Working model of a CO2 refrigerating unit for a retail food store

REVIEW OF EXISTING REFRIGERANTS

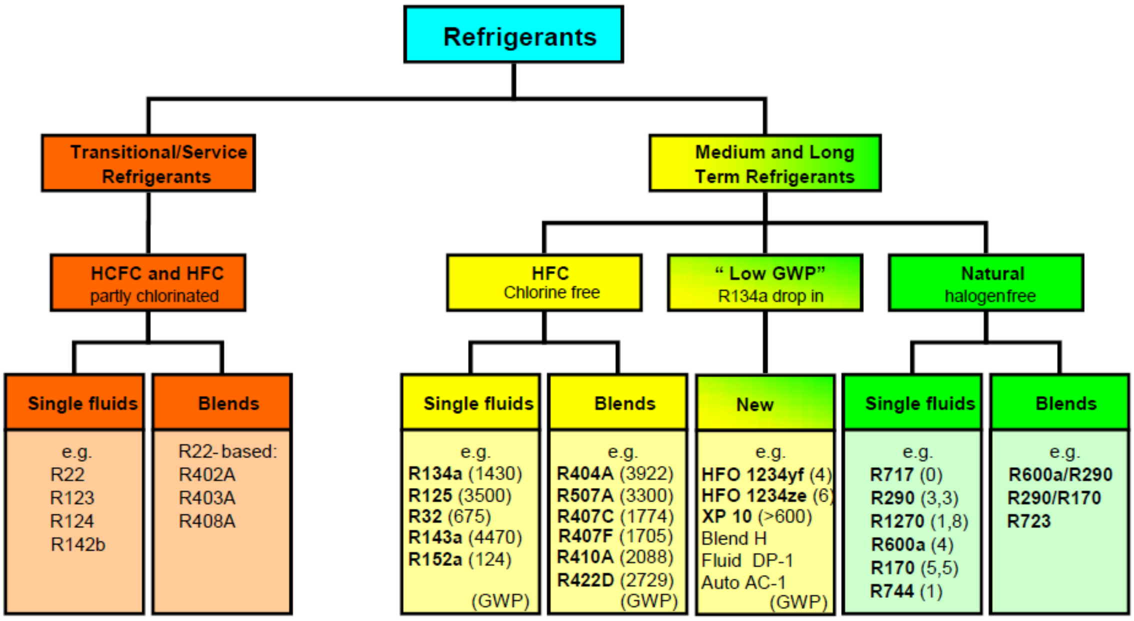


Figure 1. Global warming potential (GWP) and ozone depleting potential (ODP) of existing refrigerants

Before 1980s, chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants dominated the refrigerating sector and were considered as working fluids possessing only advantages unlike other refrigerants.

However, by mid 1980s, when scientists of several countries started addressing issues of CFC and HCFC influence on the environment, these refrigerants had become a matter of concern in light of evolving global problems: increase of greenhouse effect and probable depletion of the ozone layer.

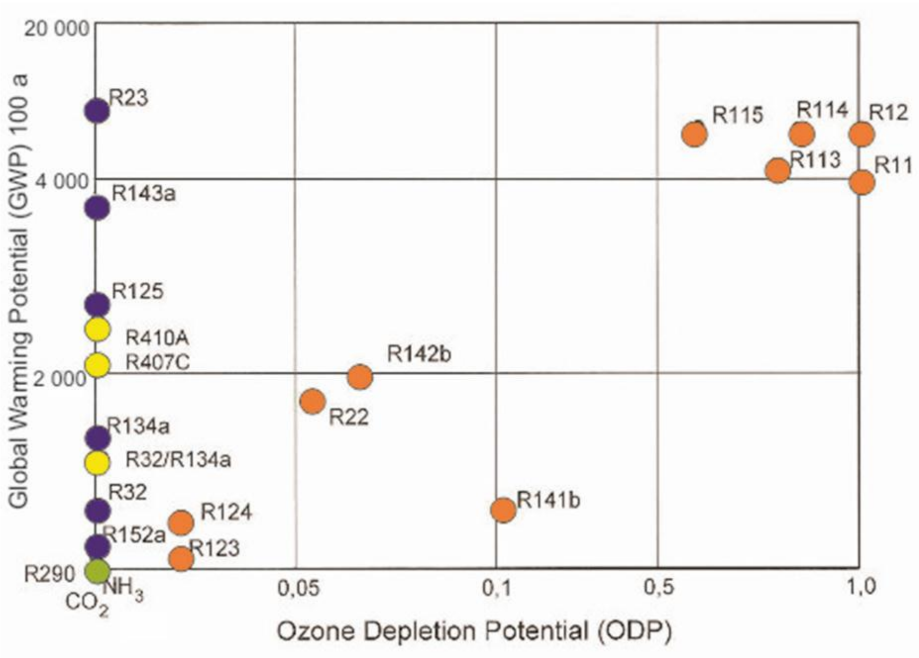


Figure 2. GWP and ODS of certain refrigerants

The greenhouse effect results from the capability of certain atmospheric gases to absorb the infrared radiation of the earth surface. It is worth noting that it is the greenhouse effect that maintains the earth surface temperature ensuring advent and evolution of life. However, since anthropogenic emissions of carbon dioxide and other greenhouse gases (particularly, halocarbon refrigerants) can enhance confinement of the earth infrared radiation as compared to the natural radiation, the temperature of the earth surface increases more than necessary, thus being responsible for the artificial greenhouse effect. Although concentration of all the CFCs in the atmosphere is lower than that of carbon dioxide, they are thousand-fold more potent absorbers of the infrared radiation.

Destruction of the stratospheric ozone is of other nature. The ozone of the upper atmosphere absorbs 99% of high-level ultraviolet radiation of the Sun, acting as a protective shield for the terrestrial life. The description of the depletion mechanism of the Earth's protective layer by chlorine- and bromine-containing substances (particularly, CFCs) was pioneered in 1974 by Mario Molina and Sherwood Rowland, University of California, USA, and Paul Crutzen, Max-Planck-Institute for Chemistry, Germany.

Because of measures taken by the global community to reduce production and consumption of ozone-depleting substances and greenhouse gases, such natural refrigerants as air, water, hydrocarbons, carbon dioxide, and ammonia become more essential.

Carbon dioxide (CO2, R744) is one of the most promising natural refrigerants. It is inflammable, safe to the ozone layer, has low GWP (1) but in concentrations over 5% vol is dangerous to health. R744 may be used as a working fluid in air conditioning systems for cars and accommodations, heat pumps, commercial refrigerating equipment and vending machines.

KEY PROPERTIES AND ADVANTAGES OF R744 (CO2)

- Carbon dioxide is a colorless gas (liquid) with slightly acid odor and taste.
- Common name: carbon dioxide.
- Chemical formula: CO2.
- Refrigerant name: R744.
- Carbon dioxide has zero ODS and low GWP (1).
- When used in closed circuits, CO2 has negligible effect on the climate.
- It is nonflammable, chemically inert, heavier-than-air, and may be used as fire-extinguishing medium.
- It may have narcotic and suffocative action on people only in rather high concentrations.
- In nature, CO2 occurs in abundant qualities. Carbon dioxide is globally available because it is a by-product of a number of technological processes and has low cost.
- International and Russian law has no restrictions.
- As natural refrigerant, CO2 does not pollute environment, so its disposal and recycling are not regulated by law.
- It is well compatible with materials and oils widely used in the refrigeration.

