Sub-critical Operation of the TU Dresden CO_2 Expander/Compressor

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1. SUMMARY

The efficiency of trans-critical refrigeration cycles with carbon dioxide as refrigerant can be greatly increased, if the throttle valve is replaced by a work extracting expander, which drives a directly coupled compressor. In Central and Northern Europe, the ambient temperature is during long periods so low, that the condensing pressure of the CO_2 refrigeration system can be kept below 70 bar, i. e. that the cycle can be operated in a sub-critical mode. Once the investment for the expander has been made, one expects of course also some benefit during this sub-critical operation. But for the expander this requirement means quite different working conditions.

2. INTRODUCTION

The primary objectives to use an expander/compressor in a CO_2 refrigeration cycle 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 [1,2]. We started our work to develop expanders for the special application with CO_2 trans-critical refrigeration in 1994. Research is also going on in many other laboratories with different types of expander designs.

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.

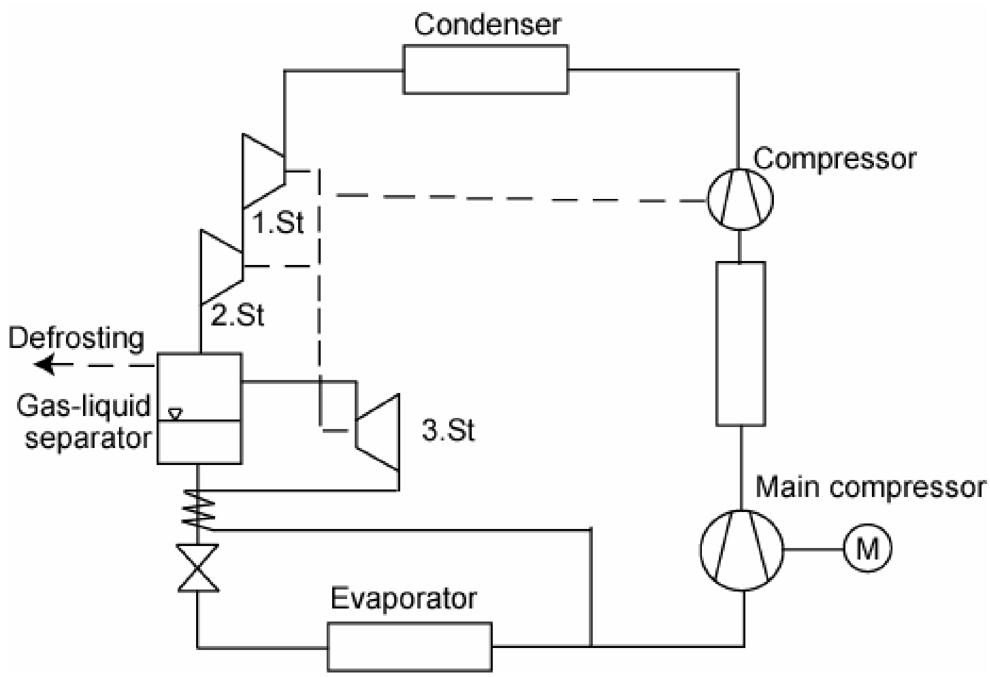


Fig. 1: Cycle with an expander, which drives the second stage of compression

In our work we were 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 favours the flow diagram shown in Fig. 1, where the expander drives the second stage compressor. Thus 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.

Fig. 2 is the drawing of our expander/compressor with three stages of expansion coupled with a one-stage compression. All pistons are double acting. The expander (1) and the compressor (2) cylinders are arranged in a way to obtain minimum internal temperature differences. 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.

