2-Stage piston compressors with individual cylinder connection

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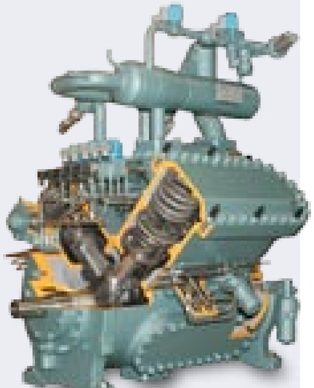
Introduction

This article provides a greater insight into the application of 2-Stage piston compressors to provide the optimum system design for installations in the application range (-15 °C to -55 °C) from the cost point of view of energy, investment and maintenance. 2-Stage operation for piston compressors has become interesting at relatively high evaporating temperatures even within the field of application of single stage operation. The extra capital outlay would result in a means to save money by the smaller energy costs and lower maintenance costs. These advantages are particularly apparent at part-load and at varying conditions.



Opened Grasso 4210 piston compressor with B-cooler

With the natural refrigerant ammonia (R717) the discharge gas temperature is the determining factor. This is caused by isentropic coefficient K of 1.3 (air K = 1.4). Excessive discharge temperatures (> 170 °C) are disadvantageous for the life time of the discharge valves, the quality of the oil and of the refrigerant itself.
With heavy density gases such as R507/404A, with K value 1.1, high discharge gas temperatures are not achieved even at part-load, see figure 2.

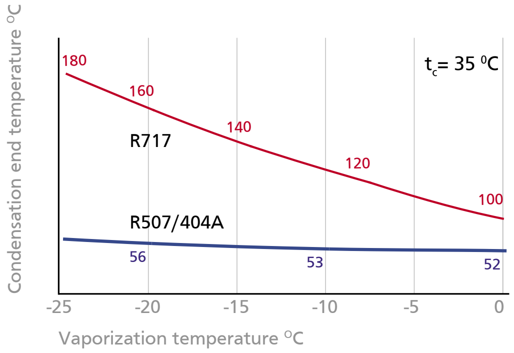


Figure 2

2-Stage compression, when?

In principle there are two main reasons to choose 2-Stage compression:

1. When single stage operation falls outside the permitted field of application.

With synthetic refrigerants the pressure-ratio is the determining factor. "The field of application"- provided by the Grasso selection programme, Comsel, shown in figure 1, provides insight into this. The higher the pressure ratio, the longer the compression stroke, the less open time available for the operation of the discharge valves. Above a certain pressure ratio the open time of the discharge valve ring is too short to allow the complete removal of the compressed gas.

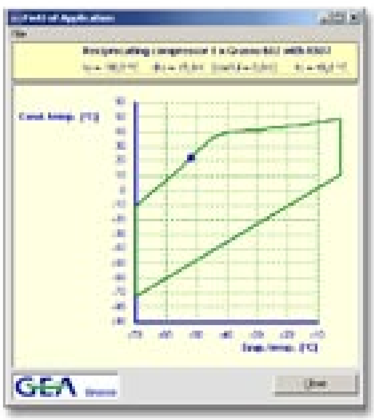


Figure 1

For most cooling processes with the difference between condensing and evaporating temperature (t_c - t_o) less than 45K, high discharge gas temperatures will not be experienced.

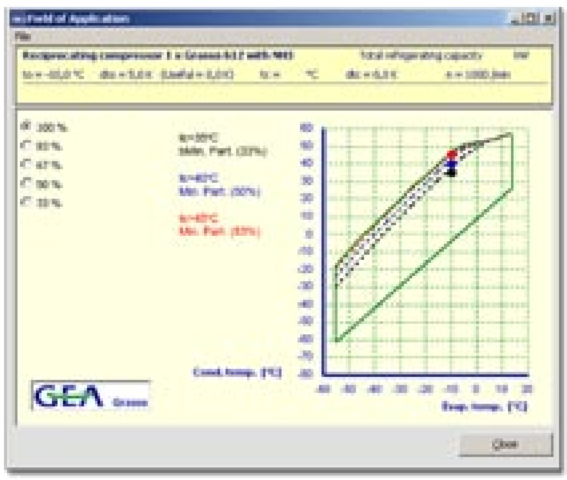


Figure 3

Figure 3 is a representation produced by the Grasso selection programme, Comsel, of a 6 cylinder compressor type Grasso 12, with the refrigerant ammonia at to = -10 °C and three different condensing temperatures of 35 °C, 40 °C and 45 °C.

