COMPRESSORS

Technical information

Practical Application of Refrigerant R600a Isobutane in Domestic Refrigerator Systems

REFRIGERATION AND AIR CONDITIONING

Refrigerant R 600a, or isobutane, is a possible replacement for other refrigerants, which have high impact on the environment, in domestic refrigerators. It has zero ozone depletion potential ODP and a neglectible global warming potential GWP. Furthermore it is a substance which is a part of petrol gases from natural sources. The refrigerant R 600a has been in use in the past, in refrigerators up to the 40'es, and has now again found a wide use in do-mestic refrigerators and freezers in Europe, especially in Germany, where more than 90% of refrigerators are manufactured using R 600a as refrigerant. Because of the availability of isobutane all over the world it has been discussed widely for CFC replacement. Isobutane R 600a is a possible refrigerant for this application, with good energy efficiency, but with a very different characteristic in several points, which implies the design to be made or adopted for this refrigerant. Special care has to be taken to the flammability of isobutane.

1 Refrigerant

The properties of R 600a differ from other refrigerants commonly used in household applications, as shown in table 1. This leads to a different design of details in many cases.

Table 1: Refrigerant data comparison

Refrigerant	**R 600a**	**R 134a**	**R 12**
Name	Isobutane	1,1,1,2-Tetra-flouro-ethane	Dichloro-di-fluoro-methane
Formula	$(CH_3)_3CH$	CF_3-CH_2F	CF_2Cl_2
Critical temperature in °C	135	101	112
Molecular weight in kg/kmol	58.1	102	120.9
Normal boiling point in °C	-11.6	-26.5	-29.8
Pressure at -25 °C in bar (absolute)	0.58	1.07	1.24
Liquid density at -25 °C in kg/l	0.60	1.37	1.47
Vapour density at t_o-25/+32 °C in kg/m³	1.3	4.4	6.0
Volumetric capacity at -25/55/32 °C in kJ/m³	373	658	727
Enthalpy of vaporisation at -25 °C in kJ/kg	376	216	163
Pressure at +20 °C in bar (absolute)	3.0	5.7	5.7

1.1 Pressure

The first large difference between R 600a and R 134a or R 12, is found in the pressure level, which is lower, e.g. at -25°C evaporating roughly 55 % of R 134a or 45 % of R 12. In connection with this the normal boiling point is at 15 K or 18 K higher respectively. This leads to operating pressures being very much lower than previously common. Evaporators of household refrigerators will thus operate below normal atmospheric pressure.

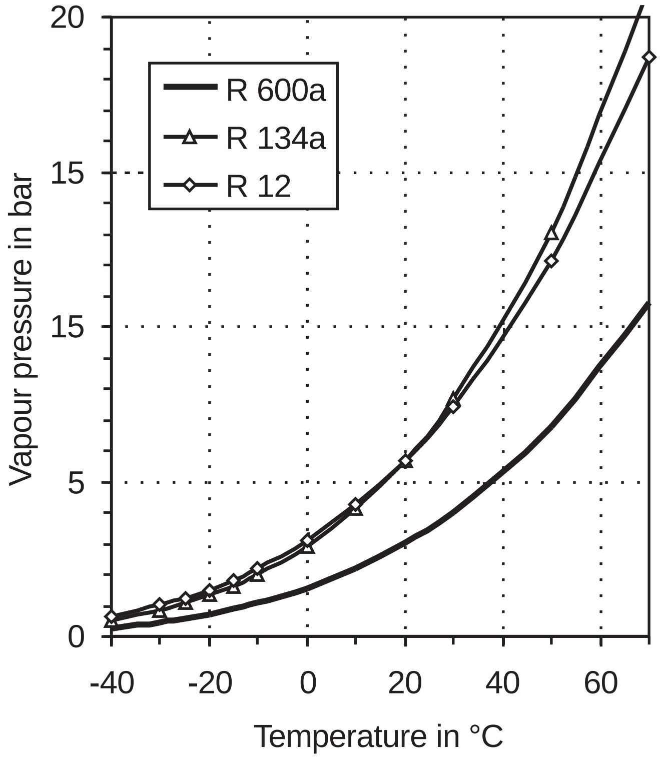

Figure 1: Vapour pressure of different refrigerants versus temperature

1.2 Capacity

The low pressure level is connected to a relatively high critical temperature. This gives a good cooling capacity even at high condensing temperature.

