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HYDROCARBONS AS SUBSTITUTES FOR HALOGENATED REFRIGERANTS IN REFRIGERATING SYSTEMS

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ABSTRACT

The paper deals with the use of R-290/600a(50/50) and R-600a, that are now considered as alternative to R-134a to substitute R-12 in domestic refrigeration. A theoretical analysis of the mixture performance shows that both hydrocarbon refrigerants may be used. Tests of certain hermetic compressors confirm that the mixture can be used both for old and new equipment, while the isobutane must be used for new equipment only .

INTRODUCTION

The need to substitute traditional CFCs with environmentally safe refrigerants is opening the refrigeration market to hydrocarbons, though strong and justified doubts still remain about the risks connected with their flammability. Hydrocarbons and their mixtures may be considered a good natural alternative to R-12 in all technical applications involving hermetic circuits with a low refrigerant charge. Their use as a substitute for R-12 is thus particularly promising in small domestic and commercial refrigerators, where it has been demonstrated that replacing R-12 with hydrocarbons raises no particular problems of material compatibility and solubility with mineral oils.

At present, the opportunities for using hydrocarbons mainly concern the R-290/600a(50/50) mixture and R-600a. In both cases, certain changes have to be made to the refrigerating systems designed for use with R-12: the mixture calls for a proper design of the heat exchangers, whereas the isobutane, other conditions being equal, requires the use of compressors with a larger displacement.

There are currently some doubts among those proposing the use of hydrocarbons in domestic refrigeration as to the choice between the R-290/600a(50/50) mixture and R-600a. This paper attempts to throw light on these doubts by testing the performance of small-displacement hermetic compressors operating with the two alternative refrigerants. Testing was also done using R-134a which still remains a feasible solution for the replacement of CFCs in domestic refrigeration.

This study does not deal with the problem of flammability, which would have to be based on a statistical evaluation of the risks involved which goes beyond the scope of our present investigations.

THEORETICAL PERFORMANCE OF THE R-290/600a MIXTURE

To theoretically compare the performance of a refrigerating zeotropic mixture and pure refrigerant calls for the definition of objective criteria that are still not well-established. Though the problem has been amply discussed, there is no universally accepted solution. A simplified method has therefore been adopted, which consists in comparing ideal cycles with pure or mixed refrigerants operating between the same evaporation and condensation temperatures. As far as zeotropic mixtures are concerned, the condensation temperature is assumed to be the arithmetic mean of boiling and dew point temperatures in the condensation process (t_4-t_5 in Fig. 1), while the evaporation temperature is assumed to be the arithmetic mean of the dew point temperature and evaporator inlet temperature at the evaporating pressure (t_1-t_7 in Fig. 1).

The performance of the R-290/600a mixture, as a function of the R-290 mass fraction, has been calculated /1/ with reference to ideal cycles with a condensation temperature of 55°C and two evaporating temperatures: -30°C and -23.3°C. The subcooled liquid temperature and the superheated vapor temperature both equate to 32°C. Figures 2, 3, 4 and 5 illustrate the results of the calculation showing that the mixture has performance similar to R-12 when the R-290 mass fraction is between 50% and 60%.

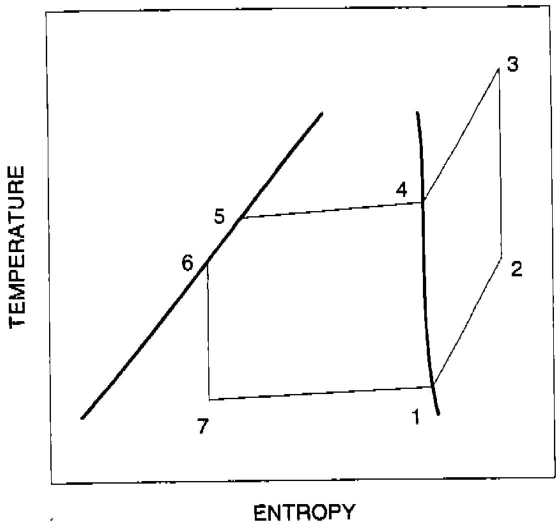

Fig. 1 - Reference cycle for refrigerating mixtures.

