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Features of the conditions for the use of refrigeration units on carbon dioxide

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Analysis of indicators of cycles of refrigeration machines with the use of CO_2

- The scientific work deals with the CO_2 use for processing, production, storage, and transportation of food products, for which, according to technological regulations, the cold consumption is specific at the following temperature levels:
  - From 2 to 5 ^{0}C – precooling mode before freezing.
  - From 0 to 12 ^{0}C – cold storage mode for products that require no freezing.
  - From -18 to -25 ^{0}C – the mode of freezing products to the temperatures specified in the range, followed by storage and transportation at these temperatures.
- For the third mode, there is currently a tendency in the world market to increase the production of frozen products with lower temperatures – from -50 to -60 ^{0}C.

- Currently, the production of R744 compressors for refrigeration equipment is limited to semihermetic reciprocating compressors. When only R744 is used as a refrigerant, it is possible to design refrigeration systems for t_o and t_m levels.
- For the subsequent analysis, the variable parameters of the refrigerant of the following temperature levels were taken:
  - Boiling point for a low-temperature level t_o = -20 – -50 ^{0}C.
  - Boiling point for an average temperature level t_m = -10 ^{0}C, -5 ^{0}C.
  - Condensation or single-phase cooling t_k = 25 – 50 ^{0}C.

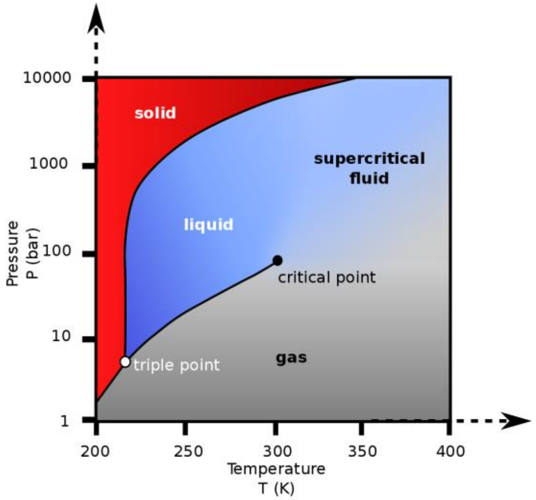

Figure 1. Carbon dioxide phase diagram

- Analysis has been performed for the refrigeration cycles comparing R744 with either single component refrigerants or azeotropic mixture refrigerants or low temperature glide refrigerants. For compressors of the lower stage, a comparison of R744 with refrigerants R404a and R507a of two standard sizes in terms of capacity has been performed (to assess the influence of the scale factor).

The types of Bitzer semihermetic compressors selected

Cooling capacity Q_o is indicated under the following cycle conditions: boiling point t_o = -35 ^{0}C, saturated liquid temperature t_m = -10 ^{0}C, and steam superheat at the compressor inlet is 10 K.

Lower stage	First type of compressor size			Second type of compressor size		
Refrigerant	R744	R404A	R507A	R744	R404A	R507A
Compressor brand	2HSL-3K-40S	4EES-6Y-40S	4EES-6Y-40S	4VSL-15K-40P	6FE-44Y-40P	6FE-44Y-40P
Q_o, kW	7,96	7,5	7,86	54,8	50,3	52,7
V_h, m³/h	4,34	22,72	22,72	28,9	151,6	151,6
Compressor weight M, kg	50	95	95	153	244	244
Upper stage	First type of compressor size			Second type of compressor size		
Refrigerant	R744	R744	R507a	R744	R744	R507a
Compressor brand	2MTE-4K-40S	4PTEU-6LK-40S	2CES-3Y-40S	4KTE-10K-40P	6DTE-40K-40P	6HE-28Y-40P
Q_m, kW	6,43	8,2	9,75	18,85	63,7	65,4
V_h, m³/h	3,3	4,5	16,24	9,6	30,3	110,5
Compressor weight M, kg	94	114	76	120	233	233