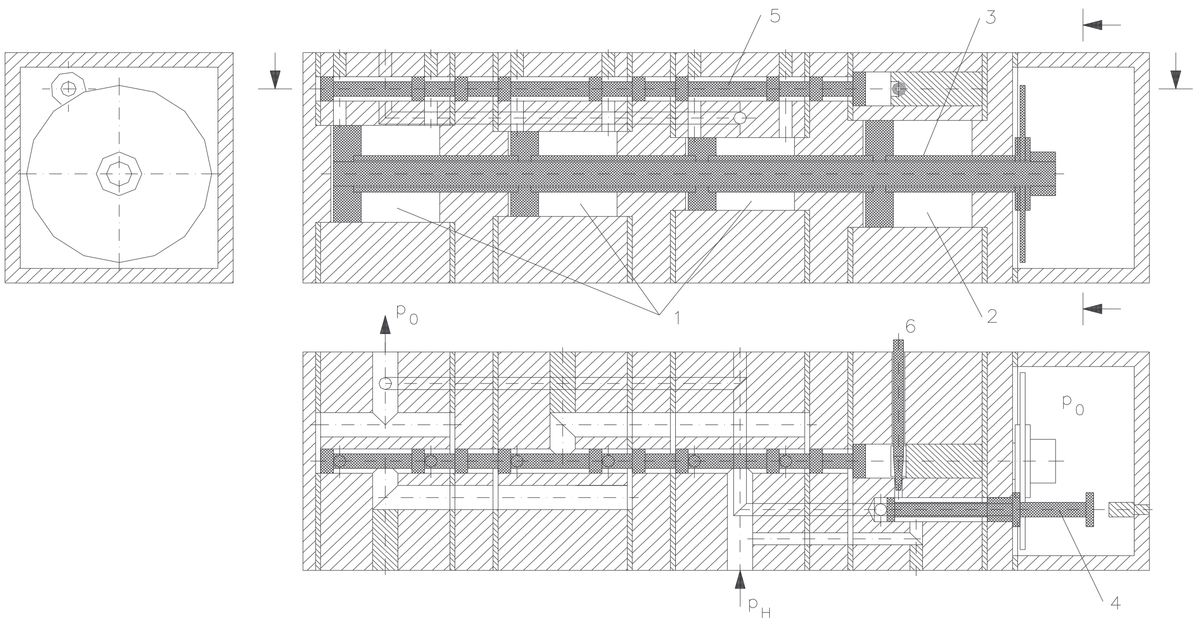
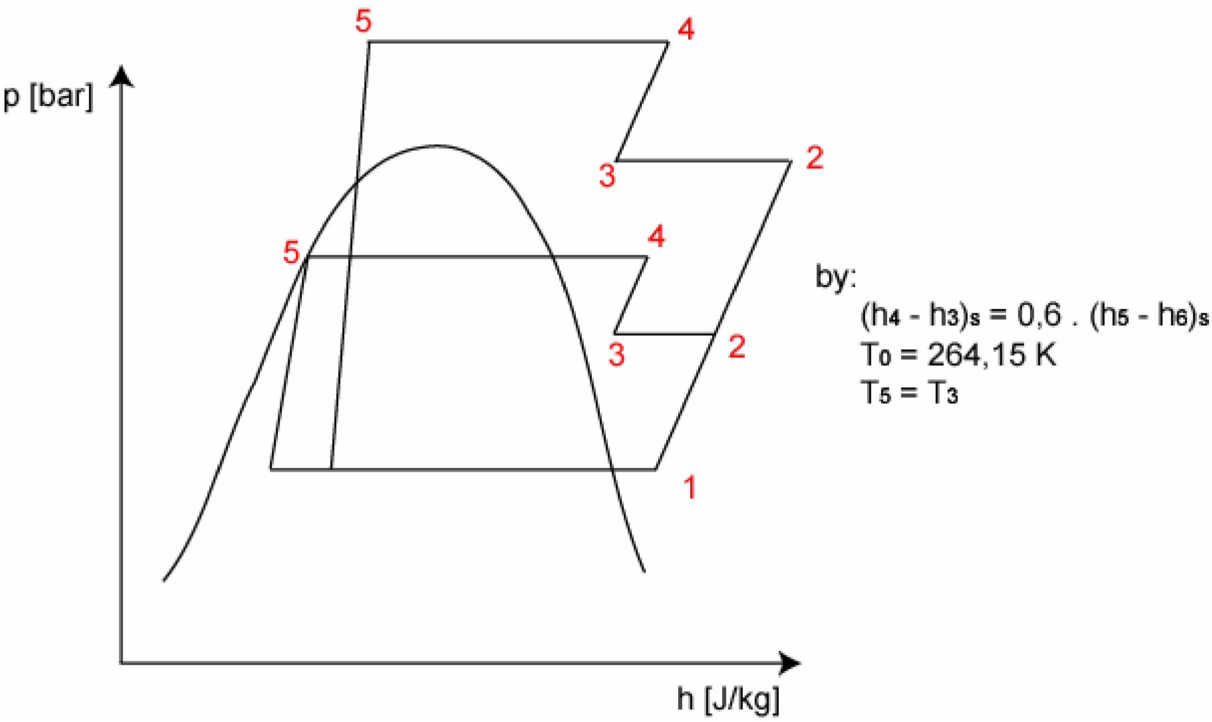


