Arkema technical note

Forane® 407A

The low-GWP and energy efficient alternative to R-404A and R-507A

Arkema – A limited liability company with capital of 623995900 euros – Nanterre Company and Commercial Registry No.445,074,685 – 09.2013 / v1

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Introduction

R-404A and R-507 properties and main applications

R-404A and R-507 are the main refrigerants used in Europe for refrigeration applications. Both fluids have a high GWP[1] (Global Warming Impact) of about 4 000[2].

Based on the refrigerant inventories report for Europe published by Armines/ERIES[3] on October 2011, we can estimate that the proportion of R-404A/507 on the total bank of refrigerants installed in Europe in 2010 in the refrigeration applications is as followed:

- **Commercial refrigeration** (super/hypermarkets, small and middle size installations like stand alone and remote systems): it can be estimated that more than 80% of the total installed bank is made of R-404A or 507, which represents about 53 KT of R-404A/507 on a total of 70 KT of refrigerants installed in commercial refrigeration systems in EU 27.
- **Transport refrigeration** (refrigerated trucks and containers): it can be estimated that 3KT of R-404A were installed in Europe in this application in 2010, which represents about half of the total bank of refrigerants in these systems.
- **Industrial refrigeration:** it can be estimated that around 18 KT of R-404A/507 were installed in industrial refrigeration systems in Europe in 2010, thus representing about one third of the total bank of refrigerants for this application.

Applications	Proportion of 404A/507 in the total installed bank (EU27)*
Supermarket refrigeration *(cold storage, food cases...)* Medium and small-sized commercial refrigeration	> 80% (53 KT)
Transport refrigeration *(refrigerated trucks, containers...)*	~ 50% (3 KT)
Industrial refrigeration	~ 30% (18 KT)

R-404A/507 main applications and estimated volumes of the installed bank in EU 27
(Source: Armines / ERIE report on the refrigerant inventories for Europe, October 2011)

[1] GWP represents how much a given mass of a chemical contributes to global warming over a given time period compared to the same mass of carbon dioxide. Carbon dioxide's GWP is defined as 1.
[2] GWP value over a 100-year time horizon (source: *IPCC 4th Assessement Report* - 2007)
[3] "1990 to 2010 Refrigerant inventories for Europe - Previsions on banks and emissions from 2006 to 2030 for the European Union", Armines / ERIE report, October 2011

Why replacing R-404A and R-507: growing regulatory pressure on high-GWP refrigerants

The ongoing revision of the F-Gas regulation may introduce very soon some bans on the use of high-GWP refrigerants, such as R-404A and R-507, for both new equipments and servicing.

At the current stage, there are different suggested scenarios for the introduction of bans. According to the European Commission proposal published in November 2012 [4] or to the amended version voted by the European Parliament on 19 June 2013, it is proposed to ban the use of fluids with a GWP higher than either 2150 or 2500 [5] (these bans will concern directly R-404A and 507) between 2015 and 2017 [6] in new equipments, and between 2017 and 2022 for the servicing of existing equipments. The ban for the servicing would not apply to small units with a refrigerant charge size – expressed in CO_2 equivalent – lower than a given threshold.