R 600a has roughly 50 % of R 12 or 55 % of R 134a volumetric capacity at 55 °C condensing temperature, as seen in figure 2. Because of this the necessary compressor swept volume will be up to 2 times the swept volume used for R 12.

The volumetric cooling capacity is a value calculated from suction gas density and enthalpy difference of evaporation. The compressor capacity characteristics, in terms of capacity over evaporating temperature, are close to those of the other refrigerants, as shown in figure 3.

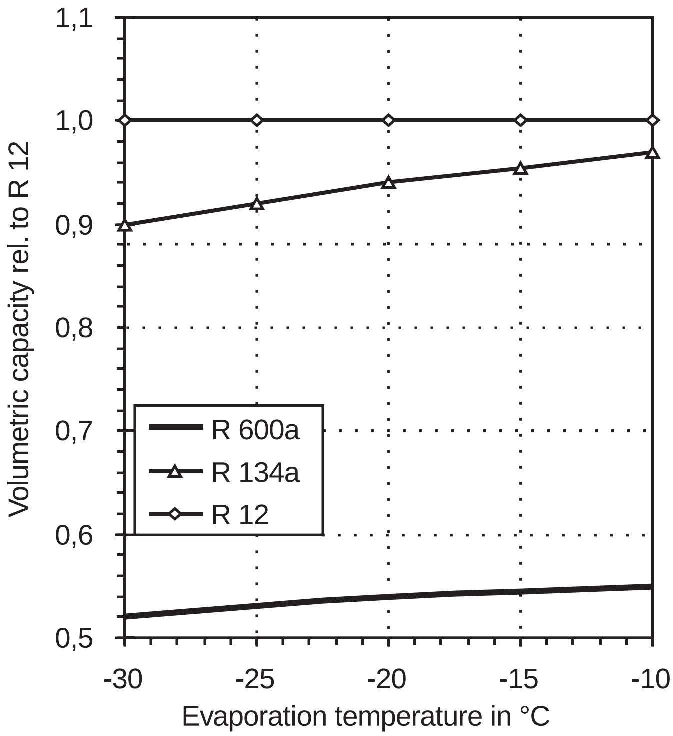

Figure 2: Volumetric capacity of R 600a and R 134a, relative to R 12, over evaporation temperature, at 55 °C condensing and 32 °C suction gas temperature, no subcooling

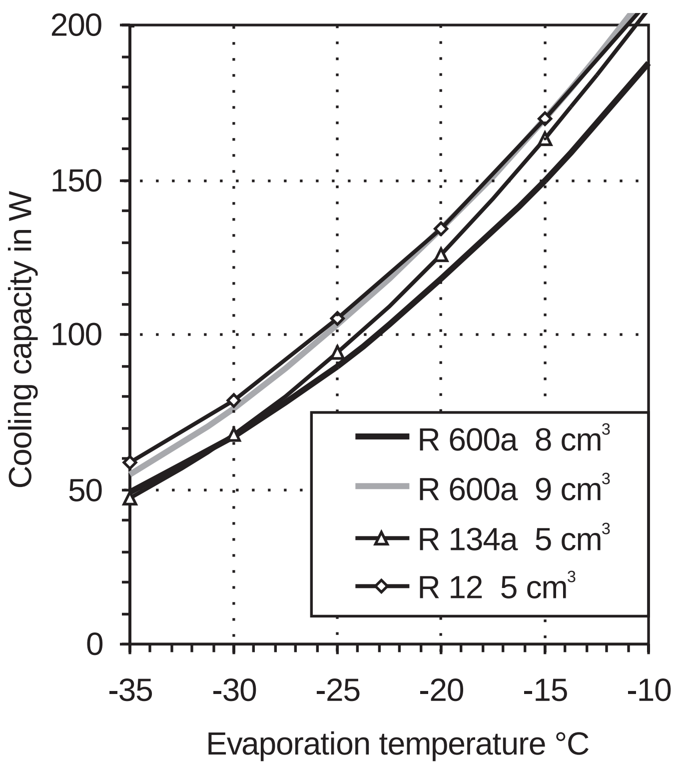

Figure 3: Cooling capacity versus evaporating temperature with different refrigerants

1.3 Refrigerant charge

If R 600a would be charged into an unchanged refrigeration system, charge amount counted in grams would be much lower. However, if you calculate in cm^3, you would have to charge roughly the same liquid volume into the system. This gives charges of approx. 45 % of R 134a charge or approx. 40 % of R 12 charge in grams, according to the data from table 1, which also corresponds with emperical values. Additionally experience has shown a higher sensitivity of the systems to charge deviations. Especially undercharging tends to give higher energy consumption. This means that charging accuracy has to improve, in cm^3 and even more in grams. On charges of approx. 20 g, which are found on small larder refrigerators, accuracy has to be within 1 g. Maximum charge according to safety regulations is 150 g for household refrigerators and similar appliances, which corresponds to approx. 360 g of R 12 or 340 g of R 134a.