2-Stage piston compression: what are the advantages?

Beside the K value of the gas the internal machine reheating also plays a large role. Because of this, the field of application is reduced or, in some cases, no longer possible. If part-load operation is needed and if the temperature difference ($t_c - t_o$) increases still further, then consideration must be given to 2-Stage compression.

2. **The second reason for choosing 2-Stage compression is when single-stage efficiency becomes too low.**
The coldfactor, or "coefficient or performance" (C.O.P.), stands for the ratio of cooling capacity to power input (Q_o/P_e). A piston compressor is a "positive displacement compressor" with construction tolerances necessary for production and clearances which are required for functioning. Between the piston and the discharge valve limiter a positive clearance will always be present.

This space is detrimental in that the hot gas trapped therein will expand first during the suction stroke. The higher the pressure ratio, the more gas will be present which will expand later during the suction stroke. The real suction volume flow is, therefore, only a part of the geometric swept volume. The proportion of the real suction volume to swept volume is expressed in the volumetric efficiency. At decreasing evaporation pressures and constant condenser pressure the real suction volume flow will also decrease. The lower gas density and resultant decreased mass flow produces a proportionally greater reduction in the cooling capacity.

The power of compression (P_c) decreases as the evaporating temperature decreases. This is also dependent on the mass flow, which is effected by the pressure ratio, and the exponentially rising discharge gas enthalpy. The friction power (P_w) remains constant. As a result, the actual power ($P_e = P_c + P_w$) decreases much less than the decrease in cooling capacity. Consequently increased pressure ratios give rise to a large decrease in coefficient of performance (Q_o/P_e).

2-Stage compression, How is it produced?
To counter the disadvantages which occur with large pressure differences between P_c and P_o the compression process can be taken in several stages. For normal refrigeration processes two stages are sufficient. Gas is sucked into the low stage cylinders and then compressed. This smaller volume is further compressed by the high stage cylinders, so that it is clear that the swept volume of the low stage cylinders must be larger than that of the high stage cylinders.

Advantages of 2-Stage compression:
- with synthetic refrigerants - increased cooling capacity and efficiency of the compressor.
- with the natural refrigerant ammonia - increased efficiency and the life span of the compressor

Firstly, we look at the impact of 2-Stage compression with synthetic refrigerants, in this case R507/404A.
In industrial installations, beside the natural refrigerant ammonia, R507/404A are most often applied. These refrigerants are considered as typical single stage refrigerants. With synthetic refrigerants the influence of condenser subcooling is enormous. The application of a suction/liquid heat exchanger is highly effective with a capacity increase of approx. 0.5% per degree liquid subcooling. With 2-Stage operation an Interstage cooling system with liquid subcooling is possible which reduces the liquid temperature much further. For example, with Grasso system B, which subcools the liquid to approx. 10K above the intermediate saturated temperature, the increase of the cooling capacity obtained from the same compressor is enormous, as can be seen in figure 4.