As the R-290/600a(50/50) mixture is already available on the market and used for table-top refrigerators, a more in-depth analysis was performed on this composition. It might, however, be more appropriate to use the 60/40 mixture, since the volumetric refrigerating effect and evaporating pressure of the 50/50 mixture are slightly lower than those of R-12.

Referring again to theoretical performance, table 1 shows a comparison of three refrigerants suitable for replacing R-12. The results show that the R-290/600a(50/50) mixture gives a slightly lower volumetric refrigerating effect than R-12, then, with the same compressor, it should give an acceptable refrigerating capacity without decreasing the COP. Moreover, evaporating and condensing pressures are similar to those of R-12. The mixture should be preferable to R134a particularly in case of retrofitting operations as it does not require the substitution of the lubricant. Some doubts still remain on isobutane because of its low volumetric refrigerating effect and evaporating pressure. To overcome the first drawback, doubling the compressor displacement is necessary, so excluding the use of isobutane in retrofitting operations. The second drawback could cause the presence of non-condensable gases in the refrigeration system. A positive feature of both the hydrocarbon refrigerants is the discharge temperature much lower than that of R-12.

Table 1 - Theoretical performance of substitutes for R-12 in domestic refrigeration.

				R-12	R-134a	R-600a	R-290/600a (50/50)
55 °C	discharge pressure	p_5	(kPa)	1364	1495	772	1297
	Δt condensation	t_4-t_5	(°C)	0	0	0	6.4
-30 °C	suction pressure	p_2	(kPa)	100	84	47	91
	suction density	ρ_2	(kg/m^3)	4.861	3.440	1.089	1.837
	Δt evaporator	t_1-t_7	(°C)	0	0	0	5.8
	refrigerating effect	h_2-h_7	(kJ/kg)	144	188	335	346
	vol. refrigerating effect	d_2*(h_2-h_7)	(kJ/m^3)	701	646	364	636
	discharge temperature	t_3	(°C)	139.1	129.6	111.2	120.7
	COP		(-)	2.36	2.39	2.53	2.39
-23.3 °C	suction pressure	p_2	(kPa)	132	115	63	121
	suction density	ρ_2	(kg/m^3)	6.45	4.703	1.471	2.454
	Δt evaporator	t_1-t_7	(°C)	0	0	0	5.6
	refrigerating effect	h_2-h_7	(kJ/kg)	144	187	334	345
	vol. refrigerating effect	d_2*(h_2-h_7)	(kJ/m^3)	927	881	491	847
	discharge temperature	t_3	(°C)	128.3	120.1	103.5	112.3
	COP		(-)	2.70	2.73	2.79	2.73

