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Josef Riha

Technical University Dresden

Hans Quack

Technical University Dresden

Joerg Nickl

Technical University Dresden

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SUB-CRITICAL OPERATION OF THE CO₂-EXPANDER/COMPRESSOR

Josef RIHA¹, Hans QUACK², Joerg NICKL³

¹Institute for Refrigeration and Cryogenics, Technische Universitaet Dresden
Dresden, Germany
Phone: +49-351-46332515, Fax: +49-351-46337247, E-mail: josef@memkn.mw.tu-dresden.de

²Institute for Refrigeration and Cryogenics, Technische Universitaet Dresden
Dresden, Germany
Phone: +49-351-46332548, Fax: +49-351-46337247, E-mail: Hans.Quack@tu-dresden.de

³Institute for Refrigeration and Cryogenics, Technische Universitaet Dresden
Dresden, Germany
Phone: +49-351-46332703, Fax: +49-351-46337247, E-mail: joerg@memkn.mw.tu-dresden.de

ABSTRACT

The primary objectives to use a combined expander/compressor unit in a CO₂ refrigeration cycle are to improve the COP and to reduce the exhaust pressure of the main compressor of the system. With the successful development of such an expander/compressor by the TU Dresden, the primary objectives have been reached. In summer as well as in warmer regions of the world the ambient temperature is higher than the critical temperature of the CO₂. That means that the refrigeration system operates in a trans-critical mode. For this operation conditions the expander was originally developed. But in Central and Northern Europe and many other regions of the world, the ambient temperature is during long periods of the year and during the night so low, that the condensing pressure of the CO₂ refrigeration system can be kept below 70 bar, i. e. that the cycle can be operated in a sub-critical mode. This requirement implicates for the expander quite different working conditions and this has to be investigated.

1. INTRODUCTION

The primary objectives to use an expander/compressor in a CO₂ refrigeration cycles are to improve the COP and to reduce the exhaust pressure of the main compressor in trans-critical operation of the system, i. e. in periods with high ambient temperature. Expanders are a standard device in cryogenics, i. e. in refrigeration at very low temperature as e. g. in air liquefaction (Quack, 1999 and 2000). At the TU Dresden the development of expanders for the special application with CO₂ trans-critical refrigeration started in 1994. Research is also going on in many other laboratories with different types of expander designs.

Our research and development was guided by the following considerations:

- Due to the large pressure differences inside the machine one has to minimize the possibilities for internal leakage. Therefore a piston machine is most advantageous.
- Two-stage compression with intercooling is important for the COP. This favors the flow diagram shown in Figure 1, where the expander drives the second stage compressor. The expander/compressor is an independent machine.
- Two machines in series, which both have their own lubrication system, bring the potential problem of oil-displacement. So we looked for a solution, where the expander/compressor does not need an independent oil system.
- We found that a linear arrangement of the pistons in the expander/compressor avoids side forces on the piston rings. Thus an "active" lubrication is not needed.

With the successful development of such an expander/compressor by the TU Dresden, the primary objectives have been reached. Fig. 1 shows a flow sheet, where a 3-stage expander drives directly the second stage of compression.

