HIGH TEMPERATURE MAGNETIC BEARING CENTRIFUGAL HEAT PUMP

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Abstract: There is great interest for high temperature industrial heat pumps. But the offer of such machines is still limited. Potential users also fear that thermodynamic machines may be complicated and unreliable. To address this concern, Johnson Controls developed a new generation of centrifugal heat pumps using refrigerant R-245fa with magnetic bearing centrifugal compressors. This technology offers superior efficiency and outstanding reliability. YORK – Johnson Controls introduced it in 1998 for nuclear submarines, where reliability and availability are highly critical. Over 100 such chillers were sold to various navies. In 2011, Johnson Controls launched a range of standard chillers called "YMC²" (York Magnetic Centrifugal Chillers) using this technology. Over 500 of these machines have been built. Heat pumps per this article are derived from these chillers. These oil free units avoid the issues of miscibility of refrigerant in oil at high temperature. This makes magnetic bearings an ideal choice for high temperature heat pumps. Their heating capacity ranges from 600 to 2000 kW. The machine is currently available for 95°C leaving water temperature; tests are ongoing to reach 120°C.

Key Words: heat pumps, centrifugal, magnetic bearings, 245fa

1 INTRODUCTION

To address the environmental issues and the growing prices of energy, more and more attention is paid to the heat pump technology. Dupont and Sapora have shown that heat demand between 60°C and 100°C is much higher than at lower temperatures for the French industrial market. Lambauer et al. carried out a similar study for Germany, underlining the big amount of energy needs between 80°C and 100°C. But there are still few products available on the market at this temperature level. This is why Johnson Controls Industries in France and EDF initiated a partnership in 2011 to develop industrial heat pumps at these temperature levels in the range of heating capacity 500 to 2000 kW. Two technologies were developed, both using the fluid HFC-245fa. The first one is using screw compressors; it was described in an article by Sapora et al. The second technology is using centrifugal compressors on magnetic bearings.

The aim of this paper is to present this technology, together with the reasons for the choices, and to present the results of the tests carried on this machine.

2 CHOICE OF THE FLUID

The choice of a working fluid for a heat pump is complex. It results from interactions between many factors: thermodynamic properties, operating pressures, safety, technology of the compressors to be used and their lubrication etc. In addition, the environmental properties are also a key issue, especially through the energy efficiency of the machine and the Gobal Warming Potential ("GWP") of the fluids

Of course, as the purpose of using heat pumps is to save energy, the energy efficiency is one of the major issues. It is rather complex to assess, because of the very wide range of operating temperatures where heat pumps can be used. To address this issue, we made a comprehensive study that was presented at the Gustav Lorenzen Conference in 2012. The fluids considered in the study are water vapor, R-245fa, R-717 (ammonia), isobutene, R-236fa, R-1234ze, R-134a and R-1234yf. The following table shows the GWP (from IPCC 4th assessment report, 2007) and critical point of each fluid within the scope of the study.

Table 1: GWP and critical points of the fluids

Type	Name	GWP	Critical point	
			T°C	P bar-a
Natural	H_2O (R718)	0	374	221
HFC	245fa	1030	154.0	36.5
HC/Natural	Isobutene (R290)	3	134.7	36.3
Natural	NH_3 (R717)	0	132	113
HFC	236fa	9810	124.9	32.0
HFO	1234ze	6	109.4	36.4
HFC	134a	1430	101.0	40.59
HFO	1234yf	4	94.7	33.8

Some key results of the study are presented in Figure 1, representing the heating COP of different fluids per a theoretical cycle calculation at the conditions detailed below. In this figure, the horizontal axis represents the condensing temperature. Indirectly, it also represents the evaporation temperature, because in the study, the difference between the condensation and evaporation temperatures is kept constant either at 45K or 70K. For instance, if the condensation is at 95°C, it means the evaporation is 45°C (or 25°C). The vertical axis represents the theoretical heating COP of the system with the following assumptions:

- The isentropic compression efficiency is 0.80.
- The thermodynamic cycle assumes 5K liquid subcooling, and a 2-stage compression with a flash economizer.

