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High temperature industrial heat pumps utilising natural working fluids

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ABSTRACT

There is a large demand for heat typically in the temperature range 100-200ºC in different industries. This is today often covered by fossil fuel burning or direct use of electricity. Heat pumps has to a lesser extent been utilized due to higher investment cost and limited availability of systems for these temperatures.

With increasing focus on reduction of emissions and demand for improved energy efficiency the interest in development of high temperature heat pumps is increasing. Through the projects HeatUp and HighEFF the aim has been to develop heat pumps meeting the demands from industry utilizing natural working fluids.

The results show that the natural refrigerants hydrocarbons, steam and fluid mixture ammonia/water all can be applied successfully to supply the required temperatures and demands within different applications. This is supported by experimental results. Economic feasibility of implementation in the industry under different conditions are evaluated and discussed depending on country.

Keywords: Heat Pumps, Natural Refrigerants, Industrial, High Temperature, Energy Efficiency.

1. INTRODUCTION

The Paris agreement and later IPCC reports gives a clear recommendation that emissions of greenhouse gases (GHG) need to be reduced drastically in order to limit the global warming. Heat pumps may contribute to this by reducing electricity needs and by replacing fossil fuels for heating purposes.

For heat pumps the direct emissions related to HFC refrigerants is also important. Chlorine containing refrigerants are being phased out according to the Montreal protocol and phasing down the use of HFC refrigerants in order to reduce the GHG contribution from the sector will take place according to the Kigali amendment to the Montreal protocol.

Refrigerant selection for the future will therefore be principally between Natural refrigerants, e.g. hydrocarbons, ammonia, water, carbon dioxide or their mixtures, or to use new synthetic refrigerants. The society now have knowledge from three generations of synthetic fluorocarbons, all believed to have no negative environmental consequences when being introduced, but afterwards proved to have very negative consequences. It is therefore difficult to understand from a precautionary principle that one should rely on a new generation of synthetic fluids if sound alternatives can be found among the natural refrigerants. The natural refrigerants are naturally occurring in the biosphere and are therefore known to have no negative effects to the environment if they are leaked to the atmosphere.

For high temperature industrial heat pumps the refrigerant selection is very relevant since technology and concepts to a lesser degree exist in the market. Arpagaus (2019) gives an overview of definitions of a high temperature heat pump from the literature. In this publication we try to concentrate on heat pumps of medium to high capacity, from 100s of kW and higher, delivering heat partly or fully above

100ºC, thus covering the temperature range above the heat sink temperatures feasible by more off-the shelf technology.

Several sources have made mapping of the heat demands at different temperature levels in various industries (Apagaus et al., 2018 and Sevault et al., 2018). Some of them also map heat sources at different temperature levels (Huang et al., 2015). The general understanding is that there should be a considerable market potential for high temperature heat pumps. Still there is a need for further mapping. The potential varies from country to country depending on industry type and structure and because the coexistence of suitable heat sources to the demands need to be further mapped. In this respect industrial heating at temperature levels above 100ºC is somewhat special due to the high temperature lift required if the heat is to be absorbed from the ambient, unless the heat pump can benefit from serving cooling demands at this temperature level.

In this paper the latest results from the activity at SINTEF-NTNU within the area of high temperature heat pumps will be presented, with emphasis on activity in a competence building project named HeatUp and activity in the research center HighEFF. Focus has to a large extent been towards finding suitable technical solutions for use of natural refrigerants in this important application area for improved energy efficiency.

2. SUITABLE REFRIGERANTS

CFC-11 and CFC-114 were much considered working fluids for high temperature heat pumps in the 1980s. Due to their ODP and very high GWP, these fluids are obviously not alternatives anymore. Alternatives are now to be found in the group of natural refrigerants or new low-GWP synthetic refrigerants. Suitability for the given application, safety aspects, environmental compliance and in the end, very important, economic aspects, are important.

Screening of refrigerants is a common scientific exercise, often a first stage in approaching new applications. With todays thermodynamic libraries, many fluids may be compared relatively efficient according to defined criteria. Thereby comparing corresponding data for different fluids for predefined parameters, such as heat source and sink temperatures and component efficiencies. For fluids with relatively similar properties, the comparison becomes relatively easy, while fluids with somewhat different properties, e.g. carbon dioxide and water, can be more difficult to implement.