Fig. 2: Expander/compressor with three-stage expansion coupled with a one-stage compression

3. SUB-CRITICAL OPERATING

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 CO_2 refrigeration system can be kept below 70 bar, i. e. that the cycle can be operated in a sub-critical mode. But once the investment for the expander has been made, one expects of course also some benefit during these sub-critical operation periods. But for the expander this requirement means quite different working conditions.



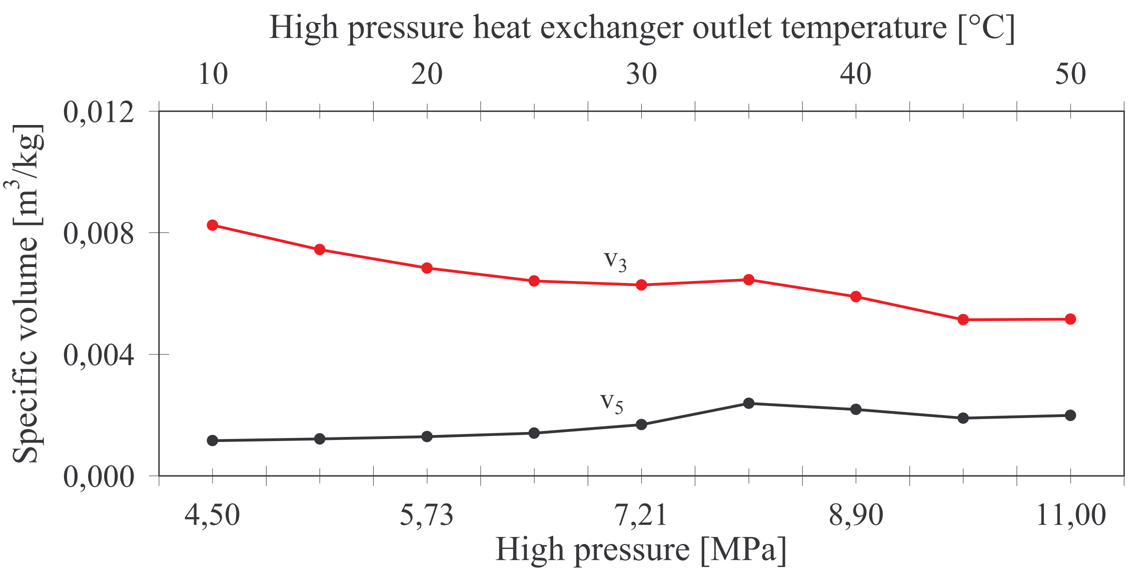


Fig. 3: Specific volume in points 3 and 5 of the refrigeration cycle depending on the high pressure level

The volumetric ratio (v_5 / v_3) in stationary operation for the expander/compressor must be constant, because this value is given by the geometry of the machine. In the Fig. 3 one can see, that in trans-critical operation this requirement is met. But in sub-critical operation the specific volume ratio between points 5 and 3 is going to be smaller. This means that in the flow diagram designed for the trans-critical operation, 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 (see Figs. 4 and 5).

Observations:

- In trans-critical operation the reduction of the exhaust pressure of the main compressor and the intercooling between the two stages of compression were important features. But in sub-critical operation with a maximum pressure below 70 bar, these aspects are not of primary concern. So one could think of parallel operation of the two compressors.
- A vapour-liquid separation at a pressure level about 10 bar above the evaporation pressure is advantageous for several reasons. The TU Dresden three-stage expander is very well suited for this feature, because the separator can be placed between the second and third stage of expansion (see Fig. 1).
- So it could be a solution to use the auxiliary compressor for the compression of the vapour separated at this intermediate pressure level, i. e. to realize the well-known "economizer" scheme. The idea is to split the vapour flow rate in the liquid/vapour separator vessel. One part is further expanded in the third stage of expansion and the other part is compressed by the auxiliary compressor.

