HEAT PUMPS WITH HYDROCARBONS AS REFRIGERANTS FOR SMALL RESIDENTIAL BUILDINGS

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ABSTRACT

The paper reports about operational experiences with a heat pump example and propane as refrigerant. It is to conclude: heat pumps with HCs as refrigerant could be a good chance for reduction of environmental stress. The handling of them is not so difficult if the special properties of HCs are considered. Therefore the widen application is no technical problem but a safety problem which could be solved only by law. Manufacturer of components and of heat pumps must not take the unreasonable risk furthermore.

Key Words: ***heat pump, residential building, refrigerant, hydrocarbon.***

1 INTRODUCTION

Heat pumps are an environmental benign alternative for customary heating systems because of their possible primary energy saving. But they contribute to the environmental impact although with a lower scale. The unit of this impact is the so-called TEWI value which consists of two parts – the direct part by refrigerant emissions and the indirect part by the power demand. The lower the environmental impact caused by the heat pump the higher the COP and lower the refrigerant emissions. The part caused by refrigerants amounts to 0 if you can use refrigerants without contribution to the GWP. These requirements are realized by hydrocarbons nearly ideally. A disadvantage is the flammability of these refrigerants. The practice correlated paper passes on experiences for the operation of a propane heat pump.

2 HYDROCARBONS AS REFRIGERANT

Hydrocarbons (HCs) are used in explosion save industrial plants of chemical industry, in small heat pumps and from time to time in commercial refrigerating systems. The HC R600a has caught on as refrigerant in the field of household refrigeration in the most European countries. Further applications of the daily life are fuel for gas stoves and gas heating systems as well as blowing agents for heat insulations and aerosols.

Hydrocarbons are especially environmental benign and cost effective refrigerants without ODP and a very low GWP. Further environmental benign properties are the trouble-free disposal, no healthy effect and the classification into the water endangering class 0. A danger for the local ambient is caused only by the flammability and the resulting explosion danger. The most important HCs which can be used as refrigerants are ethylene (R1150), ethane (R 170), propylene (R1270), propane (R290), cyclopropane (RC270) and R600a (isobutane).

2.1 Comparison to Other Refrigerants

The thermodynamic, physical and chemical properties of hydrocarbons are well known so the probable behaviour in refrigerating circuits can be pre-calculated relatively exactly. A comparison of the most important properties is to carry out for the existing application to enable an objective evaluation and selection of the refrigerants (see Table 1 and 2). The used evaluation scale for these criteria is stipulated subjectively. Other scales can be valid for other applications.

Table 1. Refrigerant comparison, evaluation criteria

Evaluation scale		AR* °C	π	Δp bar	t_{is} °C	q_{oV} kJ/m³	TEWI kg CO_2	ε_{WP} -	t_{26}
0	critical	> 0	> 9	> 25	> 100	< 400	>=17,000	< 3.8	< 50
1	bad	> -5	> 8	> 20	> 90	> 400	<17,000	> 3.8	> 50
2	enough	> -10	> 7	> 15	> 80	> 800	<16,000	> 4.0	> 52.5
3	satisfactory	> -15	> 6	> 10	> 70	> 1,200	<15,000	> 4.2	> 55
4	good	-20...0	> 5	> 5	> 60	> 1,600	<14,500	> 4.4	> 57.5
5	very good	-20...5	> 4	< 5	< 60	> 2,000	<=14,000	> 4.6	> 60

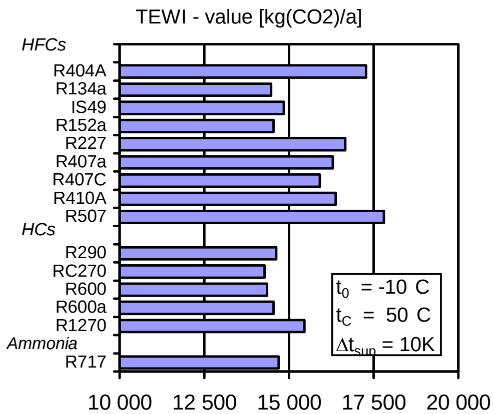
Table 2. Refrigerant comparison, evaluation matrix

