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Safety concept proposal for R744-A/C-systems in passenger cars

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Introduction

The so-called ad hoc working group of VDA OEMs was mandated by the VDA in January 2003 to develop a safety concept for the R744-A/C-system. The members of this group are Robert Mager (BMW AG), Jürgen Wertenbach (DaimlerChrysler AG), Dietmar Böhme (Ford AG), Dirk Lücke (Adam Opel AG), Peter Hellmann (Volkswagen AG) and Christian Rebinger (AUDI AG).
The result is the following proposal for a safety concept. It has to be discussed with the suppliers of mobile A/C-systems and especially of HVAC-units. The target of this concept is to avoid the generally considered scenarios of leaking evaporators and increasing CO_2-concentrations in the cabin.

The paper, like the presentation, begins with the introduction of the standard R744-A/C-system, which was defined by German OEMs in 2003. It is the starting point for the development of the safety concept. The introduction continues with the other basic requirements for the safety concept, the operating conditions that have to be considered and the safety targets that must not be violated.
The safety concept itself consists of two parts: first, the barriers or installations in the refrigerant cycle, which are already defined in the standard R744-A/C-system to keep the system in a safe condition; and second, the safety requirements for the cabin, which are the core of the safety concept proposal to protect driver and passengers.
In the end, these requirements lead to the “safe evaporator”.

Standard R744-A/C-system and basic requirements

On account of the many options to specify the arrangement and the operation of the components of the R744-A/C-system, the German OEMs Audi, BMW, DaimlerChrysler, Porsche and VW defined a standard R744-A/C-system, which was first presented at the HDT(Haus der Technik)-meeting in Starnberg in 2003.
Figure 1 illustrates the arrangement of these components – their operating limits are described below by means of figure 2:
the high pressure relief device has to be at the compressor. The pressure sensor must be positioned in the refrigerant-line between compressor and gas cooler. To control the very high gas temperatures at the compressor outlet, the pressure sensor has to be

combined with a temperature sensor. After gas cooler and internal heat exchanger, the refrigerant is expanded, by either a fixed orifice or a variable valve. The still liquid refrigerant after evaporation is collected in the accumulator and superheated in the internal heat exchanger, before it flows back to the compressor.
A second pressure relief device is necessary on the low pressure side to protect the refrigerant cycle from too high pressures when switched off. Its position is optional between evaporator and compressor. Beside the separate arrangement of accumulator and internal heat exchanger, a combined module is also specified. Any additional positions or combinations of the described components are not intended.