Table 1. The types of Bitzer semihermetic compressors selected

Temperature levels		First type of compressor size			Second type of compressor size		
		ε*	Ratio ε/ε *		ε*	Ratio ε/ε *	
t_m, °C	t_o, °C	R744	R507A	R404A	R744	R507A	R404A
	-50	2,31			2,5		
	-45	2,91	1,02	0,97	3,18	1,01	0,96
-10	-40	3,69	0,98	0,93	4,03	0,96	0,91
	-35	4,73	0,95	0,90	5,17	0,91	0,86
	-30	6,22	0,91	0,87	6,79	0,84	0,81
	-25	8,57	0,85	0,82	9,27	0,76	0,73
	-45	2,41	1,08	1,03	2,63	1,08	1,02
	-40	3,02	1,05	1,00	3,30	1,02	0,98
-5	-35	3,8	1,02	0,97	4,16	0,97	0,93
	-30	4,85	0,97	0,94	5,32	0,91	0,87
	-25	6,38	0,92	0,90	6,97	0,85	0,81
	-45	1,99	1,16	1,10	2,18	1,15	1,09
	-40	2,48	1,12	1,07	2,72	1,09	1,04
0	-35	3,08	1,09	1,04	3,38	1,04	0,99
	-30	3,86	1,05	1,01	4,24	0,98	0,94
	-25	4,91	1,01	0,97	5,39	0,93	0,89

Table 2. Comparison of refrigeration efficiency

Comparison of the refrigerants at fixed temperatures t_o and t_m

- Under the conditions considered, the refrigerants R744 and R507A are identical in terms of the main given performance indicators in the cycles of the lower stages of refrigerating machines with semi-hermetic compressors.
- The technical advantages of R744 are evident as a refrigerant at a significantly higher pressure while fulfilling the associated limitation.
- The fundamental difference between R744 and R507A cycles for the upper stage conditions is associated with the operation of the first one in the region of critical states.

Temperature levels		First type of compressor size				Second type of compressor size			
		R744		R507A		R744		R507A	
t_m, °C	t_o, °C	Q_m/Q_o	Q_o/Q_{ob}	Q_m/Q_o	Q_o/Q_{ob}	Q_m/Q_o	Q_o/Q_{ob}	Q_m/Q_o	Q_o/Q_{ob}
	-50	1,44	0,44			1,4	0,46		
	-45	1,34	0,59	1,34	0,58	1,31	0,61	1,31	0,58
-10	-40	1,27	0,78	1,28	0,77	1,25	0,79	1,26	0,77
	-35	1,21	1,00	1,22	1,00	1,19	1,00	1,21	1,00
	-30	1,16	1,26	1,18	1,28	1,15	1,24	1,18	1,28
	-25	1,12	1,55	1,14	1,62	1,11	1,52	1,14	1,61
	-45	1,41	0,58	1,38	0,58	1,38	0,60	1,33	0,58
	-40	1,33	0,77	1,32	0,77	1,30	0,79	1,28	0,77
-5	-35	1,26	1,00	1,25	1,00	1,24	1,00	1,24	1,00
	-30	1,21	1,26	1,21	1,27	1,19	1,25	1,20	1,28
	-25	1,16	1,57	1,17	1,61	1,14	1,53	1,16	1,62
	-45	1,50	0,57	1,43	0,57	1,46	0,59	1,40	0,57
	-40	1,40	0,77	1,36	0,76	1,37	0,78	1,34	0,76
0	-35	1,32	1,00	1,30	1,00	1,30	1,00	1,28	1,00
	-30	1,26	1,27	1,25	1,29	1,24	1,26	1,24	1,29
	-25	1,20	1,59	1,20	1,63	1,19	1,55	1,20	1,63

Table 3. Comparison of heat flow removed from the lower stage and relative refrigerating capacity at t_o and t_m

