominates, with 48% of the market, followed by R407C at 26% and R32 at 18%. In this category, we also find a share of 7% of heat pumps with the HFO-blend R452B.

For exhaust air heat pumps, the distribution is again different. In this case, an estimated 36% of the heat pumps use R134a, and almost as large share, 34%, use propane. Propane has been used for this type for at least ten years. The motivation has been that the systems are relatively small, have a limited charge and that the airflow around both the evaporator and condenser is large, which is expected to limit the risks of reaching a flammable concentration in the ducts in case of a leakage. The remaining 30% of the units use R410A (15%), R407C (10%) and R32 (5%).

As mentioned, the distribution in Figure 2-48 is based on a questionnaire to companies in the business, not on actual sales. Still, it gives an impression of what refrigerants were used in Sweden in new heat pumps during 2023. It is interesting to note that only one of the new HFO-containing blends is visible in the graphs. Also interesting is that the two high-GWP refrigerants, R407C (GWP=1,774) and R410A (GWP=2,088), are still quite common in new systems! The only refrigerant with a GWP lower than 600 is propane (R290), with a GWP of much less than 1.

2.3.2 Summary of latest results

Many of the research projects on low GWP refrigerants initiated during the last couple of years have also continued during 2023. A few new projects have also been started. Some journal articles, conference papers, and student theses related to these projects have been presented in the previous section. The following is a brief presentation of the latest results in the projects not mentioned above.

2.3.2.1 Safe use of flammable refrigerants

This project is Sweden's main contribution to IEA HPC Annex 64 and will only briefly be mentioned here as the subjects of the two Annexes partly overlap. The project has recently started and some of the main activities are the following:

- Simulation of leakages of flammable refrigerants in different scenarios.
- Tests of leakages of hydrocarbon refrigerants under realistic conditions.
- Design of heat pump systems for minimum risk and maximum efficiency.
- Design for minimum charge in systems with flammable refrigerants.
- Investigation of leak detectors, functionality, reliability, cost.

At this point no publications are available for the project.

2.3.2.2 EcoPack project

This project investigates the design of an isobutane (R600a) heat pump for medium to high-temperature applications. An initial concept was to design this heat pump as an active de-superheater of a larger heat pump, i.e. to use the subcooling of the refrigerant of the larger heat pump as a heat source for a small heat pump. One possible application would be to produce sanitary hot water at temperatures of 60°C or above with the smaller heat pump while supplying heating at lower temperatures with the larger heat pump for a hydronic system. Two articles were presented at the Gustav Lorentzen conference in Trondheim in 2022 [15] [16], and one journal article was published in 2023 [10].

The system has a capacity of up to 12 kW and uses a variable-speed rotary compressor originally designed to be used for heating or cooling electric vehicles. The heat exchangers were plate-type and prototype heat exchangers with asymmetric plates were used in order to decrease the charge and maximize the performance. The system has an internal heat exchanger in order to maximize its COP. It has been shown that this system can operate well with as little as 120 g of R600a. During the last year, the project has focused on the control of the expansion device. By careful control of the valve, it has been shown that it is possible to locate the valve sensors after the internal heat exchanger, i.e. directly before the compressor. Other modes of control are also investigated. No publication has been presented about the last developments, but an abstract is submitted to the Gustav Lorentzen conference at the University of Maryland in August 2024.

2.3.2.3 Low GWP refrigerants for high-temperature heat pumps

Two different test rigs have been designed for testing different refrigerants in high temperature heat pumps. The aim is to demonstrate stable operation with condensing temperatures above 120 deg C. Theoretical analysis and comparison of the performance with different refrigerants is expected but not yet completed.

2.3.2.4 Compressor oils for high-temperature heat pumps

Identifying a suitable compressor oil is one of the key questions for the application of high-temperature heat pumps, and this is the purpose of this project. Tests will be done in one of the two test rigs mentioned above. In this case, a sensor located inside the compressor will be used to measure the viscosity of the oil during operation. KTH, Department of Energy Technology, is working together with an industrial partner with the aim of developing a new oil for high temperature heat pumps.

Technology is working together with an industrial partner with the aim of developing a new oil for high-temperature heat pumps.

2.3.2.5 Energy efficiency of CO_2 heat pumps and refrigeration systems

Carbon dioxide is probably the most common refrigerant in large supermarket refrigeration systems in northern Europe. As these systems are located in shopping malls or in close connection to apartment houses, there is a possibility of using the heat from the high-pressure side of the refrigeration systems as a heat source for the building where the supermarket is located or for surrounding buildings. In two projects, both technical solutions and economic barriers to using this waste energy are investigated. Figure 2-49 shows a possible design of a supermarket refrigeration system with cooling at three temperature levels and heat recovery at two levels.

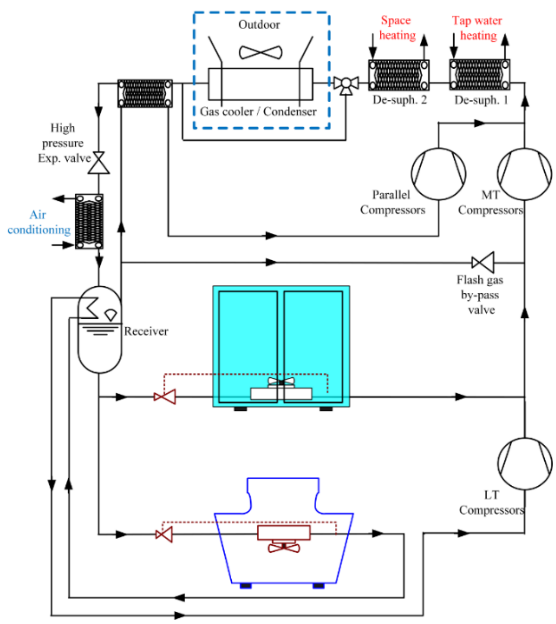


Figure 2-49: Example of design of supermarket CO2 system with heat recovery.

2.3.2.6 Cooperation between supermarkets and apartment house owners

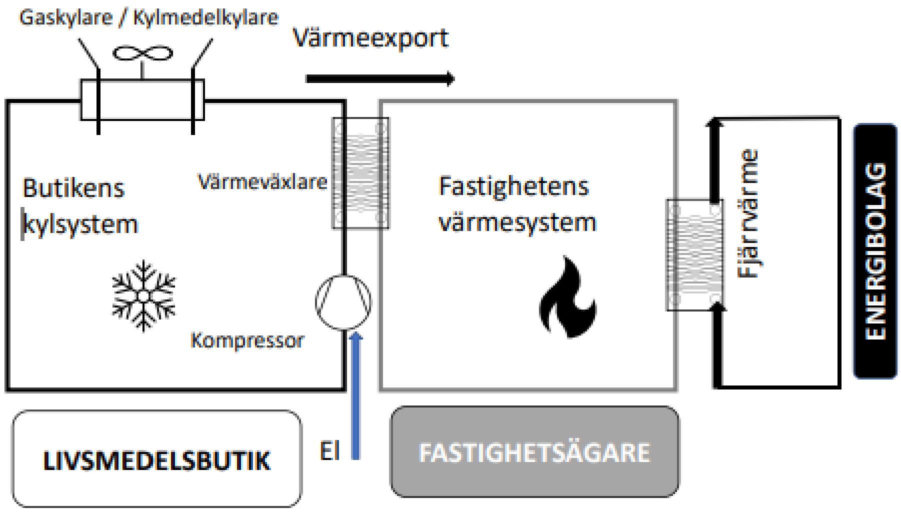


Figure 2-50: Thermal connections between the supermarket (left), the heating system of the building (middle), and the district heating system (right). [17]

In the second project related to carbon dioxide systems, the overall aim is to demonstrate that collaboration between supermarket owners and real estate owners can be beneficial for both parties. This is done by modeling, energy measurements, theoretical calculations, and business model evaluation. A report (in Swedish) has been published [17]

2.3.2.7 Handling of low-GWP refrigerants from installation to destruction

A long list of synthetic refrigerant blends with relatively low GWP has been suggested by the chemical industry during the last ten years. Most of these blends contain HFCs with double bonds, often referred to as HFOs. The advantage of these refrigerants has been considered to be the low GWP-values. These values are low because the molecules are unstable in the natural environment outside of the heat pump system. However, it is of vital importance that any refrigerant is stable for the entire lifetime of the system as long as it is contained inside. One purpose of this project is to investigate possible changes in the composition of the refrigerant blends in the actual system over time. For this purpose, the used refrigerant from systems that have been in operation for several months or years is collected and analyzed with gas chromatography. The project is also in connection with industry partners concerning problems that may be related to the refrigerant. In one case, a refrigerant bottle containing R513A (56% R1234yf, 44% R134a) gave off a foam when the valve was opened (see Figure 2-51). This foam was analyzed by FTIR, and it was found that the foam had no C=C double bonds. Further analysis will follow, but it seems that the most probable reason is that the R1234yf has polymerized in the bottle. Other sources have reported similar experiences previously. One aim of the project is thus to explain under what conditions such polymerization can take place.