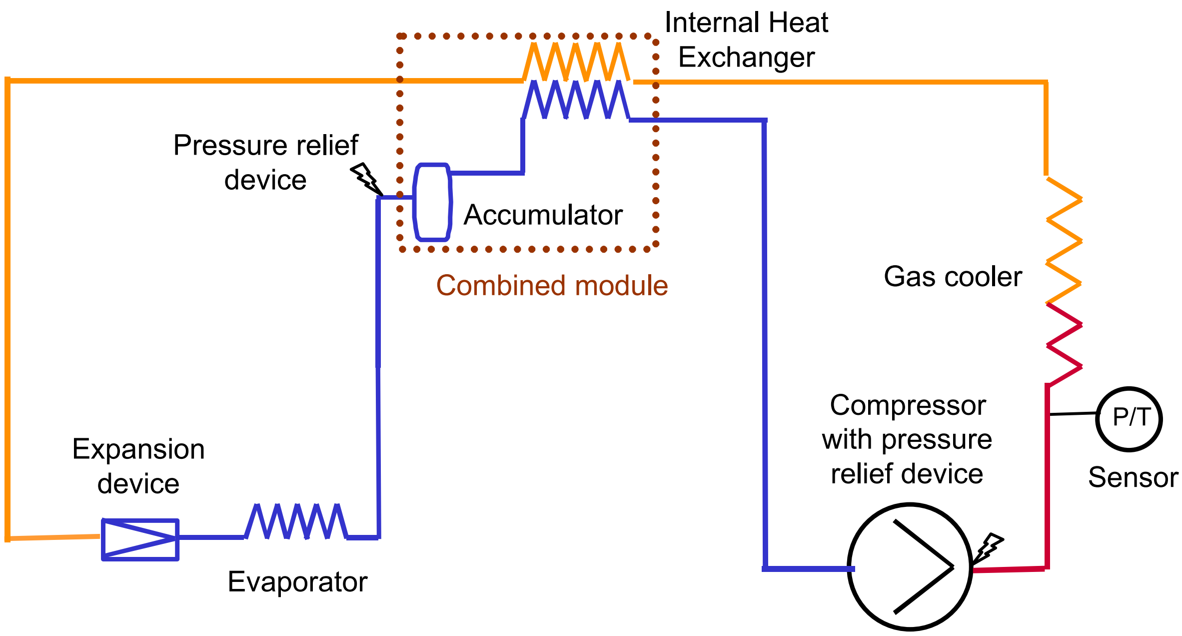

Figure 1: Standard R744-A/C-system [1]

As mentioned before, the standard R744-A/C-system is the starting point for the development of the safety concept and thus, its first basic requirement. The second requirement is the applicability of the safety concept to all kinds and all sizes of passenger cars, which are produced in the automotive industry. Because automatically controlled A/C-systems will not become standard in the near future, the applicability of the concept to all kinds of A/C-systems – down to completely manually controlled ones – is the third basic requirement.
All these basic requirements result from the intention of the ad hoc working group to be as general as possible. In case of the following operating conditions, this intention becomes a must.

Operating conditions to cover

To make the system absolutely safe, all operating conditions during the lifecycle of cars have to be considered. This includes all A/C operating modes from HVAC-blower on or off, via compressor on or off, up to recirculation or outside air mode.

The effects of the A/C-mode on the air quality in the cabin decisively depend on the driving conditions, which are continuous driving with slow, mean and fast speed, as well as driving under stop-and-go conditions. However, conditions that are actually no driving have to be covered, too. These are stopped cars with engine in idle and parked cars with people in it. Exceptional cases also have to be considered, especially when the car is not operating any more, like after break down or crash.
Only if the safety concept covers all possible combinations of these A/C-modes and driving conditions, the system is safe.

Safety targets

The last topic of the introduction into the development of the safety concept are the safety targets, which were already presented by the Risa Safety Analysis Ltd.[1] in Saalfelden in 2002 and in Phoenix in 2003 [2]. The Risa Ltd. approved the feasibility of the following safety concept proposal by conducting an FMEA according to the international standard SAE J1739 [4].
The targets for a safe system are – in order of their importance – first, to protect the driver, because the earliest impact is on his concentration and reaction and second, to protect all passengers from any negative effects to health. Third, all persons outside the car have to be protected – those uninvolved like pedestrians and those involved like technicians during service. The fourth target is to avoid any interference of the R744-A/C-safety system with any other safety relevant system in the car, like electronics or brakes.
Because this last target is related to the design and package of each specific car model, the focus of the safety concept is on the first three targets. The following bottom-up-analysis begins with the third target, the protection of people outside the car by safety barriers in the refrigerant cycle.

Safety barriers in the refrigerant cycle: temperature and pressure limits

The expression of “safety barrier”, which could cause misunderstanding in this context, is defined as safety installation – active or passive – that keeps a system within certain limits for safety reasons. If one safety barrier or installation fails, a next safety barrier or installation has to react.
To visualize these safety barriers in the refrigerant cycle, the pressure and temperature limits of the standard R744-A/C-system – according to SAE J639 [3] – are illustrated in the following pressure-enthalpy-diagram for R744 in figure 2:
Before the compressor is switched on, it has to be checked if the system pressure is within the upper (9,5 MPa) and lower (2,5 MPa) limits to prevent start-up difficulties. The absolute limit for the non-operating cycle is at a maximum of 13 MPa for the low pressure relief device to be activated at the latest – with a 2 MPa tolerance downward.

[1] The Risa Ltd. is located in Berlin and develops safety studies for all kinds of industries, from power plants to transportation systems. The Risa also runs analysis for the automotive industry and conducted a first safety-study for R744 in cooperation with the VDA in 2000.

Once the cycle is running, the focus is on the high pressure with a maximum of 17 MPa for the activation of the high pressure relief device – again with a 2 MPa tolerance downward. To prevent the pressure relief device to be activated, the maximum operating pressure is set at 14 MPa to be cut off. For stable compressor control, however, the maximum working pressure is defined at 13,3 MPa, where the compressor displacement is reduced, but no cut-off happens.
A very important topic for the compressor control is the discharge or outlet temperature of the refrigerant. The limits due to material stability are 175°C for permanent operation and 190°C for short periods up to 5 minutes.