Temperature levels		First type of compressor size		Second type of compressor size	
		Compressor delivery temperature, °C			
t_m, °C	t_o, °C	R744	R507A	R744	R507A
	-50	100,2		91,2	
	-45	79,1	34,5	71,6	29,8
-10	-40	62,2	28,3	56,1	25,3
	-35	48,3	23,3	43,6	21,7
	-30	36,6	19,1	33,2	18,7
	-25	26,4	15,6	24,2	16,4
	-45	95,7	40,5	87,1	35,7
	-40	77,1	34	70,1	30,9
-5	-35	62,1	29,2	56,5	27,3
	-30	49,5	25,4	45,2	24,3
	-25	38,7	21,8	35,6	21,9
	-45	114,1	46,70	103,7	41,8
	-40	93,2	40,1	85	36,6
0	-35	76,6	35	70,1	32,8
	-30	63	30,9	57,8	29,8
	-25	51,4	27,4	47,5	27,4

Table 4. Compressor delivery temperatures at t_o and t_m

A comparison of the value of the refrigeration efficiency Ɛ at a constant temperature is presented t_m = -10 ^{0}C for one standard type of compressor size

- In comparison with the traditional one for R507A, the cycle of the upper stage used for R744A under the considered conditions is energetically less efficient. Deterioration of the refrigeration efficiency is 24 – 37 % for subcritical and 36 – 54 % for transcritical modes.
- It should be noted that for R744 the data shown in Figure 2 at modes t_k = 45 ^{0}C and t_k = 50 ^{0}C are not optimized for the maximum exhaust pressure, the latter is the maximum permissible one.

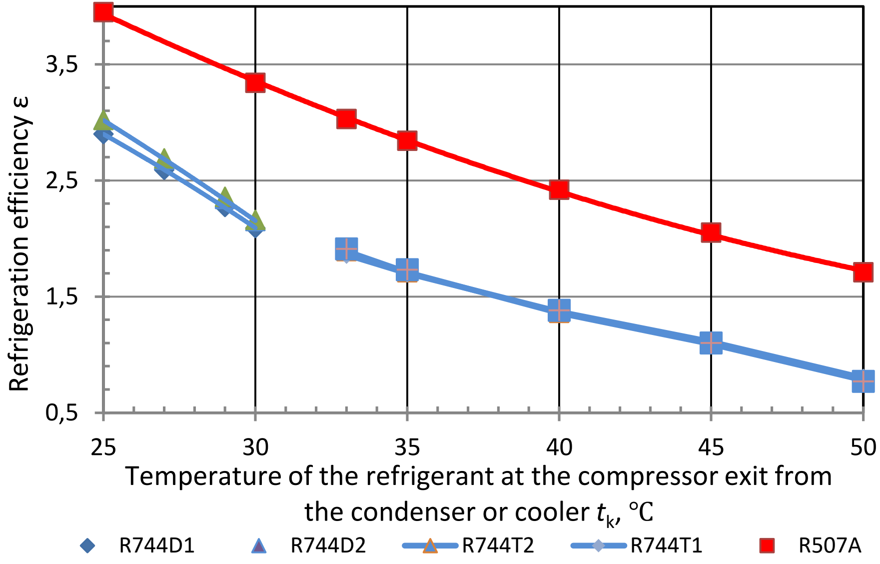

Figure 2. Dependence of Ɛ = *f*(t_k) for upper stage cycles at t_m = -10 ^{0}C

Dependence of Ɛ = $f(t_k)$ for upper stage cycles at t_m = -5 and 0 ^{0}C

At higher t_m, the general trend persists. For R744 data are given only when using the 4PTEU-6LK compressor.

* It should be noted that for R744 the data shown in Figure 3 at modes t_k = 45 ^{0}C and t_k = 50 ^{0}C are not optimized for the maximum exhaust pressure, the latter is the maximum permissible one.