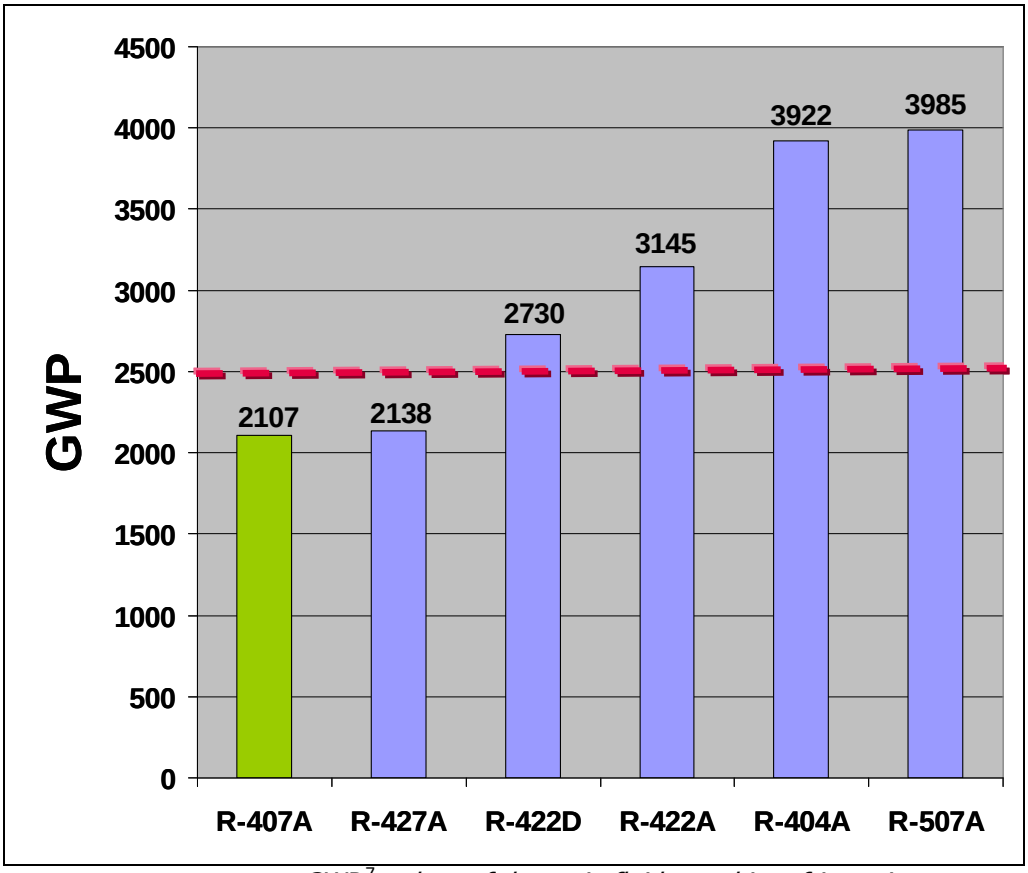
The initial proposal from the European Commission proposes to implement some bans on the use of fluids with a GWP>2500 (which includes R-404A and R-507) according to the following timeframe:

- **From 1 January 2017**: ban of **new refrigerators and freezers for commercial use** (hermetically sealed systems) that contain HFCs with GWP> 2500 ➔ this ban will be extended to HFCs with a GWP>150 starting from January 1st, 2020.

- **From 1 January 2020**: **servicing of existing equipments** with a charge size higher than 5 tonnes of CO_2 equivalent will not be permitted with fluids having a GWP>2500. 5 tonnes of CO_2 is equivalent to 1,3 kgs of R-404A (or 507), which means that the top-in (in case of leakages) of any equipment having a charge size higher than 1,3 kgs of 404A will not be allowed with this fluid after January 1st, 2020.

The following chart is showing that refrigerants such as Forane® 407A (R-404A/507 replacement with a GWP of 2107) and Forane® 427A (R-22 retrofit refrigerant with a GWP of 2138) will not be concerned by these upcoming restrictions, in either new or existing equipments since they have a GWP below 2500.

[4] "Proposal for a regulation of the European Parliament and of the Council on fluorinated greenhouse gases", European Commission, 7 November 2012
[5] The GWP limit may differ according to the applications considered.
[6] The time for entry into of force of the proposed bans differs according to the applications and to the text considered (initial European Commission proposal, or its amended version by the European Parliament).



