Part 2:

Substitution of R134a as Test Gas for Turbo Compressors

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2 Introduction

This report is the result of an ICAAMC working group on the usage and substitution of R134a as a test gas for turbo compressors. The entire report is divided into two separate parts.

This "**Part 2: Substitution of R134a**" summarises the attempts of the working group to find a substitute for R134a as test gas. As one aspect, the extended use of CO_2 as test gas has been investigated.

"**Part 1: Best Practice Guidelines**" documents the experience of the contributing companies to use R134a as a test gas while minimising the leakage to the atmosphere. These results are documented in a separate report.

This work has been done in the years 2010 and 2011 by the following companies:

- Elliot Turbo
- Siemens
- GE Infra
- Dresser-Rand
- MAN Diesel & Turbo
- Atlas Copco

3 Requirements for a substitute of R134a

Most important for the aerodynamic similarity as underlying principle of type II testing is the volume flow ratio throughout the compressor. The demand for a similar volume flow ratio and a similar circumferential Mach number at guarantee and test gas conditions results in the following requirements:

- **molecular weight M > 70 kg/kmol**
- **ratio of specific heats κ < 1.15**.

These values were identified by the working group to be sufficient for most cases where R134a is used as test gas. (R134a has M = 102 kg/kmol and κ = 1.12, CO_2 has M = 44 kg/kmol and κ = 1.28.)

Further requirements are:

- Low global warming potential **GWP < 150** and
- No ozone depletion potential **ODP = 0.0**.
- **Not toxic, not explosive, inflammable, low chemical reactivity**.
- **Unproblematic products** after burning or atmospheric decay. The products must meet the same environmental requirements (e.g. GWP < 150, ODP = 0, not toxic etc.).
- No condensation under the required operating conditions during the test, e.g. **vapour pressure at 290K higher than 5 bar**.
  The critical point should not be in the range of test temperatures and pressures.
- Low **cost**, secured **availability** in the future.
- **Compatible with all compressor materials** including lube oil and sealing materials.
- Requiring only minor changes to the **test stand infrastructure**.
- **Compliant with** present and future national and international **regulations**.
- Possibility of **mixing with other test gases**, e.g. CO_2 and N_2, would be of advantage.

4 Search for possible substitutes of R134a

A search was conducted to identify any available gases that could replace HFC-134a (R134a) for compressor performance testing. Criteria for this search were based on requirements specified in Chapter 3 above.

All CFC and HCFC gases were immediately ruled out due to their classification as having ozone depletion potential values greater than zero. As a result, the existing HFC gases 161,152a, 41, and 32 were identified as having lower global warming potential (GWP) values than R134a (GWP = 1400). All met the EU limit of < 150 GWP except HFC 32 with a GWP = 550. Out of these, the HFC 152a best met our physical properties requirements for use as an R134a substitute in compressor testing. Unfortunately it also has a class 2 flammability rating with a low minimum ignition energy value that is similar to methane. The lower the value, the more easily it is to ignite. HFC 32 was less flammable than HFC 152a but its properties did not meet our criteria for a good replacement to R134a. Based on this review, it was determined there were **no currently available HFC gases to replace R134a**.

Further internet research revealed that Dupont and Honeywell had jointly developed and patented a new refrigerant called **HFO-1234yf** and were strongly advocating it as a replacement for R134a in new vehicle air conditioning systems. The HFO-1234yf has a very low GWP of 4 and an atmospheric lifetime of 11 days. By comparison, CO2 has a GWP of 1 but a lifetime of 50 to 200 years. Although the HFO-1234yf has been demonstrated through independent testing to have the necessary refrigeration properties for R134a replacement, it is also **rated as class 2 flammable**. However, lab testing has shown it to have low flammability properties and ASHRAE is considering proposals for a new 2L (low) flammability classification. Its minimum ignition energy is much higher (hard to ignite) than the R152a and it has a very low burning velocity (effect of the flame is low), only slightly higher than R134a. In spite of this, it was concluded that flammability was the primary issue to resolve before HFO-1234yf could be adopted for factory compressor performance tests. A more detailed review of the precautions that might be required when using this mildly flammable refrigerant for compressor testing is recommended. Also, that a specialist at a company or University be contracted to evaluate our application and make recommendations relative to any hazard for explosion or fire when using the new gas. However, this activity was considered beyond the scope of the working group. We concluded that we would not want our ASME Class II tests to have to follow regulations specifically related to explosion potential with hydrocarbon gas testing. Such requirements applied to Class 1, full load full density hydrocarbon testing mandate special considerations for both the test loop piping and operating procedures.