Refrigerant	AR* °C	π	Δp bar	t_{is} °C	q_{OV} kJ/m³	$TEWI_{ges}$ kg CO_2	ε_{WP}	t_{26}	Total points
HFCs									
R404A	4	4	2	4	5	0	1	3	23
R134a	5	3	3	4	3	2	3	5	28
IS49	5	3	3	4	3	2	3	5	28
R152a	5	3	4	2	3	3	4	5	29
R227	3	3	4	5	1	1	1	5	23
R407A	5	4	2	2	5	1	2	3	24
R407C	4	4	2	2	5	2	2	4	25
R507	5	4	2	4	5	0	1	1	22
R410A	4	4	2	4	5	1	3	0	23
HCs									
R290	5	4	3	3	4	3	4	5	31
RC270	5	4	3	2	4	4	4	5	31
R600	1	2	5	5	1	4	4	5	27
R600a	3	3	4	5	1	3	4	5	28
R1270	4	5	2	3	5	2	3	4	28
Ammonia									
R717	5	3	2	0	5	3	4	4	26

* application range

π - pressure ratio; Δp - pressure difference
t_{is} - isentropic discharge temperature; q_{OV} - volumetric cooling capacity
$TEWI_{ges}$ - Total Equivalent Warming Impact; COP - coefficient of performance
t_{26} - refrigerant saturation temperature at 26 bar, result

The important criteria TEWI value and COP are shown once more as graph in Figures 1 and 2.



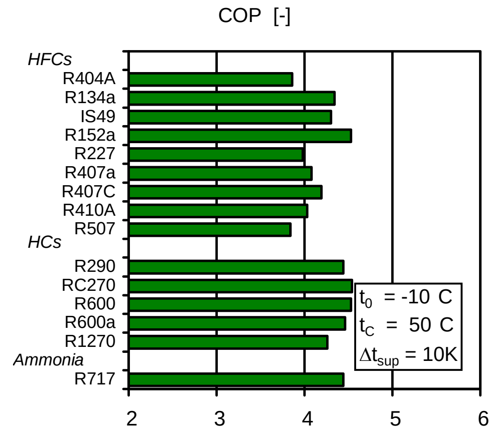


Fig. 1. TEWI value for several refrigerants

Fig. 2. calculated COP of several refrigerants

The TEWI value was determined for following conditions:

$$TEWI = GWP \cdot L_a \cdot \tau_L + GWP \cdot m_{KM}\left(1-\alpha_R\right) + \tau_L \cdot n_j \cdot \left(Q_{WP} / \varepsilon_{WP}\right) \cdot f \qquad (1)$$

Comparing conditions: $L_a = 5$ g/a, $\alpha_R = 0.75$, $f = 0.6$ kg CO_2/kWh

$\tau_L = 12$ a, $Q_{WP} = 4.5$ kW, $m_{KM} = 0.4$ kg

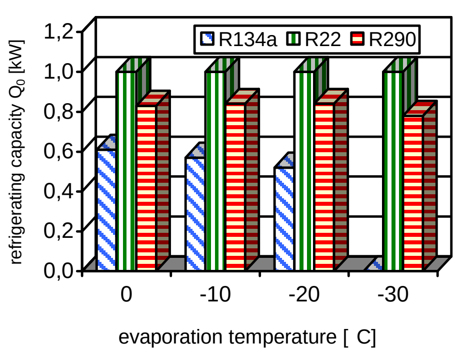
$n_j = 2{,}000$ h/a

L_a: leakage, τ_L. life time, m_{KM}: refrigerant charge, α_R: recycling ratio, n_j: running time/year, Q_{WP}: heating capacity, f: CO_2-conversion factor

The decision was made in this case for the HCs. Propane and cyclopropane reach the same points. The further information is referring to the better known refrigerant propane. The HFCs are not considered furthermore because of their higher GWP. The behaviour in the refrigerating circuit and the flammability of the HCs are to evaluate for final decision.

2.2 Refrigerating Capacity

Only cleaned HCs are to be used as refrigerant to ensure a failure-free operation of refrigerating system. The graphically shown refrigerating capacity ratios of Figure 3 results from an operation of a compressor with the refrigerants R134a, R22 and R290 at the same conditions. So you need for an R290 refrigerating system vs. an R22 system an about 15 % higher compressor displacement to realize the initial refrigerating capacity. The COPs reached with R290 vs. R22 are 1.5 % to 2.0 % (calculated) lower and are practically the same.