Figure 2-51: Bottle of R513A giving off a white foam when the valve is opened.

2.3.2.8 Heat exchanger designs

All refrigerants with low GWP (<150) used or suggested for heat pumps at moderate temperatures are flammable. To reduce the risks of flammable refrigerants, it is important to reduce the charge as much as possible. Up to now, charge reduction has not been important for the manufacturers of components or the designers of heat pump systems, but in the future, this will most probably be very different. In private communication with manufacturers, we hear that many of them have realized this and are now working on new components and systems with lower charges. As a large share of the refrigerant charge is located in the heat exchangers, the development of these components is highly important. At the KTH, three projects are running and connected to heat exchangers and heat transfer. The projects are not directly connected to low-GWP refrigerants but can contribute to a better understanding of the processes in the evaporator and condenser of heat pump systems and thereby to enhanced performance of these components and decreased charge of refrigerant.

2.3.2.8.1 Evaporative heat transfer in flat channels

To reduce the internal volume of a heat exchanger a natural step is to use flat channels rather than circular channels. This is already implemented, e.g., in plate heat exchangers, where the development is now going towards smaller pressing depths and thereby lower volume with maintained surface area. In this project, the fundamentals of evaporation in flat channels are investigated. The goal is to increase the understanding of the evaporative process around bubbles in a high aspect ratio (flat) channel. The intention is to use a high-speed IR camera to determine the temperatures on the inside surface of the evaporator channel as growing bubbles are passing through the channels. The first results are expected by the end of 2024.

2.3.2.8.2 Highly efficient heat exchangers manufactured with additive manufacturing

Additive manufacturing is a new method of producing complex structures, not only in plastic/polymer materials but also in different metals. By this method, complex heat exchanger surfaces like the ones shown in Figure 2-52 can be produced. In the initial phase of this project, surfaces for single phase heat transfer will be produced and tested, but in the following phase, designs suitable as evaporators and condensers will be developed with the purpose of enhancing heat transfer and reducing the necessary volume of the heat exchangers, thereby reducing the necessary charge of refrigerant.

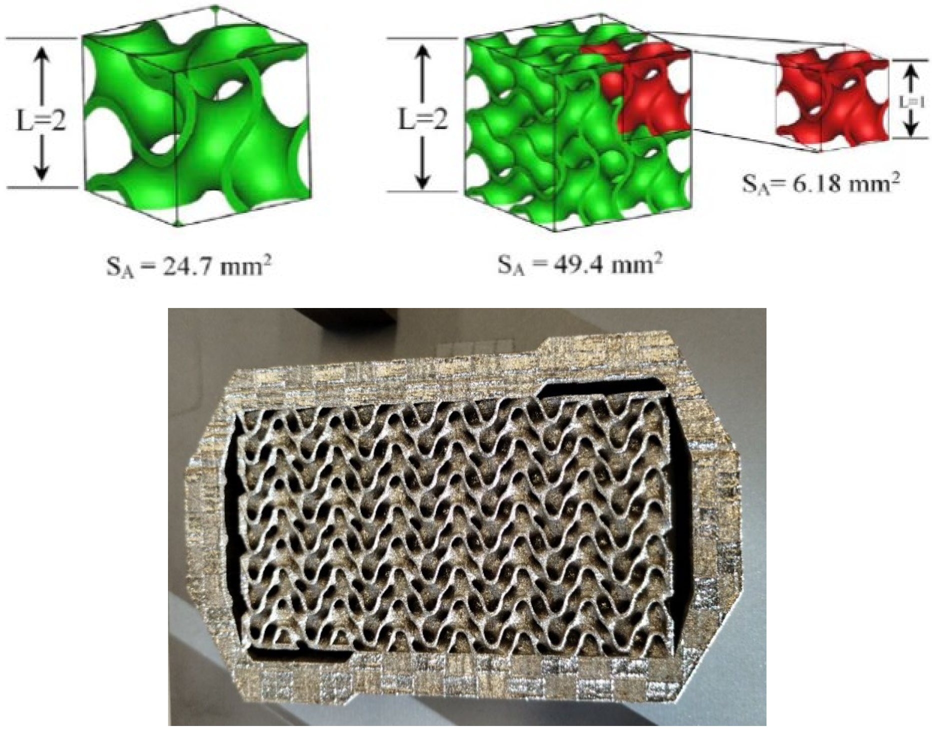
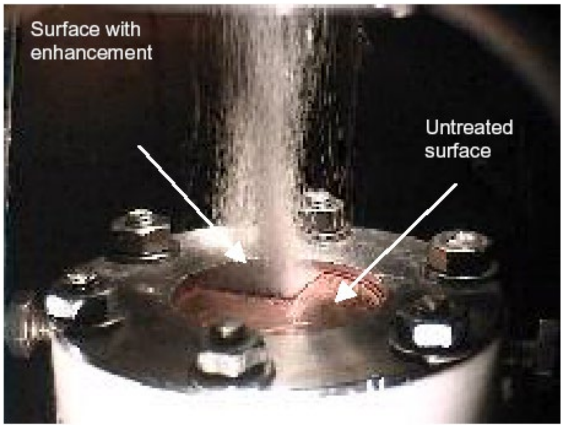


Figure 2-52: Drawing and photo of heat exchanger with large surface area compared to volume. Prototype in stainless steel produced at KTH using additive manufacturing.

2.3.2.8.3 Porous surfaces for enhancing boiling heat transfer

It is well known that boiling heat transfer can be enhanced by using porous surfaces where traces of gas can hide in pores in between the release of bubbles from the surface. In this project, electroplating is used for producing microporous nanostructured surfaces which have been shown to give extremely high boiling heat transfer coefficients, in some cases up to 10 or even 15 times higher than smooth surfaces. Figure 2-53 shows a picture of a heated plate where one-quarter of the surface is covered by this surface. As shown, boiling takes place only on this quarter of the surface. To the right is a photo of the same surface as seen through an electron microscope. Presently, a project is ongoing aiming at optimizing the structure for different refrigerants and different applications.



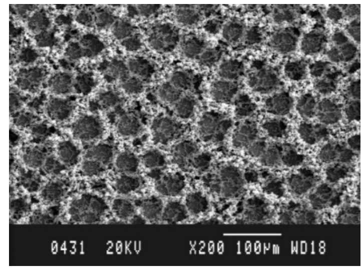


Figure 2-53: Boiling on a surface partly covered by micro-porous nano-structured surface (left); Photo of surface as seen in the electron microscope (right).

2.3.3 A study of market opportunities of low-GWP refrigerants in Sweden, Analysis of collected data from xix heat pump manufacturers

2.3.3.1 Introduction

This report is about a survey that was conducted under Work Package 4 to collect data and insights about the outlook of low global warming potential (GWP) refrigerants to 2030. The survey investigated and studied the market opportunities of heat pumps with low-GWP refrigerants and their availability while considering possible standards and bottlenecks for implementing these refrigerants within Sweden. It's important to note that the survey was conducted before the F-gas regulation was accepted, and the knowledge of the IEC 60335-2-40:2022 standard might not have been widely known at that time.

2.3.3.1.1 Background

The survey was designed to contribute to market research that investigated the impact of current standards on refrigeration, air conditioning, and heat pump applications. The findings from the study aimed to identify opportunities and research efforts necessary to implement low-GWP refrigerants in order to eliminate existing barriers in the relevant industry standards.