1.4 Purity

Refrigerant R 600a specification is not found in international standards. Some data are enclosed in a German standard DIN 8960 of 1998, which is an extended version of ISO 916. The purity of the refrigerant has to be judged from chemical and stability side, for compressor and system lifetime, and from thermodynamic side regarding refrigeration system behaviour and controllability.

The specification in DIN 8960 is a safe general hydrocarbons refrigerant specification, adopted from other refrigerants criteria catalogue and covering normal butane, propane and others. Some points can possibly be accepted a little less narrow for specific refrigerants and impurities combinations after extensive evaluation.

For the time being no refrigerant quality according to an official standard is on the market. The specifications of possible qualities have to be checked with the supplier in details. Liquified petrol gas LPG for fuel applications or technical grade 95 % purity is normally not sufficient for hermetic refrigeration. Water, sulfur and reactive compounds contents has to be on a lower level than guaranteed for those products.

Table 2: Specification of R 600a according to DIN 8960 - 1998

	Specification		Unit
Refrigerant content [1]	≥	99.5	% by mass
Organic impurities [2]	≤	0.5	% by mass
1,3-Butadiene [3]	≤	5	ppm by mass
Normal Hexane	≤	50	ppm by mass
Benzene [4]	≤	1	ppm per substance
Sulfur	≤	2	ppm by mass
Temperature glide of evap.	≤	0.5	K (at 5 to 97 % destill.)
Non condensable gases	≤	1.5	% vol. of vapour phase
Water [5]	≤	25	ppm by mass
Acid content	≤	0.02	mg KOH/g Neutralization
Evaporation residue	≤	50	ppm by mass
Particles/solids		no	Visual check

1) This content is not explicitly stated in DIN 8960. Only the impurities are listed and limited. The main content is the rest up to 100 %.
   From thermodynamic calculation an isomer content of R 600 normal butane up to 5 % in R 600a isobutane is not critical and still does not exceed the temperature glide criteria and has only very low impact on pressure, less than 0.2 K temperature at evaporation.
2) From compressor point of view a propane content up to approx. 1 % is acceptable in the R 600a.
3) This is a maximum value for every single substance of the multiply unsaturated hydrocarbons.
4) This is a maximum value for every single aromatic compound.
5) This is a preliminary value, to be reviewed with growing experience.
6) mg/kg equals ppm by mass

Because of higher pressure of propane, the vapour phase will contain higher propane concentrations. To avoid problems with demixing, charging should always be done from liquid phase.

2 Materials

Refrigerant R 600a is mostly used with mineral compressor oils, so material compatibility is almost identical to R 12 situation from oil side. Use of alkyl benzenes is also possible. R 600a is chemically inactive in refrigeration circuits, so no specific problems should occur there. Solubility with mineral oil is at least as good as was with R 12. Direct material com-patibility is less problematic. On some rubbers, plastics and especially chlorinated plastics however, problems have been observed, but these materials are normally not present in refrigerator systems. Some materials, on which problems have been reported by different testers, are listed in the table 3. On critical materials test have to be performed for the specified use.

Table 3: Material compatibility

Material	**compatible**
Butylic rubber	no
Natural rubber	no
Polyethylene	depends on conditions
PP	no
PVC	no
PVDF	no
EPDM	no
CSM	no

2.1 Driers

For domestic refrigerators the common desiccant is a molecular sieve, a zeolithe. For R 600a a material with 3 Å pores is recommended, like for R 134a, e.g. UOP XH 7, XH9 or XH 11, Grace 594, CECA Siliporite H3R. Pencil driers for R 134a can normally be used for R 600a without changes. See also note CN.86.A .

3 Flammability and Safety

The main disadvantage discussed in connection with R 600a use is the risk based in its flammability. This leads to necessity for very careful handling and safety precautions.

