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COMPRESSOR DURABILITY EVALUATION WITH THE R-1132(E) BASED REFRIGERANT R-474A FOR HIGH-EFFICIENT AND HIGH-PERFORMANT BEV HEAT PUMP SYSTEMS BASED ON R-1132(E)

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ABSTRACT

For battery-electric vehicles (BEVs), the importance of high efficient and high performant heat pump systems is increasing to reach the overall vehicle's energy efficiency targets. The electrification of the vehicle goes together with the electrification of the relevant components in the vehicle but also within the thermal systems. As the key component of thermal systems, the compressor needs to operate under various temperature conditions and thus different loads and speeds during the complete vehicle's lifetime. The common technology of electric compressors is the scroll.

The alternative refrigerant blend R-474A based on the molecule R-1132(E) is a near-drop-in for R-1234yf systems and beside performance evaluation of this new refrigerant technology, also the related compressor durability evaluation is part of the readiness activities. The lifetime evaluation has been carried out using state-of-the art automotive compressors from different manufacturers with both common compressor oil types POE and PAG on a component test bench using a defined lifetime durability test cycle covering different loads and compressor speeds.

The results also include the investigation of the compressor parts after the tear-down. The results of the most recent investigations and the study will be presented in the lecture.

Keywords: Compressor, Scroll, Refrigerant, BEV, Thermal system, MAC, Heat pump, High efficient, Durability, Testing

1. NEW REFRIGERANT BLEND R-474A

R-474A is a refrigerant blend consisting of 77 % R-1234yf and 23 % R-1132(E). Upon the PFAS restriction proposal, R-474A is affected by a potential restriction of the refrigerant R-1234yf. The HFO molecule R-1132(E) is outside of the PFAS scope as the molecular formula CHF=CHF does not contain any CF3- nor -CF2- bond. However, the availability of R-474A would be affected in case of the ban of R-1234yf following the current PFAS dossier draft [1]. The refrigerant R-474A offers the right thermophysical properties regarding the boiling point and critical point, respectively (see Figure 1) to be the ideal refrigerant fluid for BEVs with the ability of operating at a wider range of ambient temperature. The opearation range is covering the related operation ranges of both R-1234yf and R-744 aiming to offer higher performance and efficiency than the current refrigerant technologies.

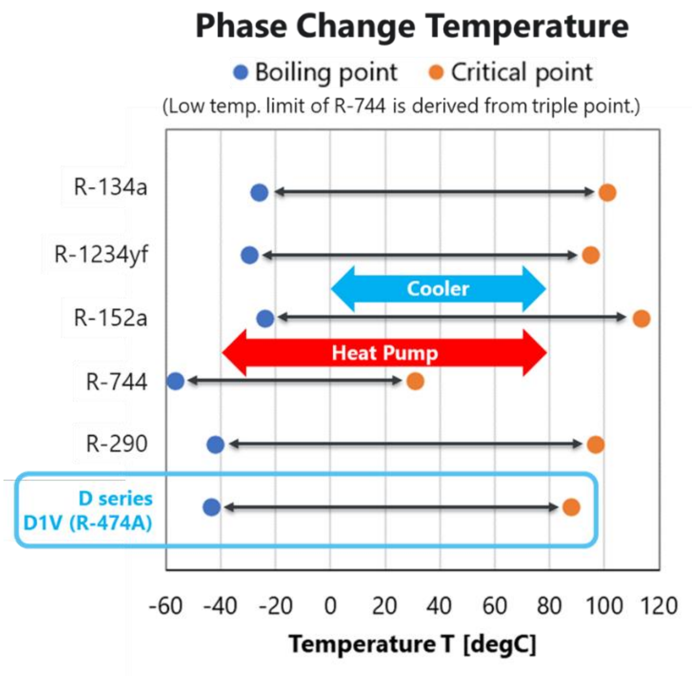

Figure 1: Temperature range between boiling point and critical point for various refrigerants

The properties of R-474A can be seen in Table 1. The GWP of R-474A is lower than the GPW of R-1234yf due to the ultra-low GWP of 0,0056 for the R-1132(E) molecule further reducing the environmental impact of the refrigerant. The presence of R-1234yf at a concentration of 77 % means that R-474A can be adopted in available series R-1234yf systems with minor modifications. This is an important fact as BEVs have a more complex thermal management compared to internal combustion engine (ICE) vehicles. Modern thermal management systems of electric vehicles consist of heat pumps that are cooling or heating not only the passengers' cabin but also the battery, the powertrain, and the power electronics. BEVs require the use of a heat pump to increase the efficiency of the thermal management system and thus the overall vehicle. This efficieny increase can be translated into higher driving range being beneficial for the market acceptance of electric vehiles.