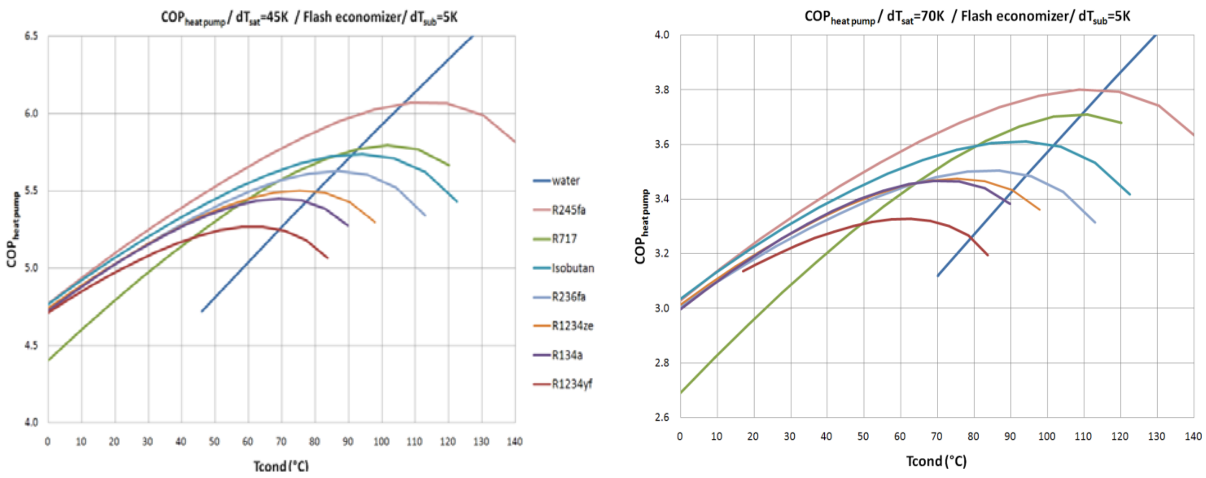

Figure 1: heating COP of various fluids at two sets of operating conditions

It is not review the details of the analysis and comments of the results as presented in the original paper, but it is seen that R-245fa is the fluid that provides the best efficiency in the temperature range of 80 to 100°C condensation. Water vapour is the most efficient above 100°C, but its compression raises difficult technological problems that make it less attractive below 100°C. Ammonia is also an interesting fluid when applicable, but its use is currently limited to about 90°C because of the very high pressures at higher temperatures. Its toxicity and flammability can also raise problems. Isobutene offers a fairly good efficiency, but is highly flammable. R-236fa cannot really be considered because of its very high GWP, while the recent European F gas regulation revision do not hit this refrigerant regardless of GWP value or application. R-245fa offers an excellent compromise between excellent efficiency, safety, environmental properties and cost of the system. This is why it was selected for this application.

The cost is indeed also a major criterion for choice. Comparison between table 1 and Figure 1 shows that the efficiency tends to be better for fluids with a higher critical temperature. But with the exception of ammonia that has a different behaviour, a fluid with higher critical temperature also requires a larger volumetric flow, meaning bigger compressors with generally higher cost.