2.3.3.1.2 Context and Research Question and Objectives

The target audience for the survey included system manufacturers, end-users, trade bodies, researchers, national authorities, contractors, technicians, distributors, and nonprofit organizations (NPOs). The survey aimed to investigate the status quo and outlook for low GWP refrigerant-based systems, including drivers and barriers for their uptake, energy efficiency, cost compared to HFCs, availability of products using multiple refrigeration circuits, expectations about future use, and willingness to work with higher refrigerant charges.

The research objectives were to study the market opportunities for heat pumps with low-GWP refrigerants and low-GWP refrigerant availability at different levels for 2030. The survey also aimed to identify possible standards and bottlenecks for implementing these refrigerants in Sweden. The findings were intended to contribute to market research that investigated the impact of current standards on refrigeration air conditioning and heat pumps (RACHP) applications and the introduction of low-GWP refrigerant-based technology in particular. Additionally, the survey aimed to identify what opportunities and research efforts were necessary to implement low-GWP refrigerants and eliminate existing barriers in the relevant industry standards.

2.3.3.2 Literature Review

The use of refrigerants in heating, ventilation, air conditioning, and refrigeration (HVAC&R) systems significantly impacts the environment. The most common refrigerants in use today, such as hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs), have been found to contribute to ozone depletion and climate change. The Montreal Protocol of 1987 and the subsequent Kigali Amendment of 2016 aimed to phase out the use of these refrigerants and promote the adoption of low GWP alternatives.

Low-GWP refrigerants, such as hydrofluoroolefins (HFOs), hydrocarbons (HCs), and carbon dioxide (CO_2), have been identified as potential alternatives to high-GWP refrigerants. HFOs do have GWPs that are up to 99% lower than HFCs, which are commonly used in HVAC&R systems. However, while HFOs have been found to be energy-efficient and safe for use in HVAC&R systems, they may not be universally safe for all applications, and more research is needed to fully understand their potential environmental and health impacts. Additionally, the use of HFOs in HVAC&R systems may require modifications to equipment and infrastructure, which can increase costs. HCs, such as propane and isobutane, are natural refrigerants with GWPs close to zero, and they have been used as alternatives to HFCs in some applications.

Heat pumps are widely used in Sweden for space heating and domestic hot water production, and they can also be used for cooling. The market opportunities for heat pumps with low-GWP refrigerants have been growing in recent years. With the phasing out of high-GWP refrigerants, there is a need for heat pumps that use low-GWP refrigerants. The European Union's F-gas Regulation has set out a timeline for the phasing down of HFCs, which is expected to create a market opportunity for low-GWP refrigerants.

Existing standards and regulations for low-GWP refrigerants vary by country and region. In Sweden, the Swedish Environmental Protection Agency (EPA) has set out regulations for the use of refrigerants with low GWP in refrigeration and air conditioning systems. The regulations require a gradual phase-out of HFCs and other high-GWP refrigerants and the adoption of low-GWP alternatives. However, there are still barriers to the implementation of low-GWP refrigerants, including concerns about safety, compatibility with existing systems, and availability. There are, of course, EU laws and directives that apply to all EU members. The F-gas regulation will influence all these countries.

In addition, the adoption of low-GWP refrigerants is also dependent on the availability of these refrigerants, i.e. synthetic fluids (HFOs). The availability of low-GWP refrigerants at different levels for 2030 is a critical consideration for manufacturers of HVAC&R equipment, including heat pumps. The availability of low-GWP refrigerants will depend on several factors, including the rate of production and the ability to scale up production to meet demand.

The implementation of low-GWP refrigerants in Sweden also requires compliance with existing standards and regulations. There are several relevant industry standards in Sweden, including the European standard EN378 and the Swedish standard SIS CEN/TR 16247. These standards provide guidelines for the safe use of refrigerants in HVAC&R systems, including heat pumps. Compliance with these standards can be a barrier to the adoption of low-GWP refrigerants, as manufacturers may need to modify their systems or obtain certification to ensure compliance.

Overall, the literature suggests that the adoption of low-GWP refrigerants in heat pumps presents significant market opportunities but also faces several barriers related to standards, regulations, and availability when it comes to synthetic refrigerants. The findings of this study aim to contribute to the existing literature by identifying the perspectives of Swedish heat pump manufacturers on the market opportunities and barriers to the implementation of low-GWP refrigerants in their products.

2.3.3.3 Methodology

The research employed a mixed-methods approach that included both qualitative and quantitative data collection methods. The study involved conducting one-to-one interviews with six Swedish heat pump manufacturers or having them complete an online survey. The survey included both open-ended and close-ended questions to collect data on various aspects of the heat pump manufacturing process. The use of both qualitative and quantitative methods allowed the researchers to collect comprehensive data that captured both subjective experiences and objective measurements.

2.3.3.3.1 Sample Selection and Data Collection Methods

The sample for this study comprised six Swedish heat pump manufacturers: CTC/Enertech, Bosch Thermoteknik AB, Qvantum Energi AB, Enrad AB, NIBE, and Thermia. The researchers chose these companies based on their market share and the number of units sold. The sample size was relatively small due to the limited number of heat pump manufacturers in Sweden. The data were collected through one-to-one interviews or online surveys. The researchers used a semi-structured questionnaire that included both open-ended and close-ended questions. The interviews were conducted by the researchers themselves and lasted approximately 30 minutes, while the online survey took around 14 minutes to complete.

2.3.3.3.2 Data Analysis Techniques

The researchers used both qualitative and quantitative data analysis techniques. The qualitative data collected from the open-ended questions in the interviews and surveys were analyzed using thematic analysis. The thematic analysis involved identifying patterns, themes, and categories in the data. The researchers used a deductive approach to identify themes and categories based on the research objectives and the literature review. The quantitative data collected from the close-ended questions were analyzed using descriptive statistics, such as mean, median, and mode. The data were analyzed using statistical software to identify patterns and trends. The researchers used a mixed-methods approach to integrate the qualitative and quantitative data to provide a comprehensive understanding of the heat pump manufacturing process in Sweden.

The questionnaire was distributed online to individuals and organizations involved in the heat pump industry in Sweden. The questionnaire consisted of multiple-choice questions, rating scales, and open-ended questions.

The questionnaire asked the companies to provide information about the current refrigerants they use and the alternative low-GWP refrigerants they are considering for high-pressure, medium-pressure, low-pressure, and refrigeration applications. In addition, the questionnaire asked about the demand for low-GWP refrigerants, the short-term, medium-term, and long-term barriers to market penetration, the growth opportunities, and the factors that have been decisive in the selection of refrigerants.

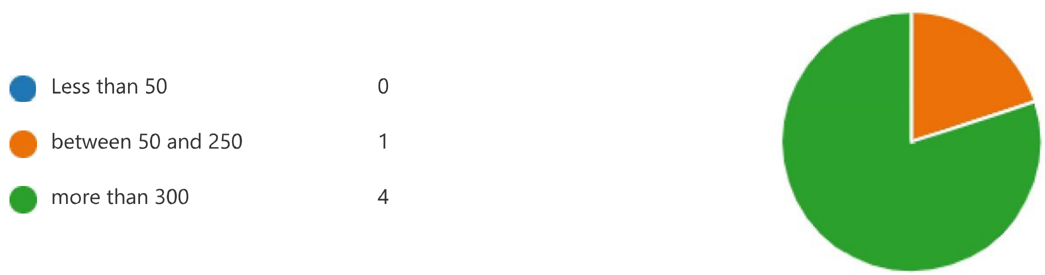
The companies were also asked about the short-term, medium-term, and long-term growth drivers for market penetration of low-GWP refrigerants, as well as issues related to flammability, toxicity, and lubricant compatibility. The questionnaire also asked about the knowledge that is needed regarding the new refrigerant, both within the company and in the industry, and whether additional developments are needed for existing product or service offerings. The companies were also asked about their commitment to the transition to low-GWP refrigerants, their interest in contributing to standardization and safety measures for the new low-GWP refrigerants, and the top players/companies of the refrigerant market in Sweden.

2.3.3.4 A Study of Market Opportunities of Low-GWP Refrigerants in Sweden: Analysis of Collected Data from Six Heat Pump Manufacturers

This section provides a comprehensive analysis of data collected from six leading Swedish heat pump manufacturers - Bosch, Qvantum, Thermia, Enrad AB, Enertech, and NIBE. The manufacturers vary in size, and all of them are engaged in the production and sale of heat pumps. The aim of this report is to present an in-depth analysis of the market opportunities for heat pumps with low-GWP refrigerants, availability of low-GWP refrigerants at different levels for 2030, standards and bottlenecks for implementing low-GWP refrigerants in Sweden, industry perspectives on the impact of current standards on RACHP applications, and opportunities and research efforts necessary to implement low-GWP refrigerants and eliminate existing barriers. This section will delve into each of these topics in detail, providing insightful findings and recommendations for stakeholders in the heat pump industry.