Key thermodynamic properties

Below is a CO2 phase diagram. Curves dividing the diagram into separate areas determine the pressure and temperature limits for the liquid, solid, vapor, and supercritical phases. Points of the curves determine pressures and respective temperatures when two phases are in equilibrium state. Under atmospheric pressure, CO2 can be only in solid or vapor phase.

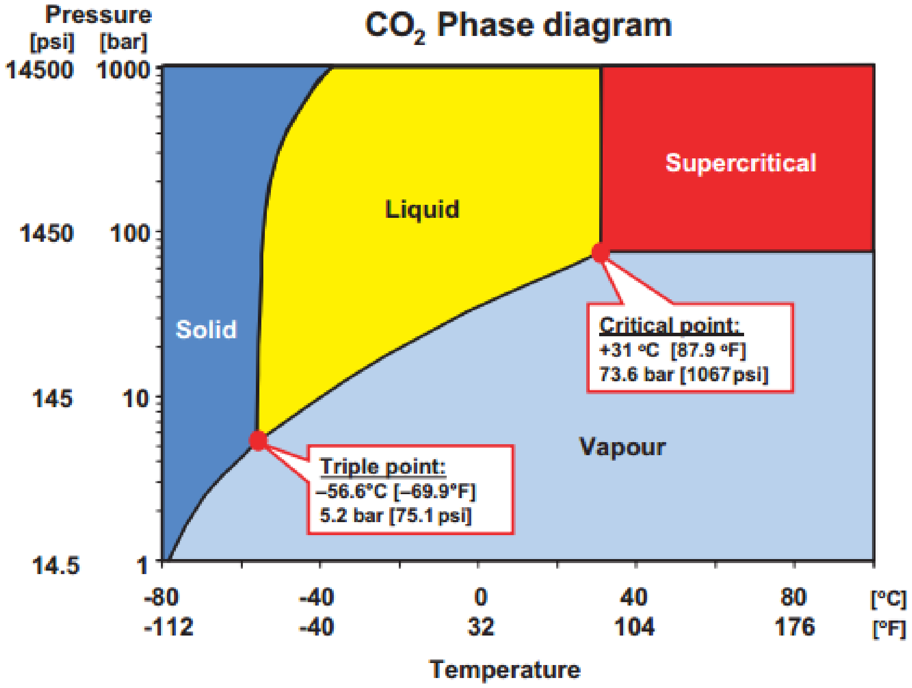


Figure 3. CO2 properties

Thermodynamic properties:

- low critical temperature;
- high triple point;
- sublimation temperature @ 760 mm Hg is -78,9 °C;
- critical temperature 31,06 °C;
- critical pressure 73,6 atm;
- boiling pressure @ -15 °C is 23 atm;
- condensing pressure @ 30 °C is 72 atm;
- high gas density:
    - increased efficiency of heat exchangers;
    - less temperature difference of refrigerant and air (ΔT);

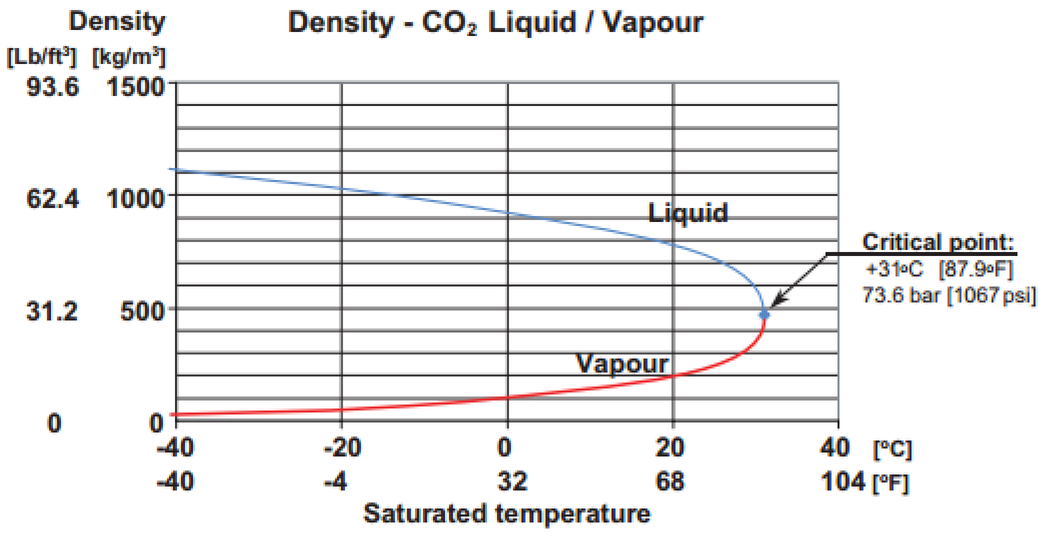


Figure 4. Density of liquid and vapor CO2

- high theoretical COP at condensation temperatures below critical temperature;
- low viscosity with resulting small pressure losses leading to minor temperature losses in the heat exchanger:
    - 1 K = 1 bar;
    - minor pressure losses in the pipeline;
- high heat transfer coefficient during evaporation and condensation;
- high volumetric capacity:
    - 4–5 times more than R22, 5–7 times more than R717;
    - smaller compressor size;
    - smaller pipeline size.