Table 1. Physical properties of refrigerants for BEVs

Refrigerant		**R-744**	**R-1234yf**	**R-474A**
GWP (AR4)		1	4	<4
Temperature in NBP	[°C]	-56.6	-29.5	-43.4
Critical Temperature	[°C]	31.0	94.7	87.8
Critical Pressure	[MPa]	7.38	3.38	4.05
Pressure at 20°C	[MPa]	5.73	0.59	0.94
ISO817 Class	[-]	A1	A2L	A2L
LFL	[vol%]	-	6.2	5.5
Burning Velocity	[cm/s]	-	1.5	2.9

As part of the evaluation of R-474A the compatibility with the thermal management system components is being tested. Among several evaluation items, a very important test is the durability of the air conditioning compressor that will be explained in the following chapter.

2. DURABILITY EVALUATION OF THE AIR CONDITIONING COMPRESSOR

The air conditioning (AC) compressor is a crucial component of an automotive HVAC (heating, ventilation, and air conditioning) system. Its primary function is to compress the refrigerant gas, raising its pressure and temperature to finally absorb and release heat efficiently. In a typical air conditioning cycle, the compressor draws in low-pressure, low-temperature refrigerant gas from the evaporator and compresses it, increasing the temperature and pressure. This high-pressure gas then travels through the condenser, where it releases heat to the outside environment, condensing into a high-pressure liquid. Eventually, the cooled liquid reqfrigerant is then sent back into the evaporator, located in the air conditioning unit inside the vehicle cabin, to absorb heat from the interior. In modern battery-electric vehicles (BEVs), the air conditioning function is extended by a heat pump that also requires a more complex system architecture and also a more sophisticated thermal management control strategy. Furthermore, a thermal system architecture is similar for the common refrigerants for mobile use.

The most common AC compressor design is the scroll that is powered by an electric motor. Figure 2 shows the schematic of the scroll are while the crank shaft is connected to the electric motor. The moving parts within the compressor need to be lubricated. For this purpose, a dedicated compressor oil is added to the refrigerant gas that primarily serves as a lubricant, ensuring smooth operation by reducing the friction between those moving parts.

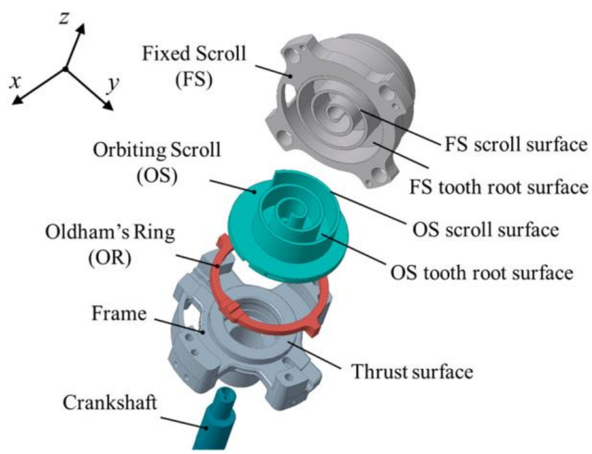

Figure 2: Structure schematic of scroll compressor [2]

Several key parameters are erelevant for the lubrication of the ccompressor: Viscosity, compatibility, thermal stability being essential for the durability of the compressor. In addition, the sealing properties as well as the general lubrication performance of the oil is important and driven not only but also the oil circulation rate (OCR), thus the amount of oil that is occurring at any position in the cycle at any time. Those parameters are defined by the compressor manufacturer and the application into a dedicated thermal management system is part of the overall validation during the vehicle's development process. The following chapters show the influence of the new refrigerant R-474A on the compressor durability. We conducted two durability tests in order to ensure the feasibility of R-474A with both oil types that are commonly used in the automotive industry: Polyolester (POE) oil and polyalkylene glycol (PAG) oil. The goal of the durability test was to confirm that the refrigerant R-474A has no impact on the lifetime of the series compressor including the used materials for the components in combination with current series compressor oils.

2.1. Durability Evaluation with POE Compressor Oil

For this first validation, a series electric scroll compressor with a displacement of 33 cc has been used. This compressor type is currently used with the refrigerant R-1234yf. Table 2 shows the overview of the compressor specification.