Bamigbetan et al. (2018a) made a screening of suitable fluids for heat delivery up to 125 ºC, focussing mainly on hydrocarbons and unsaturated HFCs, the so-called H(C)FOs. In general, for these fluids with relatively similar thermodynamic properties, the theoretical COP obtainable for given conditions was deferring with less than 10%. Such a difference may of course be important for the total energy efficiency, but on the other hand, other properties, like heat transfer capabilities and process and component adaptation could likely be influencing the differences in efficiency equally much. In this sense, it is very easy to put too much emphasis into relatively small differences in e.g. theoretical COP for given conditions. In the end a lot of practical and economic considerations will influence the choice.

Based on the history of negative experience with different generations of synthetic refrigerants from an environmental point of view, one approach may be to concentrate on finding suitable fluids among the natural refrigerants. This may require more efforts on solving engineering challenges related to e.g. flammability for hydrocarbons, pressure rating for carbon dioxide, high specific volume flows for water and toxicity for ammonia. All are however challenges that may be overcome in industrial applications, where standards and other non-technical aspects is less of a hinder for introducing e.g. flammable fluids, than in household and commercial applications.

3. TECHNOLOGIES AND RESULTS FOR DIFFERENT APPLICATIONS

Bamigbetan et al. (2017b) gives an overview of natural refrigerants in the perspective of high temperature heat pumps for vapor compression systems. It substantiates that it is possible to find suitable natural refrigerant alternatives for most applications, though technological advancements are required. Some such advancements are discussed here.

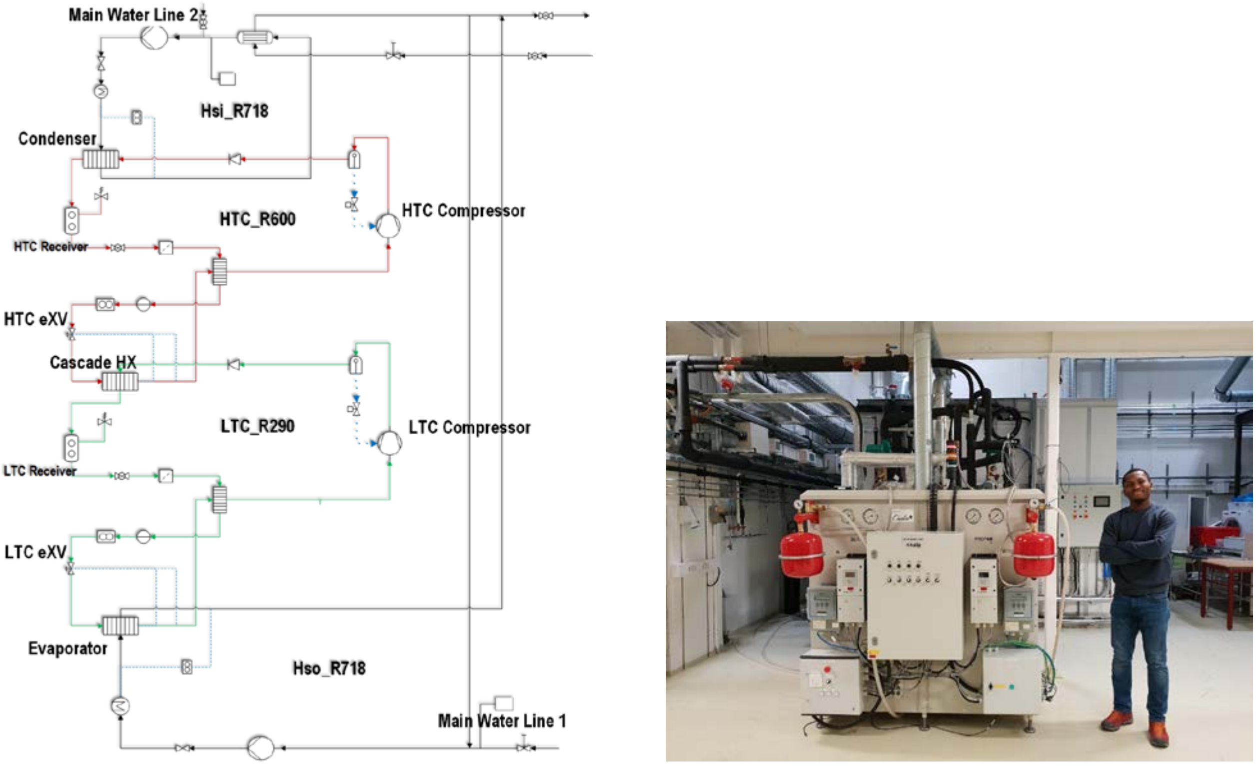
3.1. Hydrocarbons

Hydrocarbons are a family of fluids suitable to serve most temperature levels, from cryogenic temperatures to high temperature heat pumps, due to its overlapping vapor compression curves depending on the molecular weight of the different hydrocarbon molecules. They are also known to have very favourable transport properties, leading to good heat transfer properties, enabling efficient heat exchange.