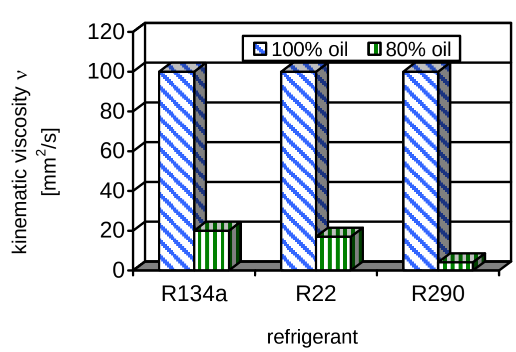


Fig. 3. Refrigerating capacity of a reciprocating piston compressor, Q_0, t_c = 40 °C

Fig. 4. Viscosity reduction of the oil Shell G100 by refrigerant, concentration changing from 100 mass-% oil to 80 mass-% of oil at 40 °C

2.3 Solubility in Refrigerating Machine Oil

An important difference between propane and the other refrigerants is the solubility of the refrigerant in oils. Compared to the use of HFCs in heat pumps mineral or semi-synthetic oils are usable too. The oil return is ensured through the viscosity reduction caused by the solubility of propane. But the solubility influences negatively the compressor lubrication. This disadvantage is equalized by the use of oils of a higher viscosity class. The selection of the oil should be carried out by the compressor producer or agreed with it. Figure 4 shows the essential differences of R290 vs. R22 and R134a according to solubility behaviour. Practical experiences are discussed in item of the application example.

2.4 Refrigerant Charge

A further remarkable difference of propane vs. the other refrigerants is the low density (saturation temperature 40 °C: $\rho'_{R290} = 0.47$ kg/dm^3, $\rho'_{R134a} = 1.15$ kg/dm^3). This circumstance results in a 50 % lower refrigerant charge referred to the mass (Figure 5).

2.5 Heat Exchanger, Piping

There are only small differences between the dimensioning of the heat exchangers and refrigerant pipes for the operation with R22 and R290. It is possible to assume the same dimensions.

2.6 Leakage

Higher leakage rates are to expect for HCs caused by the lower viscosity. This results in an about 50 % higher leakage rate for R290 vs. R22 (calculated) at the same leak and the same pressure difference. This matter is shown in Figure 6.

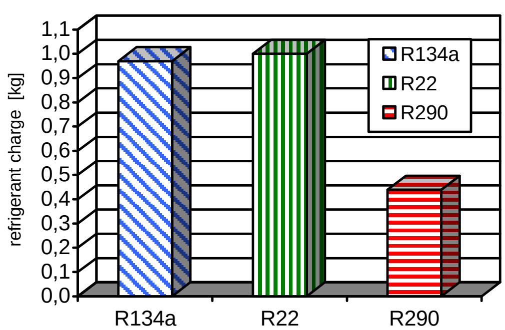


Fig. 5. Refrigerant charge [kg], $t_0 = 0$°C, $t_c = 40$ °C

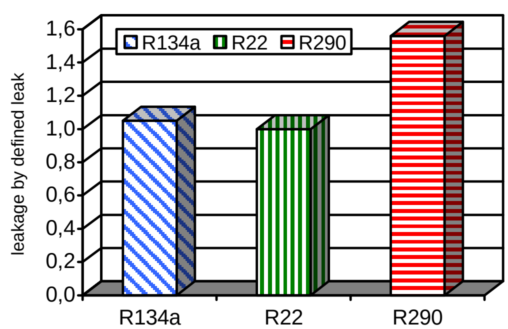


Fig. 6. Leakage by defined leak

2.6 Material Digestibility

Limitations for the material selection are not known. Propane is usable for heat pumps with semi-hermetic and hermetic compressors.

3 SAFETY CONDITIONS

The flammability and the explosion danger are to consider. HCs are heavier than air and therefore leakage or damage will result in higher refrigerant concentrations in deeper ranges of plant or at the range of floor of installation and machine rooms. A safe drainage of coming out flammable refrigerants is to realize by according ventilation measures. The safety measures which are to realize depend on the refrigerant charge and the installation place. The safety requirements are fixed in standards and rules. For this aim in Germany the DIN 7003 (exists as “yellow print”) was acquired. It was fixed a charge limit of 150 g for HCs as refrigerants. No additional safety measures are required for closed refrigerating circuits with a charge of 150 g. With this charge heat pumps with 3 to 4 kW heating capacity can operate sufficiently. The forced ventilation of machine room and the avoiding of flash sources for a defined range are the essential measures for larger capacities and resulting larger charges.

The later introduced European Norm EN 378 is the basic standard for refrigerating systems and heat pumps and contains hints to other rules (electrical engineering) which are to consider. In this time the EN 378 is revised. The use of flammable refrigerants is not excluded by any safety measures but an additional expenditure is required.

4 APPLICATION EXAMPLE

In the last part of paper it was indicated norms and rules of safety conditions for the production, installation and operation of refrigerating systems and heat pumps. Although they do not exclude the flammable refrigerants from use only a few of heat pumps with propane as refrigerant are known. At first the heat pump manufacturer were orientating on use of HCs as refrigerant after coming into force of the HFC halon banning order. This development was retarded or stopped by the compressor producers. They did not open the compressors for use. The cause are law problems in connection with product liability. The heat pump producers alone have to take the risk and have to give up the claim to guarantee if they install heat pump systems with propane without the agreement of the compressor producer.