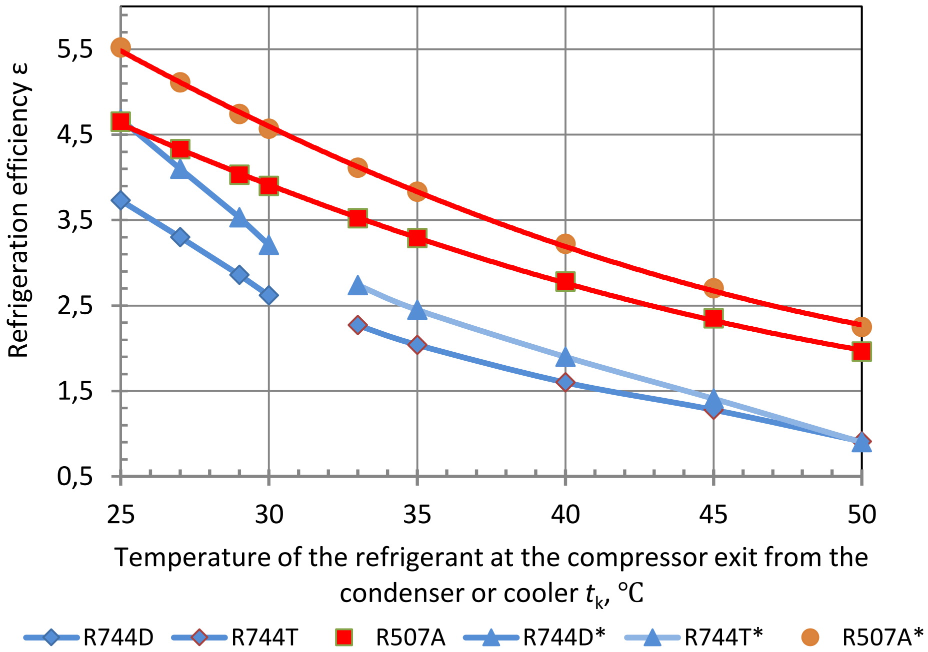

Figure 3. Dependence of Ɛ = $f(t_k)$ for upper stage cycles at t_m = -5 and 0 ^{0}C
Index * stands for the data at t_m = 0 ^{0}C

Comparison of the specific heat flow rate transferred to the environment

When operating on R744, in comparison with R507A, the value of Q_k/Q_m is 6–13 % higher for subcritical and 15–44 % higher for transcritical modes.

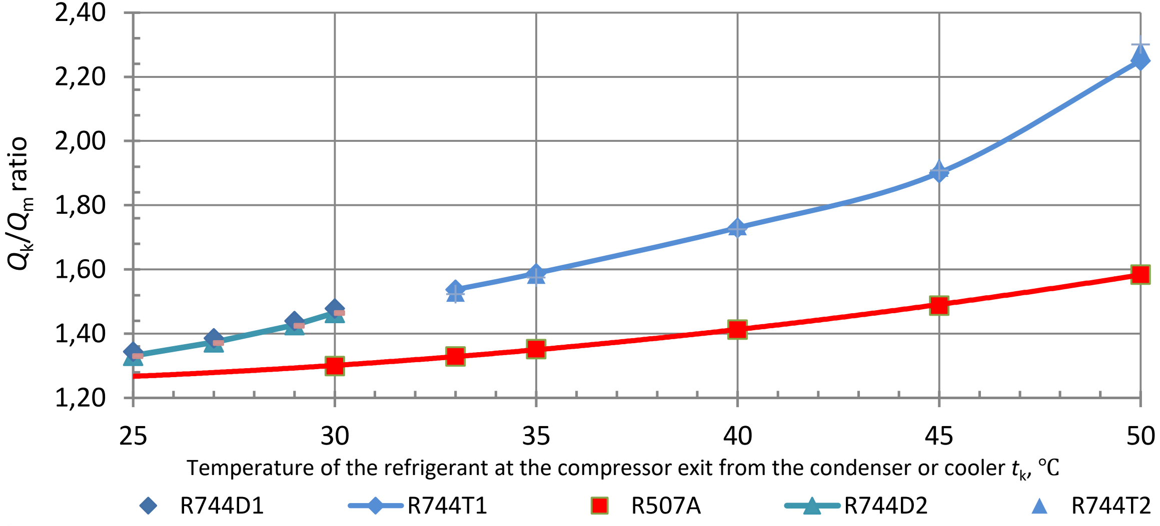

Figure 4. Dependence of $Q_k/Q_m = f(T_k)$ for upper stage cycles at t_m = -10 °C

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Dependence of $T_{Ke} = f(t_k)$ for upper stage cycles at t_m = -10 – 0 ^{0}C

Quality factor of the transferred heat flow Q_k was estimated by the absolute equivalent thermodynamic temperature of the refrigerant in the process T_{Ke}, K:

$$T_{K_e} = \frac{\Delta h_k}{\Delta s_k}$$

Equivalent thermodynamic temperature of the refrigerant in heat transfer processes is the average potential of the heat flow, which determines its energy value.