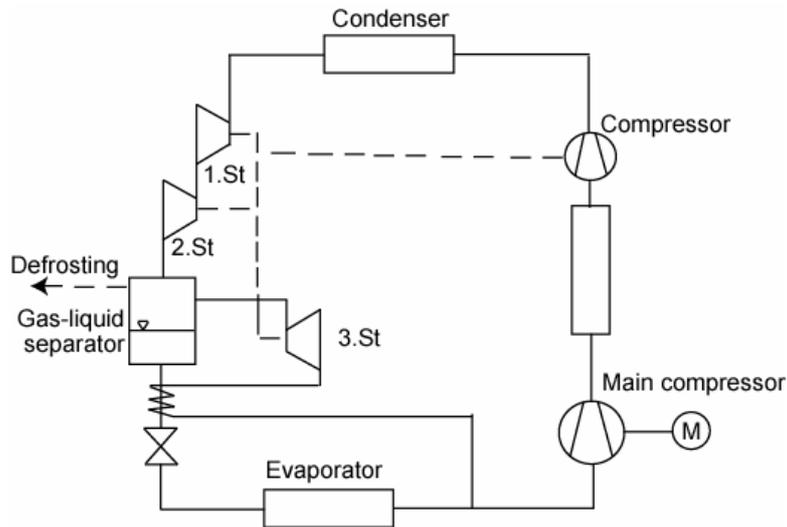


Figure 1: Cycle with an expander, which drives the second stage of compression

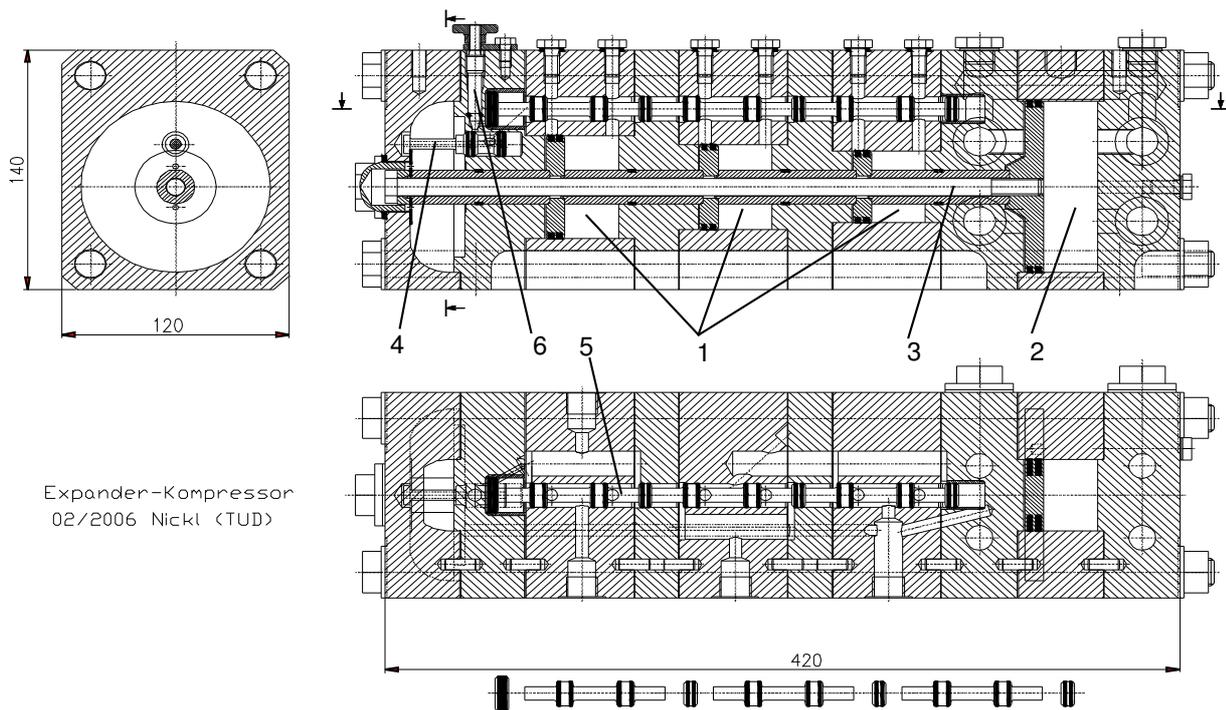


Figure 2: Expander/compressor with three-stage expansion coupled with a one-stage compression

In Figure 2 the fourth generation of the expander/compressor with three stages of expansion coupled with a one-stage compression is shown. All pistons are double acting. The expander (1) and the compressor (2) cylinders are arranged in a way to obtain minimum internal temperature differences. The warm side of the machine is on the right, the cold side on the left. To control the charging and discharging an auxiliary (4) and a main (5) sleeve valve are being used with a throttle valve (6) in between.

2. SUB-CRITICAL OPERATION

It should be the goal of the system and machine designer to obtain the lowest annual power consumption. Therefore with air cooled refrigerators he has to take into account, how the ambient air temperature varies during the year (Figure 3) and how the needed refrigeration rate depends on the ambient temperature.