With no acceptable, commercially available refrigerant as a replacement, the manufacturers of R134a listed below were contacted directly. The goal was to determine if they had any other products in development that could meet our needs.

- **Dupont**	www.refrigerants.dupont.com
- **Honeywell International Inc**.	www.honeywell.com
- **Arkema Inc.**	www.arkema-inc.com
- **Solvay**	www.solvay-fluor.com

Dupont is actively pursuing acceptance of HFO-1234yf for mobile A/C (air conditioning). It will be commercially available in late 2011 and known as Opteon YF within Dupont. They also announced in Oct. 2010 the development of a new gas called **Opteon XP10**.

- Its properties are a close match to R134a, it is non flammable, and has a **GWP equal to 600**.
- Is currently undergoing laboratory and field testing.
- Details of its gas properties were requested for our comparison with R134a but refused by Dupont on grounds of confidentiality.

Opteon XP10 is referenced to their research development gas DR-11 and reported in a technical paper by Kontomaris, et al at the International Refrigeration and Air Conditioning Conference, Purdue University July 12-15, 2010.

Honeywell is also actively pursuing acceptance of HFO-1234yf for mobile A/C.

Mr. Mark W. Spatz was contacted regarding Honeywell's development program of other low GWP, non flammable gases and also the flammability issue with HFO-1234yf. He indicated that some earlier reported new gases (Fluid H, DP-1, and R-JDH discussed in his presentation at the SAE Conference of July 17, 2007) have been dropped for various reasons. One of the reasons was with respect to "stability" of some gas components. However, he did discuss a new gas developed solely by Honeywell called **HFO-1234ze**. It has the following features:

- GWP = 6 Lifetime 18 days.
- Slightly less **flammable** than HFO-1234yf. Rated Non Flammable at room temperature and for transportation (per M. Spatz phone discussion).
- It has nearly the same properties as HFO-1234yf and meets our performance testing criteria except for vapor pressure (may require special procedures to avoid condensation in instrument lines).
- Approximately ¼ of the cost of HFO-1234yf (per M. Spatz phone discussion).

HFO-1234yf flammability studies are reported by Spatz at the VDA Winter Meeting, Saalfelden Austria Feb. 11-12, 2009.

At the conference CHILLVENTA (Nuremburg, Oct. 2010) W. Spatz also reported about actual developments on HFO-blends. For example a blend named **L-20** has a GWP < 150 but is mildly flammable, whereas a blend called **N-20** is non-flammable and has a GWP < 1000. Detailed information about these blends was not available.

Arkema has launched a program for the industrialization of HFO-1234yf to meet the time frame required by the EU Directive for mobile A/C. It currently manufactures R134a and other refrigerants in Calvert City, Kentucky USA and also in facilities in France, Spain, and China. A phone conversation with Mr. Gus Rolotti provided the following:

- Arkema plans to produce HFO-1234yf but have not released when and where that will be.
- They have an active development program for low GWP refrigerants, but currently do not have an alternate for HFO-1234yf.
- Arkema is actively developing gases with GWP between 150 and 1400, with some possibly available by end of 2011.
- Mr. Rolotti stated that flammability will always be a matter of compromise.

Arkema has also several HFO-blends under development. They reported at the conference CHILLVENTA (Nuremburg, Oct. 2010) about blends called **ARM01** … **ARM06** which are in the GWP region between 50 and 1000. Detailed information about these blends was not available.

Solvay manufactures R134a but does not offer any HFO-refrigerants. They announced that they are developing low-GWP-refrigerants, but they have not reported results up to now. A new dropin for R22 is called **22L**. It is non-flammable and has a GWP greater than R134a.

4.1 Conclusion on possible substitutes

1. **No currently available refrigerant has been found to replace R134a** due primarily to concerns regarding flammability properties.
2. The new Dupont/Honeywell refrigerant **HFO-1234yf** is proceeding toward commercial availability, possibly by late 2011. It meets physical properties requirements for R134a replacement. However, it is recommended that **flammability** concerns be explored further (by qualified consultants) before it can be approved for ASME Class II performance testing.
3. The newly developed **Opteon XP10** by Dupont offers an alternative that is non flammable and has a **GWP of 600** that is lower than the R134a GWP of 1400. At this writing it has not been released for commercial sale.
4. The newly developed **HFO-1234ze** by Honeywell is another possible alternative that has a very low GWP of 6 and is slightly less flammable than HFO-1234yf. However it is still classified at this time as **flammable** and would require a similar study of its flammability properties as the HFO-1234yf. It meets our testing criteria except for vapor pressure and may require special procedures to avoid condensation in instrument lines.