A technological challenge is of course the flammability of the fluids, being categorised as A3 according to ISO 817. In industry, where these systems are to be installed, this can be handled safely by following the applicable standards and codes of good practice, but it is of course required to have proper training of personnel for installation, maintenance and operation.

Bamigbetan et al. (2018b) describes a laboratory prototype built up to investigate a butane-propane cascade heat pump able to deliver heating up to 115ºC at condensing temperatures up to 120ºC. The capacity of the prototype rig was 20 kW. Aim for a commercial size industrial plant is 300 kW.

Fig. 1a shows a process flow diagram of the laboratory plant. The system is built up with copper brazed plate heat exchangers and single stage compressors and expansion valves in each stage. The system is placed in a ventilated cabinet with leak detectors that stop the system in case of a system break down. The system is prepared for operation also with hydrocarbon mixtures as refrigerant but has so far only been tested with pure propane and butane.



a) b)

Figure 1: a) Process flow diagram of the butane-propane cascade laboratory prototype b) Picture of ventilated cabinet with the hydrocarbon high temperature heat pump

Special attention was on the prototype butane compressor for the high temperature stage. The compressor installed is a four-cylinder semi-hermetic piston compressor made by Dorin. The butane stage will experience evaporation temperatures in the range of 40-60ºC. Temperature control to obtain sufficient motor cooling and to avoid excessive discharge temperatures is therefore a challenge. Further, installed in an ambient of room temperature it also requires special attention to avoid the suction gas to condense before entering the compressor. In order to enable proper monitoring, 11 temperature sensors and two pressure sensors was installed. The results of the testing so far look very promising. Operation with condensing temperatures up to 120ºC (about 21 bara) was performed over a longer period in the laboratory, without any visible degradation of the lubricant. The compressor is due to detailed investigation for possible wear when this is written.

Fig. 2 shows measured compressor efficiencies. As may be observed the efficiencies are very acceptable. The total compression efficiency measured as the isentropic work based on the suction pipe temperature for the given mass flow divided by the electric motor power consumption is between 70 and 75 % for all pressure ratios up to 5. More results may be found in Bamigbetan et al. (2018c, 2019).

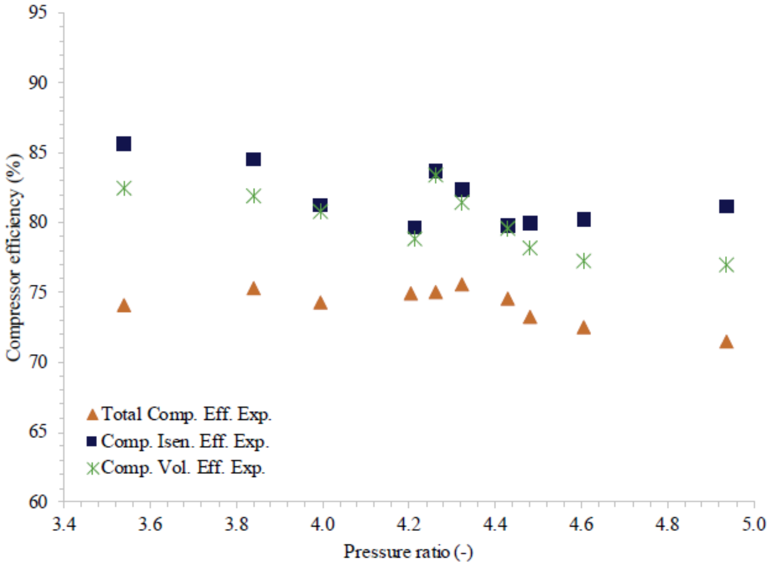


Figure 2: Compressor efficiencies of the prototype hydrocarbon compressor

Further testing in the laboratory pilot plant is planned to be performed with hydrocarbon mixtures as refrigerants. This may enable temperature adaptation for gliding temperature heat sink and source, thus potentially improving the efficiency for such applications. This was investigated from a theoretical point of view by Bamigbetan et al. (2016) for mixtures of propane, butane and pentane. The results showed the potential of improving the COP by up to 13.5% for temperature glides of respectively 10 and 30 K for the heat source and sink.