Table 2. Electric compressor specification for durability validation with POE/R-474A

Item	Details
Compressor model	Mass production for R-1234yf
Displacement	33 [cc]
Voltage level	350 [V]
Oil type	POE
Refrigerant	R-474A

For a comprehensive evaluation of the compressor durability with the new refrigerant R-474A, the tested criteria beside the durability itself included the insulation, and the performance as well as NVH (Noise, vibration, and harshness). Table 3 shows the judgment criteria for all tested items.

Table 3. Test criteria for compressor durability judgment

Item	Details
Insulation	Before/After the durability test 3 times measured Oil amount 150[g], fully liquid refrigerant
Performance/NVH	Before/After the durability test Cooling condition Microphone distance 1[m]
Durability	Steady-state operation Heating condition

The compressor durability was carried out using a state-of-the-art durability bench using the following test conditions (see Table 4).

Table 4. Test conditions for compressor durability test with POE oil

Item		Details
Compressor speed	Nc	8,500 [rpm]
Discharge/Suction pressure	Pd/Ps	27.71/2.13 [barA]
Superheat/Subcool	SH/SC	6.5[*)]/10 [K]
Oil circulation rate	OCR	3.0 [%]
Ambient temperature	Tam	0 [°C]
Operation time	tOp	640 [h]

[*)] Target SH=5K, but it couldn't be reached due to bench operation limit

As first step the starting condition of the compressor has been set in order to be able to evaluate any impact on the performance metrics Insulation and Performance/NVH after the durability test. To do so, the compressor was checked with a NVH and calorimeter bench with regards to those performance criteria. After this step, the durability test was running following the test conditions in Table 4, before installing the compressor again at the NVH and calorimeter bench. At the end of the test procedure including the test items described in Table 3, the compressor was disassembled to investigate possible wear or other issues coming along with the use of a new refrigerant.

Following the test protocol, the durability test was running without any problem. Both the insulation and the performance/NVH test criteria showed no degradation after the compressor durability test with the new refrigerant R-474A and POE oil. Figure 3 and Figure 4 show the comparable compressor behavior before and after the durability cycle confirming that R-474A has no negative impact compared to the current series refrigerant R-1234yf.