5 Extended use of CO_2 as test gas

5.1 Theoretical considerations

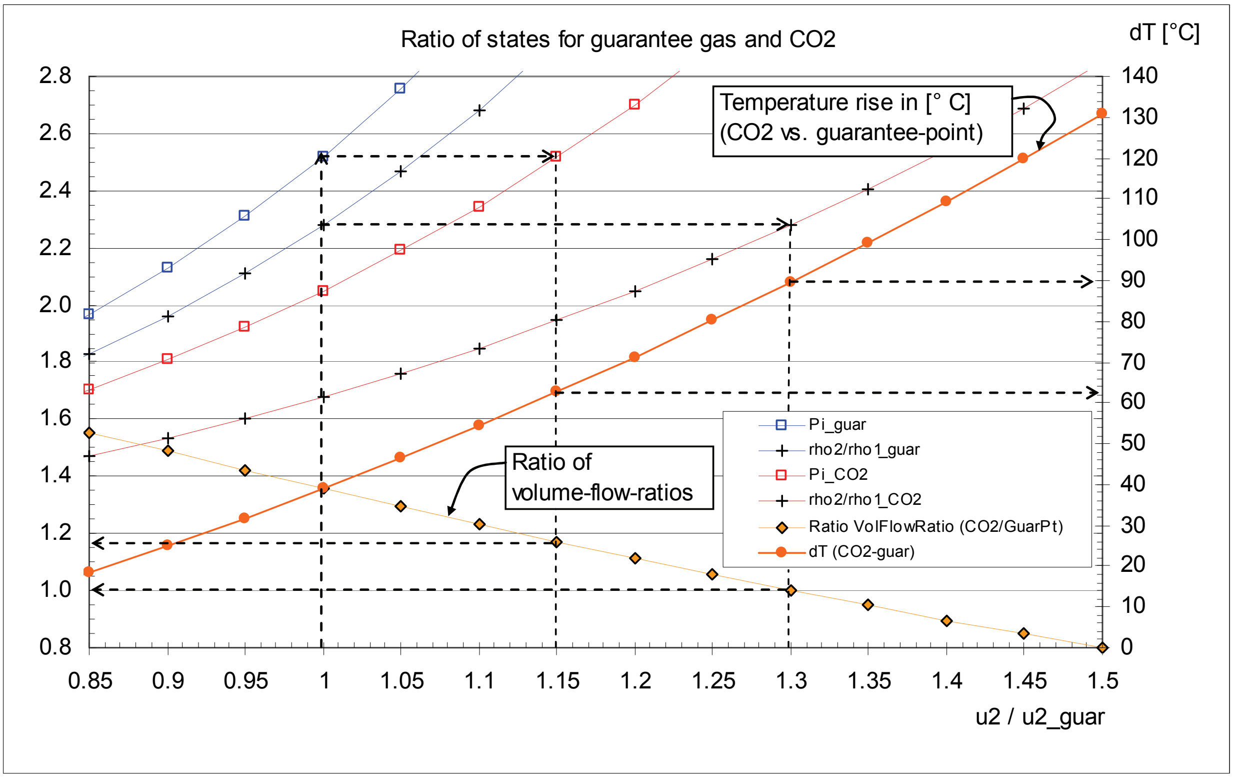
Relevant codes for performance testing compare non-dimensional quantities as efficiency and head factor, assume them to be the equal under guarantee and appropriate test conditions and apply only minor corrections for *Re*-dependence.

These codes relay on "**similarity conditions**": **Similar** velocity triangles, incidences and **volume flow ratios**. This is ensured by running each stage at the specified flow coefficient and by using a similar Mach number to minimise the deviation of stage properties.

In addition, the choice of test gas, speed, pressure and temperature must not damage the compressor.