2.3.3.4.1 Results and Analysis of data collected.

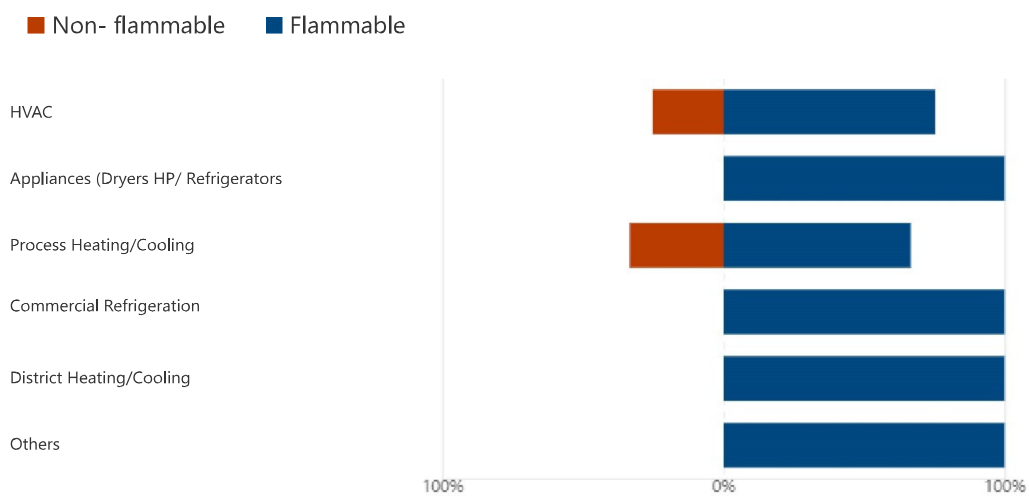
The purpose of this report is to analyze the data obtained from a questionnaire designed to investigate the market opportunities of heat pumps with low-GWP refrigerants and the availability of these refrigerants in Sweden. The study was conducted with a focus on the year 2030 and the possible standards and bottlenecks for implementing these refrigerants within the country. Below each question will be discussed based on the results obtained from the manufacturers.



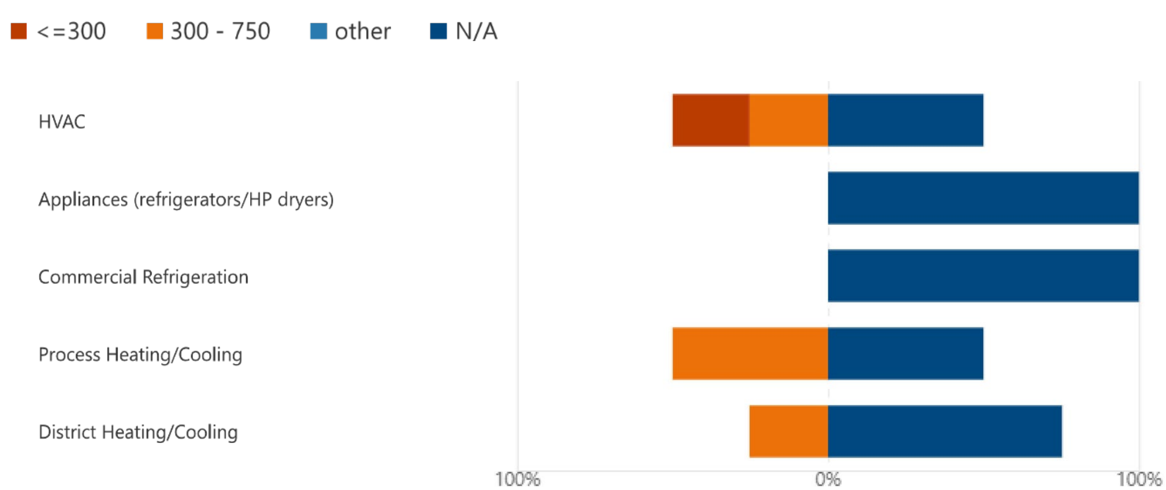
This question asks for the number of employees the company has, with three answer choices: less than 50, between 50 and 250, and more than 300. There were 4 respondents who selected "more than 300", and one company selected between 50 and 250.

This question asks which of the following the company deals with the production of heat pumps, the sale of heat pumps, the production of components, the installation of heat pumps, or "other".

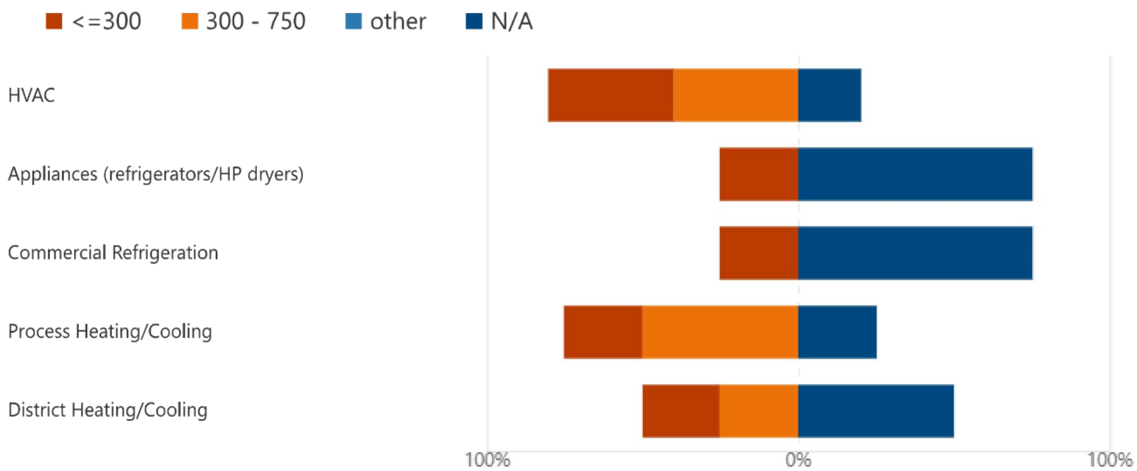
There were 5 respondents who selected "the production of heat pumps" and 4 who selected "the sale of heat pumps".



This question asks which end-uses the respondent considers their primary target(s) to support the global transition to low-GWP refrigerants, with options including HVAC, appliances (dryers/HP refrigerators), process heating/cooling, commercial refrigeration, district heating/cooling, and "others". There is also a choice between non-flammable and flammable refrigerants. The respondent can choose multiple answers.



This question asks which GWP range the respondent is currently targeting for alternative low-GWP non-flammable refrigerants for HVAC, appliances (refrigerators/HP dryers), process heating/cooling, commercial refrigeration, and district heating/cooling, with answer choices including <=300, 300-750, "other", and N/A.



This question is similar to the question above but for low-GWP flammable refrigerants.

This question asks which low GWP refrigerant substitutes the respondent is working on, with answer choices including high-pressure equivalent, medium-pressure equivalent, low-pressure equivalent, refrigeration (R-404A-like), and "other". The majority of respondents (3 out of 5) are working on developing high-pressure equivalent refrigerants. One respondent is working on developing medium-pressure equivalent refrigerants.

5

Responses

Latest Responses

"R-410A R290"

"R410A, R452B, R454B"

"R32"

This question asks respondents to list the current refrigerant and the alternative low-GWP refrigerants they are considering for each of their **high-pressure applications**. There are 5 responses for this question, which mentions R407C replaced by R454C or R290 and R410A replaced by R290, (R407C → R290), R32, (R410A R452B, R454B) and (R-410A, R290) as their high-pressure applications.

2

Responses

Latest Responses

"R32, R513"

"R290"

This question asks respondents to list the current refrigerant and the alternative low-GWP refrigerants they are considering for each of their **medium-pressure applications**. There are 2 responses to this question, which mention R290 (R32, R513) considered as their medium-pressure applications.