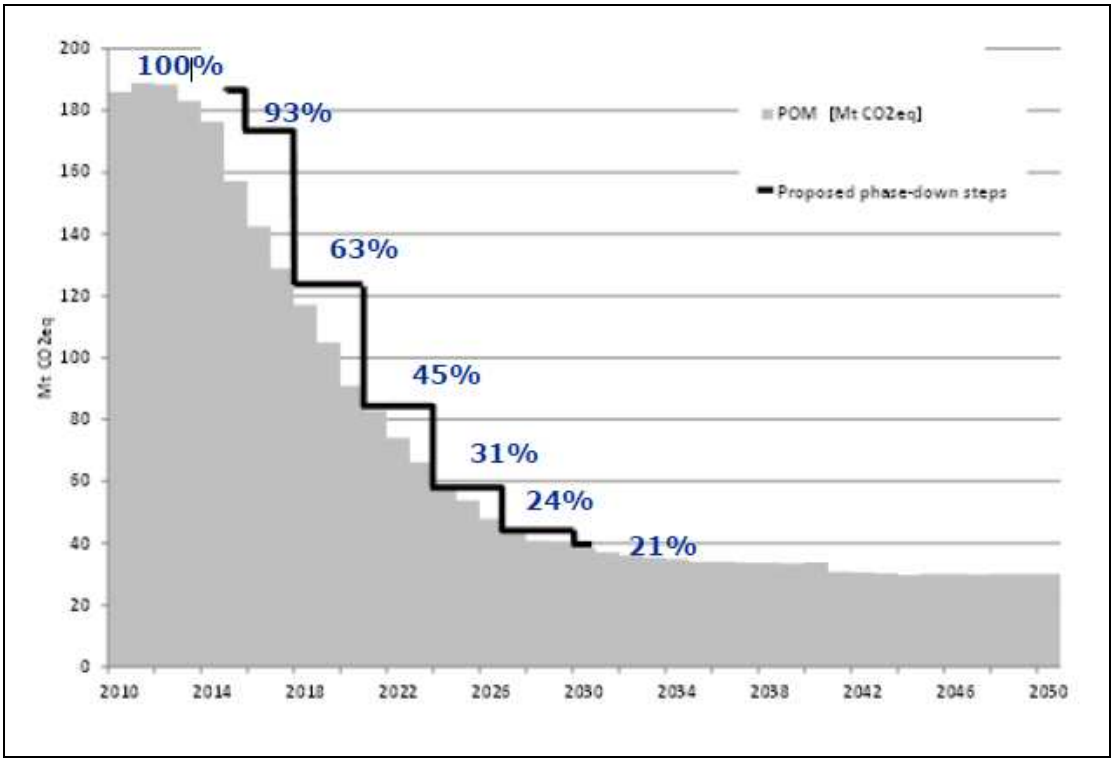
GWP[7] *values of the main fluids used in refrigeration*

In addition to these bans, the European Commission proposed to introduce a phase-down mechanism (see figure below) to progressively reduce the quantity of bulk HFCs allowed to be placed on the market, with a first freeze from 2015 at 100% of the baseline (the baseline corresponds to the annual average of the total quantity of HFCs placed on the market in the European Union from 2008 to 2011). Then the maximum quantity allowed to be placed on the market will be limited to 93% of the baseline in 2016-2017, and will continue to decrease along the time to reach a final step at only 21% of the initial baseline by 2030. The allocated quotas for the placing on the market will be expressed in CO_2 equivalent; and will be calculated from the GWP of the fluids.

Since R-404A and R-507 are high-GWP refrigerants, they may represent an important share of the quotas. For instance, 1 tonne of R-404A or R-507 represents almost 4'000 tonnes of CO_2 equivalent.

The European Commission has based its phase-down mechanism on one of the scenarios described in the SKM report[8]. It is explained in the SKM report that reducing from 93% of the baseline in 2016-2017 to 63% in 2018 can be achieved if only a quick transition from R-404A/507 to refrigerants with a lower GWP like R-407A is made, in both new and existing equipments.

[7] GWP values over a 100-year time horizon (source: *IPCC 4th Assessment Report* – 2007)
[8] "Phase Down of HFC Consumption in the EU – Assessment of Implications for the RAC Sector", SKM ENVIROS, September 2012



Phase-down mechanism involving a progressive reduction of the total quantity of HFCs allowed to be placed on the market as proposed by the European Commission[9]
(quantities expressed in CO_2 equivalent and as a percentage of the 2008-2011 baseline)

[9] "Proposal for a regulation of the European Parliament and of the Council on fluorinated greenhouse gases", European Commission, 7 November 2012.