Guarantee gases with a high molecular weight M and with a low ratio of specific heats κ often have a low speed of sound. Compared to them, **CO_2 has** lower molecular weight and a higher κ, hence **a higher speed of sound** (typically e.g. 20%-30% higher). Running at the same Mach number as at guarantee conditions would **require a higher speed** for CO_2. The lower values of κ result in **higher exit temperatures**. Here, CO_2 does not allow testing the compressor under similarity conditions without **damaging the compressor**.

To isolate the conditions were CO_2 could possibly be used under "non-similarity conditions", the following **typical example** of a stage group is investigated (M = 54 kg/kmol and κ = 1.08). As speed is the most important free parameter for the tests, several quantities are shown as a function of speed in the following plot.



In this plot, the pressure ratio π and the density ratio ρ_2/ρ_1 for guarantee gas (index _guar) and CO_2 (index _CO2) are plotted as a function of the relative speed u_2/u_{2_guar}. Furthermore, the temperature difference between the exit temperature with CO_2 to the exit temperature at guarantee conditions is given (scale on the right hand side).

At the same speed as the guarantee case, CO_2 has a lower pressure ratio, a lower density ratio (35% in this case!) but already a higher temperature ratio.

To reach similarity conditions, a speed increase of 30% would be required. Here, CO_2 has a higher pressure ratio, a higher temperature ratio and the same density ratio. **The temperature rise increases from 35°C to 125°C**.

The same pressure ratio is obtained at 15% speed increase. This is about half the speed increase needed for similarity conditions. Here, CO_2 has a higher density ratio (18%), a higher temperature ratio and the same pressure ratio. The temperature rise increases from 35°C to 95°C.

Tests at similarity conditions would require higher speeds up to approx. 30%. However, only ~10 % speed increase seems possible due to mechanical reasons and ~10 % speed deficit seems possible due to thermodynamic reasons. Hence, a gap of at least 10% in speed opens, preventing to chose an appropriate test speed for CO_2.

Only **operating points at guarantee conditions with very low speed or guarantee gases with properties close to CO_2 can be tested with CO_2** giving meaningful results.

At **mechanical tests** with 100% speed and CO_2, a **severe stage mismatch** is obtained. This could possibly prevent a smooth operation of the compressor.

These **limitations dominantly reduce the applicability of CO_2** and hence, the potential for a beneficial application of this attempt is low.

The **ISO-Standard 5389:2005** describes tests under non-similarity conditions in annex B (normative).

5.2 Assessment of selected applications

R134a or mixtures of R134a with N_2 and He as test gas are used for a number of different applications and tests, e.g.

5.2.1 Performance tests according to ASME PTC 10 Type 2

5.2.1.1 Compressors for gases with higher molecular weight > 44 kg/kmol and, or low isentropic exponent < 1.15

- **Refrigerant compressors for olefin or ethylene plants (propane, propylene)**
- **Refrigerant compressors for LNG plants**

Normally, these compressors consists of several process stages with internal side loads and, or extractions.

As already stated within Chapter 5.1 ‘Theoretical considerations’, the use of CO_2 as test gas will result in higher speed and corresponding higher temperatures, i.e. a “standard” Type 2 test with CO_2 is not possible.

An option could be to define a reference point at a reduced speed for the specified gas at about the specified side load and, or extraction ratios.

This reference point could then be verified using CO_2 as test gas in between the limits for specific volume ratios, Mach numbers etc. according to ASME PTC -10 Type 2. The deviations between the predicted reference point and the test results could then be transferred to the design or guarantee point.

However, depending on the individual design of the compressor, the ratio between design and reference speed might be limited, thus leading to a comparative speed for the reference point which is still higher than maximum continuous speed, resulting in exit temperatures being also too high.

For a number of applications, reference points with the specified gas at further reduced speeds can only be defined at totally different volume flow ratios at the side loads, e.g. much smaller side load flows, no side loads or even extractions instead of a side load. There could also be the need to define reference points at different speeds individually for each process stage.

For these applications, depending on the individual design of the compressor, a performance map for CO_2 at design speed might be predicted and a reference point with similar side load conditions and similar process stage efficiencies might be chosen directly for CO_2.

This will be possible for compressors, where, while using CO_2 as a test gas, no extreme shifting of the operating points on the individual impeller curves from stonewall to surge in between a process stage occurs, e.g. compressors with only one impeller at each process stage. Otherwise the deviation between the efficiency for the specified gas and CO_2 would be too significant.

However, results of a performance test following this approach might be questionable.