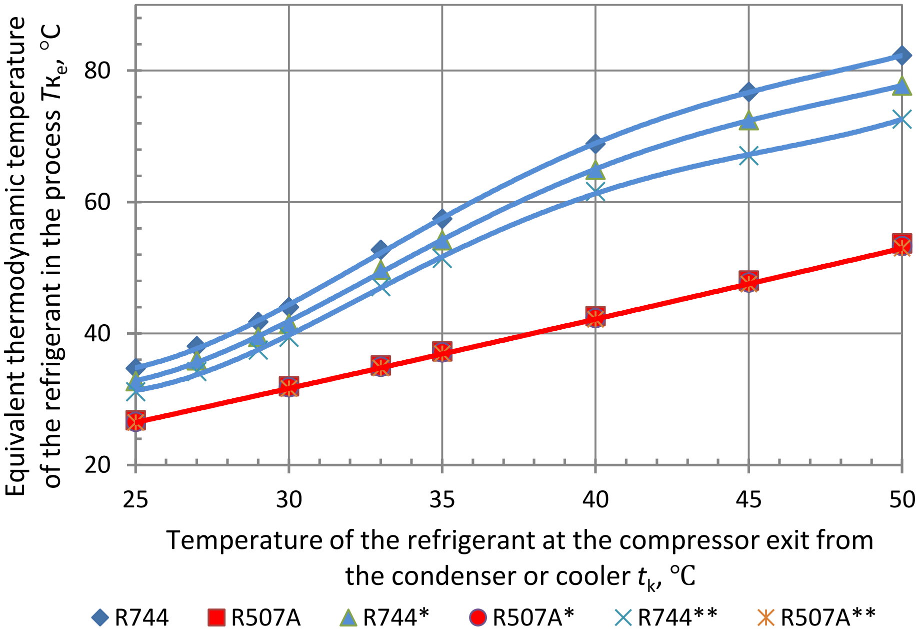

Figure 5. Dependence of $T_{Ke} = f(t_k)$ for upper stage cycles at t_m = -10 – 0 ^{0}C
Indices stand for the data: * – at t_m = -5 ^{0}C; ** – at t_m = 0 ^{0}C

Comparison of the relative change in the cooling capacity of the upper stage Q_m/Q_{mbase}

- Figure 6 shows a comparison of the relative change in the cooling capacity of the upper stage Q_m/Q_{mbase}, which is essential for the selection and operation of automatic control devices. At the same time, a mode with a minimum temperature $t_k = 25\ ^0C$ for all t_m and steam superheating at the compressor inlet 10 K is taken as the basic one.
- According to the considered indicator, there are no advantages of using R744 in comparison with R507A for the upper stage.
- Figure 6 shows two zones of a significant decrease in refrigeration capacity when operating on R744: the first one is in the entire range of subcritical operation modes of the stage, the second one is at high values of t_k up to the maximum permissible.