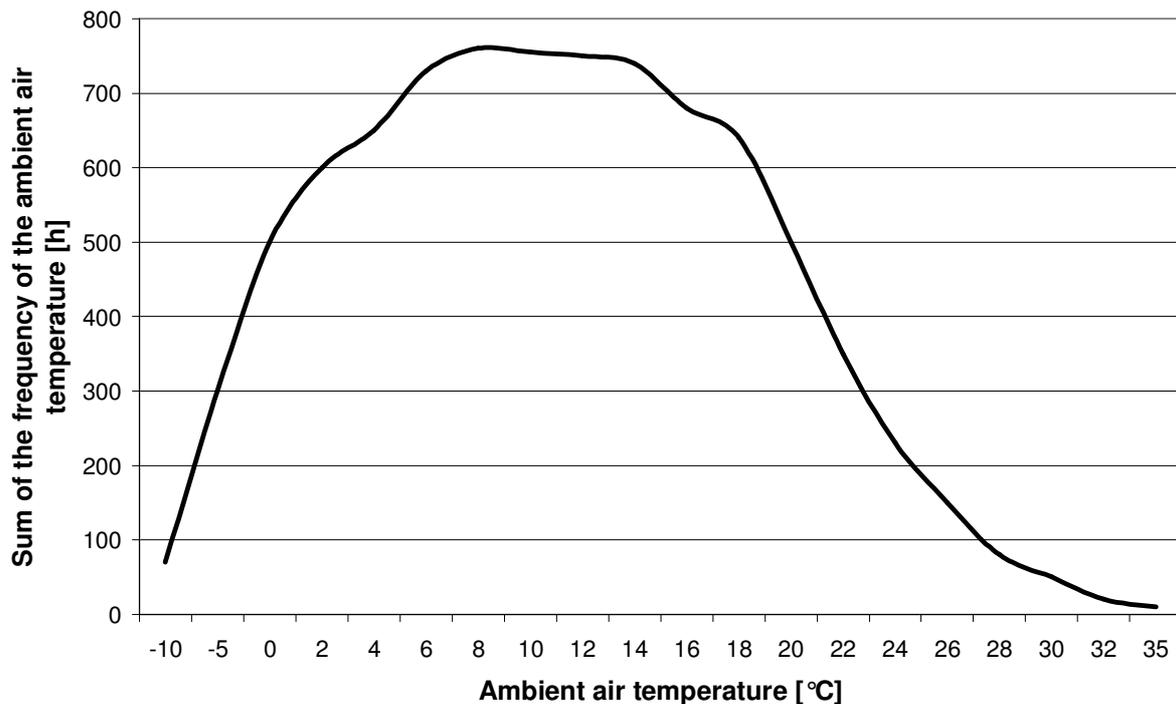


Figure 3: Distribution of the ambient air temperature in Central Europe (Haaf et al., 2004)

So in Central Europe, CO₂ refrigerators will operate most part of the year in the sub-critical mode. The introduction of the expander was originally motivated to improve the COP in the trans-critical operation. But once the investment for the expander has been made, the owner of the system expects of course also some benefit during the sub-critical operation periods. But, as it turns out, this requirement means for the expander working conditions, which are quite different from the trans-critical operating conditions.

While the throughput through the expander/compressor can be varied by changing the speed, the relative volumes of the compressor cylinder and the first stage expander cylinder are fixed once a machine is built. So the volumetric ratio (v_5 / v_3) in stationary operation for the expander/compressor is fixed, if the mass flow rates are identical in both parts of the machine. Figure 4 shows the absolute values of v_3 and v_5 in function of the gas cooler outlet temperature and the associated optimum high pressure level. One sees that above about 32 °C, i. e. in all supercritical conditions the ratio between v_5 and v_3 is about constant. But below 32 °C the ratio becomes smaller: The liquid stream, which has to be expanded, becomes smaller and the vapour stream, which has to be compressed in the second stage becomes larger, the lower the temperature level gets.

This means that in the flow diagram designed for the trans-critical operation (Figure 1), the expander will in sub-critical operation not be able to assist in the compression of the main stream. One has to look for a new scheme for the sub-critical operation (Riha et al., 2005 and 2006).