Forane® 407A presentation

1. Main properties

- Forane® 407A is an HFC blend made of 40% of R-134a, 40% of R-125 and 20% of R-32.
- It is classified A1 by the ASHRAE[10], it is non-toxic and non-flammable.
- Reduced carbon footprint: GWP nearly 50% lower than R-404A and R-507 (2107)
- It is compatible and miscible with POE oils (polyolester), as R-404A and R-507.

Composition	R-134a (40%) 	R-125 (40%) 	R-32 (20%) 
Type	HFC blend		
ASHRAE safety classification	A1 - non-toxic and non-flammable		
GWP	2107		
Recommended lubricant	POE		

2. Applications

Forane® 407A is a low-GWP refrigerant designed for the **replacement of R-404A and R-507** (in new and existing systems) for low and medium temperature refrigeration.

Common applications include:
- commercial refrigeration (super/hypermarkets, food display, storage cases…),
- refrigerated transports (trucks, containers…),
- food processing…

3. Main thermodynamic properties

Forane® 407A has close thermodynamic properties to R-404A and R-507 (see following table). The two main differences are:
- The 6.4°K temperature glide of Forane® 407A, compared to R-404A which is a near-azeotropic blend and R-507 which is an azeotropic blend. The use of Forane® 407A is not recommended in flooded evaporators because of this glide.
- GWP nearly 50% lower than R-404A and R-507.

[10] ASHRAE : American Society of Heating, Refrigerating and Air Conditioning Engineers

Properties[a]

	Forane® 407A	R-404A	R-507A
• Bubble point (° C)	-45	-46.2	-46.7
• Temperature glide	6.4 K	0.7 K	0 K
• Latent heat of vaporisation at n.b.p. (kJ/kg)	238	200	197
• Critical temperature (° C)	83.2	72	71
• Liquid density at 25° C (kg/m³)	1145	1044	1048
• Pressure at 25° C	12.5/10.9 bar	12.5/12.4 bar	12.8 bar
• Pressure at 50° C	23.2/21.2 bar	23.1/23.0 bar	23.6 bar
• ODP	0	0	0
• GWP[b]	2107	3920	3985
• Safety classification	A1	A1	A1

[a] : REFPROP version 9.0
[b] : GWP value for 100-year time horizons according to IPCC AR4

Forane® 407A experimental evaluation results

Arkema ran an intensive R&D program to find the best alternative to R-404A/507 with close performance and properties and a reduced GWP, in order to comply with the future restrictions on these products. In this program, we tested both commercial fluids as well as new blends in an experimental system reproducing the conditions found in commercial refrigeration.

We tested the different fluids in "drop-in" conditions using an equipment designed for R-404A.

1. Description of the test equipment

The test equipment is a 4.4 kW walk-in freezer, equipped with a scroll compressor with liquid injection. The condensing unit and the evaporator are placed in two different psychometric chambers, with controlled humidity rate and temperature.

Some pictures of the test equipment: the two chambers on the left, evaporator at the bottom (placed in one of the chambers), and condensing unit on the right (placed in the other one).

Detailed description of the unit:

- **Condensing unit**
  - Scroll compressor (Copeland ZF15K4ETF5)
  - Capacity (-34.4°C SST[11], 35°C[12]) : 4.396 kW
  - Capacity (-18°C SST[13], 35°C[14]) : 8.206 kW
  - Liquid line size: 13mm
  - Suction line size: 29mm
  - Energy efficient PSC condenser fan
  - Flooded head pressure control
  - Liquid receiver capacity: 90% of the volume = 10 kg

- **Evaporator**
  - Capacity (-28.9°C SST[15], 5°C TD[16]) : 5.569 kW, 3810 CFM

- **TXVs (expansion device)**
  - Low temperature TXV: Sporlan EGSE2ZP, 2 tons R404A
  - Medium temperature TXV: Sporlan EGSE2C, 2 tons R404A

2. Test conditions

The different fluids were tested at the following temperatures:
- Indoor temperatures: -4, -18 and -32°C
- Outdoor temperatures: +32 and +43°C

These temperatures were selected to cover a wide range of R-404A applications.