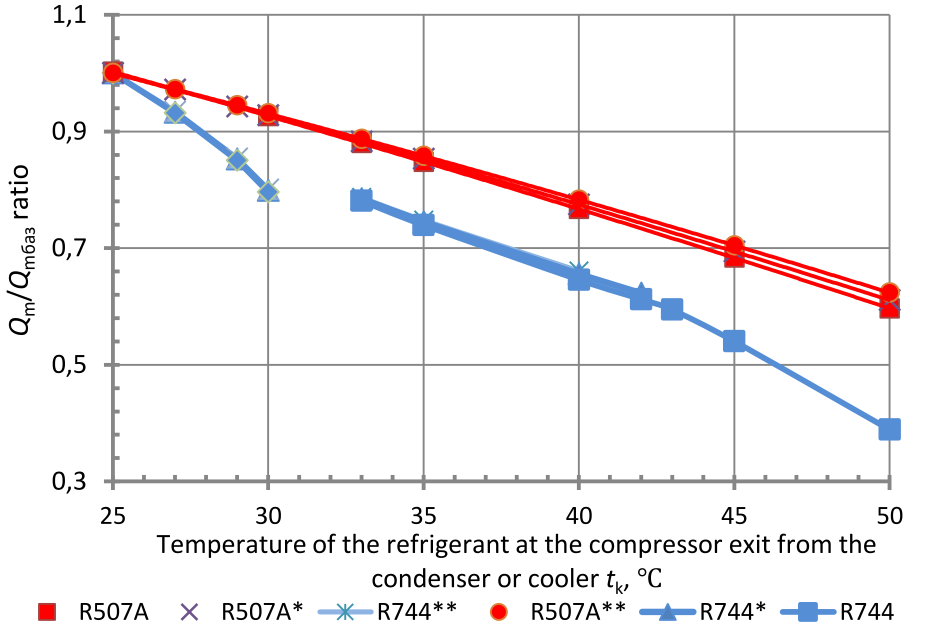

Figure 6. Dependence of $Q_m/Q_{mbase} = f(t_k)$ for upper stage cycles at t_m = -10 – 0 ^0C
Indices stand for the data: * – at t_m = -5 ^0C; ** – at t_m = 0 ^0C

Results of comparison of R744 and R507A in the upper stage cycle

- The main well-known and significant technical advantage of using R744 is associated with a decrease in the relative volumetric capacity of compressors. For example, according to Table 1, the V_h/Q_m ratio is three times less for the first standard size and 3.6 times less for the second with a close relative compressor mass M/Q_m.
- According to the indicators discussed above, R744 has no advantages for single-purpose systems, the main of which is a low energy efficiency.
- The use of R744 with a GWP = 1 does not guarantee the absence of a negative impact on the operating equipment condition. The low energy efficiency has a direct and permanent impact.
- A quantitative assessment of internal processes requires a thermodynamic analysis of an unconventional solution associated with the operation of the upper stage near critical or transcritical modes.

Analysis of the process indicators in the upper stage compressors in terms of exergy efficiency

- Net exergy efficiency of the stage $\eta_{net} = \dfrac{\Delta Ex_{usef}}{\Delta Ex_{ex}}$
- The energy efficiency of the compressors’ processes when operating on R744 is higher in the considered range in frames of variable parameters.
- From the results shown in Figure 8, it follows that when operating on R507A, the share of losses in the compressor monotonically decreases with increasing t_k for each temperature t_m in the overall limit from 52 % to 74 %. When operating on R744, the shares of similar losses vary from 36 % to 45 % with different patterns.

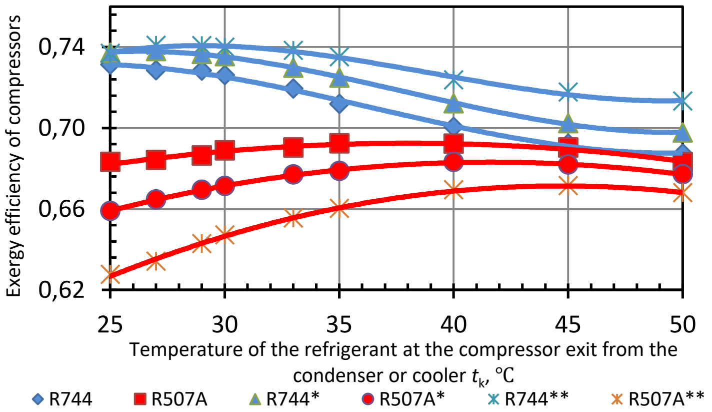

Figure 7. Dependence of exergy efficiency $\eta_{comp} = f(t_k)$ at t_m = -10 – 0 ^{0}C