Table 4: Flammability of isobutane

Lower explosion limit (LEL)	1.5 %	approx. 38 g/m^3
Upper explosion limit (UEL)	8.5 %	approx. 203 g/m^3
Minimum ignition temperature	460 °C	

Because of the flammability of isobutane in a wide concentration range safety precautions are necessary, on the appliance itself and in the manufacturing factory. The risk assessments behind these two situations are quite different. Main common starting point is, that accidents need to have two essential preconditions. One is the flammable mixture of gas and air and the other is the ignition source of a certain energy level or temperature.
These two have to be present together for combustions, so avoidance of this combination has to be proven.

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Figure 4: Yellow warning label

Danfoss compressors for R 600a have internal protectors and PTC starters, both preventing from sparks coming out, because it can not be guaranteed to hold sur-rounding air below LEL in case of leaks close to the compressor.
They are equipped with a yellow label warning for flammable gas, like shown in figure 4.

3.1 Appliance

For safety testing of household refrigerators a standard has been established in Europe, IEC Technical Sheet TS 95006. It is also transferred to an amendment to IEC / EN 60 335-2-24, which is the normal electrical safety standard. Approvals of refrigerators using hydrocarbons as refrigerant are done according to the proceedures of the TS in Europe since 1994. The methodology of TS and the amendments derived from this are base for the following short description. Other applications have to take different national standards and legislation into account, e.g. EN 378, DIN 7003, BS 4344, SN 253 130, which can have different demands.

- All electrical elements switching during normal operation are taken to be possible ignition sources. This includes thermostat, door contacts for lighting, on/off and other switches, like superfrost, compressor relays, external klixon, defrost timers and so on.
- All refrigerant containing parts are taken to be possible refrigerant sources through leaks. This includes evaporators, condensers, door heaters, tubings and the com pressor.
- Maximum refrigerant charge is set to be 150 g. By keeping the charge to max. 25 % of lower explosion level LEL, which is approx. 8 g/m^3, for a standard kitchen, ignition risk is very low, even if refrigerant distribution in case of leakage is uneven for some time first

The main target of the safety precautions is to seperate rooms with refrigerant containing parts from rooms with switching elements.

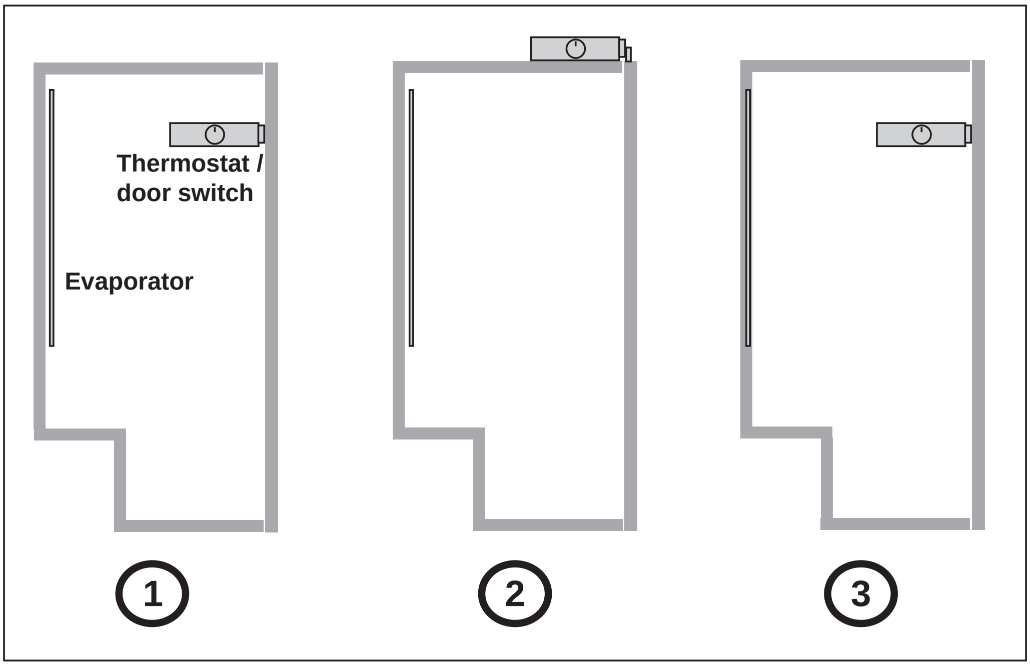

Figure 5: Appliance design variants

In figure 5 three principal possibilities are shown. Option 1 has evaporator and thermostat/ door switch both located in the storage volume. This is critical for flammable refrigerants and should not be used. Option 2 has evaporator inside and thermostat/door switch outside, on top. This normally gives a safe solution. Option 3 has thermostat/door switch inside, but evaporator foamed in place behind the inner liner. This is a possible solution used in many cases. Choosen option has to be designed and proven in leakage test according to TS 95006 and IEC / EN 60 335 demands.