3. Results for the medium temperature refrigeration (-4°C)

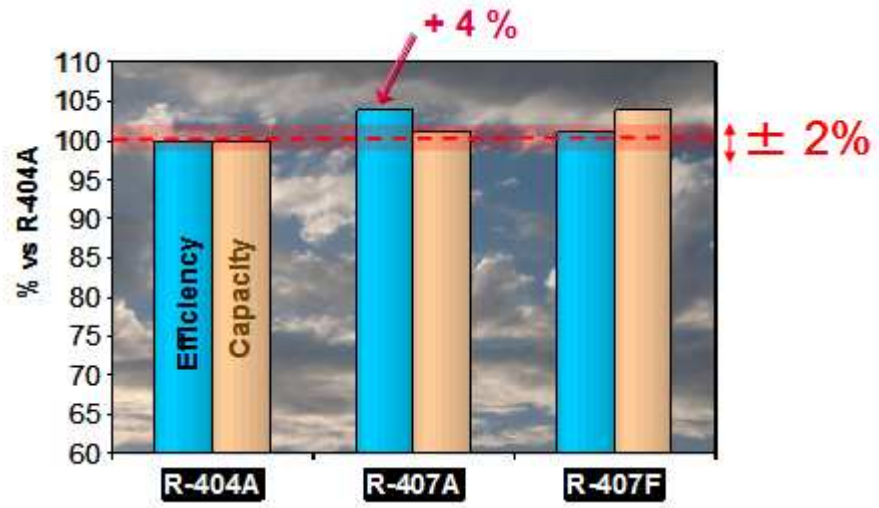
Our main criteria to find the best alternative to R-404A and R-507 were the following:
- keep a close cooling capacity to R-404A and R-507,
- improve the energy efficiency (COP),
- reduce significantly the GWP (to reduce the direct CO_2 emissions).

The charts below sum up the tests results. COP is represented in blue and the cooling capacity is represented in orange. Results are expressed in % versus R-404A which is the reference.

The red dotted lines represent the experimental tolerance of the results.

At an outdoor temperature of +32°C:
- The cooling capacities of R-407A and R-407F are equivalent or higher than R-404A.
- R-407A has a higher energy efficiency (COP): +4% vs. R-404A.

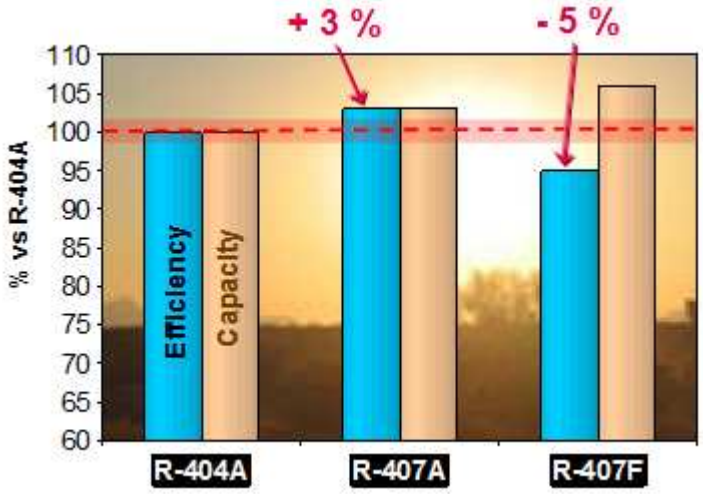
[11] Saturated suction temperature
[12] Ambient temperature
[13] Saturated suction temperature
[14] Ambient temperature
[15] Saturated suction temperature
[16] Temperature Difference between ambient temperature and evaporator temperature



Results for an indoor temperature of -4°C and an outdoor temperature of +32°C

At an outdoor temperature of +43°C (maximum average temperature during summer time):

- The cooling capacities of R-407A and R-407F are higher than R-404A.
- R-407A has a higher energy efficiency (COP): +3% vs. R-404A and +8% vs. R-407F.