3.2. Water or Steam as Refrigerant

Water is a very good refrigerant, with good heat transfer characteristics and a very high heat of vaporisation. It is also abundant in the nature and dewatering by drying is a very important process in the industry.

For drying purposes, it is obviously a very interesting option to utilise the vapour from the drying process as refrigerant in an open type process. The concept is named mechanical vapour recompression (MVR). The vapour from drying is compressed, and the hot water vapour is used as heat source by condensation to heat and thus contribute to further drying of the product. It may also be used in steam driers, see Figure 3. Such systems can achieve very high coefficients of performance and are being used in e.g. the dairy industry.

Water may also be used in a closed cycle in a conventional vapor compression cycle. A challenge is however the very large swept volumes required for steam and the fact that evaporation below

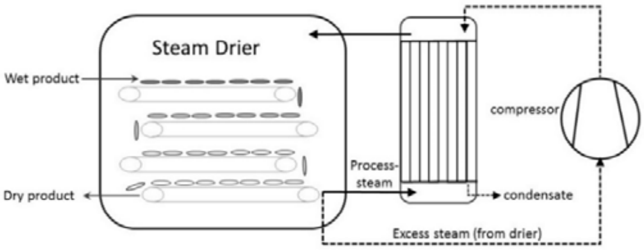
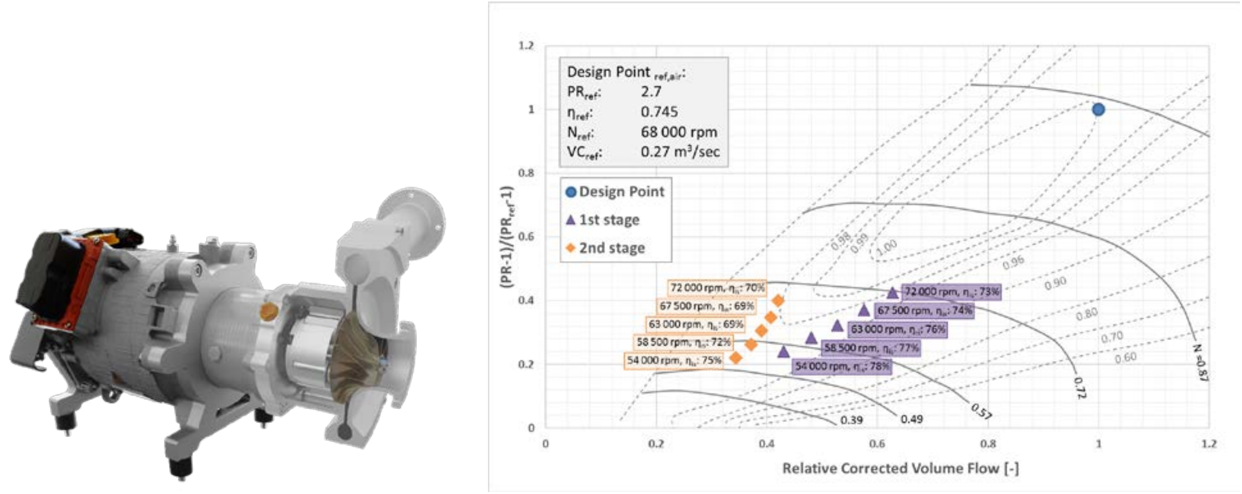


Figure 3: Simplified schematic layout of a superheated steam drier with energy recovery through mechanical vapour recompression

100ºC will happen at a sub-atmospheric pressure. The latter may be overcome by using steam in a high temperature stage with another refrigerant in the lower stage. The low stage, for instance using butane, will then be lifting the heat to temperatures above 100ºC, where the steam stage take over. Steam has the prospects of delivering heat at very high temperatures when compressed in oil-free compressors not affected by degradation of the lubricant, condensation temperatures up to 200ºC has been investigated in the HeaUP project. Potentially it could go higher.