In spite of these marginal conditions refrigerating systems and heat pumps with propane are commercially used. So the Alwin Otten company of Meppen/Germany possesses a long-period experience with propane as refrigerant in commercial refrigerating plants and heat pumps which are discussed at the example of a selected heat pump. This heat pump was installed for the heating of a one-family-house.

The technical main features are:

- heating capacity: 10.2 kW (brine inlet temperature 0 °C, hot water supply temperature 35 °C)
- heated living area: 300 m^2
- heating system: underfloor heating
- heat source: 3 vertical ground coils every, 50 m, parallel on brine side
- hot water generation alternating to heating mode

The basis variant is a customary device which was completed by a measuring system and modified step by step through the collected operational experiences. The refrigerant circuit is compact and simply designed. The main components are the hermetic scroll compressor with heat insulated housing, soldered plate-type evaporator and condenser as well as thermostatic expansion valve. The refrigerant charge amounts to 1,200 g propane and as refrigerating machine oil was used the high-viscose mineral oil SP 100. It was abstained from a refrigerant accumulator. The heat pump is installed in a plastic housing. A simple safety facility exhausts the air from the inner housing by a fan through an air pipe to the ambient and generate by this way a low housing under-pressure. This technique avoids the coming out of refrigerant into the heating room in case of leakage. Here it is abstained from further information about component specification and manufacturers.

The heat source consists of three parallel switched vertical ground coils. The parallel scheme was selected because of the view of operational costs. The resulting high flow cross section for the heat agent enables a low pressure loss of 11 % compared to a 150 m coil with the same cross section. So the capacity input of the heat source pump is lower. The number of drilled meters is important for the evaluation of investment costs. The division in three coils influences these costs only a few. A coil capacity of 40 W/m at permanent loading and existing ground conditions was achieved. With this solution the installed coil capacity of 6 kW is broad-minded designed. An up-to-date underfloor heating system operates as heat sink/ consumer.

A customary heat storage is used for hot water generation but its heating surface is too small for the heat pump application. Meanwhile storages with larger heat exchange surfaces are on market. A change is prepared in order to save operational costs.

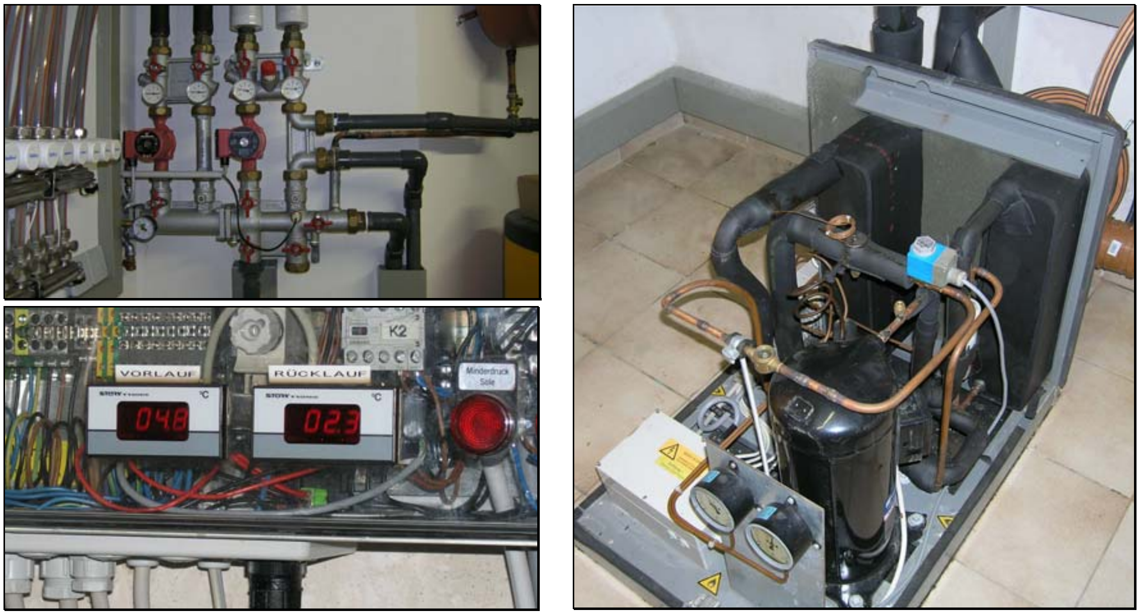


Fig. 7. Installed heat pump

4.1 Operational Experience and Conclusions

The installed refrigerating plants and heat pumps with propane of Otten company have shown more compressor failures compared to other systems. The reason of failure was a non sufficient lubrication of compressors during starting phase caused by foaming up of the oil. The result are earth connections of motor winding which are attributed to small metallic particles. Obviously they result from abrasion at non sufficient lubrication. A detection of a reduced capacity by wear was not carried out. Mechanically caused failures are the exception.