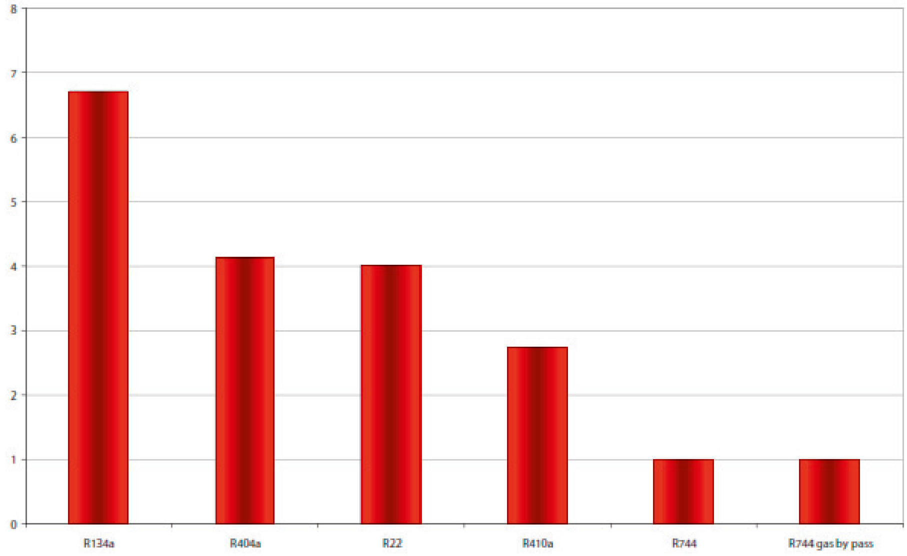


Figure 5. Compressor volumetric capacity with equal cooling efficiency

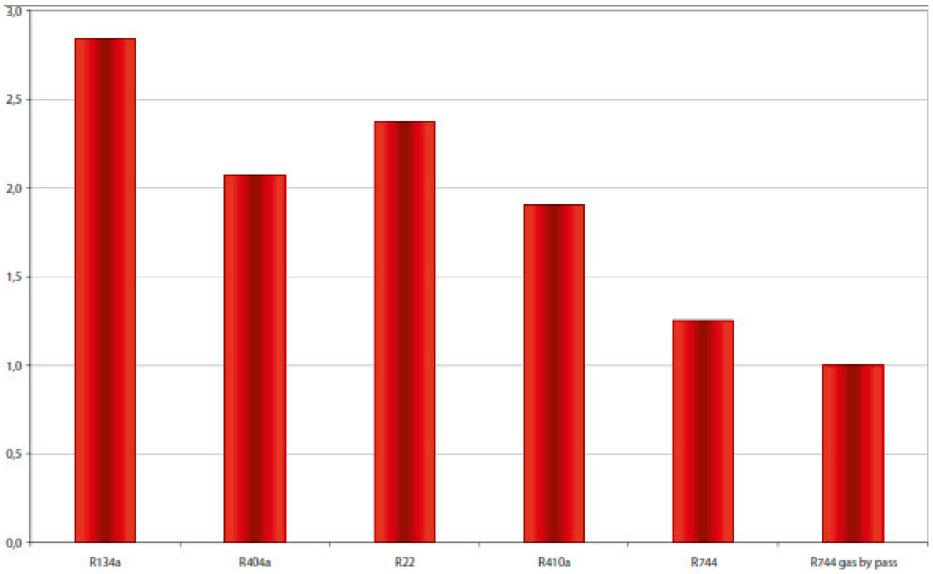


Figure 6. Diameters of suction lines with equal cooling efficiency

Table 1. CO_2 vs. common refrigerants

Refrigerant	R134a	R404A	NH3	CO2
Natural refrigerant	NO	NO	YES	YES

ODP	0	0	0	0
GWP	1300	3260	0	1
Critical point				
bar	40,7	37,3	113	73,6
°C	101,2	72	132,4	31,1
Triple point				
bar	0,004	0,028	0,06	5,18
°C	-103	-100	-77,7	-56,6
Flammability or explosibility	NO	NO	(YES)	NO
Toxicity	NO	NO	YES	NO

DIAGRAMS AND TECHNICAL FEATURES OF R744 SYSTEMS

CO2 may be used as a refrigerant in various refrigerating systems, both subcritical and transcritical. In any CO2 systems, triple and critical points should be taken into account.

The key diagram of the refrigeration sector is the pressure-enthalpy one. Below you can find the expanded diagram reflecting solid and supercritical phase.

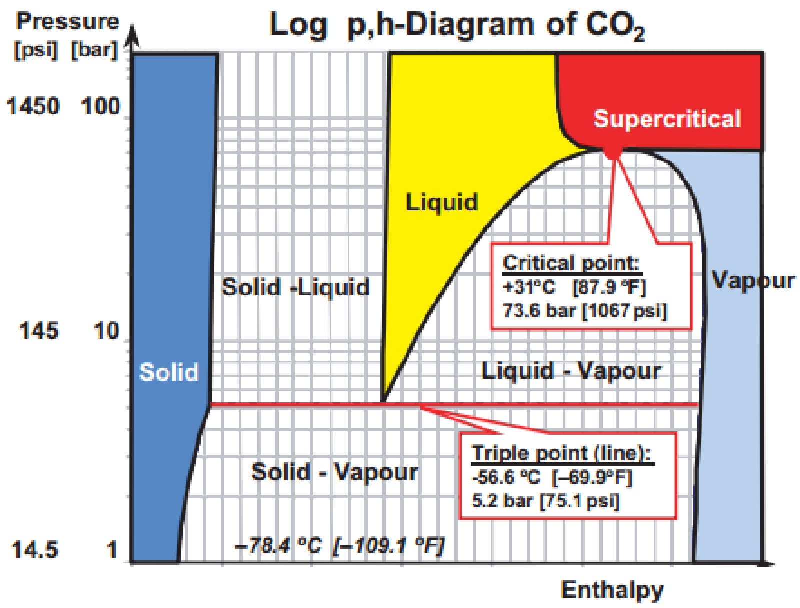


Figure 7. Pressure enthalpy diagram

Subcritical systems

In a typical subcritical refrigerating cycle, the whole range of operating temperatures and pressures is below the critical point and above the triple one.

CO2 is mostly used in cascade systems for industrial refrigerating plants because the operating pressure range for this application allows using typical equipment (compressors, valves and controllers) available on the market.

CO2 cascade systems include: direct evaporation, pump circulation, secondary or their combinations.

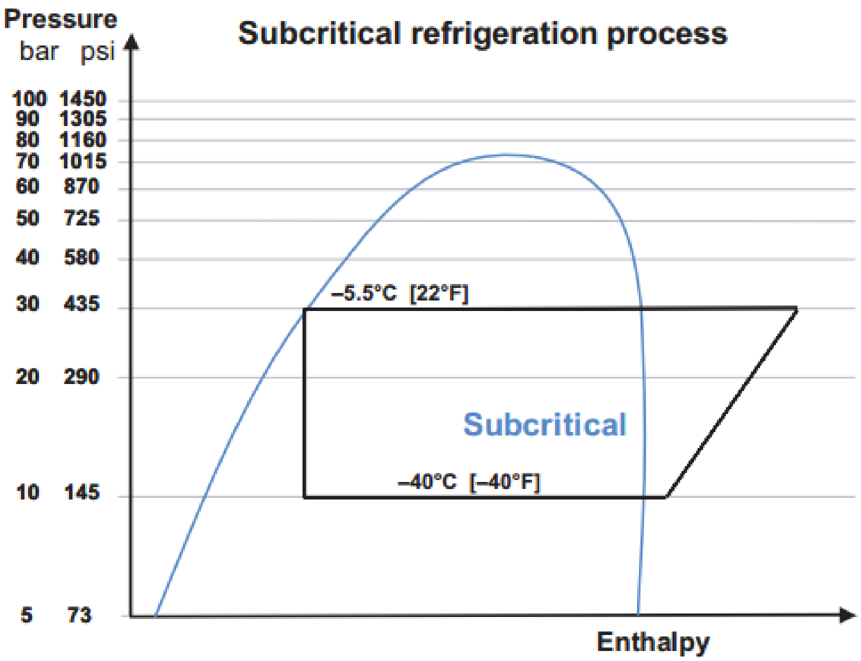


Figure 8. Subcritical refrigerating cycle

Use of CO2 in cascade systems gives a number of advantages:

- rather high efficiency even in hot climate;
- small charge of refrigerant for the high temperature stage;
- relatively low temperature difference of a cascade heat exchanger;
- possibility of using halocarbon refrigerants or ammonia at the high temperature stage of various refrigerating plants;
- NH3/CO2 cascade systems have the highest COP. In case of using halocarbon refrigerants at the high temperature stage, R134a should be selected due to its thermodynamical properties and lower, as compared to R404A, adverse effect on the environment (GWP).