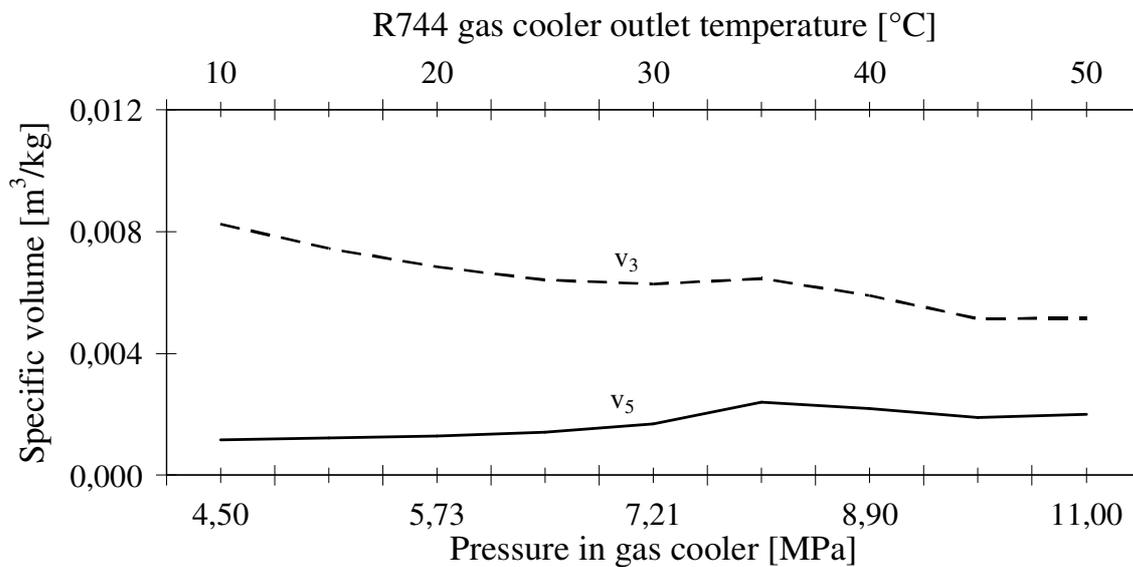
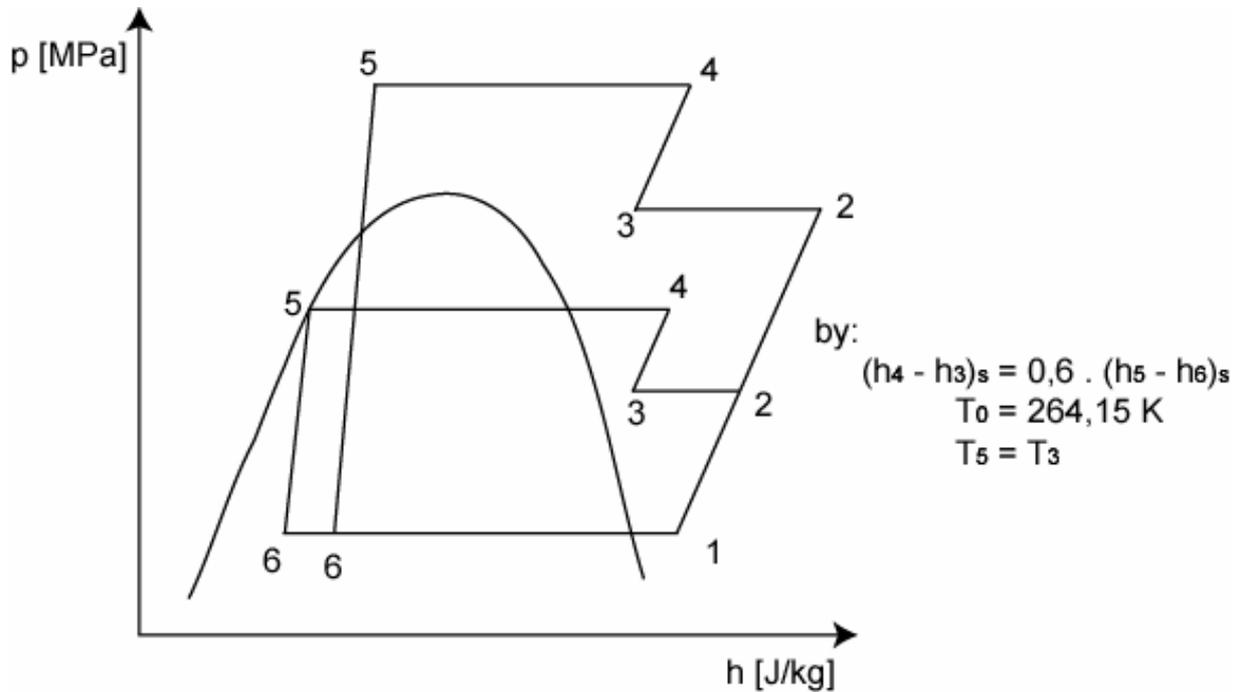