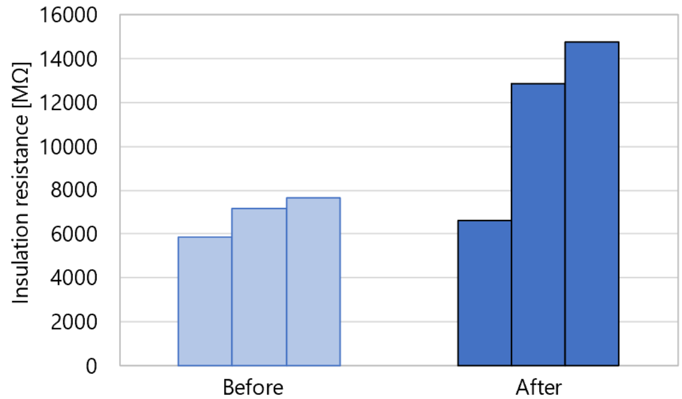

Figure 3: Test result of insulation before/after compressor durability test

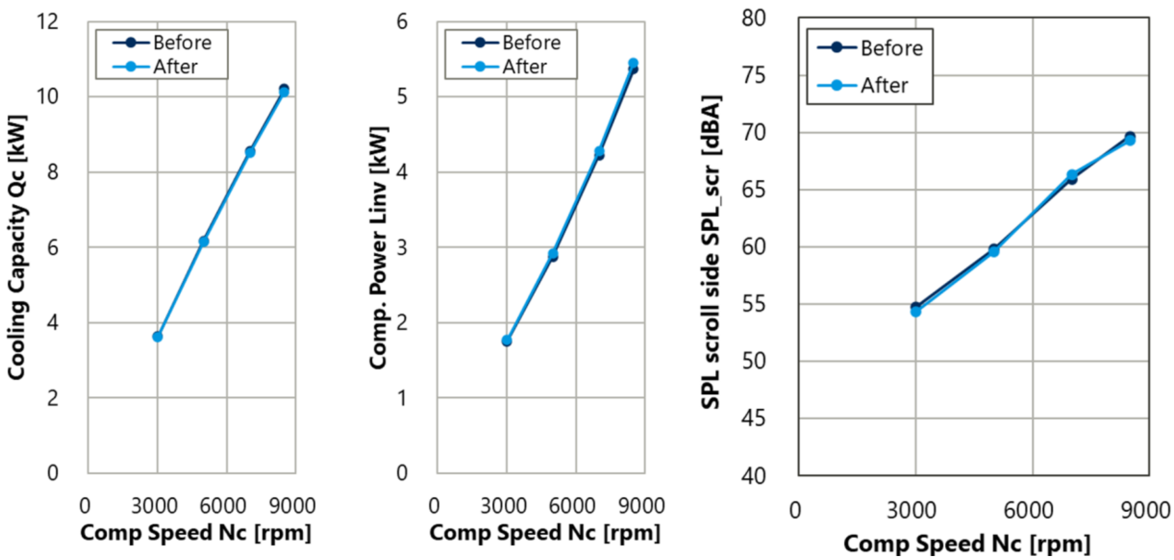

Figure 4: Test result of performance and NVH before/after compressor durability test

The final tear down of the compressor was done with the focus on possible wear at the scroll area as the most critical component requiring a proper lubrication. Both scroll parts did not show any seizure nor sludge (see Figure 5) and thus it can be summarized that the compressor durability showed no problem with the new refrigerant R-474A using the current mass-production AC compressor designed and validated for R-1234yf.

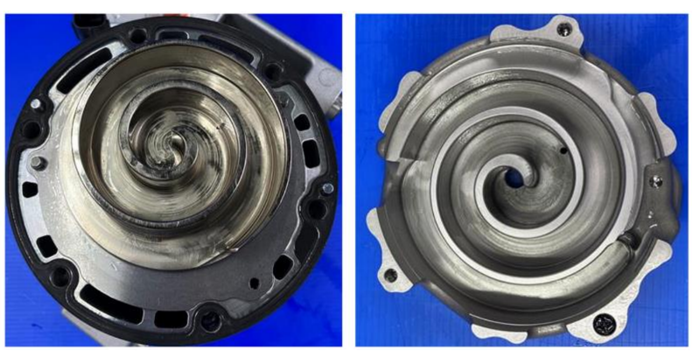

Figure 5: Disassembled scroll after compressor durability test

2.2. Durability Evaluation with PAG Compressor Oil

Today in the automotive industry for mobile air conditioning applications, especially in Europe, beside the POE oil also the PAG oil is widely spread. Therefore, we also carried out a compressor durability test using a series AC compressor that is applied at an application with PAG oil. Table 5 shows the relevant compressor information.

Table 5. Electric compressor specification for durability validation with PAG/R-474A

Item	Details
Compressor model	Mass production for R-1234yf
Displacement	34 [cc]
Voltage level	400 [V]
Oil type	PAG
Refrigerant	R-474A

We observed that the automotive OEMs (Original Equipment Manufactuers) recently increased specificational requirement for AC compressors regarding a higher lifetime. This is necessary due to the increase operation time for the heat pump (HP) mode in addition to the classic air conditioning (AC) mode. In order to reflect that fact, a test protocol with a higher duration as well as more severe operation conditions has been chosen (see Table 6). The test matrix describes several steady-sate conditions that correspond to a related operation condition in the vehicle. Each test item lasts 72 hours reaching a total test time of 504 hours. The complete durability test consists of two of those cycles with a total length of 1,008 hours. During the complete durability cycle, the compressor inverter received a regular incoming air flow of 6m/s. The chosen test matrix shall confirm the complete lifetime in a vehicle required by the car manufacturers.

Table 6. Test conditions for compressor durability test with PAG oil (one cycle)

Item	Condition (Nc / Pd / Ps / SH / Tamb)	Operation Time (tOp)
Boost	7,000 [rpm] / 25 [barA] / 3 [barA] / 25 [K] / 70 [°C]	72[h]
Extreme idle	1,500 [rpm] / 20 [barA] / 3 [barA] / 25 [K] / 70 [°C]	72[h]
Max compressor speed	8,500 [rpm] / 28 [barA] / 3 [barA] / 25 [K] / 70 [°C]	72[h]
Low load	1,500 [rpm] / 8 [barA] / 5 [barA] / 10 [K] / 70[°C]	72[h]
Inverter load	5,000 [rpm] / 20 [barA] / 5 [barA] / 35 [K] / 70 [°C]	72[h]
Fast charging	8,000 [rpm] / 28 [barA] / 5 [barA] / 25 [K] / 70 [°C]	72[h]
Heat pump	7,000 [rpm] / 20 [barA] / 2 [barA] / 10 [K] / -10 [°C]	72[h]

The compressor durability validation has been performed using a component test rig that allows to adjust the ambient temperature around of the compressor as well as an air flow towards the compressor. This allows to repliate real-world conditions in the vehicle during the operation. Figure 5 shows the connected compressor before the start of the durability test. Aftter the completion of the test the compressor was tested regarding its function and possible inner wear due to the long operation time at high loads and thus mechanical stress for the compressor inner parts.