A pump off circuit acc. to state of art was re-installed to avoid further compressor failures of heat pump. For this aim a solenoid valve was installed immediately in front of the expansion valve. The switching off of the heat pump is realized by shutting of the solenoid valve. Than the compressor is putting out of operation by the suction pressure supervision of the compressor. By this way the solving of refrigerant in oil is essentially reduced during standstill. The nominal value for switching off is constantly prescribed by the compressor safety device. An adjustable nominal value would be better for a plant specific adaptation. After realization of this measure there were no further failures. In this connection the compressor housing insulation was not installed again because of high compressor surface temperature.

There were liquid droplets in the suction line of the heat pump at a superheating of 8 K but they are not the reason for the compressor failures. Propane is a refrigerant with a high evaporation enthalpy (Δh_{R22} = 157.8 kJ/kg, Δh_{R290} = 272.2 kJ/kg at t_0 = 0 °C, t = 45 °C, Δt_u = 2 K). Liquid droplets can stay for a long time in the suction gas flow and from time to time they are swept up to the compressor too. But it is to assume that the droplets are caused by the unequal refrigerant distribution in the plate-type evaporator. Some technical solutions for equalizing of the refrigerant distribution like distribution lance or porous bodies at the evaporator inlet are offered. But in this case an inner heat exchanger (IHE) for the additional superheating of the suction gas was re-installed into the heat pump.

The effect of such a heat exchanger depends on the refrigerant properties and was determined for propane by cycle calculation for following conditions: t_0/t: -7 °C / 40 °C, $\Delta t_{Ü}$ = 6 K, Δt_{sup} = 2 K.

Table 3 shows the calculation results. Two capacity values were fixed for the IHE to recognize the temperature differences of refrigerant vapour and liquid.

Table 3. Influence of IHE on operational parameters of the heat pump

	Δt_{SG}	Δt_L	Δh_E	Δh_c	T_D	$\dot{m}_{KM}$	COP	$\dot{Q}_H$
without IHE	0	0	274.8	351.9	57.7	100	4.56	100
IHE 1	17	10.9	305.0	388.8	74.5	92	4.63	99.6
IHE 2	34	22.4	335.5	425.9	91.4	86	4.71	99.2

Δt_{SG}: temperature rise suction gas
Δt_L temperature reduction refrigerant liquid
Δh_E: enthalpy difference at the evaporator
$\dot{Q}_H$ heating capacity
Δh_c: enthalpy difference at the condenser
T_D : discharge temperature
$\dot{m}_{KM}$ refrigerant mass flow

The heating capacity is nearly constant at the application of an IHE. The higher enthalpy difference at the condenser is compensated by the smaller refrigerant mass flow. The refrigerant mass flow is reduced through the rising specific volume of suction gas. The IHE influences the COP only marginally. The compression final temperature is rising on maximum 91 °C and lies widely under the application limit. Liquid droplets at the compressor inlet can be avoided by IHE but that did not result in an efficient energetic advantage. The IHE is not the best solution because of the hardware costs. The better solution would be an optimum evaporator design with dry suction gas at the outlet.

4.2 Condenser Pollution

The condensing temperature was rising by 4 K because of pollution in the heating circuit. This results in a reduction of the COP by 10 %. The possibility for cleaning of the plate-type heat exchanger is limited on washing and chemical cleaning but in this case the procedure does not lead to an important improvement. The use of filters and an optimum inhibition of heating water is an alternative to avoid corrosion. Today the application of filters at water inlet into the condenser is prepared.

5 CONCLUSION

Hydrocarbons (HCs) are environmental benign substances which are well usable refrigerants according to their thermodynamic properties. The disadvantage is the flammability because additional safety measures are required if the refrigerant charge exceeds 150 g. The availability of components is limited since especially the compressor manufacturers do not open the refrigerant compressors for use with HCs because there are law problems in connection with product liability.

The paper reports about operational experiences with an example of a heat pump and the refrigerant propane. It is to conclude: heat pumps with HCs as refrigerant could be a good chance for reduction of environmental stress. The handling of them is not so difficult if the special properties of HCs are considered. Therefore the widen application is no technical problem but a safety problem which could be solved only by law. Manufacturer of components and of heat pumps must not take the unreasonable risk furthermore.

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