For this investigation one has to observe the constraint, that the geometry of the expander/compressor is already fixed from the requirements of the trans-critical operation. But the pressure level of the separator is not absolutely fixed, i. e. it may be moved upwards or downwards by a few bar. (Fig. 4 and 5).

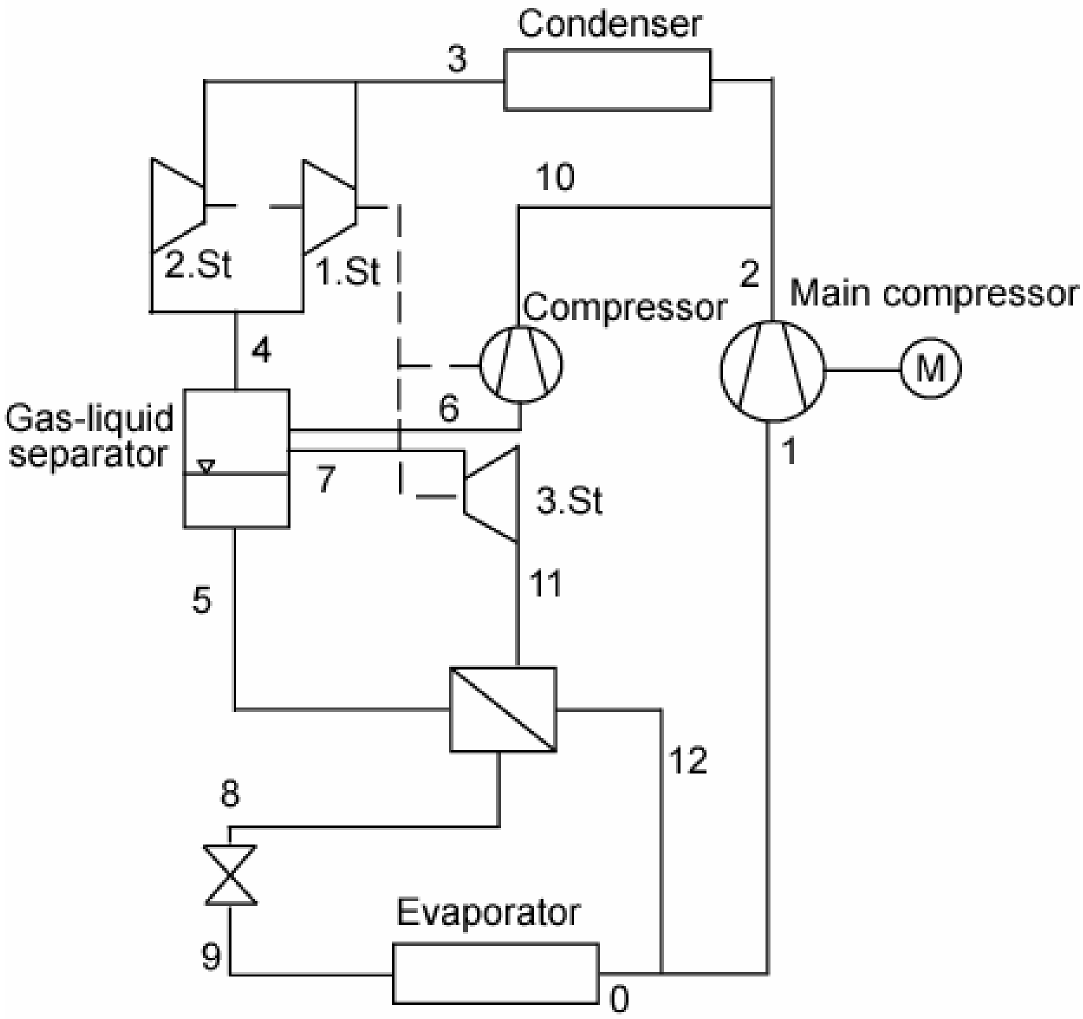


Fig. 4: Schema of the sub-critical operation

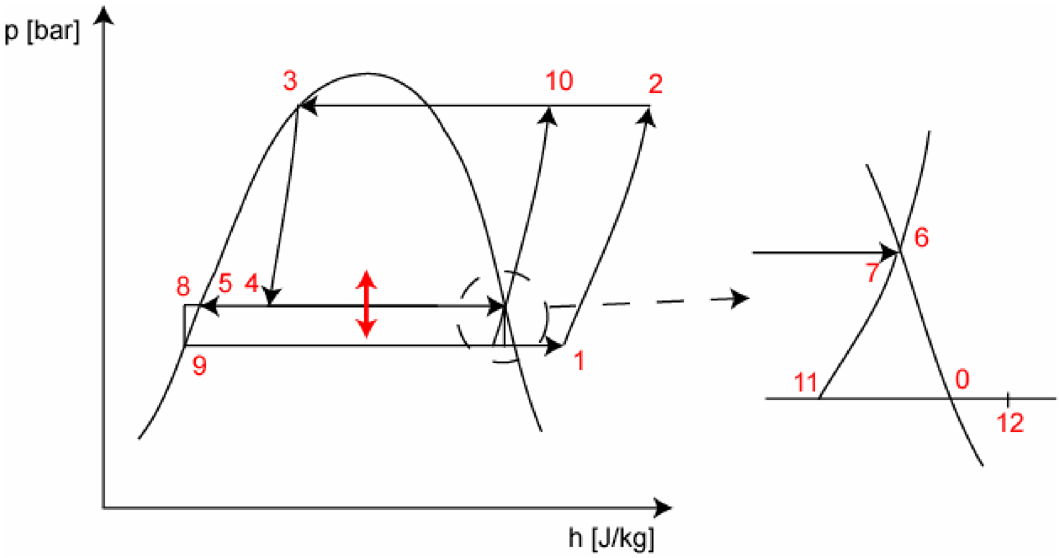


Fig. 5: Sub-critical cycle in p-h diagram

It turned out, that it would be advantageous to use one additional degree of freedom, which the three-stage expander offers: The two first stages of expansion, which are operated in series in trans-critical operation, should be operated in parallel in sub-critical operation.

4. PERFORMANCE OF THE COOLING CYCLE