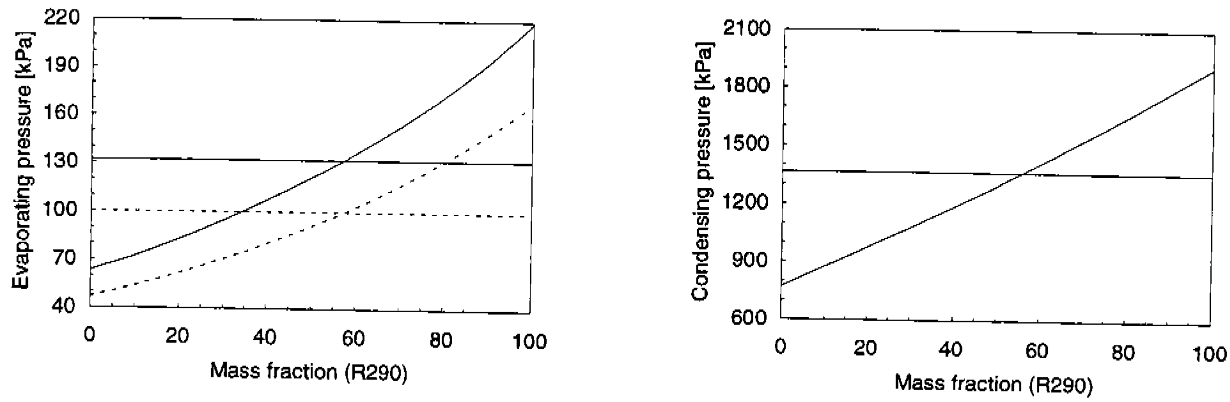

Fig. 2 - Evaporating (left) and condensing (right) pressure of the R-290/600a mixture in relation to the mass fraction of R-290 with reference to ideal cycles. Condensing temperature: 55°C; evaporating temperatures: -23.3°C (———) and -30°C (- - - -). The straight lines refer to R-12.

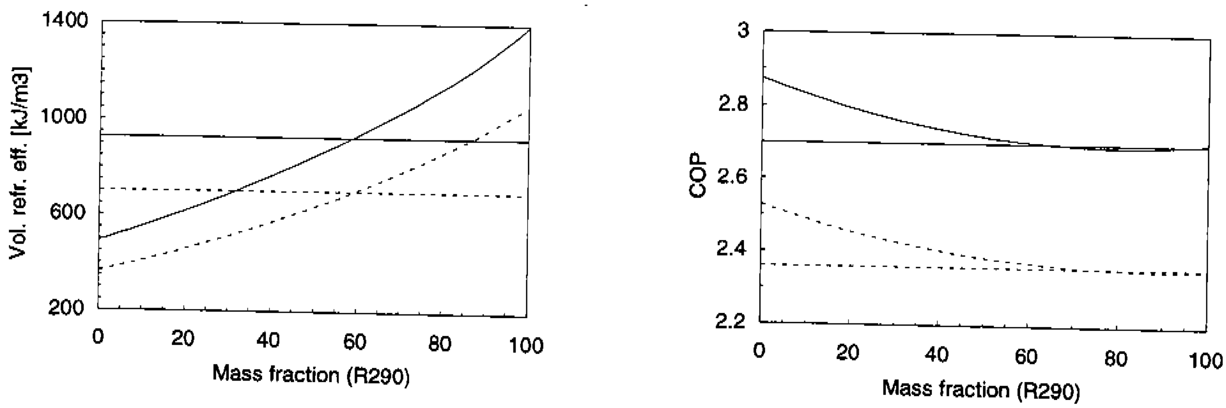

Fig. 3 - Volumetric refrigerating effect (left) and COP (right) of the R-290/600a mixture in relation to the mass fraction of R-290 with reference to ideal cycles. Condensing temperature: 55 °C; evaporating temperatures: -23.3°C (———) and -30°C (- - - -). The straight lines refer to R-12.

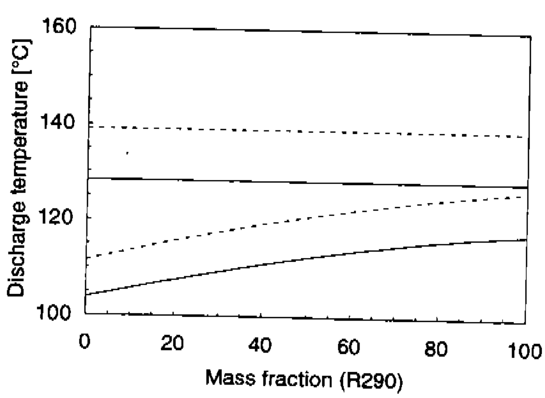

Fig. 4 - Compressor discharge temperature in relation to the mass fraction of R-290 with reference to ideal cycles. Condensing temperature: 55 °C; evaporating temperatures: -23.3°C (———) and -30°C (- - - -). The straight lines refer to R-12.