Figure 4: Specific volume in points 3 and 5 of the refrigeration cycle depending on the gas cooler outlet temperature and the associated optimum high pressure level

2.1 The new cycle

If the geometry of the machine is fixed and the built-in volume ratio of the expander and compressor cylinders can not be changed, the only option is to change the mass flow rate through the compressor part of the machine. This can be realised with a bypass line, where a part of the CO₂ flow is throttled in an expansion valve from the high to the middle pressure (Figure 5)

This side stream is also used to reduce the enthalpy of the main portion of the high pressure CO₂ stream, which flows to the expander, in an internal heat exchanger.

This cycle provides an additional degree of the freedom in the construction of the expander/compressor. It is possible to fit the geometry of the machine for the most important operating regime. The diameter of the compression cylinder of the expander/compressor can be chosen, so that the machine starts to compress above a selected condensation temperature, e. g. 10 °C. Above this selected condensation temperature the expander will bring a COP improvement. Below this chosen temperature, the expander will function as a simple throttle valve. The higher the condensation temperature gets, the more the bypass throttle valve has to be opened, but simultaneously the contribution of the expander/compressor will become more and more effective. Since the enthalpy at the outlet of the expander at point 10 in Figure 5 is being reduced by the functioning of the internal heat exchanger IHX, the expander/compressor provides also an increase in the refrigeration capacity of the main compressor.