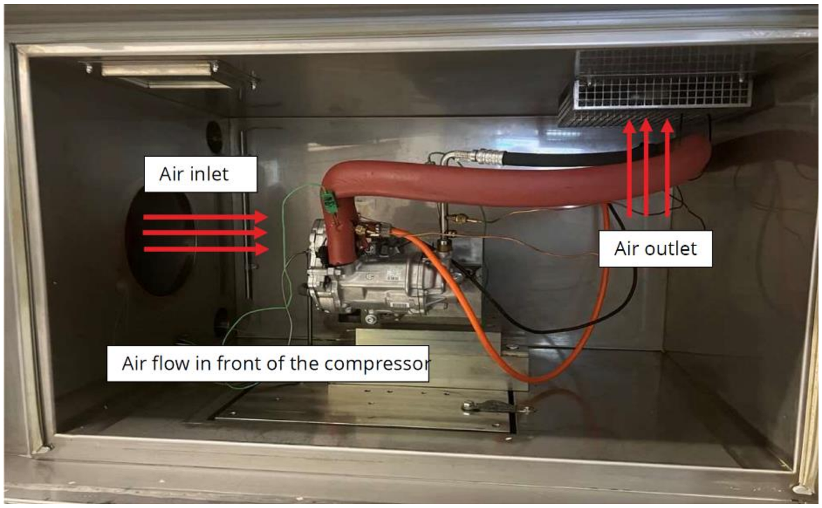

Figure 6: Compressor durability test bench

At the end of the two durability test cycles and therefore after the operation of 1,004 hours, the operation of the compressor showed no issues. The ability of the compressor to create the related cold or heat at dedicated conditions confirmed that there are no functional problems existing.

After the confirmation of the functional behavior of the compressor a teardown was done to investigate the inner parts with the focus on possible wear. Beside the investigation of the surfaces also the compressor oil was visually checked accordingly to confirm that the new refrigerant R-474A has no negative impact on the durability performance of the compressor. Figure 7 shows the rear housing as well as the orbiting scroll. Both parts show no abnormal wear and especially the remaining oil film at the inner side of the rear housing shows that there was no wear occurring during the durability evaluation.


Figure 7: Compressor rear housing and orbiting scroll after teardown

The first visual inspection shows some deposit on the surface of the fixed scroll that require more detailed investigation by the compressor manufacturer (see Figure 8). The investigation also includes the review of operation conditions and the oil circulation rate during the durability test.

Figure 7: Compressor fixed scroll after teardown showing some deposit

3. CONCLUSIONS

Through the last years of comprehensive evaluation of the new refrigerant technology, the refrigerant R-474A has been already confirmed with regard to the achievable performance and efficiency covering a wide ambient temperature range that today is split between R-1234yf for AC and R-744 for HP while offering the possibility of being operated transcritical. Ahead of the described compressor durability tests, various material compatibility evaluations so far showed no negative impact of R-474A in combination with both POE or PAG oils.

As a logical consequence, the final compressor durability required the confirmation through dedicated testing. The shown first test results of the compressor durability as part of overall refrigereant-compatibility evaluation also confirms no negative impact with mass-production compressors for the industry-established oil type POE whereas the final results for the oil type PAG can be shared after a detailed analysis of compressor wear and friction parts that is underway.
This allows to use the already released component materials and compressor oils for a future series implementation of R-474A.

NOMENCLATURE

Nc	Compressor revolution (rpm)	*Tamb*	Ambient temperature (°C)
Pd	Discharge pressure (barA)	*AC*	Air conditioning
Ps	Suction pressure (barA)	*HP*	Heat pump
SH	Super heat (K)	*OEM*	Original equipment manufacturer
SC	Subcool (K)	*POE*	Polyolester
PAG	Polyalkylene Glycol	*BEV*	Battery electric vehicle
ICE	Internal combustion engine		

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