3

Responses

Latest Responses

"R-410A R290"

"R290, R452B, R454B, R32"

"R290"

This question asks to list the current refrigerant and the alternative low-GWP refrigerants the respondents are considering for each of their refrigeration applications. There are 3 responses to this question, which mention R407c replaced by R454c or R290 and R410A replaced by R290, R32, R452B, R454B, and (R-410A, R290) for their considered refrigeration applications. R290, R452B, and R454B were identified as the alternative low-GWP refrigerants that are being considered for high-pressure applications. For medium-pressure applications, R32 and R573 are being considered as alternative low-GWP refrigerants. R290, R4528, R4548, and R32 are being considered as alternative low-GWP refrigerants for refrigeration applications.

2

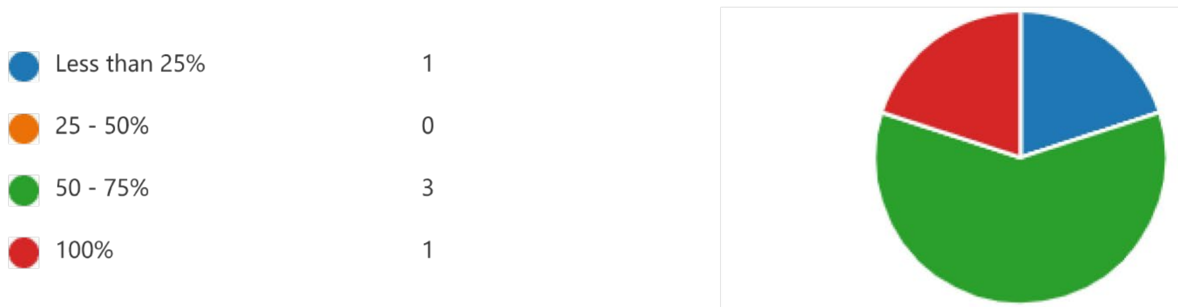
Responses

Latest Responses

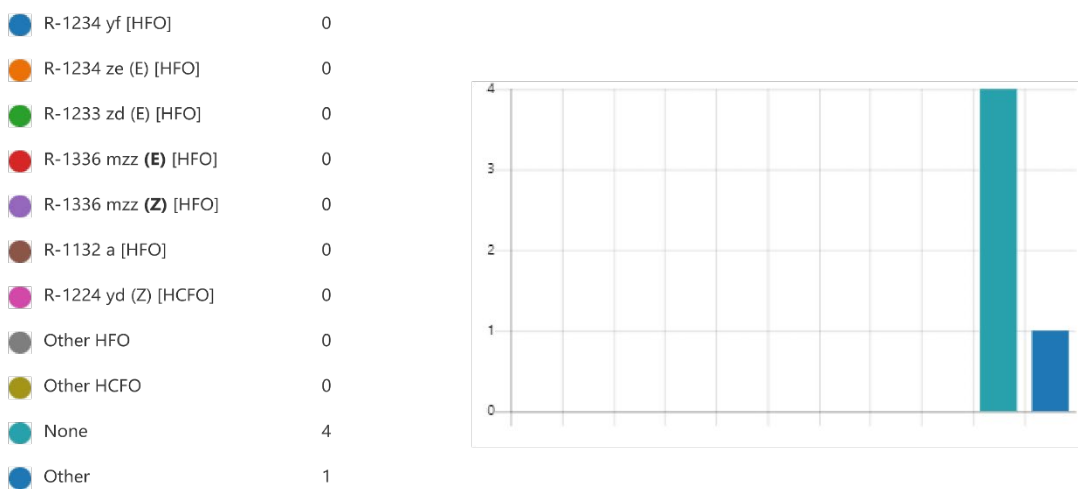
"N/A"

"R290, R32"

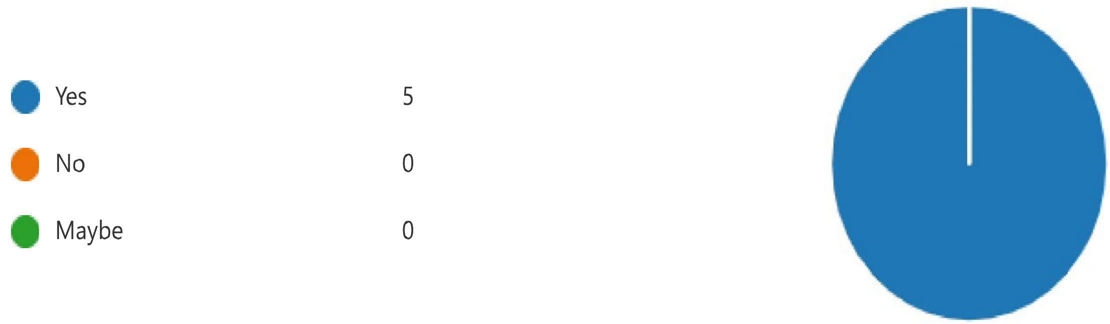
Please list the current refrigerant and the alternative low GWP refrigerants you are considering for any other applications. There are 2 latest responses to this question, both of which mention R290 and R32 as alternative low GWP refrigerants.



This question asks for the approximate percentage of the respondent's production facilities that can produce products that use low GWP refrigerants with a GWP < 700, with answer choices including less than 25%, 25-50%, 50-75%, and 100%. Out of the 5 responses, 3 companies reported that 50-75% of their production facilities can produce products that use low GWP refrigerants. In contrast, 1 company reported that 100% of their production facilities can produce products that use low GWP refrigerants. One company reported less than 25%, and no company reported 25-50% of their production facilities as capable of producing low GWP refrigerants.



This question asks which low GWP single-component refrigerants the respondent produces, with answer choices including R-1234yf [HFO], R-1234ze(E) [HFO], R-1233zd(E) [HFO], R-1336mzz(E) [HFO], R-1336mzz(Z) [HFO], R-1132a [HFO], R-1224yd(Z) [HCFO], other HFO, other HCFO, none, and "other". Out of the 5 responses, 4 companies reported that they do not produce any of the listed low GWP single-component refrigerants.



This question asks whether the market demand for low-GWP refrigerant is growing, with answer choices including yes, no, and maybe. All 5 companies responded that the market demand for low-GWP refrigerants is growing.

5
Responses

Latest Responses

"Risk for diffrent flameabale regulations for outdoor produkts in differe...

"Safety issues due to its flammability and the requirements that needs ...

"Availability of products to install"

This question asks the respondent to identify the greatest short-term barrier to market penetration of low-GWP refrigerants. The 5 latest responses to this question mention the following as the greatest short-term barrier to market penetration of low-GWP refrigerants:

Safety issues due to its flammability and the requirements that need to be fulfilled for higher charges are mainly related to R290.

- Different flammable regulations for outdoor/indoor products in different countries,
- Availability of products to install.
- Regulation, e.g. critical charge volumes of mildly flammable refrigerants. and
- Availability of mature and reliable components

5
Responses

Latest Responses

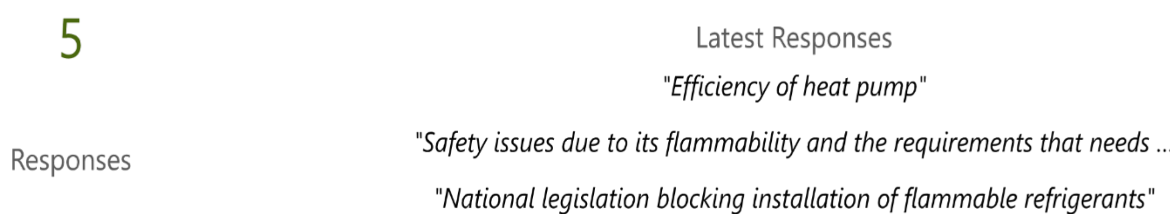
"Risk for diffrent flameabale regulations for Indoor produkts in differen...

"Safety issues due to its flammability and the requirements that needs ...

"availability of installers and service technicians with proper training t...