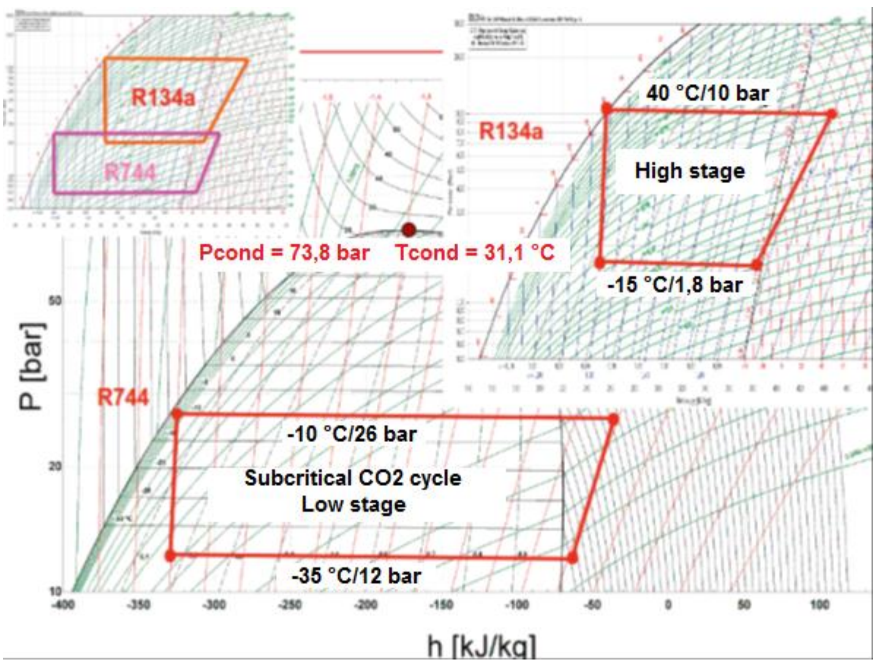


Figure 9. R134a/CO2 cascade

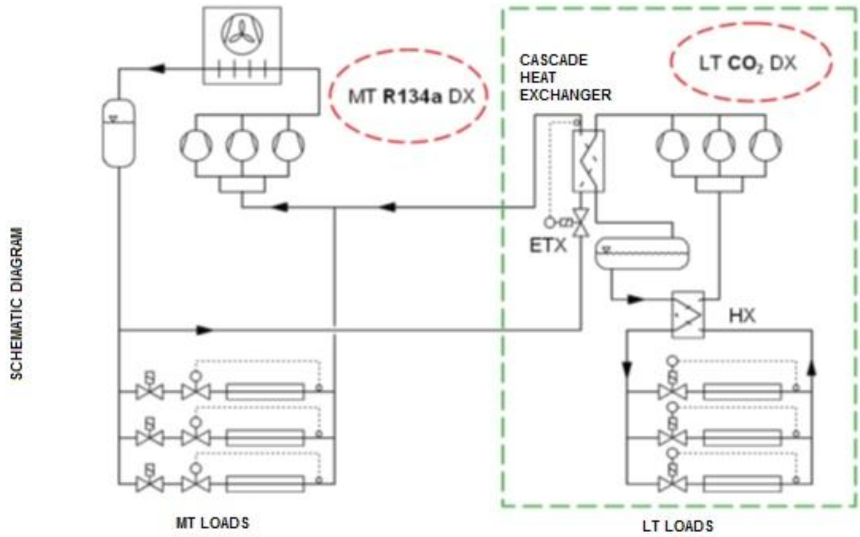


Figure 10. Schematic diagram

The interstage temperature of cascade systems is depends on the required temperature for cold rooms operated under high ambient temperature, so these rooms may be cooled directly by CO2. Besides, in systems only for low-temperature application, the medium temperature stage may be optimized to reach maximum energy efficiency.

Since the cascade really consists of two different interconnected refrigerating systems isolated by a cascade heat exchanger, their design operating pressure may vary. The design CO2 pressure usually depends on available components, and is equal to 40–45 bar (which corresponds 5–10 °C).

It is important that the high temperature stage of a cascade system was equipped at least with one compressor to start the first compressor of the low temperature stage. Otherwise, the latter will shut off due to high pressure. The same sequence should be observed when filling the system. First of all, the high temperature stage is filled with a halocarbon refrigerant and put into operation. Then the low temperature stage may be filled with carbon dioxide, and after increase of CO2 pressure in the suction line, low temperature compressors are put into operation.

Transcritical systems

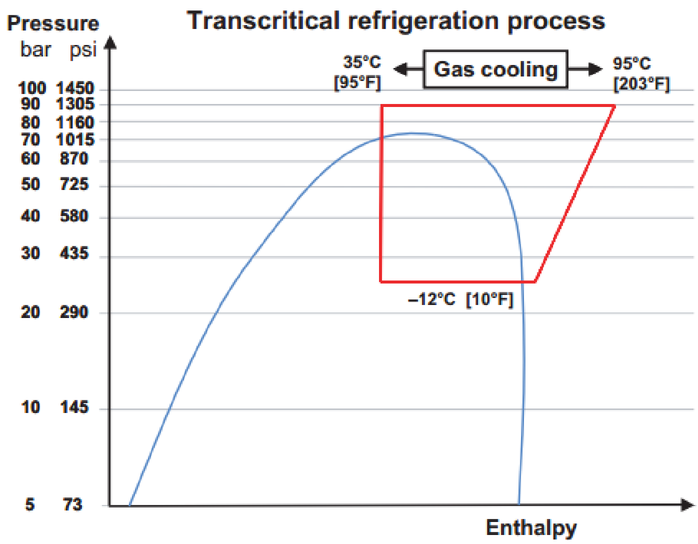


Figure 11. Transcritical refrigerating cycle

A transcritical booster system is one of the most promising for cold and moderate climate. The reason is that the energy consumption, and the design, are better than those of R404A systems.

The high pressure section is made of the high pressure compressor, then gas cooler and high pressure regulating valve. The design pressure in the section is 90–120 bar.

The intermediate pressure section is made of high pressure expansion valve separating gas and liquid in the receiver. Through a by-pass valve the gas is fed into the suction line of the high pressure compressor.

The liquid is distributed through expansion valves where it expands before low and medium temperature evaporators.

The gas of the low temperature evaporator is compressed in the low temperature compressor and mixed with gasses of the medium temperature evaporator and by-pass line. Then it is fed into the suction line of the high pressure compressor and into the circuit.

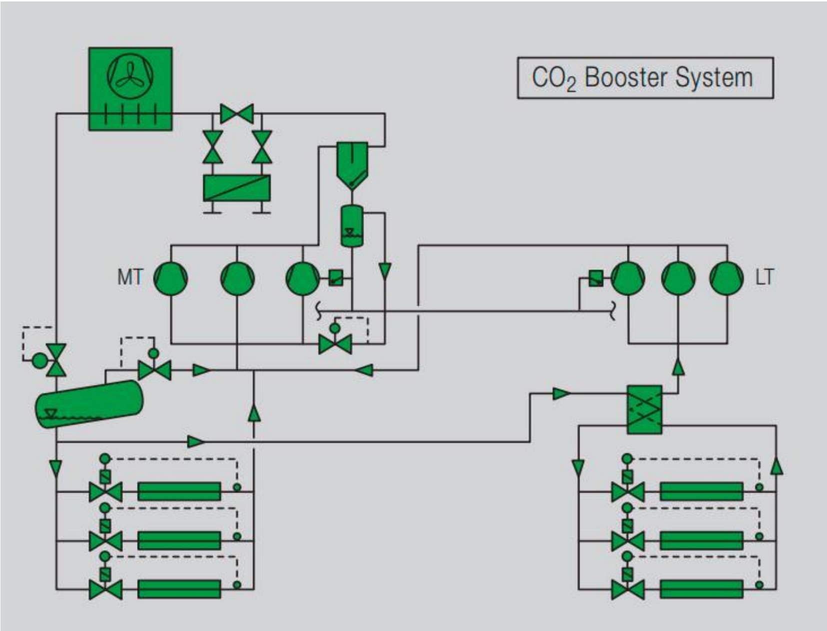


Figure 12. Simplified diagram of a booster central cooling machine

The design pressure of the medium temperature section is 40–45 bar, and low temperature one, 20–35 bar. There is a trend to design medium and low temperature sections for the same pressure.