Results for an indoor temperature of -4°C and an outdoor temperature of +43°C

The table below gives the main parameters measured for R-407A and R-407F compared to R-404A.

- Discharge temperature is 6°C higher than R-404A. This value was measured with the liquid injection running and remains close to R-404A discharge temperature.

- Mass flows for both R-407A and R-407F are lower than R-404A, therefore TXV adjustments will be required. It can be noticed that R-407A mass flow is closer to R-404A than R-407F.

- Suction pressures and vapor refrigerant velocities are close for all three blends. We did not observe any oil return difference with R-407A and R-407F vs. R-404A.

Properties vs R-404A

Outdoor box : 32° C	R-407A	R-407F
Suction Pressure	**-0.6 bar**	**-0.5 bar**
Discharge Temperature*	**+6° C**	**+6° C**
Mass Flow	73%	68%
Vapor refrigerant velocity	**102%**	**100%**
TXV adjustment	**5 turns**	**4.75 turns**

** With liquid injection running*

Results measured with R-407A and R-407F vs. R-404A for medium temperature refrigeration (-4°C)

Conclusion:
For the medium temperature refrigeration, Forane® 407A provides the best energy efficiency compared to R-404A and R-407F at these operating conditions, while maintaining an equivalent, and sometimes even higher, cooling capacity than R-404A.

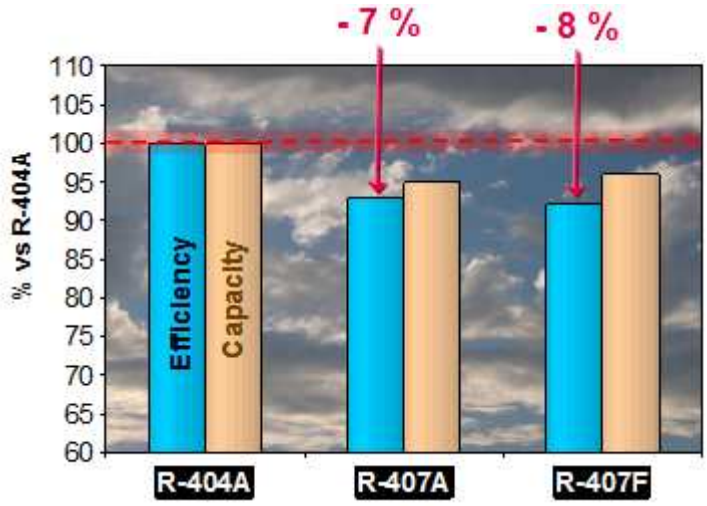
This energy efficiency improvement reduces the overall energy consumption of the equipment while keeping a cold production equivalent to R-404A. This allows savings on the operating costs of the unit and a reduction of the indirect CO_2 emissions resulting from the energy consumption of the equipment.

4. Results for the low temperature refrigeration (-32°C)

The same tests were performed at an indoor temperature of -32°C. The results are presented below.

At an outdoor temperature of +32°C:

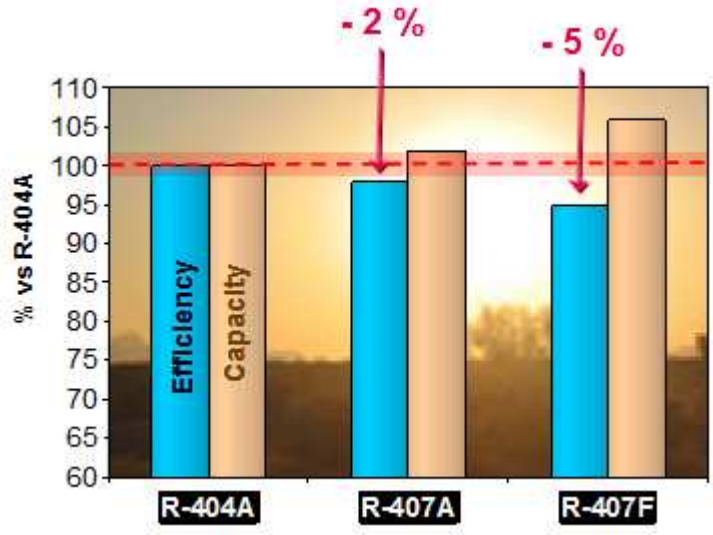
- The cooling capacities of R-407A and R-407F are lower than R-404. However, this decrease is slight: less than 5% lower than R-404A.
- Energy efficiency (COP) is also a few percents lower compared to R-404A.