This question asks the respondent to identify the greatest medium-term barrier to market penetration of low-GWP refrigerants. Similarly, the 5 latest responses to this question mention the following as the greatest medium-term barrier to market penetration of low-GWP refrigerants:

- Safety issues due to its flammability and the requirements that need to be fulfilled for higher charges, mainly related to R290,
- Different flammable regulations for outdoor/indoor products in different countries,
- Availability of products to install,
- Regulation, e.g. critical charge volumes of mildly flammable refrigerants, and
- In case HPs using low-GWP refrigerant cause accidents in the near future, it will be very detrimental for this technology



This question asks the respondent to identify the greatest long-term barrier to market penetration of low-GWP refrigerants. The 5 latest responses to this question mention the following as the greatest long-term barrier to market penetration of low-GWP refrigerants:

- The efficiency of the heat pump,
- Safety issues due to its flammability and the requirements that need to be fulfilled for higher charges and mainly related to R290,,
- National legislation blocking the installation of flammable refrigerants,
- Regulation, e.g. critical charge volumes of mildly flammable refrigerants, and
- Ban of synthetic refrigerants might limit the refrigerant choice

Which type of refrigerant presents the major growth opportunity in your business over the next five years? Of the 5 responses, 3 companies mentioned R290 and one mentioned “Natural refrigerants”. Two companies mentioned CO2, and another mentioned Hydrocarbons (HC) and Ammonia (NH_3) as the major growth opportunities in their business over the next five years.

3

Responses

Latest Responses

"More climate friendly."

"Customers requesting products that are environmental friendly and w...

In response to the question, "What do you see as the greatest short-term opportunities for market penetration of low-GWP refrigerants?" Two companies responded that customers are increasingly requesting products that are environmentally friendly, and one company mentioned that the revision of the FGAS regulation would push the industry towards low-GWP refrigerants.

3

Responses

Latest Responses

"Supports the green deal."

"increasing costs of high GWP refrigerants will make products with low...

Regarding the greatest medium-term opportunities for market penetration of low-GWP refrigerants, two companies responded that increasing costs of high-GWP refrigerants would make products with low-GWP refrigerants more competitive, and one company mentioned that low-GWP refrigerants support the green deal, and one company mentioned the revision of the REACH (2025) and the possible ban of PFAS.

3

Responses

Latest Responses

"Supports the green deal."

"Big scale replacement of gas and oil boilers with heat pumps require l...

For the greatest long-term opportunities for market penetration of low-GWP refrigerants, one company responded that low-GWP refrigerants support the Green Deal. One company mentioned that there would be a big-scale replacement of gas and oil boilers with heat pumps that require low-GWP refrigerants. One company mentioned most of the HPs will use low GWP refrigerants: components will be widely available, costs will drop, the installer will be trained, and HPs will become the norm.

5

Responses

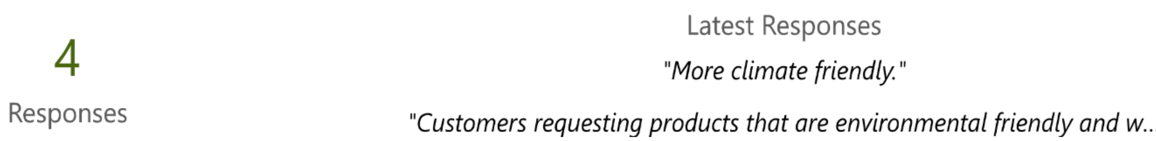
Latest Responses

"EU Regulations . "

"The level of GWP and flammability."

"Fulfilling future regulations and gives high efficiency"

In response to the question, "Please describe what has been decisive in the selection of refrigerant?" three companies mentioned fulfilling future regulations and ensuring high efficiency, and two companies mentioned EU regulations and the level of GWP and flammability.



The greatest short-term growth drivers for market penetration of low-GWP refrigerants, according to four companies:

- The revision of the FGAS regulation,
- End-customer expectations of regulatory need to shift to low-GWP in combination with the end-customer internal sustainability targets,
- Customers requesting products that are environmentally friendly and will fulfill future regulations, and
- More climate-friendly

The greatest medium-term growth drivers for market penetration of low-GWP refrigerants, according to four companies:

- They are more climate-friendly,
- The upcoming F-gas regulations,
- Tightening regulation for high-GWP refrigerants and enabling regulation for low-GWP, and
- Obligation to minimize the environmental footprint of HPs

4

Responses

Latest Responses

"More climate friendly."

"Competitive cost of products and installations"

The greatest long-term growth drivers for market penetration of low-GWP refrigerants, according to four companies:

- They are more climate-friendly,
- Have a competitive cost of products and installations,
- Tightening regulation for high-GWP refrigerants and enabling regulation for low-GWP, and
- Our own will to make more sustainable products

In response to the question, "We have sufficient knowledge within the company regarding the new refrigerant, for example:

- Flammability", four companies agreed, and one company responded Neither agree nor disagree,
- Toxicity", one company agreed; two companies selected Neither agree nor disagree and one company responded disagree, and one company selected Strongly disagree
- Lubricant compatibility ", two companies agreed, and three companies responded Neither agreed nor disagreed

3

Responses

Latest Responses

"Increased knowledge within the area of PFAS and toxicity."

"how to handle high flammability refrigerants"

Regarding the knowledge needed within the company and industry regarding the new refrigerant, one company responded that increased knowledge within the area of PFAS and toxicity is needed, one company mentioned knowing how to handle high flammability refrigerants, and one company mentioned knowledge in thermodynamic and mechanical design are needed.

5

Responses

Latest Responses

"mayor changes in factory and commpressor units . "

"Don´t know"

"Yes, most of the time completely new products"

In response to the question, "Are additional developments needed for the existing product or services offerings or do the existing products meet the customer demands?" one company responded that major changes in factory and compressor units are needed, one company said that they do not know, one company said that most of the time completely new products are needed, and one company mentioned need to reduce the charge size and to ensure compliance with safety standards.

Yes	4
No	0
Maybe	1
Other	0

In response to the question, "Do you trust that the compressor manufacturer has full knowledge of the choice of lubricating oil?" four companies answered yes, and no companies answered no.

4

Responses

Latest Responses

"Yes"

"Do not use refrigerants in the to be banned list in new products"

Regarding PFAS/TFA in refrigerants, one company responded yes, which is a topic we are closely following. One company responded yes and mentioned not using refrigerants in the to-be-banned list in new products.

5
Responses

Latest Responses

"LOW GWP and high efficincy "

"Safety issues and fulfill the requirements of ventilation."

"requirement of GWP < 150 in products to be installed indoors with > ...

When asked about the most difficult legal requirements to deal with, five companies mentioned low GWP and high efficiency, and one company mentioned safety issues and fulfilling the requirements of ventilation. One company mentioned the requirement of GWP < 150 in products to be installed indoors with > 12 kW. One company mentioned Critical charge levels, and one responded with compliance with the safety directives.

2
Responses

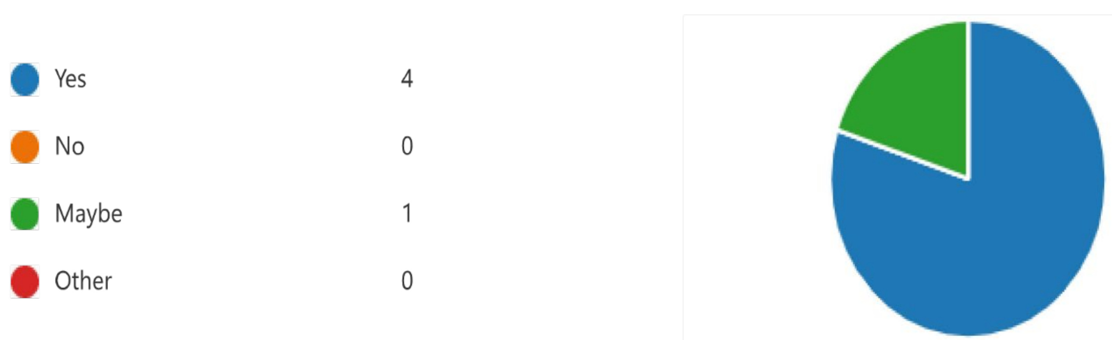
Latest Responses

"?"

"Safety concepts for highly flammable refrigerants"

In response to the question, "What are the recent innovations in the market?" one company mentioned safety concepts for highly flammable refrigerants.

Regarding commitment to the transition to low-GWP refrigerants, three companies responded as 10/10 committed, and two companies responded as 8/10 committed.



When asked if they were interested in contributing to standardization and safety measures for the new low GWP refrigerants, four companies answered yes, and no companies answered no.