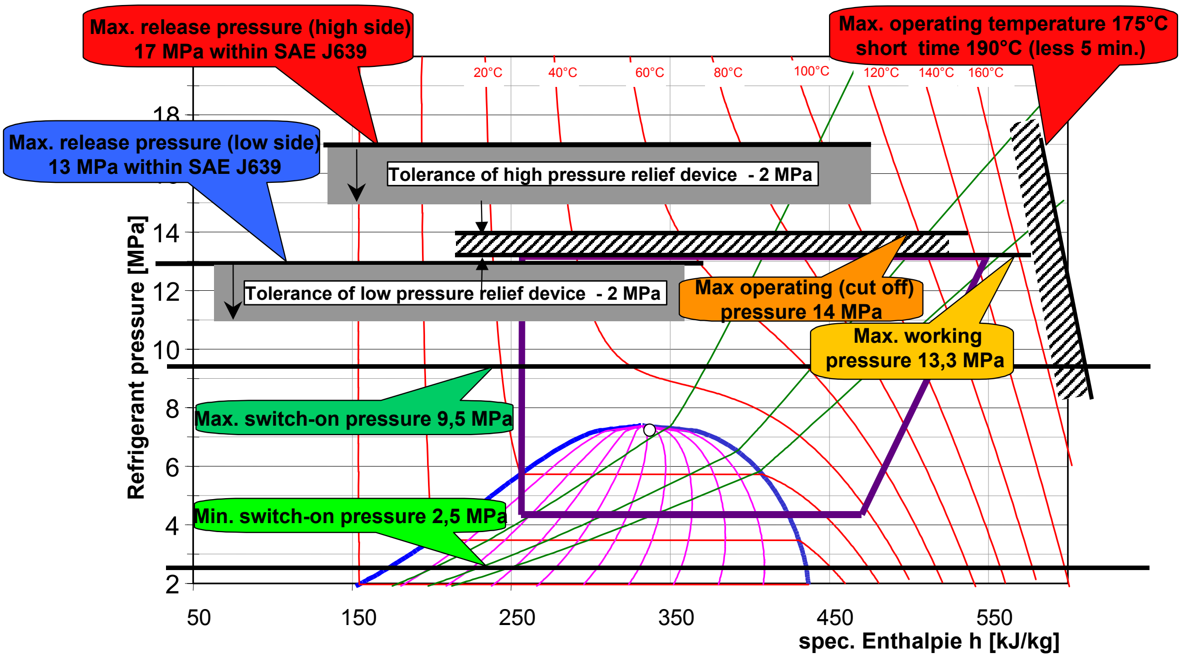

Figure 2: Temperature and pressure-limits in the R744-refrigerant cycle [1]

Thus, the detailed safety barriers are – in order of their actuation:
First, the conditional compressor start, which depends on the pressure and the temperatures in the non-operating condition. If everything is all right and the compressor runs, the compressor control is the next barrier or installation to avoid high pressures and temperatures.
If the compressor control fails and does not cut-off cycle, the pressure relief device on the high pressure side is the next barrier of the running cycle against overpressure, while the pressure relief device on the low pressure side is the barrier for the non-operating cycle.
Should these pressure relief devices also fail, the last barrier is the minimum design or burst pressure. It has to be twice the maximum relief pressure, which is 34 MPa on the high pressure side and 26 MPa on the low pressure side – according to SAE J639 [3]. Breaking or even bursting of any cycle component can not occur, neither in off-mode nor during operation of the refrigerant cycle.
Thus, the third safety target, the protection of persons outside, is not violated at any time.

Safety requirements for the cabin

The still remaining safety targets are those related to the passenger cabin: first, to protect the driver from loss of concentration and reaction and second, to protect all passengers from any negative effects to health. To avoid such interference, the CO_2-concentration in the cabin must not exceed certain levels.
In addition to the safety barriers for the refrigerant cycle, that are already defined, the following safety features for the cabin are requirements, that are proposed here:
because screwed connections are not as reliable as brazed or welded connections, all such connections in the refrigerant cycle have to be outside the cabin. In other words, all refrigerant cycle parts inside the HVAC-unit, like the evaporator and its in- and outlet-pipes, have to be brazed.
Once the evaporator and its pipes are in the HVAC-unit, they cannot be checked again. Therefore, the in- and outlet pipes need mechanical support in the HVAC-unit to avoid any damage of evaporator or pipes during assembly or operation.
While the realization of these two requirements is more or less simple, the third safety requirement for the cabin is a real challenge, as it is the “safe evaporator”.