On many refrigerator or freezer designs this separation is already the existing situation.

- Large free standing freezers and fridge freezer combinations often have all electrical switches in the top panel.
- Some refrigerators have the evaporators hidden behind the liner, in the foam and not in the cabinet space where thermostats and so on, are allowed in this case.

Critical situation is given whenever it is not possible to avoid evaporator and thermostat or switches being in the cabinet. In this case two possibilities are left.

- Thermostats and switches have to be changed to sealed versions preventing gas from penetrating them and thus reaching the switching contacts.
  Danfoss offers electronic thermostats suitable for this application.
- Evaporators of rollbond type can be made extra leak proof by manufacturing them with double metal layers, called safety rollbond. In this case the suction tube connection point has to be outside and sealed from the refrigerated space.

Every R 600a appliance type has to be tested and approved according to the TS / IEC / EN proceedures, even if all above mentioned criteria are included in the design. The standards also specify minimum burst pressure for heat exchangers and tubings, depending on the used refrigerant. Please see the standards for details. Instructions for use should contain some information and warnings for careful handling, such as not to defrost freezer compartments with knives, and for installing in a room with at least 1 m^3 of space per 8 g of refrigerant charge, the latter to be seen on the type label.

3.2 Factory

The refrigerant containing system and the safety system design is to be approved and controlled regularly by local authorities, normally. Below the design principles for installations in Germany are given.
In many details this is based on regulations for liquified gas installations. Specialities are found around the charging stations, where gas connectors are to be handled frequently and a charging of the appliances occurs.

The basic principles for safety are
- Forced ventilation to avoid local accumulation of gas.
- Standard electrical equipment except for the ventilation fans and safety systems.
- Gas sensors continously monitoring in possible leakage areas like around charging stations, with alarm and doubling of ventilation at 15 % to 20 % of LEL and with disconnec tion of all non explosion proof electrics in the monitored area at 30 % to 35 % of LEL, leaving the fans running at full speed.
- Leakage test on appliances before charging to avoid charging of leaking systems.
- Charging stations designed for flammable refrigerants and connected to the safety sys tems.

Safety system design can be supported by suppliers of charging stations and gas sensing equipment in many cases.

4 Refrigeration system design

In many cases of transition from non flammable refrigerants to R 600a the appliance cabinet has to be modified for safety reasons as listed in section 3.1. But changes can additionally be necessary for other reasons.

4.1 Heat exchangers

The refrigeration system efficiency will normally not cause a need for changing evaporator or condenser size, which means, the outer surface can be left the same as with R 12 or R 134a.
Inside design of the evaporator could possibly need some modification, because the refrigerant volume flow increases by 50 % to 100 % according to the larger compressor swept volume. This leads to increased pressure drop in the refrigerant channels or tubes, if the cross flow section stays the same. To keep the refrigerant flow speed within the recommended range of 3 to 5 m/s it may be necessary to make the cross flow sections wider. In rollbond evaporators this can be done by either increasing channel system height, e.g. from 1.6 mm to 2 mm, or by designing parallel channels instead of single ones. A parallel channel design however has to be developed very careful to avoid liquid accumulations.

4.2 Capillary

Special care has to be taken when designing the accumulator in a rollbond evaporator system. When using R 12 or R 134a the refrigerant is heavier than the oil used, while with R 600a the refrigerant is less heavy, as can be seen in the data table 1. This can lead to oil accumulation if the accumulator is too large, especially too high, and has a flow path which does not guarantee emptying sufficiently during startup phase of the system. Evaporator design hints can be found in note CN.82.A .