2.3.3.5 Discussion

The survey results showed that R290 is the most widely considered low-GWP refrigerant substitute, followed by R32, R454B, R452B, and R513. For high-pressure applications, R290 is considered a substitute for R407C and R410A, while R290 and R32 are considered substitutes for R513 in medium-pressure applications. For refrigeration applications, R290 is the most commonly considered substitute, followed by R452B, R454B, and R32. R290 and R32 are also considered as alternative refrigerants for other applications.

All six Swedish heat pump manufacturers interviewed acknowledged the growing demand for low-GWP refrigerants in the market. It's important to note that the survey was conducted before the F-gas regulation was accepted, and the knowledge of the IEC 60335-2-40:2022 standard might not have been widely known at that time.

They all agreed that there is a significant market opportunity for heat pumps that use low-GWP refrigerants, especially in commercial and industrial applications. The manufacturers indicated that they were investing in research and development to produce heat pumps that meet the growing demand for low-GWP refrigerants. Around 70% of the respondents believed that there would be a significant increase in the demand for heat pumps with low-GWP refrigerants by 2030. The narrative brings up a critical point regarding the potential application of low-GWP refrigerants in domestic heat pumps. Despite the regulatory framework favoring low-GWP refrigerants and their evident market potential, the respondents' divergence in opinion suggests a gap in understanding or strategy. The restriction on HFCs and HFOs for systems below 12kW underscores the significance of targeting this segment for low-GWP refrigerants, yet the reasons for the respondents' differing views warrant exploration. Understanding the rationale behind their perspectives could shed light on potential barriers or opportunities in the domestic heat pump market, facilitating informed decision-making and strategic planning for industry stakeholders.

The survey results also revealed the greatest short-term barrier to market penetration of low-GWP refrigerants to be the availability of mature and reliable components, followed by regulation, availability of products to install, and safety issues due to flammability and requirements that need to be fulfilled. For the medium term, the greatest barriers are regulation, availability of installers and service technicians with proper training to handle flammable refrigerants, and safety issues due to flammability and requirements that need to be fulfilled. For the long term, companies reported that the ban on synthetic refrigerants might limit the refrigerant choice, national legislation blocking the installation of flammable refrigerants, and the efficiency of heat pumps as major barriers to market penetration.

Furthermore, the results also show that the lack of government policies and regulations was the most significant barrier. Around 45% of the respondents believed that the lack of regulations and policies was the most significant challenge. Other bottlenecks for synthetic refrigerants included the high cost of low-GWP refrigerants, lack of training and awareness, and the limited availability of low-GWP refrigerants.

The heat pump manufacturers identified several standards and bottlenecks that could hinder the implementation of low-GWP refrigerants in Sweden. However, the IEC and F-gas regulations will change this once implemented. They mentioned the need for new regulations and policies to support the use of low-GWP refrigerants, as well as the need for standards to be updated to reflect the use of these refrigerants. They also noted that the lack of awareness and knowledge about low-GWP refrigerants among end-users and installers was a significant bottleneck.

The heat pump manufacturers identified several opportunities and research efforts necessary to implement low-GWP refrigerants and eliminate existing barriers. They mentioned the need for increased research and development of low-GWP refrigerants and heat pumps that use these refrigerants. They also highlighted the importance of education and awareness campaigns to increase knowledge and understanding of low-GWP refrigerants among end-users, installers, and policymakers. Additionally, they emphasized the need for regulations and policies to support the use of low-GWP refrigerants and reduce the use of high-GWP refrigerants.

2.3.3.6 Conclusions and Recommendations: Key Takeaways from the Survey

The survey aimed to collect data and insights about the outlook of low GWP refrigerants to 2030. The findings were intended to contribute to market research investigating the impact of current standards on RACHP applications and low GWP refrigerant-based technology. The survey identified opportunities and research efforts necessary to implement low-GWP refrigerants and eliminate existing barriers in the relevant industry standards. The survey was available online, and heat pump manufacturers could participate through interviews or by completing the online survey.

Based on the responses provided, it appears that the companies are interested in transitioning to low-GWP refrigerants, but there are some short-term, medium-term, and long-term barriers to market penetration. The companies identified the availability of mature and reliable components, the ban on synthetic refrigerants, and legal requirements as some of the challenges that need to be addressed. However, the companies also identified the revision of the FGAS regulation and the transition to low-GWP refrigerants as growth opportunities.

In addition, the medium-term barrier was identified as a safety issue due to flammability and the availability of installers and service technicians with proper training. The long-term barrier was identified as the difficulty in finding skilled workers with knowledge and experience to work with low-GWP refrigerants.

The survey results suggest that the market demand for low-GWP refrigerants is growing, and HVAC is identified as the primary target for the transition to low-GWP refrigerants. The greatest short-term barrier to market penetration of low-GWP refrigerants is the risk of different flammable regulations for outdoor products in different countries, while the greatest medium-term barrier is safety issues due to the flammability of low-GWP refrigerants and the requirements that need to be met. Lack of government support and incentives is the greatest long-term barrier to market penetration of low-GWP refrigerants.

All companies reported that they were working on high-pressure equivalent substitutes for their applications, and only two companies reported working on medium-pressure equivalents. In contrast, no companies reported working on low-pressure equivalents or refrigeration substitutes. Regarding the production of low-GWP single-component refrigerants, none of the companies reported producing them.

The survey results reveal that low-GWP heat pumps and refrigerants are gaining momentum in the Swedish market, and the demand is expected to grow in the future. However, there are several barriers to market penetration, especially related to regulation, safety issues, and the availability of mature and reliable components. **The companies that participated in the survey are working on low-GWP refrigerant substitutes, mainly R290, and are considering it as a substitute for various applications**. The availability of products to install and the efficiency of heat pumps are also major factors that need to be considered for the long-term success of low-GWP refrigerants. Overall, the findings of this survey suggest that the Swedish market has significant potential for low-GWP heat pumps and refrigerants, and further research and development efforts are required to overcome the barriers to market penetration.

The study concludes that there is a significant market opportunity for heat pumps with low-GWP refrigerants in Sweden. However, the lack of government policies and regulations is a significant bottleneck for implementing these refrigerants. The study recommends that the Swedish government introduce new regulations and standards to promote the use of low-GWP refrigerants. Additionally, the study suggests that more training and awareness programs be initiated to increase the knowledge and understanding of low-GWP refrigerants among stakeholders in the heat pump industry.

Overall, the questionnaire provides valuable insights into the market opportunities and challenges related to the transition to low-GWP refrigerants in Sweden. The information collected can be used to inform policy decisions, promote the development of new technologies and products, and guide the efforts of companies in the HVAC, appliances, process heating/cooling, commercial refrigeration, and district heating/cooling sectors.

2.3.4 Highlights of the most significant accomplishments during the entire Annex 54 period

The most important event for the introduction of low-GWP refrigerants during the Annex 54 period from a European point of view is probably not a research accomplishment or a new product. Instead, it is the formulation of the new F-gas regulation, which was finally negotiated in October 2023 and signed by the European Parliament and the Council of Ministers at the beginning of February 2024. This regulation will force the phase down of the use of HFC refrigerants at a rapid pace in the coming six years, and a total phase out until 2050. For units below a nominal capacity of 12 kW, there will also be a ban on the use of HFOs from 2035. The regulation has been negotiated for a couple of years and the industry has known what changes were coming. Many producers of heat pumps have therefore already started the development of new, low-charge systems with propane as refrigerant. One example is the Spanish company EcoForest which offers liquid to water propane heat pumps with capacities from 6 to 16 kW. The 6 kW unit has a charge of 150 g of propane. The larger units have about 500 g. The larger units are built to comply with the IEC 60335-2-40:2022, having a tight enclosure which is ventilated to the ambient in case of a leakage inside the enclosure. At least one other company already has a propane unit for placing indoors on the market. Air to water units is usually placed outside and the use of propane is thereby not restricted. Statistics of the applications for government support for heat pump installations in Germany indicate that the share of propane heat pumps was above 20% already in 2022. It is thus clear that the F-gas regulation, and the concerns for the environment connected to the use of HFC and HFO refrigerants is having a direct impact on the type of refrigerant used in heat pumps in Europe. The development may be similar to that of the household refrigerator market, where isobutane systems completely forced the CFC and HFC systems out of the market in a few years. The effect of this regulation is thus larger than any research result or technical invention.