3 MAGNETIC BEARING COMPRESSORS TECHNOLOGY

3.1 Conventional arrangement of centrifugal compressors

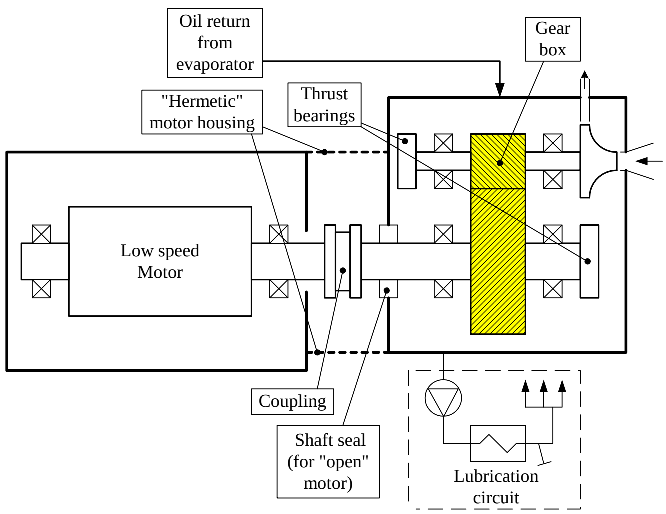

Figure 2: Sketch of a conventional centrifugal compressor driveline

In centrifugal compressors, the impeller is typically rotating at speeds of the order of 10000 to 20000 RPM. In the traditional arrangement, the driveline is driven by a low speed motor (3000 or 3600 RPM), with a gear speed increaser between the motor and the impeller. The gears and bearings need to be lubricated. This requires a lube oil circuit, and also an oil return system to return the oil that is carried over at compressor discharge.

3.2 Alternative solution

An alternative is to mount the impeller directly at the end of a high speed motor rotating at the desired speed for the impeller(s). Many centrifugal compressors are single stage; but it is also possible to make two-stage compressors, with one impeller at each end of the shaft, or both impellers stacked at one end. As the motor is running at high speed, a Variable Frequency Drive (VSD) is needed on these machines to provide the required frequency to run the motor.

In case of direct drive high speed motor, various technologies can be used for the bearings: rolling elements, oil film bearings, gas bearings. All these technologies have drawbacks and can present reliability issues. It was found that the best combination with direct drive high speed motors is to use magnetic bearings. In this technology, the shaft is magnetically levitated, and is rotating without any mechanical contact.

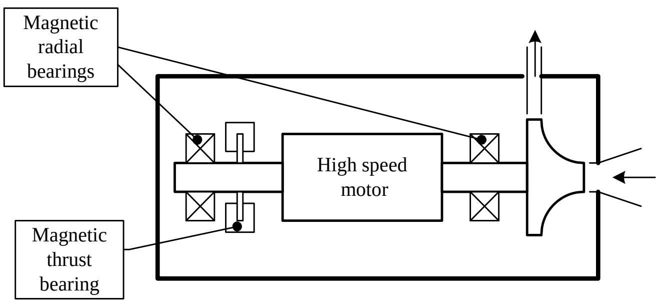

Figure 3: Sketch of a magnetic bearing compressor driveline

3.3 The principle of active magnetic bearings

An Active Magnetic Bearing is made up of two parts: the bearing itself, and the electronic control system.

3.3.1 Radial bearings

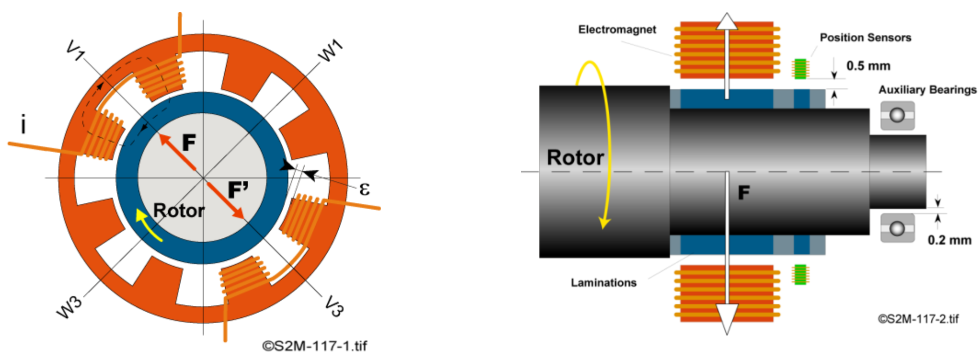

Figure 4: Magnetic radial bearing, with sensor and auxiliary bearings

The radial bearing rotor is equipped with ferromagnetic laminations, and is held in position by magnetic fields created by the electromagnets placed on the stator. The rotor is levitated without touching the stator. The rotor's position is monitored by inductive sensors that detect any deviation from nominal position and emit signals that command currents to the electromagnets in order to bring the rotor back to its nominal position.