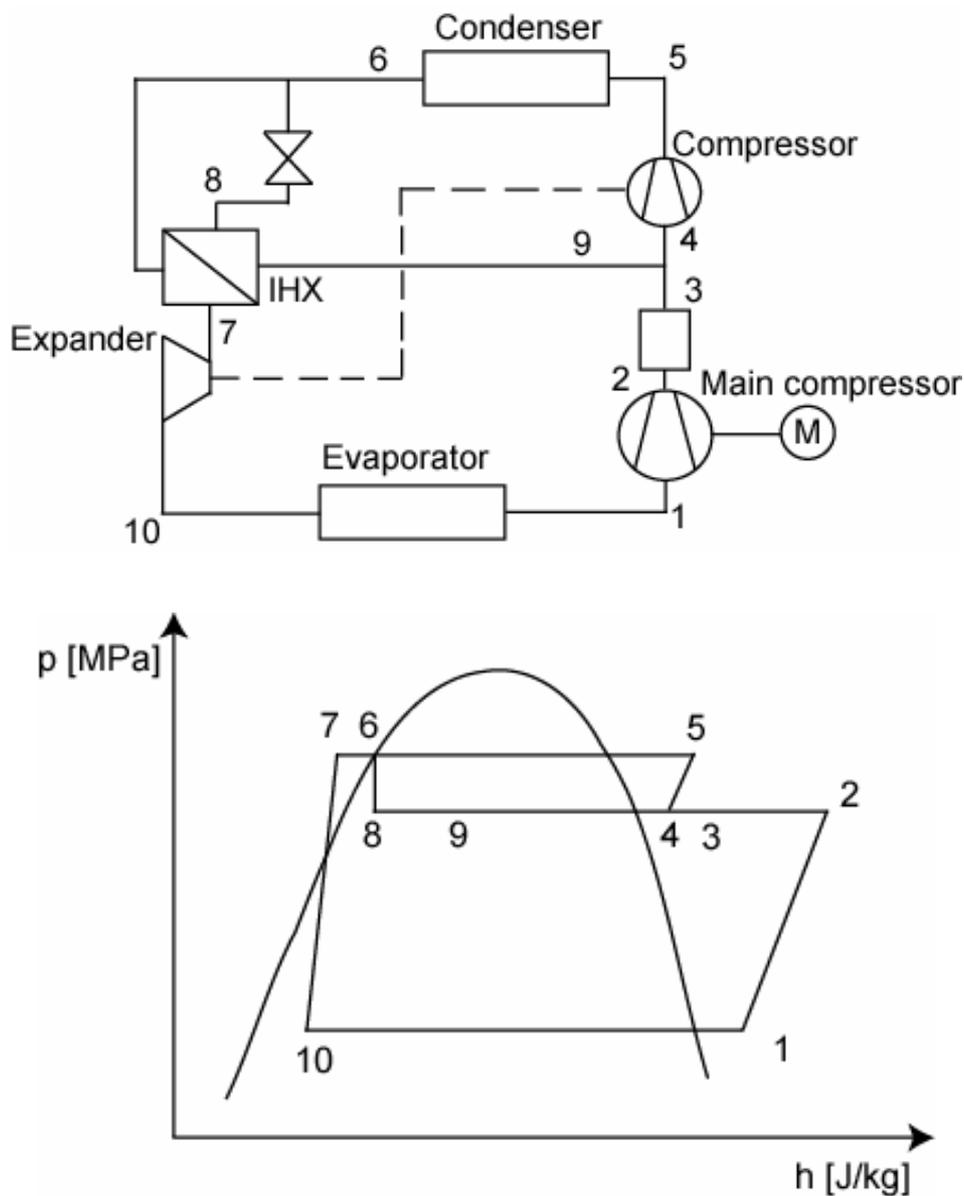


Figure 5: The cooling cycle in p-h diagram and his construction

3. PERFORMANCE OF THE COOLING CYCLE

To demonstrate the influence of the expander/compressor on the COP of the cooling cycle we have chosen the comparison between different cycles. Figure 6 shows four cycles and the inverse of the COP, i. e. the power consumption per unit refrigeration, in function of the outlet temperature of the CO₂ from the gas cooler/condenser. The diagram is valid for an evaporation temperature of -10°C.

Cooling cycle 1 is the standard cycle, of which is known, that is become less competitive at higher ambient temperatures. Cooling cycle 2 with two stages of compression and two-stage throttling brings already a substantial improvement. Cycles 3 and 4 make use of the expander/compressor. Cycle 3 is especially suitable for trans-critical applications. In this range it is superior to all other cycles.

Cooling cycle 4 is suitable and efficient in the whole temperature range and therefore recommended especially for countries with moderate climate. To calculate the COP of all cycles we have assumed an isentropic efficiency of the main compressor of 70%. For the expander/compressor we have used the efficiencies measured in our experimental plant: 80% for the expander and 85% for the auxiliary compressor.