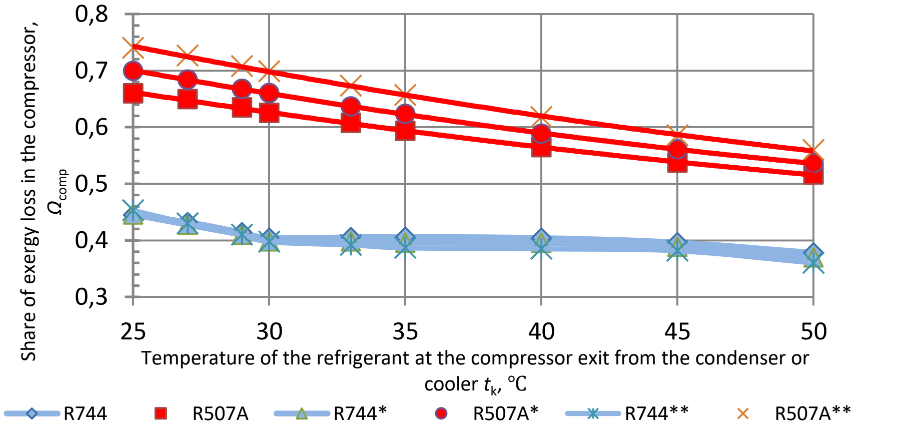

Figure 8. Dependence of the share of exergy losses in the compressor $\Omega_{comp} = f(t_k)$ at t_m = -10 – 0 ^{0}C

Dependence of refrigerant throttling losses. Analysis of the share of throttling losses

- The exergy losses ratio during throttling and the useful used $DEx_{thr}/\Delta Ex_{usef}$ taken as an indicator of the energy comparison of the throttling processes of the considered stage cycles. The latter is equal to the exergy performance of the upper stage ΔEx_m.
- From the results shown in Figure 9, it follows that in comparison with R507A, the specific throttling losses per unit of exergy performance for R744 are higher. These exergy losses are 2 – 3.2 and 2.2 – 3.3 times for subcritical and transcritical modes, respectively.
- The analysis results of the influence of t_k and t_m temperatures on throttling losses shown in Figure 10 also differ in the operation zone of the transcritical mode. It seems to be an external influence associated with the optimization of the exhaust pressure required only for transcritical modes.

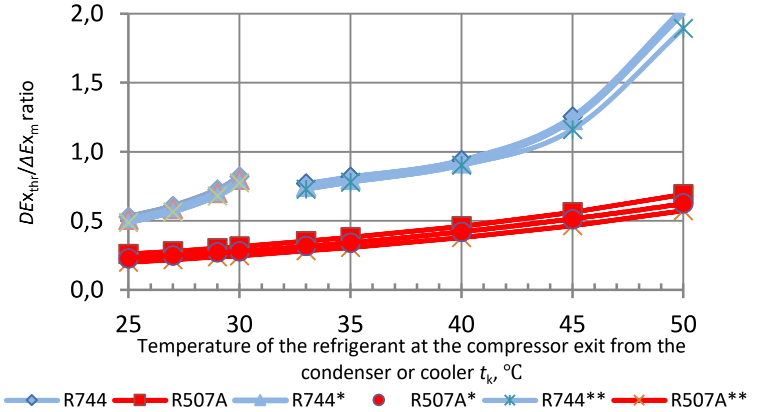

Figure 9. Dependence of refrigerant throttling losses $DEx_{thr}/\Delta Ex_m = f(t_k)$ at t_m = -10 – 0 ^{0}C