Auxiliary bearings are also used to support the rotor while the machine is turned off or in the event of failure in the magnetic suspension system. Auxiliary bearings are stationary in normal operation. These are dry-lubricated ball bearings.

3.3.2 Axial bearing

The axial bearing is based on the same principle. In the most basic arrangement, a disk is clamped to the rotor, perpendicular to the rotation axis, with the electromagnets on opposite sides in the axial direction. Other arrangements are possible, but the principle remains the same.

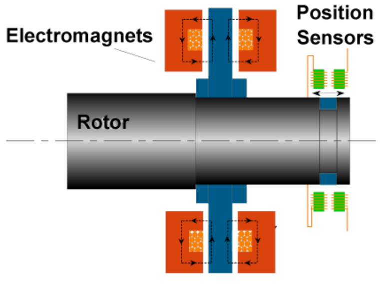

Figure 5: Magnetic axial bearing, with sensor

3.3.3 Electronic control system

The electronic control system controls the position of the rotor by modulating the current in the electromagnets based on the information from the position sensors. The signal from the position sensor is compared with the reference signal, which defines the rotor's nominal position. The error signal is proportional to the difference between the nominal and the actual position of the rotor; it is transmitted to the processor, which in turn sends a correction signal to the power amplifier.

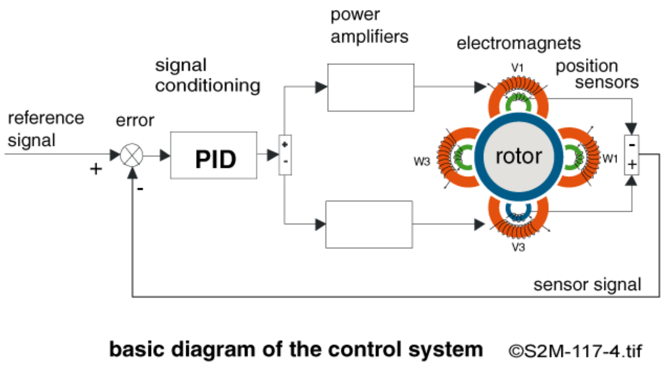

Figure 6: Control system

3.4 History

The implementation of magnetic bearings in water chillers was initially developed in the late 1990's for French nuclear submarines. Later on, it was simplified and cost reduced for surface ships, with over 100 machines sold. Then, the technology was further developed and industrialized, to make it a standard land-based product called YMC² (York Magnetic Centrifugal Chiller), launched in 2011 and now sold worldwide with over 500 units built.

In addition to magnetic bearing compressors, the YMC² unit features a hybrid falling film evaporator. This new technology substantially reduces the amount of refrigerant charge (about -30% versus a unit with a traditional flooded evaporator), while also improving the heat transfer.

What was done within the scope of this study is deriving a high temperature heat pump from the YMC² unit, by making the suitable modifications.

4 THE CENTRIFUGAL HEAT PUMP

The major deviations from a standard YMC² unit to convert it into a heat pump are:

- The refrigerant is changed from the standard R-134a to R-245fa, for the reasons explained above. Thanks to this change to a lower pressure fluid, the operating pressures are not substantially different than those of the same machine operating at air conditioning duty with fluid R-134a.
- The principle of the heat exchangers is kept as standard, including the Falling Film evaporator; but their mechanical design is revisited to accommodate the higher evaporating temperatures.
- In this machine, the motor is semi-hermetic, meaning that it is rotating in the refrigerant in gas phase. As the motor is cooled by the refrigerant that is at much higher temperature in a heat pump than in standard chillers, the cooling scheme of the motor had to be completely redesigned.
- In addition, at this stage of the development, the heat pump is using an industrial VSD (Variable Speed Drive) instead of the standard York VSD, and an industrial PLC (Programmable Logical Controller) instead of the standard control panel of the YMC².