Compressors of several types, e.g. screws and turbo compressors, or more fan like concepts, like roots blowers and centrifugal fans, exists in the market place. Thus, this type of systems can and are being built today. However, the existing compressors often become relatively costly for various reasons, for instance the fact that they for high temperatures need to do oil-free compression. Bantle et al. (2018a/b) describes development of a high speed turbo compressor based on a commercial turbo-charger for vehicles, able to run with speeds up to 80.000 rpm. Fig. 4a shows a picture of the prototype compressor and efficiency figures from the compressor tests are shown in Fig. 4b.



a) b)

**Figure 4: a) Picture of the compressor, length 50 cm, width 40 cm and height 35 cm, 40 kg
b) Achieved measured efficiencies for the compressor**

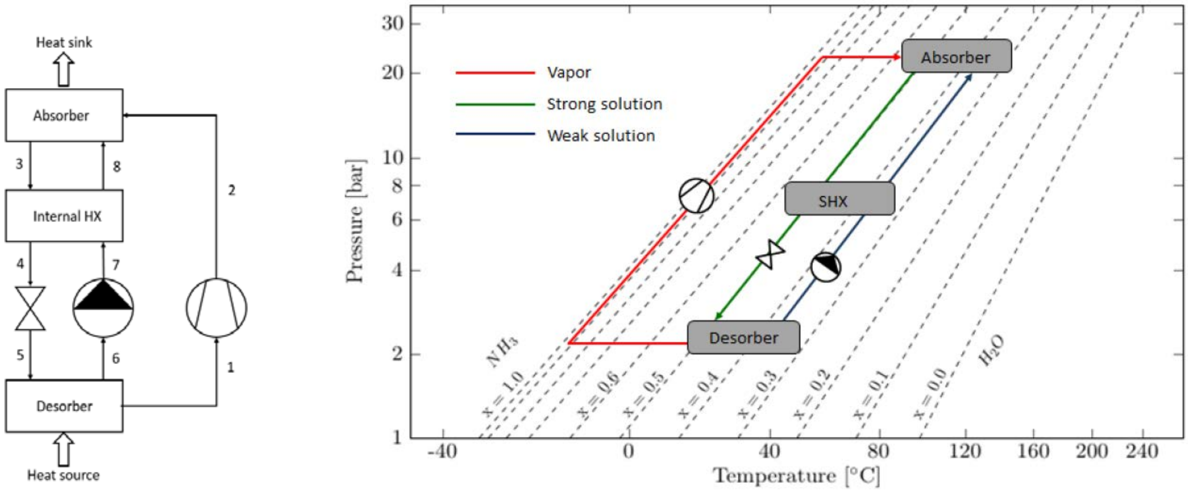
As seen from the picture and measures, the compressor is very compact and consequently it has the potential to reach a low cost. This, and the relatively high efficiency, may contribute to achieve cost efficient implementation of steam high temperature heat pumps.

3.3. Ammonia-Water

Ammonia is known to be a very good refrigerant and is the dominantly used refrigerant in industrial refrigeration systems. To reach condensing temperatures above 100ºC is however not feasible yet with standard equipment, even though 60 bar compressors has been introduced on the market, enabling temperatures close to 100ºC. One possibility might be to utilise it in a low temperature stage as investigated by Bamigbetan et al. (2017a).

Another possibility is to utilise ammonia in mixture with water in a compression-absorption cycle, see simplified process flow diagram in Fig. 5a. A great advantage of this cycle is that you may reach much higher temperatures with ammonia while operating at lower pressures. The cycle has gliding temperatures during heat absorption and rejection. These glides can be adjusted with different ratios of water-ammonia mixture in the system and solution circulation rates. In this way one may adjust the glides to match the temperature glides of the heat sink and source.

The cycle, also called the Osenbrück cycle, is shown schematically in a p – (1/T) diagram in Fig. 5b. As heat is absorbed by the zeotropic mixture of ammonia and water, a gas phase very rich in ammonia is formed. The gas and liquid are separated, and while the gas is compressed in an ordinary ammonia compressor, the weak solution is pumped in parallel to the high pressure. The two phases are then mixed and heat rejected in the absorber/condenser before throttled to the inlet of the desorber/evaporator.



a) **b)**

Figure 5: a) Simplified process flow diagram of the vapour compression cycle
b) Illustration of the process in a p - 1/T diagram

Several systems with this concept using 25 bar equipment have already been installed and are operating in the market (Nordtvedt et al., 2011). At this pressure rating heating up to 120ºC can be obtained. Ellingsen et al. (2018) presents a two-stage concept for heating at two different temperature level, which could be of interest in some industries, for example in dairies.

Wersland et al. (2017) investigated the cycle for heating of process water from 95-115ºC for a heat source temperature of 30ºC at varying loads from 10-130%. Absorber pressures required for this conditions varied from 26 to 27 bar, thus slightly above a standard pressure rating of 25 bar.