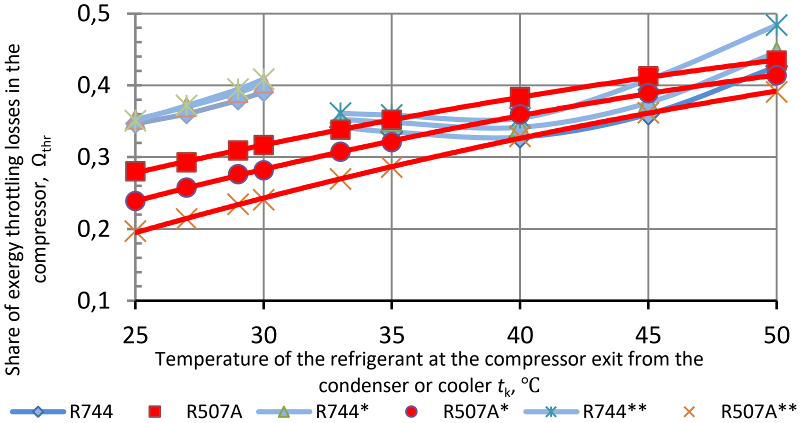

Figure 10. Dependence of the share of throttling losses $\Omega_{thr} = f(t_k)$ at t_m = -10 – 0 ^{0}C

The ratio of available exergy is taken as an indicator of the energy capabilities of the compared cycles

- The ratio of available exergy $\Delta Ex_k/\Delta Ex_m$ (for heating and cooling) is taken as an indicator of the energy capabilities of the compared cycles. The results shown in Figure 11 mostly reflect the fundamental differences between the traditional upper stage cycles and those implemented on R744.

- Conclusion: when operating in near-critical and transcritical modes, R744 is a refrigerant for the combined systems of heat and cold cogeneration.

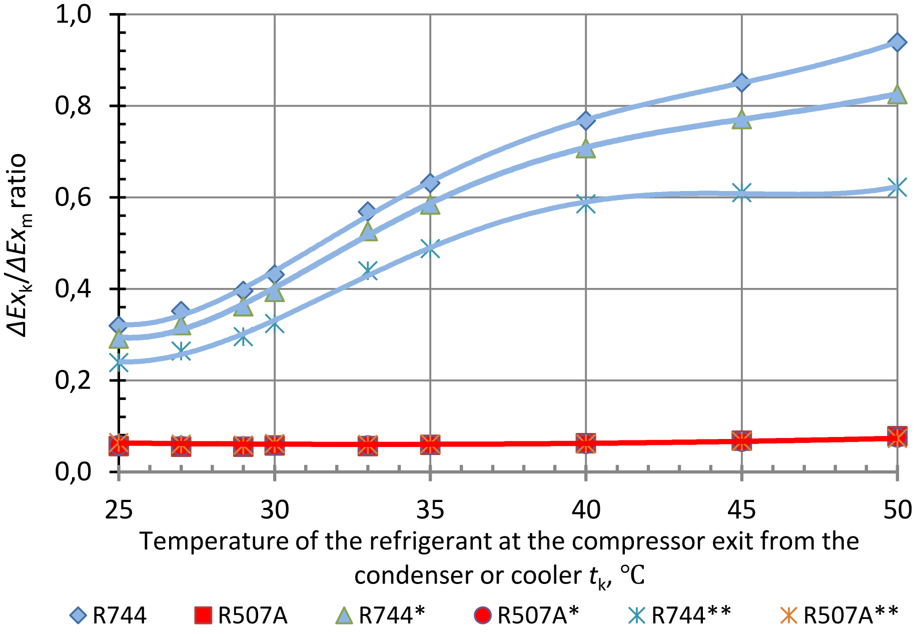

Figure 11. Dependence of ratio $\Delta Ex_k/\Delta Ex_m = f(t_k)$ at t_m = -10 – 0 ^{0}C

Conclusions

- At present, for the considered conditions of cold consumption, requiring the use of low-temperature two-stage or cascade cycles, R744 is the only natural refrigerant of the A1 safety group that meets the existing environmental prohibitions.
- With the technical advantages of R744 as a refrigerant of a significantly higher pressure, its use additionally provides high performance in the cycle of the lower stage of refrigeration machines with semi-hermetic compressors.
- For the upper stage, the combination of the thermodynamic properties of R744 and the specifics of operating modes in the area of critical states leads to significant differences in the qualitative and quantitative indicators of the cycle from the traditional one. The qualitative difference is associated with the expansion of the possibilities for the effective use of the heat flow Q_k, removed from the refrigerant into the external environment with an improvement in the system efficiency. Quantitative differences are determined by the significant increase in throttling losses; and additional performance degradation in case the advantages of quality differences are not realized.

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