Definition of the “safe evaporator”

The “safe evaporator” is defined as fundamental safe, which means no breaking or bursting under any operating condition of the car is allowed. To avoid bursting in the sense of “flying parts” is not a problem in case of the evaporator. To avoid breaking in the sense of longer cracks is more difficult, but achievable.
The ultimate challenge arises with the leakage rates and sizes. The safe evaporator must not have any leak during its whole lifecycle, but – unlike breaking and bursting – exceptions are possible.
To guarantee this, a complete chain of quality assurance for evaporator and HVAC-unit is required. This starts with the planning of a new car, continues with the production of the components at the supplier and ends with the final inspection at the OEM’s assembly line.
The last aspect of the safe evaporator, which is not further discussed here, is the regular inspection whether the introduced standards are fulfilled.

Leakage rates and sizes

Figure 3 illustrates the topic of leakage rates and sizes. It shows the leakage rates of R744 in g/min as a function of the diameter of a circular leak. This curve was measured by Jürgen Wertenbach from DaimlerChrysler. His test setup had a bottle of superheated R744-gas at a temperature of 50°C with a starting pressure of 6 MPa, which represents a worst case scenario for the evaporator during operation. After opening the circular leak, the blow-off-time was measured until the pressure in the bottle was below 0,5 MPa. The illustrated leakage rates are average values for the related time periods.

To get a feeling for the dimension of these numbers, the following consideration is helpful. Passengers in the car permanently produce CO_2 by breathing, or as you can also say, respiration. Never ever, even in the worst case of a full midsize car with five people traveling with low or no speed and the A/C-unit in recirculation air mode, the resulting concentration of CO_2 in the cabin caused any harm to passengers and driver.
This human respiration can go up to about 3 g/min. And these 3 g/min, in turn, correlate to a leak diameter of about 0,13mm, thus, leaks up to that size cause no safety problems. However, larger leaks could result in a violation of the safety targets. The emphasis is on “could”, because any violation also depends on the A/C-operating mode and the driving condition.
Nevertheless, the safe evaporator must not leak, and if, the limits for leak size and rate are defined here.