Results for an indoor temperature of -32°C and an outdoor temperature of +32°C

At a higher outdoor temperature (+43°C), R-407A is very close to R-404A in terms of performance:

- The cooling capacities of R-407A and R-407F are higher than R-404A.
- Energy efficiency (COP) is still lower than R-404A, but R-407A provides the closest COP to R-404A (-2% for R-407A versus R-404A, and -5% for R-407F versus R-404A).



Results for an indoor temperature of -32°C and an outdoor temperature of +43°C

The table below sums up the main parameters measured for R-407A and R-407F. The values are expressed in % of R-404A values.

- The discharge temperature increase of both R-407A and R-407F is limited to only 1°C compared to R-404A (with liquid injection running).

- R-407A and R-407F mass flows are lower than R-404A. TXV adjustment will be required. Again, R-407A mass flow is the closest to R-404A.

- Suction pressures and vapor refrigerant velocities are close for all three blends.

Properties vs R-404A

Outdoor box : 43° C	R-407A	R-407F
Suction Pressure	**-0.3 bar**	**-0.3 bar**
Discharge Temperature*	**+1° C**	**+1° C**
Mass Flow	68%	61%
Vapor refrigerant velocity	**97%**	**91%**
TXV adjustment	**1.25 turns**	**1 turn**

** With liquid injection running*

Results measured with R-407A et R-407F vs. R-404A for low temperature refrigeration (-32°C)

Conclusion:
For the low temperature refrigeration, Forane® 407A provides the closest performances to R-404A in these test conditions.

When working under the most extreme conditions, such as low evaporating temperature and high condensing temperature, R-407A provides much better performances than R-407F.

5. Discharge temperature management

The previous results were obtained with the liquid injection running.

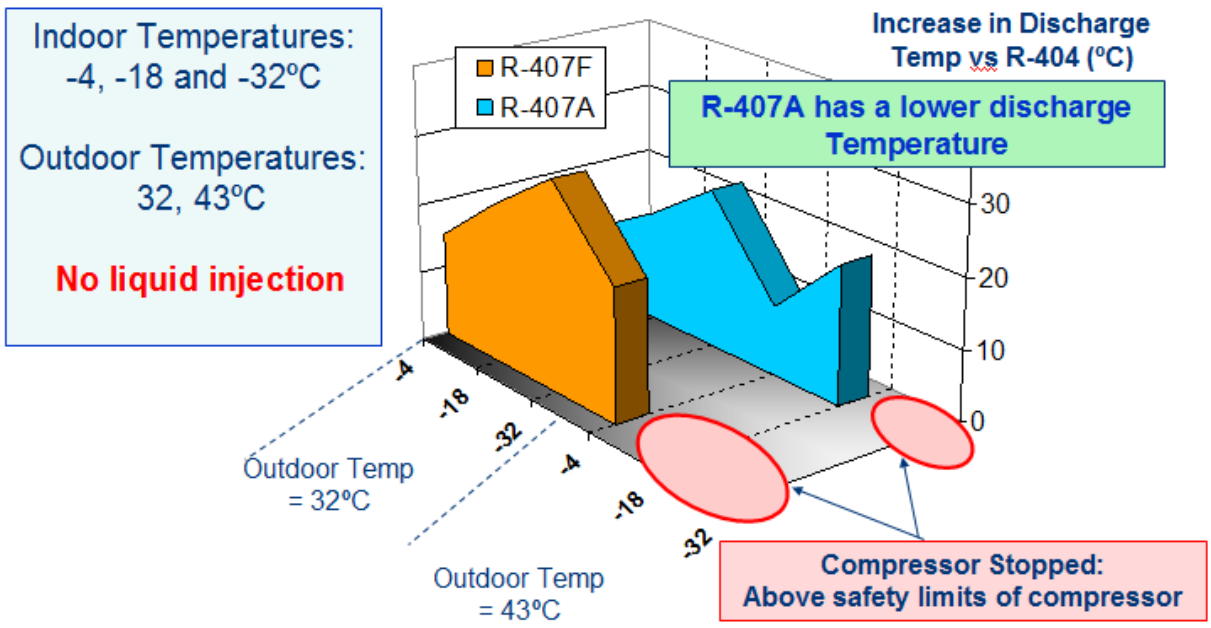
We wanted to evaluate the impact of the liquid injection on R-407A and R-407F discharge temperatures. We performed the same tests again without the liquid injection.