Performance tests with CO_2 for the above type of compressors are therefore not considered as practicable.

- **Coker gas compressors, wet gas compressors, butane compressors**

These compressors normally consist of 1 to 2 process stages without internal side loads.

A „standard“ Type 2 test with CO_2 for the design point, normally at about 100% speed, might be possible but at comparative speeds up to 105% or even higher.

Depending on the individual design, exit temperatures might be high but still within the design limits or the machine could be designed for the higher temperatures.

As for the refrigerant compressors, there might be the option to define a reference point at a reduced speed, which could then be verified using CO_2 as a test gas. However, there will be the need for additional tolerances to be applied for efficiency and head, which requires some further investigations as well as an approval of all parties to the test.

5.2.1.2 Compressors with low suction temperatures

- **Ethylene compressors with suction temperatures < -50 °C**

Normally, these compressors consist of several process stages with internal side loads and, or extractions.

A „standard" Type 2 test with CO_2 for the design point might be possible at about 100 - 105% comparative speed.

Depending on the individual design, exit temperatures might be high but still within the design limits or the machine could be designed for the higher temperatures.

As stated in 5.2.1.1, there is an option to define a reference point for the specified gas at about the specified side load and, or extraction ratios.

Nevertheless, it should be noted that either the definition of a reference point as well as creating a new compressor map for CO_2 constitutes a new approach, which needs the agreement and approval of all parties to the test.

5.2.2 Performance tests at non similarity conditions in case of compressors for low molecular weight gases with very low suction temperatures

- **Methane boil off gas compressors with suction temperatures below -100°C and down to -160°C**

Due to the very low suction temperatures, performance tests for typical boil off gas compressors have to be done at non similarity conditions, although using R134a as a test gas.

Any change to another test gas with lower molecular weights would inevitably result in high exit temperatures, which are not acceptable as the design of the compressor already reflects the operation at very low temperatures.

As for the compressors discussed in 5.2.1.1, there might be an option of defining a new reference point at a reduced speed.

Another option might be to do the test at low suction temperatures, using N_2 as a test gas. However this would result in quite important changes to the test stand infrastructure in order to handle a liquid N_2 injection for closed loop cooling.

5.2.3 Full load tests in case of compressors with molecular weights > 44 kg/kmol and, or low suction temperatures

- **Refrigerant compressors for LNG plants**

For large refrigerant compressors in LNG plants, there might be requirements for a full load test. The intention of this test is to demonstrate the mechanical integrity of the compressor while operating at design or maximum continuous speed and a load which is usually close to the main guarantee point.

Comparing to a performance test, there is no requirement to fulfill similarity conditions. However, full load testing with CO_2 can only be achieved at higher suction pressures. Due to the higher specific volume ratio, respectively lower pressure ratio with CO_2, no stable operating point might be found for most of these compressors. Exit temperatures will be too high with an additional potential of overloading the first sections of the compressor due to a severe stage mismatch.

A mechanical full load test with CO_2 for the above type of compressors is therefore considered as not practicable.

5.2.4 Summary of the applications discussed above

Generally, it can be stated that some of the tests of compressors as mentioned above may be performed with CO_2 instead of R134a as a test gas. However, for these tests a reference point has to be defined at a test speed reduced as much as necessary but nevertheless still as high as possible. For this reference point additional tolerances have to be taken in to account.

For other tests like performance tests of refrigerant compressors with side loads or mechanical full load tests of compressors for high molecular weight gases, R134a can not be replaced by CO_2. A test gas with higher molecular weight and lower isentropic exponent than CO_2 is required.

6 General summary

- **No substitute for R134a is identified yet** that meets all of our requirements.
- **Development of new refrigerants ongoing** at different manufacturers.
  New substances could come up any time. Prior information through manufacturer is unlikely.
- Partial improvement might possibly be achieved with "**HFO-1234-technology**" e.g.
- **Opteon XP10**: Rated „non-flammable“ but **GWP = 600**. Physical properties not yet fully disclosed by manufacturer, hence no further assessment possible yet.
- **HFO-1234yf** and **HFO-1234ze: „Flammable“**, lower GWP.
- None of the approaches provides a comprehensive solution to the use of R134a.
- The use of CO_2 as test gas is limited to guarantee gases with properties close to CO_2.
  CO_2 can not serve as a **general substitute** of **R134a**.
- For operating points at low speed, some tests might be performed with CO_2 instead of R134a.