For the demonstration of the influence on the cooling performance (COP) of the cooling cycle of the expander/compressor we have chosen the hypermarket refrigerator in Switzerland built by the company Linde [3]. In Fig. 6 the comparison of the energetic efficiency of cycles with R404A and CO_2 is presented. We have added to this comparison the data for the operation with an expander/compressor. It is clearly to see, that with this step we can considerably improve the COP of this real application. The operational regions of the trans-critical and sub-critical flow diagrams are overlapping, so it is not necessary to switch often between the two modes.

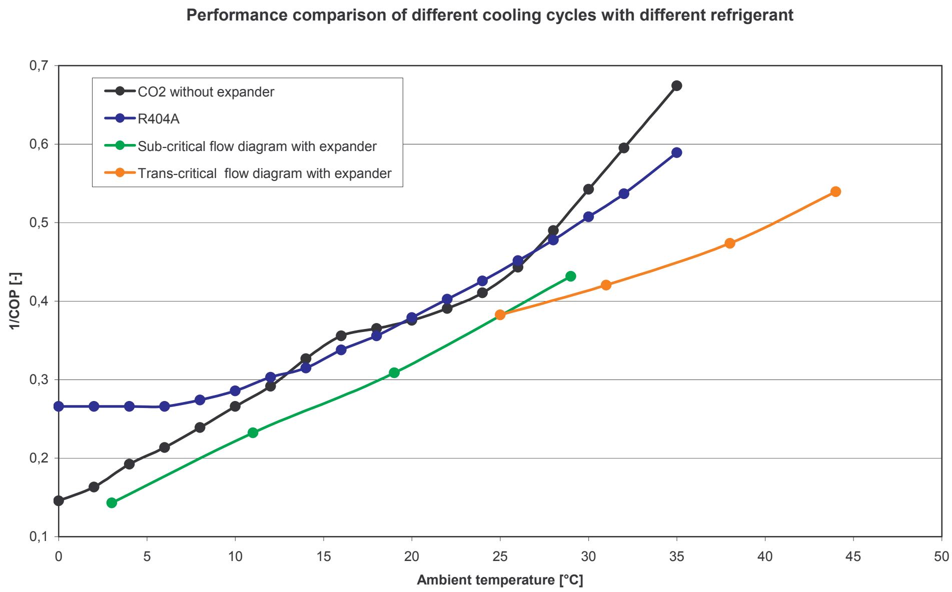


Fig. 6: Diagram of the inverse COP of the hypermarket in Switzerland [3]

5. REFERENCES

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