A very interesting possibility for reaching even higher temperatures opens with the new ammonia compressors, developed for higher pressures up to 60 bar. Figure 6 shows dewpoint temperatures as function of pressure for various mass fractions of ammonia in water. With 60 bar compressors, such a cycle should be able to deliver heating with temperature glides approaching 160ºC.

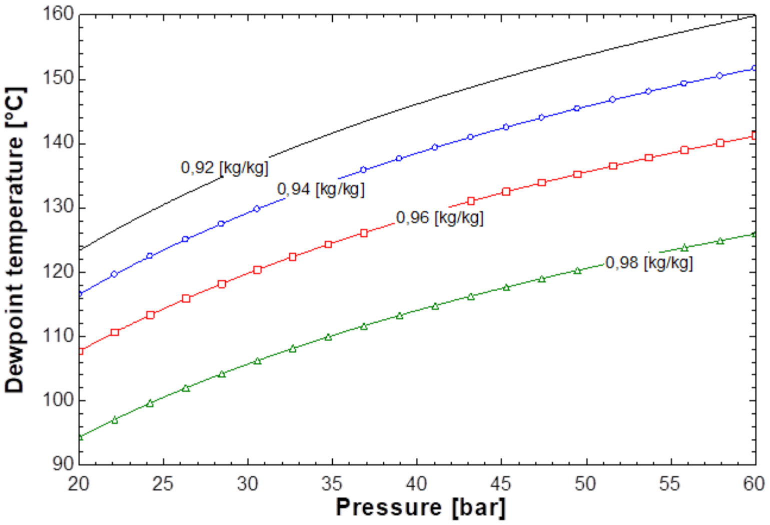


Figure 6: Dew point temperature at varying pressure for varying ammonia concentration in water

4. ECONOMIC CONSIDERATIONS

The economy of implementing high temperature heat pumps in the industry will vary very much depending of country, e.g. due to the ratio between gas and electricity price, and between industries, e.g. due to availability of heat sources to limit the required temperature lift or required installation cost, which may vary with a factor of 10 depending on if it is a brown or greenfield installation. An advantage is the high number of running hours in industry.

Figure 7 shows simple payback time as a function of the cost ratio of electricity to gas for an assumed COP and investment cost, gas versus a heat pump. In Norway, where the cost ratio is close to 1, it obviously becomes more favourable for implementation than in a country like Germany, where this ratio may be up to 4. An important factor here may be that the cost of emitting CO_2 must go up in the future if the countries should be able to comply with their obligation to reduce greenhouse gas emissions.

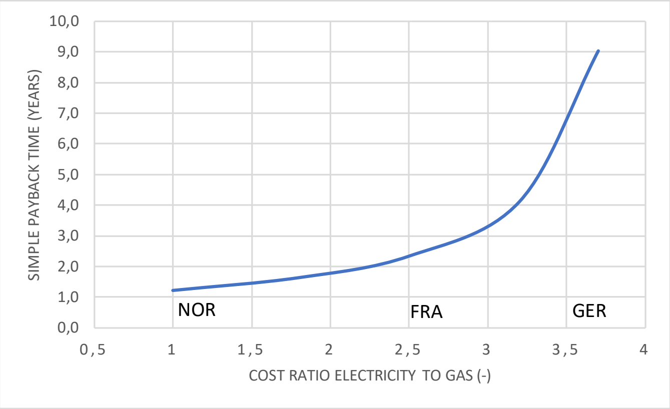


Figure: 7 Simple payback time vs cost ratio of electricity to gas
Additinal investment 550 EUR/kW, Gas price 0,06 EUR/kWh
COPhp 3,5 Running hours 8500 h/y

5. CONCLUSIONS

High temperature heat pumps can be an important possibility for enabling reduced energy use and limiting the greenhouse gas emissions from the industry.
Natural working fluids can offer heating at all relevant temperature levels for the industry, and thus avoiding the uncertainty of introducing new synthetic refrigerants that eventually may turn out to be harmful to the environment, as have been the case for the three first generations of halocarbons.
Characteristics of three categories of refrigerants utilising vapour compression principles, namely hydrocarbons, water and ammonia-water, has been discussed regarding their characteristics and specific development requirement based on recent research activities. All candidate natural working fluids have potential to fill market potential in different industries based on their characteristics.
Economic feasibility of implementation of high temperature heat pumps in the industry varies depending on the boundary conditions, which may vary very much between countries and individual industries. Increased cost on carbon emissions will benefit high temperature heat pump implementation.

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