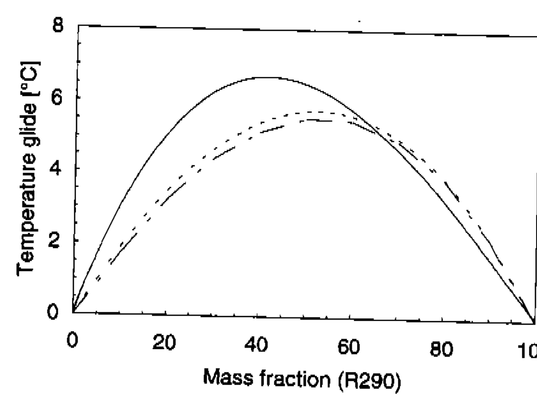

Fig. 5 - Condensing temperature glide [t_c= 55°C (———)] and evaporator temperature glide [t_e = -23.3°C (–·–·–) and -30°C (- - - -)] of the R-290/600a mixture in relation to the mass fraction of R-290 with reference to ideal cycles.

TESTS OF COMPRESSORS

Several hermetic compressors with different displacements were tested with the secondary refrigerant calorimeter method. The tests were perfomed with R-12 and with the three substitutes listed in Table 2. Test conditions were as follows:

saturated refrigerant suction vapor temperature	-23.3°C ; -30°C
saturated refrigerant discharge vapor temperature	55°C
suction vapor temperature	32°C
temperature of liquid refrigerant upstream from the refrigerant control	32°C

Table 2 - Power input (P), refrigerating capacity (q) and energy efficiency ratio (EER) for hermetic compressors operating with R-12 and its substitutes.

Refrigerant	d (cm^3)	p_s (bar)	p_d (bar)	$t_{s\ sat}$ (°C)	$t_{d\ sat}$ (°C)	t_{so} (°C)	t_w (°C)	P (W)	q (W)	EER (-)
R-12	3.00	1.00	13.68	-30.0	55.1	67	92	68	49	0.72
	3.50	1.00	13.65	-30.0	55.0	73	85	75	61	0.82
	5.12	1.00	13.67	-30.0	55.1	85	108	103	91	0.88
	5.50	1.00	13.68	-30.0	55.1	92	113	120	102	0.84
	3.00	1.32	13.64	-23.3	55.0	73	95	79	75	0.95
	3.50	1.32	13.66	-23.2	55.1	79	87	88	89	1.02
	5.12	1.32	13.67	-23.3	55.1	93	108	123	132	1.07
	5.50	1.32	13.68	-23.3	55.1	99	115	143	144	1.01
R-134a	3.00	0.84	14.82	-30.0	54.6	64	90	59	33	0.56
	3.50	0.84	14.80	-30.0	54.6	73	79	64	43	0.67
	4.10	0.84	14.82	-30.1	54.6	72	95	74	50	0.67
	5.12	0.84	14.82	-30.1	54.6	80	102	94	71	0.76
	5.50	0.84	14.97	-30.1	55.1	88	108	106	82	0.77
	7.75	0.84	14.83	-30.0	54.7	90	104	122	113	0.93
	8.19	0.84	14.98	-30.1	55.1	86	104	133	127	0.95
	9.07	0.84	14.98	-30.1	55.1	87	107	149	147	0.99
	10.64	0.84	14.84	-30.1	54.7	77	92	177	167	0.95
	3.00	1.15	14.83	-23.3	54.7	73	93	72	61	0.86
	3.50	1.15	14.84	-23.3	54.7	73	82	78	75	0.96
	4.10	1.15	14.84	-23.3	54.7	81	99	90	87	0.96
	5.12	1.15	14.84	-23.2	54.7	90	106	120	124	1.03
	5.50	1.14	14.99	-23.4	55.1	94	110	129	127	0.98
	6.99	1.15	14.84	-23.3	54.7	91	101	137	156	1.14
	8.19	1.14	14.98	-23.4	55.1	94	105	172	200	1.16
	9.07	1.14	14.97	-23.4	55.1	97	112	192	220	1.15
	10.64	1.15	14.82	-23.3	54.6	88	96	227	265	1.16
R-290/600a(50/50)	3.00	0.93	13.04	-29.6	55.3	67	84	64	42	0.66
	3.50	0.93	13.05	-29.6	55.3	69	86	70	54	0.78
	4.10	0.93	13.06	-29.6	55.3	73	92	79	62	0.78
	5.12	0.93	13.05	-29.5	55.3	81	96	96	86	0.90
	5.50	0.93	13.05	-29.6	55.3	86	99	109	95	0.87
	6.99	0.93	13.05	-29.6	55.3	86	96	119	117	0.98
	3.00	1.24	13.06	-22.7	55.3	72	85	73	66	0.90
	3.50	1.24	13.04	-22.7	55.3	75	87	81	84	1.03
	4.10	1.24	13.04	-22.8	55.3	82	95	97	102	1.05
	5.12	1.24	13.06	-22.8	55.3	87	96	115	130	1.13
	5.50	1.24	13.02	-22.8	55.2	91	99	128	140	1.09
	6.99	1.24	13.03	-22.8	55.2	93	98	147	178	1.21
R-600a	5.98	0.46	7.79	-30.0	55.4	68	85	69	54	0.78
	6.50	0.46	7.80	-30.0	55.4	70	87	72	57	0.80
	7.75	0.46	7.79	-30.0	55.4	71	83	80	72	0.90
	10.64	0.46	7.80	-30.0	55.4	72	83	92	96	1.05
	5.98	0.63	7.79	-23.3	55.4	74	84	82	88	1.07
	6.50	0.63	7.78	-23.3	55.3	76	87	85	93	1.10
	7.75	0.63	7.79	-23.3	55.4	76	81	96	120	1.25
	10.64	0.63	7.80	-23.3	55.4	79	84	115	162	1.40