5 THE RESULTS

The heat pump was tested at various conditions, with:

- Evaporation temperature between 40 and 55°C.
- Condensation between 70 and 95°C.
- Difference between evaporation and condensation between 30 and 45K.

The heat capacity and heating COP are shown on the following graphs.

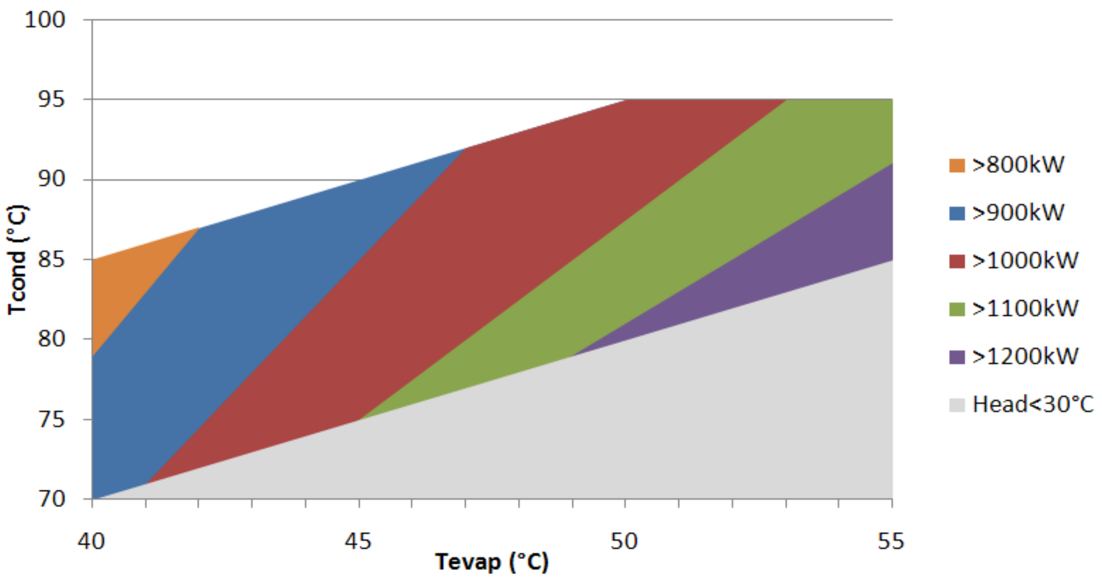

Figure 7: Heating power delivered by the condenser

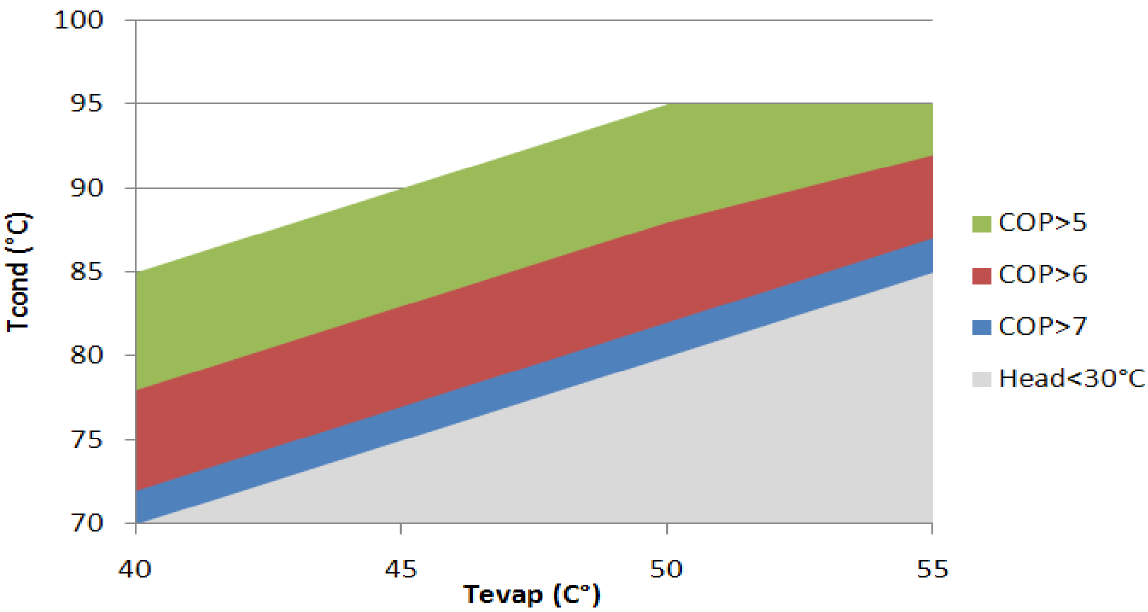

Figure 8: COP = Heating power / Power input

Data about lower "head" (or temperature difference) are not presented here, but the magnetic bearing technology lends itself extremely well to very low heads. Such applications are rather unusual, but we measured COPs over 20 with temperatures differences of the order of 10K.

6 RELIABILITY AND FLEXIBILITY

HPs are derived from chillers. Yet, they are subject to additional operating constraints resulting from high temperatures. These constraints can result in reliability issues if they are not addressed properly. A major advantage of this technology is its very high reliability. This is why it was chosen for nuclear submarines, where reliability, instant availablility and ultra-quiet operation are of utmost importance. The absence of mechanical contact eliminates mechanical wear. The absence of oil eliminates all the lubrication issues. This is especially important for heat pumps, because the use of new refrigerants raises problems related to mutual miscibility between the oil and refrigerant, in addition to the lower oil viscosity resulting from high temperature. This can cause mechanical reliability problems in steady-state operation, but even more when re-starting the unit after a stop. This makes this technology particularly well suited to applications where the unit may be subject to relatively frequent cycles of stops and starts. The time to reach full capacity after an order to start is typically of two minutes, while it may be of the order of 30 minutes or more with other technologies.