When changing a refrigeration system with capillary from R 12 to R 134a, very often the capillary flow rate, expressed in litres of nitrogen per minute at specific conditions, was reduced by elongating the capillary, or by taking a smaller inner diameter. For R 600a experience and theoretical modellings show the need for a flow rate almost similar to R 12 again.
As with R 134a the suction line heat exchanger is very important for system energy efficiency of R 600a. Effect on efficiency is even higher for R 600a, than for R 134a. For both it is more important than for R 12, see figure 6, which shows increase of COP with superheat from 0 K up to +32 °C return gas temperature. A range from +20 °C to approx. +32 °C is usual for household appliances. This large increase in COP for R 600a is caused by a high vapour heat capacity. In combination with the need for keeping the refrigerant charge close to maximum possible in the system, thus giving no superheat at evaporator outlet, the suction line heat exchanger has to be very efficient for preventing air humidity condensation on the suction tube. In many cases an elongation of the suction line and capillary gives efficiency improvements. The capillary itself has to be in good heat exchanging contact with the suction line for as long a part of total length as possible.

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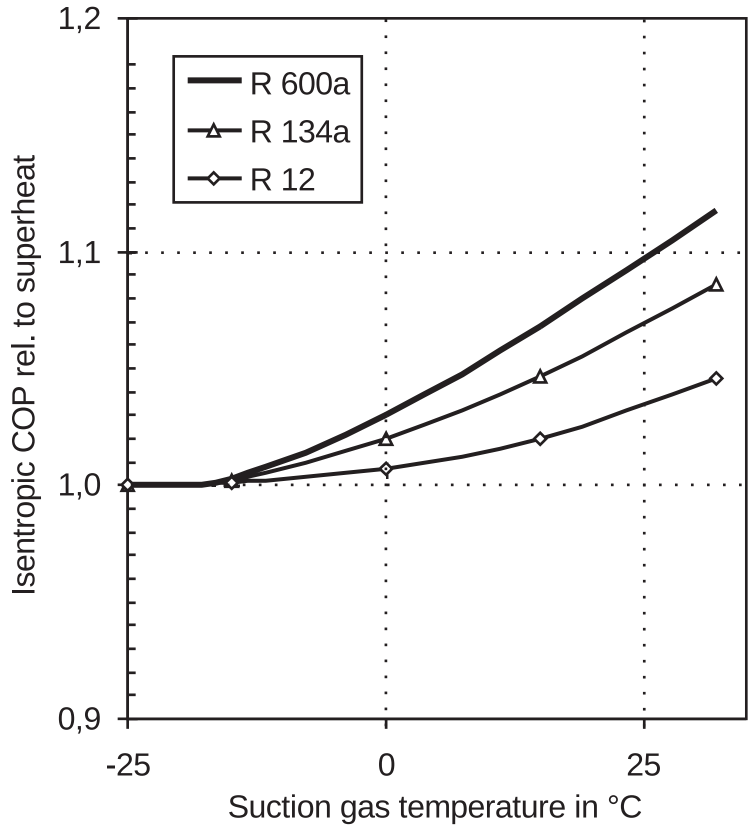


Figure 6: Theoretical COP increase of different refrigerants versus suction temperature with adiabatic compression, internal heat exchange, at -25 °C evaporation, 55 °C condensation, no subcooling before internal heat exchanger

4.3 Noise

While the compressors tend to be less noisy with R 600a at low cooling capacity, partly because of the lower working pressure levels, some other noise problems can occur on appliances.
The larger required displacement can cause higher vibration and thus create noise in the appliance. The increased volume flow can give higher flow noise in evaporators, especially at the injection point. But even if this noise in many cases is not increased, it can be a problem. If compressor noise is reduced, the flow noise appears to be the loudest part, not covered by the compressor noise any longer, and it is an unexpected noise, a hiss. Additionally the higher volume flow can result in higher gas pulsations and by that increase flow noise or even create vibrations on appliance parts. Increased suction line heat exchanger length can reduce flow noise too, because it equalizes the flow and thus stabilizes injection.

4.4 Evacuation

At -25 °C evaporation temperature R 600a has a pressure of 0.58 bar, while R 12 has 1.24 bar and R 134a has 1.07 bar, which means only 47 % or 54 %, or roughly half of previously handled pressure values are present.
This means that non condensable gases contents in a refrigeration system will have double the negative effect than with the other two refrigerants, or, taken from that, necessary maximum level for non condensables residue has to be halved. Because of a main part of non condensables coming from the compressor oil, which takes some time to extract and shows to be an effect not linear with time, minimum necessary evacuation times will be more than double.