The chart below shows the discharge temperature increase for R-407F (in orange) and R-407A (in blue) versus R-404A for the different test temperatures (indoor: -4, -18 and -32°C; outdoor: +32 and +43°C).

At each test temperature, the discharge temperature increase versus R-404A is always lower with R-407A than R-407F. R-407A discharge temperature is on average 10°C lower than R-407F.

We observe that the operating range without liquid injection is wider with R-407A than R-407F. For some temperature conditions, the discharge temperature increase versus R-404A was too high that the compressor stopped (discharge temperature above safety limits).

With R-407A, it only happened under one test condition: $T_{outdoor}$ = +43°C and T_{indoor} = -32°C, while the compressor goes beyond safety limits twice with R-407F: $T_{outdoor}$ = +43°C and T_{indoor} = -18°C and -32°C.



Discharge temperature comparison when the liquid injection is turned off: discharge temperature increase with R-407A (in blue) and with R-407F (in orange) versus R-404A discharge temperature

R-407A has a wider range of operating conditions without liquid injection than R-407F.

It is a major advantage for R-407A vs. R-407F when the compressors are not equipped with liquid injection or any other additional cooling system: R-407A can be used in a wider range of temperature conditions than R-407F.

6. Conclusion

a) Performances

- **Forane® 407A** is a very efficient alternative to R-404A and R-507 for both **low and medium temperature refrigeration (retrofits and new equipments).**
- Its cooling capacity is similar to R-404A and R-507 on a wide range of applications.
- **Forane® 407A improves the energy efficiency**, especially at high ambient temperature, which results in energy costs savings.

b) Ease of use

- Forane® 407A is easy to use as **it does not require any oil replacement**: Forane® 407A is compatible with POE oils, just as R-404A and R-507.
- **Forane® 407A has a lower discharge temperature than R-407F**. Forane® 407A can be used in a wider range of operating conditions without liquid injection than R-407F. There are much more models of compressors approved with R-407A than R-407F.

- It might be necessary to readjust the expansion device in existing equipments as the mass flow is lower than with R-404A or R-507A.

c) References

- Forane® 407A is not a new refrigerant. It has been used for many years in several countries such as the USA and the UK, and more recently, France and Spain, by more than 12 supermarket chains, including Walmart, Marks and Spencer, Condis supermarkets…

- **R-407A is approved by several compressor manufacturers** including Emerson, Bitzer and Carlyle.

d) Environmental benefits

- Forane® 407A enables to reduce the global CO_2 emissions of an equipment, thus reducing its carbon footprint thanks to two properties:

    - The GWP of Forane® 407A (2107) is almost half lower than the GWP of R-404A or R-507 => this will reduce the direct CO_2 emissions by half.

    - Forane® 407A has a higher energy efficiency (COP) than R-404A or R-507 in certain conditions => this reduces the indirect CO_2 emissions due to the energy consumption of the equipment.