These units are extremely quiet. The airborne noise level of a YMC² chiller is 73 dB-A sound pressure level at 1 meter from the unit, versus about 80 to 90 for conventional centrifugal units, and often 85 to 95 for most screw units. The structure borne vibrations are also extremely low, eliminating the need for spring mounting and flexible connexions on the water piping. The combination of flexibility and quiet operation makes these units fully compatible with environments where they are intended to replace gas boilers.

7 ENVIRONMENTAL IMPACT

The environmental impact of a heat pump can be evaluated by various indicators. Per the European criteria, for instance, the "20-20-20" objectives for year 2020 are:
- Reduce the energy consumption by 20%
- Reduce the emissions of Green House Gasses ("GHGs") by 20%.
- Increase the share of renewable energies by 20%.

Heat pumps are inherently classified as renewable energy, because their cold source is either waste heat that is upgraded to a suitable temperature level, or taken from ambient air, sea, rivers, geothermal water etc.

The energy consumption is a target in itself for many reasons even besides its cost: scarcity of fossil fuel resources, quest for energy independence etc. It is also closely related to the emissions of GHGs, because much of the electricity production comes from burning fossil fuels, thereby releasing some CO2 into the atmosphere.

Therefore, the emissions of GHGs from a heat pump come from two sources:
- When the fluid being used has a significant GWP, there are so-called "direct" emissions of GHGs coming from the accidental release of refrigerant to atmosphere through leaks, incomplete recovery of the fluid at end of life etc. Although they are small, these leaks exist, and are relatively well known statistically. They can be converted into equivalent CO2 emissions based on the GWP of the fluid.
- In addition, energy consumption of the system through its life time causes "indirect" emissions related to the carbon intensity of the electricity being consumed.