Regarding the research done in Sweden during the cause of the Annex, two projects should be mentioned in particular, EcoPack and Propac. Highlights from these two are described more in detail below.

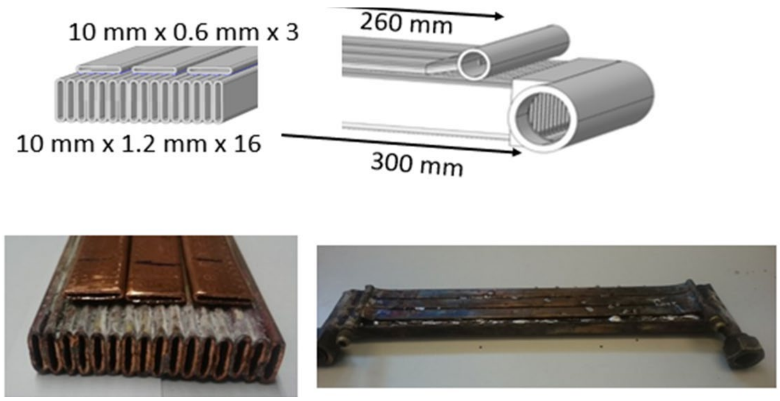


Figure 2-54: Design of internal heat exchanger prototype [15]

In the EcoPack project, it was demonstrated that a heat pump with a heating capacity of 12 kW could be designed to use only 120 g of isobutane as refrigerant [15], [16]. We believe this may be the lowest charge per capacity ever recorded, or at least on par with previous records. This was achieved with a good thermal performance in terms of COPs. The low charge was achieved by using asymmetric plate heat exchangers with low pressing depths as an evaporator and condenser and a rotary compressor with small internal volume and extremely low oil charge. The compressor was of a type normally used for air conditioning of electric vehicles. A prototype desuperheater was used to achieve better performance of the system even though this increased the charge slightly. Figure 2-54 shows drawings and pictures of this heat exchanger.

Figure 2-55: Compressor, Sanden SHS33, used in EcoPack and ProPac projects

The project called ProPac investigated the possibility of designing a split AC unit with 3,5 kW cooling capacity with less than 150g of propane [18]. This project partly built on the experiences of EcoPack described above, and the same compressor was used, see Figure 2-55. A major challenge in this case was the design of the air coil evaporator and condenser. To reduce the charge, multiport flat aluminum tubes were used, but the volume of the headers still was a problem, as indicated in Figure 2-56. Several solutions were investigated, but inevitably these heat exchangers required a larger charge of refrigerant than the plate heat exchangers used in the EcoPack project. Within the project, a new prototype subcooler was also produced, see Figure 2-57, based on the first prototype shown in Figure 2-54. With a connecting tubing of 6 m between the indoor and outdoor unit, the system could run with only 147g of propane, which may be a record for this type of system.

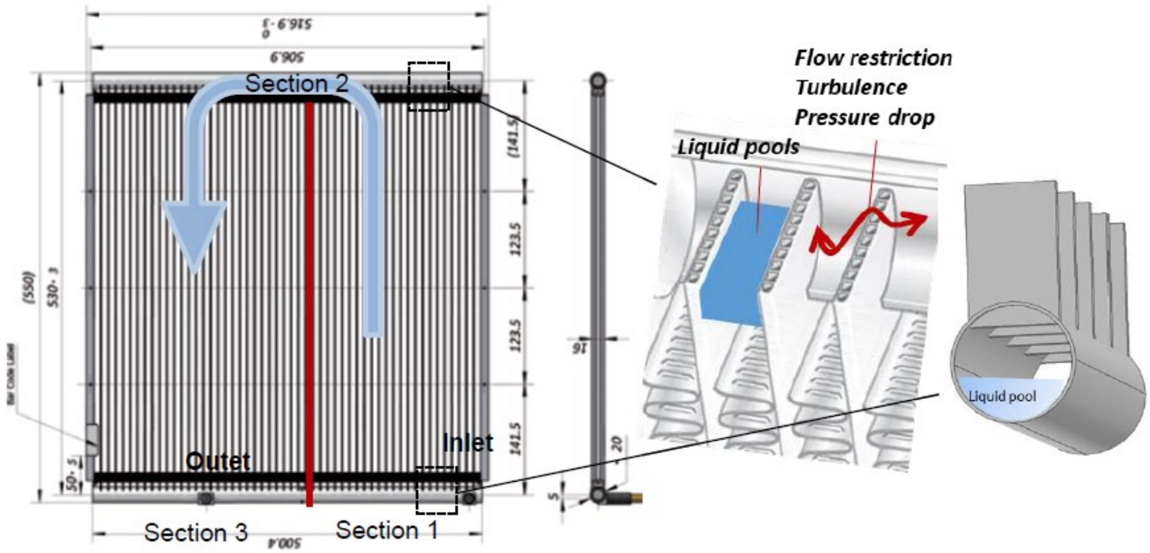


Figure 2-56: One of several condenser designs tested in ProPac.

Figure 2-57: Prototype internal heat exchanger, design based on the experiences from the one shown in Figure 2-54.

Finally, it should be stated that the market investigations done by RISE, and presented in 2.3.3 of this report as well as by the Swedish Refrigeration and Heat Pump Association, presented in the chapter 2.3.1.4, clearly show that the interest in low-GWP refrigerants, and in particular natural refrigerants, has increased substantially during the four years of Annex 54.

2.3.5 Suggestions for tasks for follow-up Annex

From a European perspective, it is obvious that the market will be forced to use low-GWP refrigerants within the coming ten-year period. This is the result of the new F-gas regulation, which will force a fast phase down and then a slow phase-out of HFC-refrigerants. This regulation will also prohibit the use of any F-gases, including HFOs, in systems with capacities below 12 kW, which is the majority of the consumer market. The industry has been complaining about this "fast" change to flammable refrigerants, and there is, therefore, a need for support in terms of research to realize this change.

Independently if HFOs or natural fluids are used, the future refrigerants for normal temperature ranges will be flammable (except for CO2). For this reason, safety aspects will be an interesting area for continued research. This is also specifically the target for the newly started Annex 64. Mentioning tasks for future research will, therefore, include some topics covered by that Annex. Some topics we think may be interesting for the future are the following:

- Compressor designs for low charge
- Heat exchanger designs for low charge
- Selection of oil for low-charge systems
- Methods of mitigating risks in case of leakages

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2.4 Overall conclusions

This report is a summary of work done on several different projects during the last few years. Most of these have been funded by the Swedish Energy Agency or by the EU. Most projects have been connected to either of two research groups: The Division of Applied Thermodynamics and Refrigeration, Department of Energy Technology, KTH, and a branch of RISE Research Institutes of Sweden.

More details about the projects reported here can be found by following the links and references in the text. Some general and specific conclusions from the work are presented here:

- As low GWP refrigerants are, with CO_2 as an exception, flammable, safety has to be considered in a different way than when using high GWP, non-flammable synthetic HFC fluids.
- As a result, the charge of refrigerant in the systems should be minimized, especially if they are to be located indoors.
- As HFC fluids have been considered safe, the volume or mass of refrigerant has not been a concern in the design of HFC systems. Re-thinking the designs to reduce charge is, therefore, to some extent, easy.
- Prototype systems with about 10g of hydrocarbon (or ammonia) per kW of heating capacity have been demonstrated. Components or solutions from the automotive industry (flat aluminum multi-port tubes, compact compressors) could be an inspiration for future developments.
- A large share of the charge of hydrocarbons may be solved in the compressor oil and cannot easily be released. When calculating charges, the standards should take this into account.
- Compressors with less oil should be developed, and the selection of oils should prioritize oils with low solubility.
- In Europe, the new F-gas directive and the discussion on total bans for all PFAS fluids are rapidly driving the development towards the use of natural refrigerants such as hydrocarbons and carbon dioxide.
- Contacts with manufacturers, installers, and importers through Interviews and questionnaires have shown that the industry in Sweden is prepared for the transition but that only a few new products are on the market yet, with the exception of exhaust air heat pumps where propane has been common since many years.
- Hydrocarbon heat pumps for multi-family buildings and industries/offices are marketed by a number of Swedish companies. Some examples of such installations are given in the report.
- CO_2 is becoming the standard choice for supermarket refrigeration systems. Such systems may be combined with heat recovery at different temperature levels, air conditioning, thermal energy storage, etc.

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