The receiver pressure is controlled by a stepper motor valve. To ensure pressure difference at the medium temperature expansion valve, the receiver pressure should be higher than the evaporation pressure of medium temperature evaporators, and lower than the design pressure.

After high pressure expansion, the gas is separated from liquid and fed directly to the suction side of the compressor. The liquid is distributed to the evaporators. The process makes it possible to use standard pressure components.

To control and maintain the receiver pressure at the set point, a valve and pressure transmitter are required.

To maintain the receiver pressure higher than the minimum permissible level, the minimum permissible pressure can be set. If the pressure falls below this value, the high pressure regulating valve will open gradually in the respective frequency range.

The receiver pressure does not depend on the environment, so only cooling capacity influences on the evaporator stream.

The gas cooler of a refrigerating system is controlled in three zones.

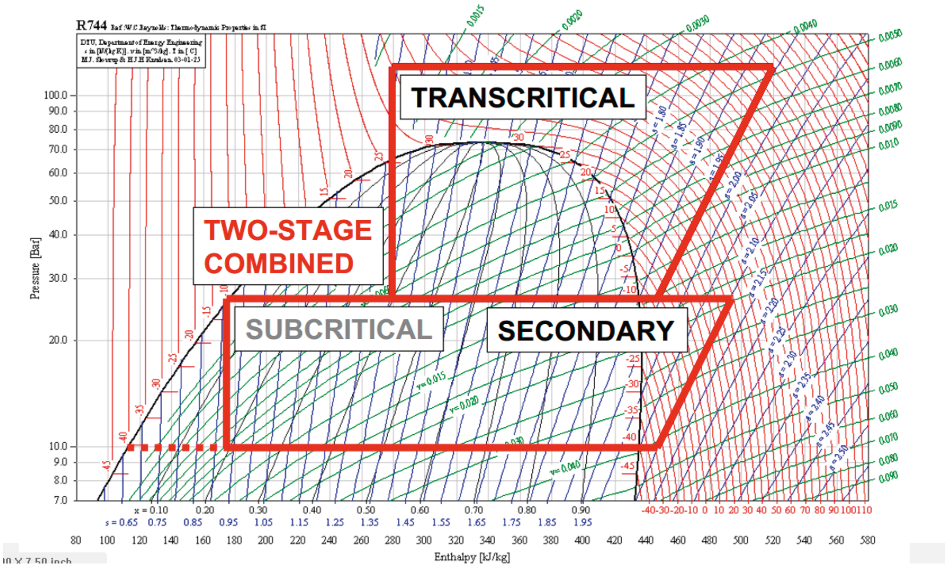


Figure 13. CO2 booster cycle

Under low temperatures, the control is similar to that of traditional refrigerating systems where supercooling is a regulated variable (during condensation of the refrigerant no control is necessary).

With approaching to the critical point, the control algorithm changes by gradually increasing the supercooling. Here the difference between control of traditional and transcritical systems disappears.

Under transcritical conditions, the pressure is a function of temperature at the gas cooler outlet. The control is aimed at reaching the maximum COP under the given temperature.

Operation of the gas cooler fans is adjusted with the CO2 temperature at the gas cooler outlet. If the real temperature is below than the set one, the fans are slowed down. If all the compressors are stopped, the fans do not move.

In traditional systems, the pressure is often a controlling variable (the system performance increases with condensation pressure loss), but under cold weather, subcooling of transcritical systems may increase thus leading to significant pressure decline in the receiver. As a result, the difference pressure may be insufficient for normal operation of the expansion valve.

The common problem of sub- and transcritical systems is pressure buildup during the down time. This can be overcome in several ways:

- to maintain pressure of the refrigerating system at the acceptable level, extra small refrigerating plant may be used;
- the system may be equipped with an expansion tank capable of compensating the pressure buildup in the system during the down time;
- the system may be designed to withstand the standstill pressure (pressure of saturated vapor under ambient temperature) about 80 bar.

As practice shows, the better decision is to use a small refrigerating plant to cool liquid CO2.

ECONOMIC ASPECTS

Of all numerous factors influencing the adoption of new technologies, specifically the selection of refrigerants and ways of using them, initial investments and operating costs are among the paramount. Of them, operating costs bear most responsibility for energy consumption.

Improvement of energy efficiency is the best and realistic response to calls for reduction of greenhouse gas emissions and energy consumption.

Of course, the food industry consumes considerable amounts of energy for refrigeration.

Today, about 10–15% of the global energy consumption comes to the refrigeration, and the major loads are surely supermarkets. As may be seen from the diagram below, half of the energy consumed by a supermarket is delivered to refrigeration (compressors, cases, etc.). Of that, compressors consume about 30% of energy.

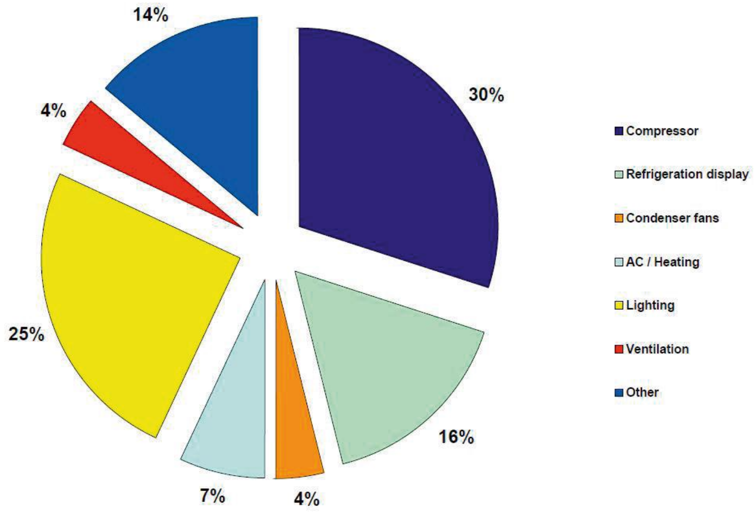


Figure 14. Distribution of energy consumption in the supermarket

Annual energy costs of large supermarkets may reach about 1% of the total revenue. Reduced by half, energy consumption leads to 15% profit markup of medium-size supermarkets.

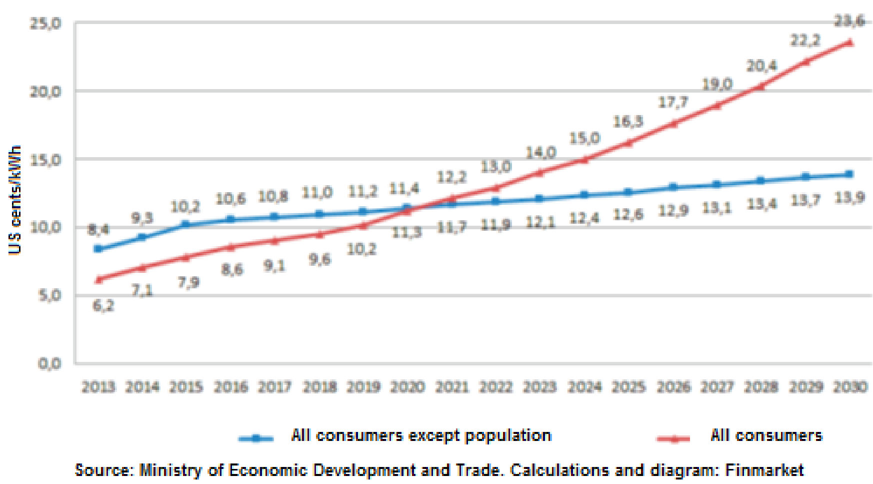


Figure 15. Yearly average energy price movement for population and other consumers, conservative scenario, forecast of November 2012

Another essential factor that should be taken into account is continuous growth of energy price which annually amounts 2–11%.