In reality, the greatest part of the equivalent CO2 emissions comes from the energy consumption that can represent up to 99% of the total emissions, even when using a fluid with medium GWP like R-245fa (GWP=1030). The potential climate impact of a system over its life time, can be evaluated through its "LCCP" (Life Cycle Climate Performance), that is very close to the "TEWI" (Total Equivalent Warming Impact), defined for instance in the European standard EN-378.1. It quantifies the overall direct and indirect emissions of a system over its life time, in kg of equivalent CO2. This approach does not lend itself to comparisons between systems of different capacities or technologies. So, there is growing interest in reformulating it into "specific TEWI". This parameter gives a equivalent CO2 emissions per unit heating or cooling capacity, expressed in [g (of equivalent CO2) / kWh], somewhat similar to the [g/km] used to evaluate the automobile emissions of CO2.

Using the specific g/kWh enables simple comparisons of CO2 emissions between heat pumps and other heating sources. The following example gives the comparison between burning natural gas with an efficiency of 0.9, and running a heat pump with characteristics per the following table:

Table 2: Input data for TEWI calculation

Heating power	100	kW
Heating COP	5	
Equivalent running hours at full load	5000	h/year
Life time of the system	25	years
Refrigerant GWP	1030	(for R245fa)
Refrigerant leakage rate	1	%/year
Fluid recovery at end of life	90	%
Carbon intensity of electricity	0.45	kg/kWh (average EU value)
Carbon intensity of natural gas	0.23	kg/kWh

Calculations about CO2 emissions show the following:

- The overall specific emissions of the heat pump are 0.090 kg/kWh, versus 0.256 if burning gas: the heat pump is releasing 2.84 times less CO2 than burning gas.
- Over the life time, the saving is 20600 tons of CO2.

About the TEWI or LCCP:

- The indirect emissions from refrigerant leaks and partial end of life recovery are equivalent to 126 tons of CO2, which is only 1.1% of the total emissions. These direct leaks are equivalent to only 0.61% of the savings in overall emissions resulting from the use of the heat pump.
- This very impressive ratio is observed although the fluid R-245fa is an HFC with a medium value of GWP=1030. This is a bit lower than R-134a for instance (GWP=1430), but much higher than “natural” refrigerants, or some new generation synthetic fluids.

These ratios show that the climate performance is driven almost exclusively by the energy efficiency, while the GWP of the fluid has a negligible impact. This is characteristic of a package unit with a relatively large number of operating hours, as is normally the case for a heat pump. It confirms that for an optimum climate performance, the choice of the fluid must focus on the energy efficiency, much more than on the GWP of the fluid. Even the leak rate of 1% is very conservative for this kind of unit, thanks to the magnetic bearing technology. A magnetic bearing chiller has 57% less joints and fittings compared to a similar centrifugal chiller of conventional lubricated technology, greatly reducing the risk of leaks. In reality, the leak rate is much more likely to be substantially below 0.5%.

The technology of the heat exchangers also gives quite a low refrigerant charge. The combination of heat pump principle, high efficiency, low refrigerant charge and low leaks makes this machine very attractive from a sustainability stand point.

8 ONGOING DEVELOPMENTS

The results as presented are very interesting and promising. We see a wide interest and potential applications in food & beverages, paper industry, sugar, concentration and/or drying applications. Yet, some of these applications require still higher temperatures, and higher temperature differences between evaporation and condensation. Regarding the temperatures, the current limitation is 95°. We are working at pushing it to 120°. Tests are currently ongoing and promising.

Regarding the temperature difference, the current limitation is 45K. We are working at pushing it to the range of 55 to 60K. It will extend the applicability of this technology to larger temperature differences this currently require the use of screw compressors that have the capability to achieve higher compression ratios.

9 CONCLUSION

A high temperature heat pump was developed, using the fluid R-245fa with a centrifugal compressor on magnetic bearings, a technology that has proved it outstanding reliability in water chiller applications. The operation proved to be satisfactory, with excellent performance. It was tested extensively to temperatures up to 95°C condensation, and with difference up to 45K between evaporation and condensation. The operating range is currently being extended with the targets of reaching 120°C condensation and up to 60K temperature difference.

The study also shows the environmental performance of this technology. It is confirms that a fluid for heat pumps must be chosen primarily for its energy efficiency, while the GWP of the fluid has only a very small impact on the environment.

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