An analysis of the test data in table 2 confirms the indications emerging from the theoretical calculation of the performance of the R-12 substitutes considered. The analysis has to distinguish between two very different cases: the replacement of R-12 in retrofitting operations and the choice of a refrigerant other than R-12 for newly-designed systems. In the former, as the compressor is not replaced, the refrigerating capacity can be considered as the most important feature and performance can be compared at the same compressor displacement; in the latter case, it would seem more significant to compare the energy efficiency ratio of the compressor at the same refrigerating capacity.

At the same displacement, both R-134a and R-290/600a(50/50) cause a drop in refrigerating capacity by comparison with R-12, and the refrigerating capacity with mixture is higher than with R134a. It is noteworthy that the loss of refrigerating capacity becomes smaller the greater the compressor displacement. Clearly, the performance of R-12 and R-600a cannot be compared at the same displacement, as R-600a calls for almost twice the displacement in order to compare with R-12.

Figure 6 shows the outcome of comparison of the four refrigerants considered at the same refrigerating capacity and shows the trend of the EER for the compressors involved. The compressors tested with the R-290/600a(50-50) mixture have an EER very similar to those operating with R-12, whereas the compressors tested with R-134a have a much lower EER. Moreover, the compressors tested with R-600a have an EER considerably higher than those using R-12, but this is mainly attributable to the presence of the start capacitor. In fact, the compressors tested with R-600a had RSCR motors, whereas the compressors tested with the other refrigerants had RSIR motors. If the value of the EER is separated from the positive influence of the start capacitor, the isobutane can be assumed to cause a slight increase in the EER by comparison with R-12.