Under subcritical temperatures (below 31,2 °C), CO_2 is more efficient than synthetic refrigerants.

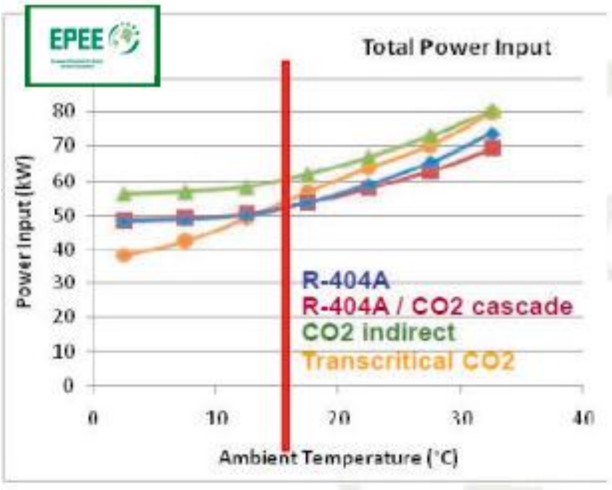


Figure 16. CO_2 vs. R404A systems power consumption

Under transcritical temperatures (over 31,2 °C), CO_2 are generally less efficient than synthetic refrigerants. But on an annualized basis, CO_2 systems in moderate climate are 10–30% more energy efficient than synthetic refrigerants, because much of the year they operate under subcritical temperatures.

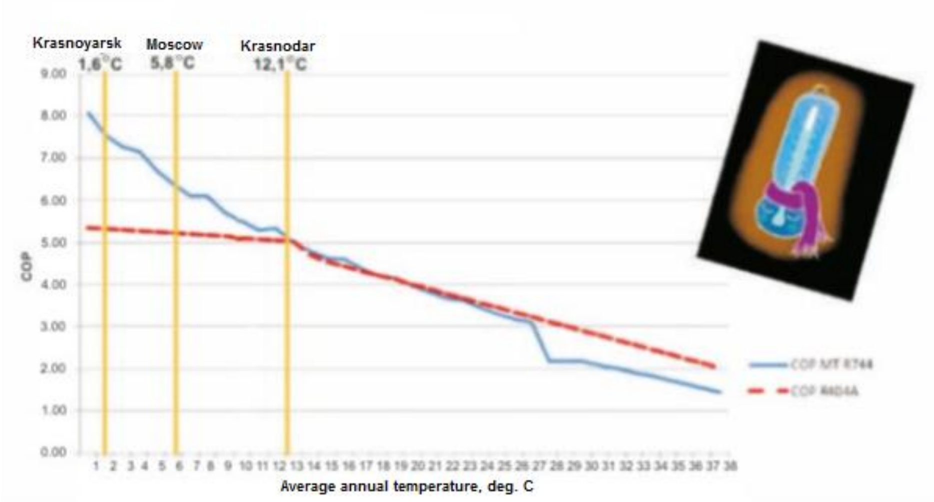


Figure 17. Transcritical CO_2 vs. traditional R404A system COP

The diagrams above show that energy efficiency of CO_2 systems is in direct relationship to the place of operation, i.e. geography. To be more precise, to the average annual temperature.

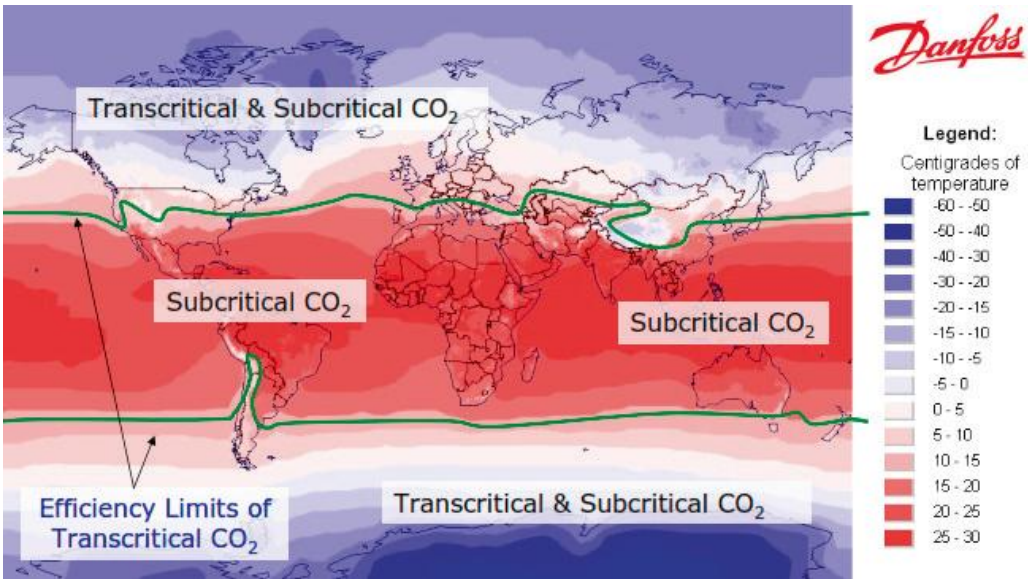


Figure 18. Areas of efficient use of transcritical CO2 systems

Table 2. Average annual temperature in Russia, °C

Krasnodar	12,1	Ufa	3,8
Rostov-on-Don	9,9	Orenburg	5,3
Volgograd	8.2	Ekaterinburg	3,0
Astrakhan	10,5	Chelyabinsk	3,2
Elista	8,6	Tyumen	2,2
Voronezh	6,9	Kurgan	2,6
Moscow	5,8	Khanty-Mansiysk	-0,8
Saint-Petersburg	5,8	Omsk	2,1
Vologda	3,1	Tomsk	0,9
Nizhy Novgorod	4,8	Kemerovo	1,3
Saratov	7,1	Krasnoyarsk	1,6
Kirov	3,1	Chita	-1,4
Samara	5,6	Yakutsk	-8,8
Izhevsk	3,0	Perm	2,7

The data above show that almost the whole territory of Russia falls into the zone where use of transcritical CO2 systems is economically viable.

By no means unimportant factor is high relative volumetric refrigerating effect of R744.

Table 3. Properties of certain refrigerants

Refrigerant Type	**HFC**	**Hydrocarbons**		**NH3**	**CO2**
Refrigerant	R134a	R290	R600a	R717	R744
Common name	-	Propane	Iso-butane	Ammonia	Carbon dioxide
Refrigerant nature	Synthetic	Natural	Natural	Natural	Natural
ODP	0	0	0	0	0
GWP	3200	3	3	0	1
Critical temp, °C	101,2	97	135	132,4	31,1
Critical pressure, MPa	4,1	4,2	3,6	11,3	7,4

Flammability	-	+	+	+	-
Toxicity	-	-	-	+	-
Relative volumetric refrigerating effect	1	1,4	0,6	1,7	8,4

Finally, this factor influences pipe and compressor sizes which, in their turn, lead to reduction of consumable and component cost.