Working with single side evacuation on the process tube of the compressor only, necessary evacuation times will raise, depending on the appliance design. Changing to two side evacuation, on process tube and a second connection at the drier, reduces necessary time again, but increases cost.
Too high level of non condensables increases energy consumption because of higher condensing temperature and a portion of the transported gas being inactive. It can additionally increase flow noise. On two temperature one compressor systems it can give problems with the cyclic defrosting of the refrigerator cabinet, where risk for ice block forming is increased.

4.5 Cleanliness of components

The specifications for cleanliness are generally comparable to R 12 or R 134a. The only official standard on cleanliness of components for refrigeration use is the DIN 8964, which also is used in several countries outside Germany. It specifies maximum contents of soluble, insoluble and other residues. The methods for determining soluble and insoluble contents are to be modified for the actual refrigerant R 600a, but in principle the same limits are useful.

5 Service

Servicing and repair of R 600a refrigerators is possible for skilled and well trained service technicians. Please see note CN.73.C for details. Local laws and standards have to be taken into account also. It needs very careful handling because of the flammability of the gas, which is a potential danger during work on the refrigeration system. A good ventilation of the room is necessary and the discharge of the vacuum pump has to be lead to open air. The equipment of the service technician has to meet the requirements of R 600a in terms of evacuation quality and refrigerant charge accuracy. An electronic scales is recommended to control refrigerant charge to within the needed accuracy.

Conversion of a R 12 or R 134a refrigerator to R 600a is not recommended by Danfoss, because R 12 and R 134a appliances are not approved for flammable refrigerant use, so electrical safety is not proven to be according to the needed standards.

References

TS 95006 — *Refrigerators, food-freezers and ice-makers using flammable refrigerants*, Safety Requirements, Ammendment to IEC 60 335-2-24, CENELEC, July 1995

DIN 8964 — *Kreislaufteile für Kälteanlagen* Beuth Verlag GmbH, Berlin

CN.86.A — *Driers and Molecular Sieves Desiccants*

CN.82.A — *Evaporators for Refrigerators*

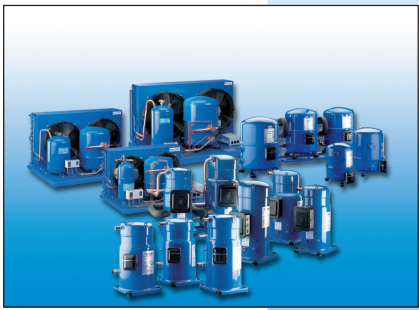
CN.73.C — *Service on Household Refrigerators and Freezers with New Refrigerants*

CK.50.A — *Compressors for R 600a 220 - 240 V 50 Hz* Collection of Datasheets

EN 60335-2-24 — *Safety of household and similar appliances Part 2: Particular requirements for refrigerators, food freezers and ice-makers*

The Danfoss product programme for the refrigeration industry contains:

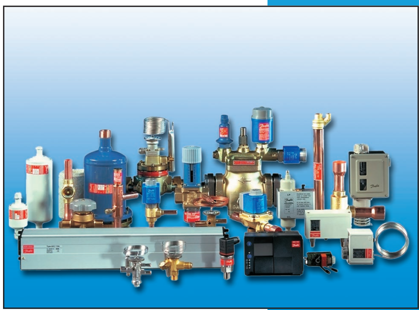
Compressors for Refrigeration and Air Conditioning
A wide range of hermetic reciprocating compressors and scroll compressors as well as aircooled condensing units. The product range is applied in air conditioning units, water chillers and commercial refrigeration systems.



Compressors for Refrigerators and Freezers
Hermetic compressors and fan-cooled condensing units for household refrigeration units such as refrigerators and freezers, and for commercial installations such as sales counters and bottle coolers. Compressors for heating pump systems. 12 and 24 V compressors for refrigerators and freezers in commercial vehicles, buses, and boats.

Appliance Controls
For the regulation of refrigeration appliances and freezers Danfoss supply a CFC-free product range of electromechanical thermostats for refrigerators and electromechanical thermostats for refrigerators and freezers produced according to customer specification; Hermetic valves for refrigerator/freezer combinations and for energy saving applications; Service thermostats – for all refrigerating and freezing appliances.

Refrigeration and Air Conditioning Controls
With our full product range we cover all the requirements for mechanical and electronically controlled refrigeration systems. The functions cover: control, safety, system protection and monitoring. Our products are applied for all commercial- and industrial refrigeration applications as well as for air conditioning.



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