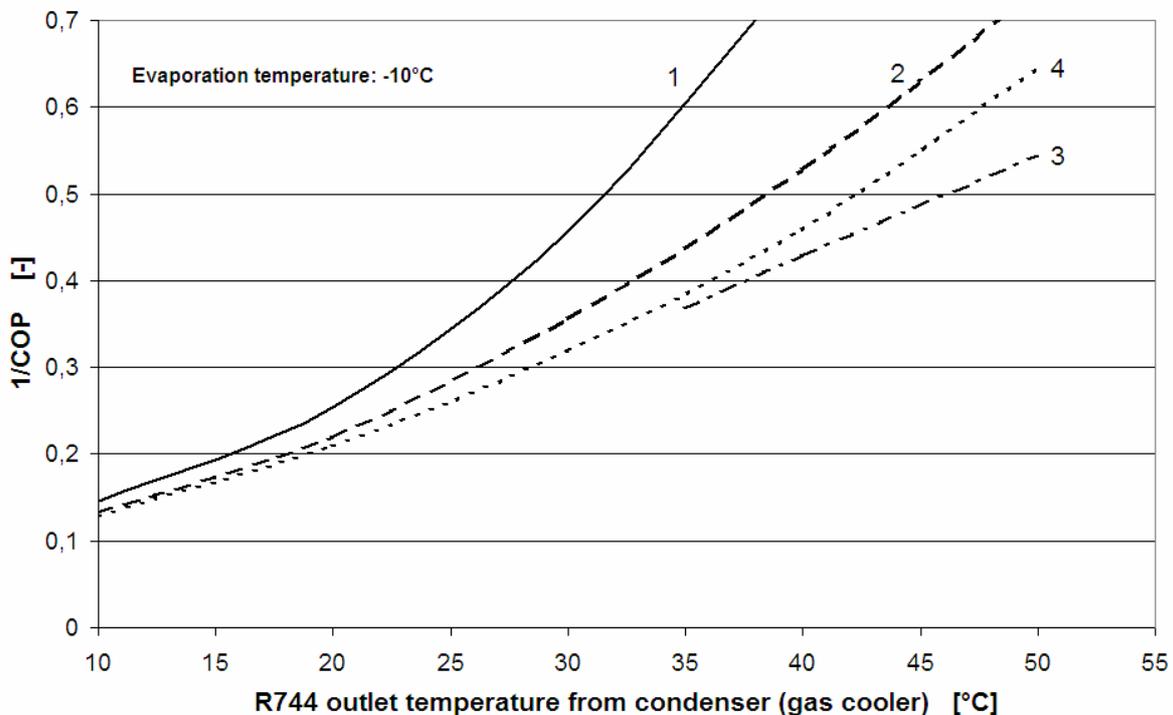
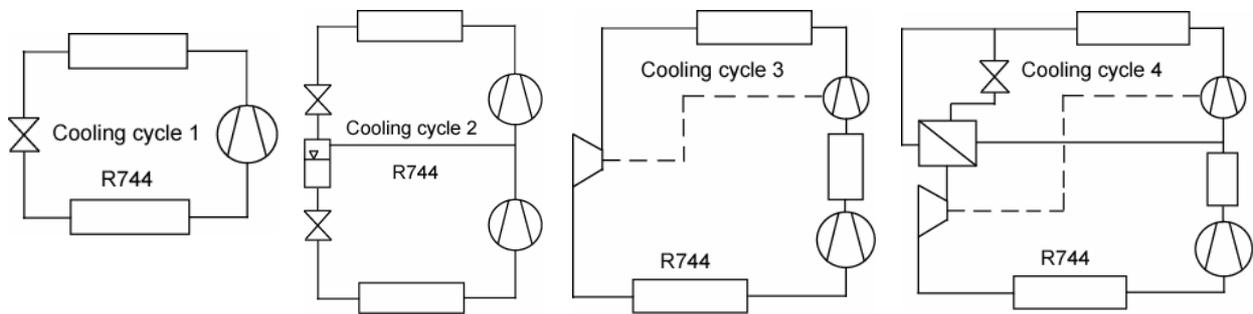


Figure 6: Diagram of the COP comparison of the different types of cooling cycles and different sizes of the diameter of the compression part of the machine

4. CONCLUSIONS

Most refrigerators have to cope with variable ambient conditions, i. e. a large range of condensation temperatures. One general advantage of CO₂ is, that due to the high pressure level, it allows a reduction of the condensation temperature to even 5 °C without disadvantage to the safe and reliable operation of the thermostatic expansion valves.

It was known already in the past, that an expander/compressor can improve the COP of CO₂ refrigeration plants in supercritical operating modes. In this paper we have shown, that there is also a considerable improvement possible, when the ambient temperatures are low. A new cycle is proposed for systems, where the ambient temperature varies widely. It contains a new bypass section around the auxiliary compressor of the expander/compressor. Besides improving the COP it also increases the refrigeration capacity of the main compressor.

The cost of the expander/compressor is estimated to be less than 30% of the associated main compressor. The power saving, which is possible with this addition to the plant, will easily pay for the extra cost, especially when one considers the permanently rising cost of power.

REFERENCES

- Haaf, S., Heinbokel, B., Gernemann, A., 2005, Erste CO₂-Kälteanlage für Normal- und Tiefkühlung in einem Schweizer Hypermarkt, *Kälte & Klimatechnik*, 2/2005, p. 41 – 46.
- Quack, H., 1999, Arbeitsleistende Expansion in Kaltdampf – Kältekreisläufen, *In: DKV-Tagungsbericht 26*, Band I: p. 109 – 123.
- Quack, H., 2000, Cryogenic Expanders, *ICEC 18 – Mumbai*: p. 33 – 40.
- Riha, J., Nickl, J., Quack, H., 2005, Sub-critical operation of the TU Dresden CO₂ Expander/Compressor, XI *European conference on technological innovations in air conditioning and refrigeration industry*, Centro Studi Galileo.
- Riha, J., Nickl, J., Quack, H., 2006, Integration of an Expander/Compressor into a supermarket CO₂ cooling cycle, *7th IIR Gustav Lorentzen Conference on Natural Working Fluids*.