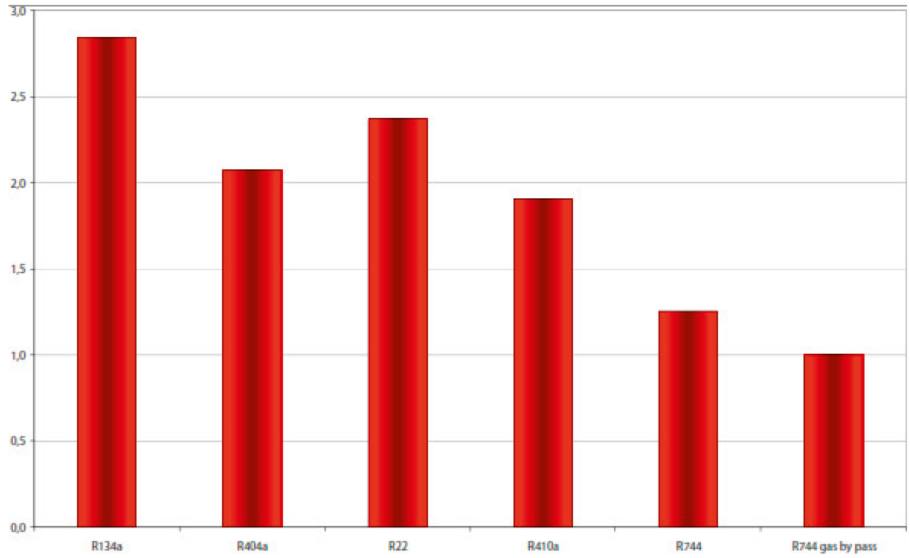


Figure 19. Diameters of suction lines with equal cooling efficiency

Besides, due to smaller refrigerating systems the area of the machine room reduces.

Figure 20. Machine room

Another essential factor related to transcritical CO2 systems should be mentioned, possibility to use heat recovery to produce hot water for hot-water supply and heating. Unlike halocarbon refrigerants, systems where high potential heat is hard to generate, transcritical CO2 systems do not have such problem. All heat is of high potential. In practice, all superheating may be used with the gas cooler disabled, if necessary.

For heat recovery, CO2 refrigerating systems must operate under high discharge pressure and temperature with reduced COP. The advantage of this mode is heat for further use.

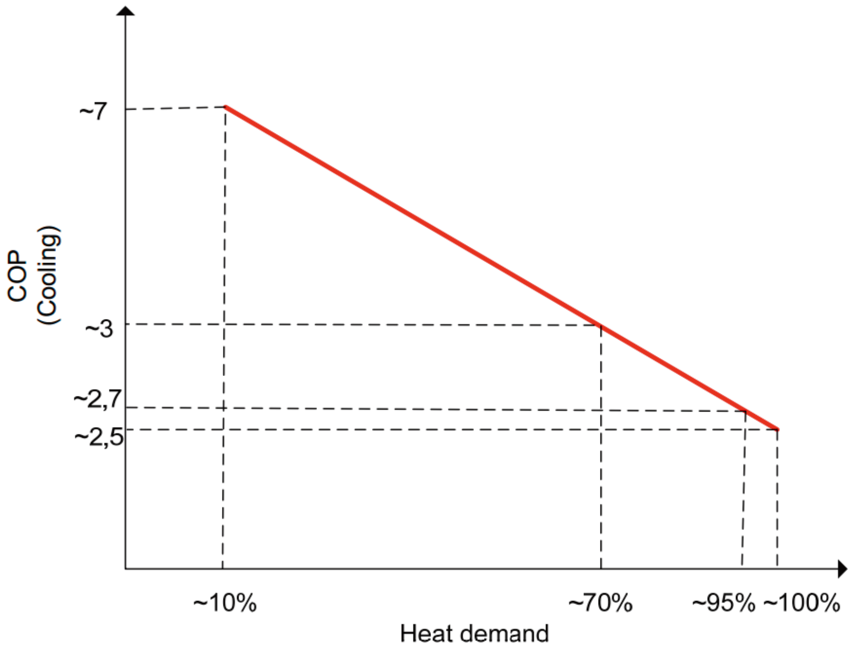


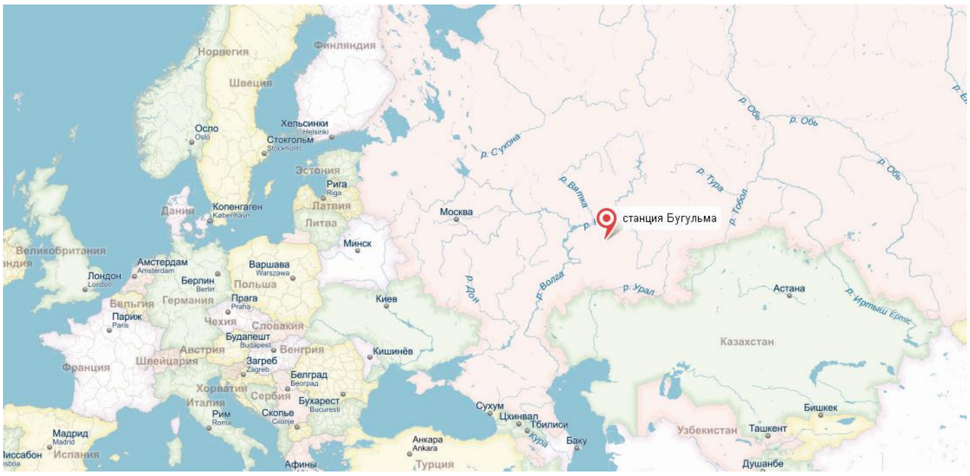
Figure 21. CO2 system COP

The last but not least factor is cost of charging the system. CO2 is widely used in industry, so it is easily accessible and cheap as compared to synthetic refrigerants.

COMPARISON OF ESTIMATED ECONOMIC INDICATORS OF VARIOUS REFRIGERATING SYSTEMS THROUGH THE EXAMPLE OF AN AVERAGE 1000 M2 HYPERMARKET IN BUGULMA

To compare efficiency of various types of systems, we will study a typical operating hypermarket located in the center of Russia, city of Bugulma, Republic of Tatarstan.

Republic of Tatarstan, 54°32'11"N (54.536413), 52°47'22"E (52.789489)



Average annual temperature 3,5 °C

Relative air humidity 74,4%

Average wind speed 4,2 m/s

Bugulma													
Indicator	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average temperature, °C	-11,5	-11,1	-5,3	4,7	12,3	17,3	18,8	16,2	10,9	3,6	-5,2	-10	3,5

Existing system

Refrigerant: R404A;
Condensing temperature: +45 °C;
Step control of compressors and condenser fans: mechanical TEV.

MT equipment

Commercial equipment: 25 pcs;
Rooms: 13 pcs;
T_{evap}: –10 °C;
Total refrigeration consumption: 218 kW.

LT equipment

Commercial equipment: 12 pcs;
Rooms: 4 pcs;
T_{evap}: –35 °C;
Total refrigeration consumption: 30 kW.