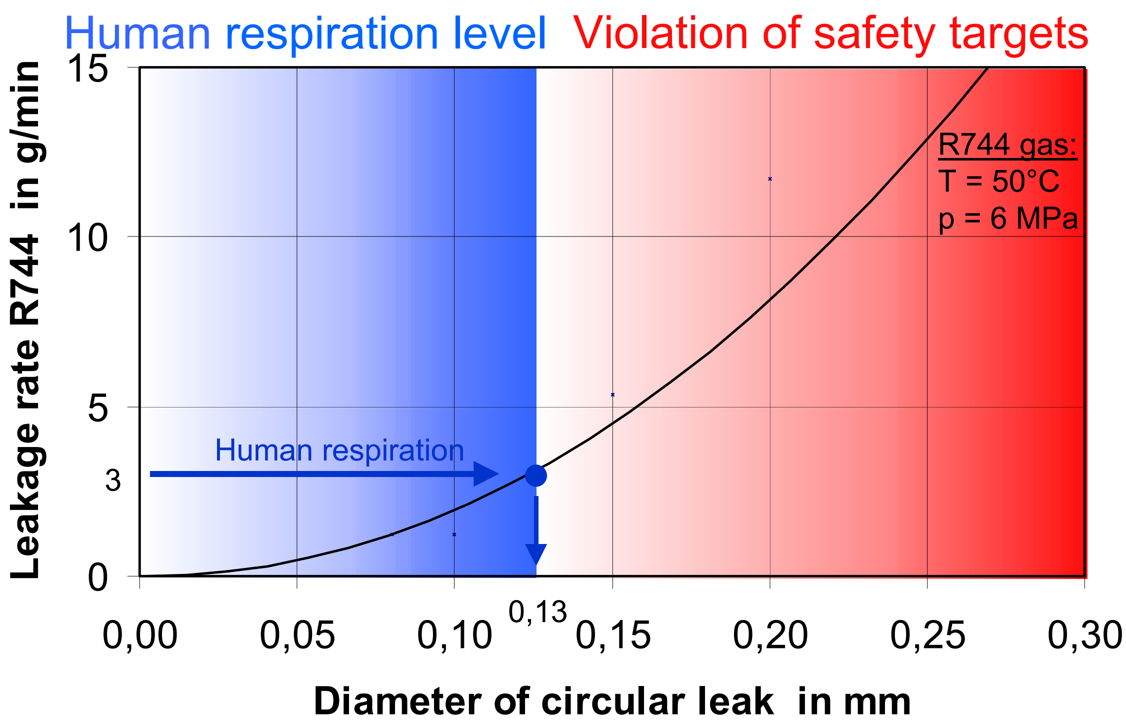

Figure 3: Leakage rates and sizes of the R744-evaporator

Quality assurance

As already described, to guarantee this safe evaporator, a complete and perfect quality assurance is necessary, which is divided into the following three parts:

- Planning and design

For the manufacturers of evaporators and HVAC-units, the planning and design starts already today with the right material selection. The next step is the fundamental design of the evaporator core, of its in- and outlet pipes and of the HVAC-unit. The HVAC-unit is

important, because the evaporator – as described above – has to be fixed softly inside and its pipes need mechanical support.
Therefore, proper test procedures for evaluating the evaporator and HVAC-unit are very important, which include new or at least more extensive pressure-impulse-, temperature-cycling-, vibration- and corrosion-tests. These tests have to be developed by the suppliers in cooperation with the OEMs.

- Production

The next and probably most critical part of this quality assurance is mainly the task of the suppliers, which is the production of the evaporator and HVAC-unit. This already begins with the examination of the semi-finished parts by permanent non-destructive tests like ultrasonic and x-ray as well as further analysis concerning corrosion. For best quality, only full-automatic brazing of core and pipes is acceptable. Additional repair brazing should not be allowed.
To document the production quality, daily tests of each production lot are necessary, which could include e.g. pressure-impulse-test, leak-test and burst-test.
The final 100%-leak-test should be conducted in the vacuum chamber. The best test medium would be R744. The test pressure, which has to be clearly above the maximum low pressure of 13 MPa, should not be less than 18 MPa.
Finally, the proper qualification of the employees in production is important. Nevertheless, it is not further discussed here, because it has to be good anyway.

- Transport and assembly

Once the evaporator is produced and mounted into the HVAC-unit, negative impacts are still possible until, after all, the HVAC-unit is fixed in the car. Therefore, full and detailed monitoring is necessary for storing and transport. During all phases of transport, either at the supplier or on the way from the supplier to the OEM or finally at the OEM, complete monitoring is a challenge. Many different persons are involved in the handling of these parts, the means of transport are manifold and thus, all kinds of incidents or even accidents are possible.
If the evaporator – separate or mounted in the HVAC-unit – is subjected to any abrupt acceleration, i.e. falls hard, no repairing or further use is allowed. At the pre- and final-assembly-line, proper handling is necessary for mounting the HVAC into the cockpit and the cockpit into the car, but also for connecting the refrigerant lines to the evaporator.
This very accurate care is necessary, since the final check of the refrigerant cycle with evacuating, charging and leak test does not allow direct access to the evaporator anymore.

Summary

The idea, motivation and intention of this proposal for a safety concept can be summarized as follows:
Starting point is the standard R744-A/C-system, which requires a safety concept that, in the end, has to result in the definition of safety installations. For the refrigerant cycle itself, those installations are already defined and specified. They guarantee the safe operation of the cycle and the protection of all persons outside the car.
To protect the persons inside the car from excessive CO_2-concentrations, the adhoc working group of VDA OEMs proposes the “safe evaporator”. This proposal was developed together with the Risa Ltd., which conducted a FMEA according to international standard SAE J1739. It approved the feasibility of the safe evaporator.
The concept of the safe evaporator is applicable to all car segments and all A/C-systems. It does not need any additional safety features for the passenger compartment, which makes the safety concept virtually simple. But to really make the R744-A/C-system appropriately safer than today’s R134a-A/C-systems, this safe evaporator is a challenge which suppliers and OEMs have to meet now.

References

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