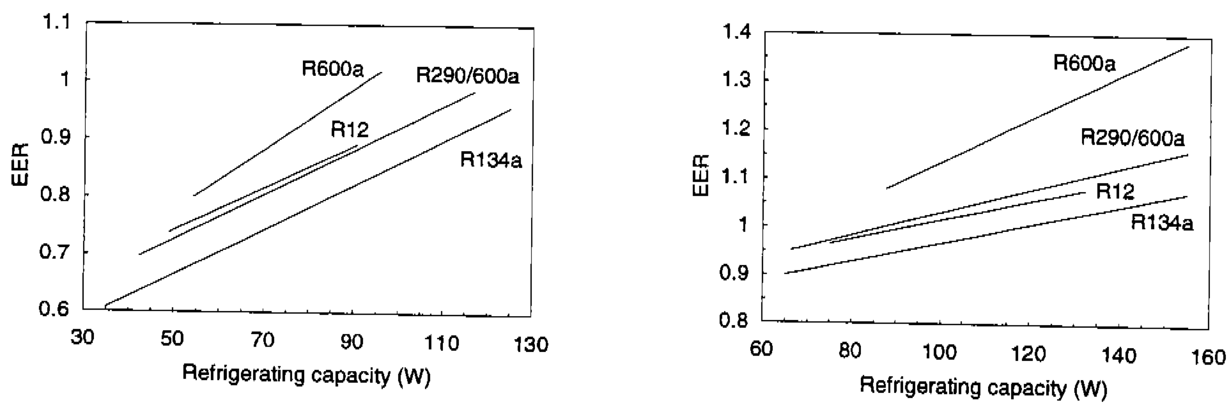

Fig. 6 - Tested compressors EER in relation to refrigerating capacity [t_e = -23.3 (left) and -30 °C (right)].

CONCLUSIONS

The measurements made on hermetic compressors demonstrate that hydrocarbons are a valid alternative to R-134a in replacing R-12 in domestic refrigeration. With our present knowledge, it is difficult to know whether to opt for R-290/600a (50/50) or R-600a; however, with a view to making a choice, the following conclusions can be drawn on the two refrigerants examined.

The mixture offers the following advantages:
- the compressor displacement used for R-12 can be maintained without severely influencing refrigerating capacity;
- EER and evaporating pressures remain similar to R-12;
- its glide temperature could be a useful feature in two-temperature domestic refrigerators;

and the following disadvantage:
- its zeotropy implies charging and maintenance problems.

On the other hand, isobutane offers the following advantages:
- uncomplicated charging and maintenance because it is a one-component refrigerant;
- less noise from the compressor because the delivery pressures are lower than in the case of R-12;

and the following disadvantages:

- a larger-size compressor because of its low volumetric refrigerant effect;
- a very low evaporating pressure.

Having evaluated the advantages and disadvantages of the mixture vis-à-vis the isobutane, another point has to be considered before a dependable choice of one or the other can be made: leakages may be critical in small refrigerating systems, particularly because using hydrocarbons involves using half the charge required in the case of R-12 and R-134a.

In the case of isobutane, a reduction in the performance of the refrigerating system may be caused both by leakages from the high pressure side of the circuit and by the inlet of air in low pressure side of the circuit.

In the case of the mixture, leakage from the circuit leads to a reduction in the performance of the refrigerating system both because of the loss of refrigerant and because these losses enrich the mixture in the high-boiling component (i.e. the isobutane).

To overcome any doubts as to the choice between the two options, more detailed information is needed on the long-term behavior of a significant range of domestic refrigerators operating with R-600a and R-290/600a. These long-term tests could also provide useful information contributing towards a more detailed definition of the risks necessarily involved in the use of hydrocarbons in refrigeration.

NOMENCLATURE

d	compressor displacement
p_s	suction pressure
p_d	discharge pressure
$t_{s\ sat}$	saturated refrigerant suction vapor temperature
$t_{d\ sat}$	saturated refrigerant discharge vapor temperature
t_{so}	temperature of the refrigerant at the shell outlet
t_w	winding temperature
P	power input
q	refrigerating capacity
EER	energy efficiency ratio

REFERENCES

1 *NIST* Thermodynamic properties of refrigerants and refrigerant mixtures. *v. 4.0, National Institute of Standards and Technology, Gaithersburg, MD.*