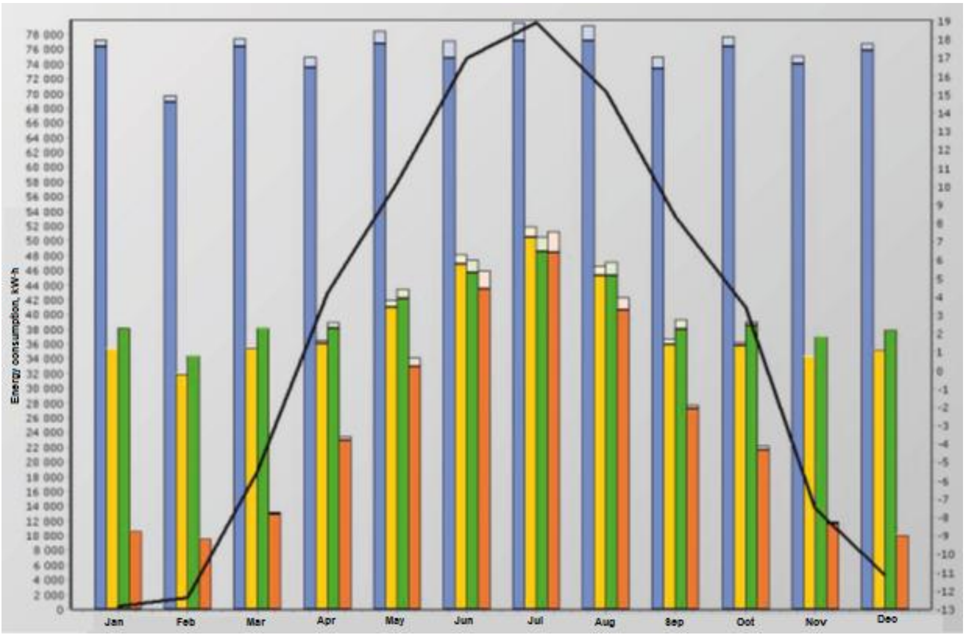
Through the example of the hypermarket, we will simulate the energy consumption of various systems and compare it with the existing one.

In the first table we compare energy consumption of existing refrigerating plants (R404A, T_{cond} const) with refrigerating machines with such improvements as stepless control, EC condenser fans, floating condensing point (R404A, T_{cond} var). The comparison is using the transcritical CO2 central booster.

As can be seen from the table, the transcritical CO2 system shows better energy consumption on an annualized basis. Its energy consumption is worse than that of a modern halocarbon refrigerants system only 3 months of the year.

Month	**R404a (Tcconst=45 °C)**	**R404a (Tcvar, ΔT=30 °C)**	**R744**	**Economy as compared to R404a (Tcconst=45 °C), %**	**Economy as compared to R404a (Tcvar, ΔT=30 °C), %**
January	69289,9	31553,6	17469,1	74,8	44,6
February	62499,5	28437,6	15597,2	75	45,2
March	69351,4	31614,6	18174,3	73,8	42,5
April	66817,3	32927,5	25488,2	61,9	22,6
May	69983,8	40717,3	40572,4	42	0,4
June	68687	45379	49593,3	27,8	-9,3
July	70821,4	48786	56031,8	20,9	-14,9
August	70730,4	45475,7	49581,3	29,9	-9
September	66903,6	36412,6	34064,6	49,1	6,4
October	69373,8	32697,7	24322,3	64,9	25,6
November	67253,71	30660,8	17782,3	73,6	42
December	68817,8	31319,9	17386,2	74,7	44,5
Total year	820529,61	435983,1	366063	55,4	16

The diagram below shows energy consumption of various systems by months. For comparison, a cascade R134a/CO2 system is added.



	R404A, step control, Tcond-const compressor
	R404A, step control, Tcond-const fans and pumps
	R404A, new options, compressor
	R404A, new options, fans and pumps
	R134a/CO2 cascade, compressor
	R134a/CO2 cascade, fans and pumps
	Transcritical CO2, compressor
	Transcritical CO2, fans and pumps
______	Average ambient temperature

Figure 22. Energy consumption of refrigerating plants of a hypermarket in Bugulma for various refrigerants, kW·h, %

- Energy efficiency of an R134a/CO2 cascade is similar to modern R404A systems.
- In a climate of Bugulma, energy consumption of CO2 equipment is 16% less than that of similar R404A equipment (with floating condensing point with $\Delta T=30$ °C).
- In a climate of Bugulma, energy consumption of CO2 equipment is 55% less than that of similar R404A equipment (with constant condensing point with $T_c=45$ °C).
- With initial equipment cost difference of 20%, the total cost at the end of the operating lifetime (7–10 years) is equal.
- If heat recovery systems are used, total cost is equal at 4–5 years.

Description of the R744 training stand

As part of UNIDO/GEF-MNRE Project "Phase Out of HCFCs and Promotion of HFC-Free Energy Efficient Refrigeration and Air-Conditioning Systems in the Russian Federation Through Technology Transfer", an R744 training stand to show advantages of CO2 was created at the production site of KPP Nord.

Figure 23. Transcritical central booster

The stand includes:

- transcritical CO2 central booster refrigerating system;
- gas cooler;
- commercial refrigerating equipment (low-temperature cooling chest 1 pcs., medium temperature multi-deck cabinet 1 pcs.);

- additional intermediate heat exchangers with a hydro kit to simulate operation of a heat recuperation system;
- monitoring system.

The R744 transcritical central booster refrigerating system is a full-size central refrigerating system which may be installed in a medium-size supermarket of 400-500 sq.m.

Technical specifications of an R744 transcritical central booster refrigerating system:

- refrigerant: R744;
- compressors: FRASCOLD:
- MT: 3 compressors, 1 with variable speed drive;
- LT: 1 compressor with variable speed drive;
- net refrigerating effect:
  - MT: 39,35 kW, T_{boil} -10 °C;
  - LT: 6,61 kW, T_{boil} -35 °C;
- rated pressure:
  - high stage 100 bar;
  - intermediate stage 45 bar;
  - low stage 30 bar.
- intermediate pressure (receiver pressure) maintenance: by-pass;
- LT suction supercooler for liquid refrigerant — available;
- LT gas cooler — available;
- heat rate of a recuperative heat exchanger — 28 kW;
- refrigerant conservation during down time — partial atmosphere exhaust.

The stand demonstrates operation of a CO2 refrigerating plant on the real commercial equipment. The online monitoring system ensures real-time display of all operation parameters of the refrigerating plant, re-parametrization and parameter change control. The central plant is also equipped with energy input measuring devices to demonstrate change of energy consumption in various modes.

The stand provides for simulation of the operation of a heat recovery system.

The above makes it possible to demonstrate the operation of an R744 transcritical refrigerating plant in every mode with reference to energy consumption.

CONCLUSION

The project meets all requirements to demonstration projects being created as part of the UNIDO/GEF-MNRE Project:

Energy efficiency: power demand, as compared to HCFC and HFC systems, is 3-18% less (depending on the climate zone and without account of heat recuperation systems). In case of heat recuperation systems, the energy efficiency increases by up to 30%;

Sustainability: natural refrigerant R744 (ODP 0, GWP 1) is used;

The facility is standard, and may be replicated on the territory of the Russian Federation as an example of success;

Visits of representatives of concerned federal executive bodies, ICSTI and business units — potential customers for purpose of studying specific features of its implementation are agreed.

The project energy efficiency will be proved by documents and calculations that reflect increased energy efficiency obtained via transition from ozone-depleting substances (such as CFC, HCFC) or greenhouse gases (HFC) to natural refrigerants, and by long-term operation data.

The stand created as part of the demonstration project ensures studying operation features of R744 refrigerating systems.

By end 2015 three groups—of specialists of the construction sector, representatives of federal executive bodies and other target groups interested in studying installation, repair, maintenance and operation of R744 refrigerating equipment—will undergo training at the training and production complex of NORD-SM (Moscow, TiNAO, village Nastas’ino, 24 km MKAD of the Kievskoe highway).