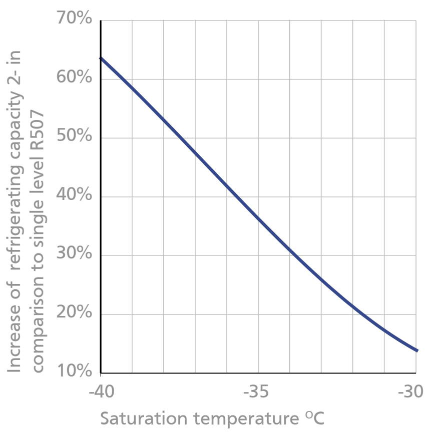


Figure 4

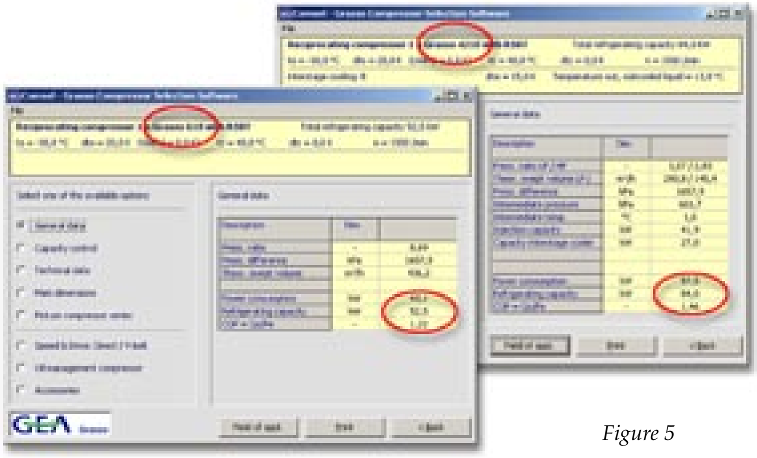


Figure 5

Table 1

t_o (t_c = 35 °C)	Q_o single level kW	Q_o two level kW	$T_{compression}$ in full load single level ´C	$T_{compression}$ two level ´C	Min. part load single level %	Reduction in oil use 2-compared to single level
-13	366	294	135	90	50	25%
-15	330	272	142	93	50	40%
-17	296	252	149	96	67	50%
-19	264	233	157	100	100	70%

The illustrations above (figure 5), taken from the Grasso selection programme, Comsel, refer to a Grasso 10 six cylinder compressor with both single stage and 2 Stage Interstage Cooling System B. (see photograph on page one)

Thanks to the enormous increase in cooling capacity, despite the requirement of an interstage cooling system, a 2-Stage R507/404a package is cheaper than single stage, in both purchase and in running cost. This is shown in graphic format (figure 6) for several different swept volumes.

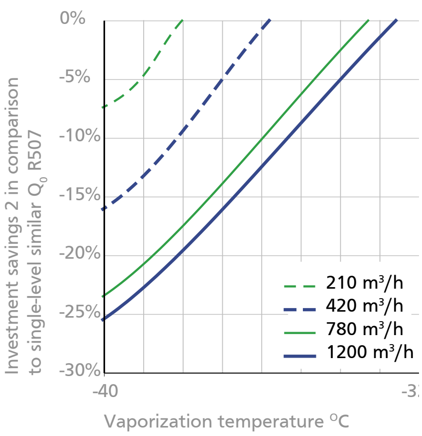


Figure 6

The effect of 2-Stage compression with ammonia remains restricted to reducing the discharge temperature.

As already described, with rising temperature difference Tc-To (actually the pressure ratio P_c/P_o) the discharge gas temperature will increase still further. In table 1 the performance of a 2-Stage 6-cylinder Grasso 12 compressor has been calculated for conditions where single stage operation is still permitted. The C.O.P. is the same for both. However, the cooling capacity decreases by 10-20% for the same swept volume

With single stage operation the individual cylinder temperature will increase still further. Because of this there is a restriction to the minimum capacity. By the application of 2-Stage compression in this area the discharge gas temperature will fall by approx. 50 K. Consequently there is no capacity restriction for 2-Stage and the life span of wearing parts will increase because of this.

Compared to a Single stage machine a 2-Stage compressor, including built-in Interstage cooling system, is approx. 30% more expensive. Taking into account the reduction in cooling capacity then the increase in investment costs rise by approx. 50%. However, it is clear that with the reduced maintenance costs and the improved efficiency these extra investment costs will be quickly recovered.

Ammonia -15 °C to -25 °C
a "gray" area for piston compressors?

To compare the impact of both refrigerants in the same 2-Stage compressor (Grasso 4210, 1470rpm), R507/404A provides approx. 10% less cooling capacity than ammonia but requires approx. 45% more energy! (see table 2)

Table 2

t_o (t_c= 35 °C)	Q_o R717 kW	Q_o R507 kW	COP R717	COP R507/404a
-15	149.1	x	3.21	x
-20	122.3	122.8	2.81	1.95
-25	98.7	104.1	2.43	1.79
-30	79.3	87.4	2.14	1.64
-35	62.5	72.9	1.87	1.49
-40	47.2	59.9	1.58	1.35

x = Outside the application area (pressure in between too high)

Ammonia -15 oC to -25 °C "a grey" area for piston compressors?

The Grasso 2-Stage piston compressors have been designed and constructed for use with the natural refrigerant ammonia in the higher suction pressure range between -15 and -25 °C, an area which is now dominated by screw compressors. Up to a swept volume of approx.. 1800 m³/h this could prove an expensive misunderstanding, an explanation of which is given later.

1. A screw compressor with economizer and variable Vi provides more cooling capacity per suction swept volume, but requires disproportionate more energy. A screw compressor has a higher volumetric output, as a result of which a higher cooling capacity is obtained according to its true constructional swept volume. However, the isentropic output of a screw compressor is lower than that of a piston compressor and results in a higher energy usage.

2. In part load the relative energy of a screw compressor further increases when compared to that of a piston compressor. In Diagram 7 the graph is based on the same swept volume and at the conditions to/tc = -35/+35 °C.

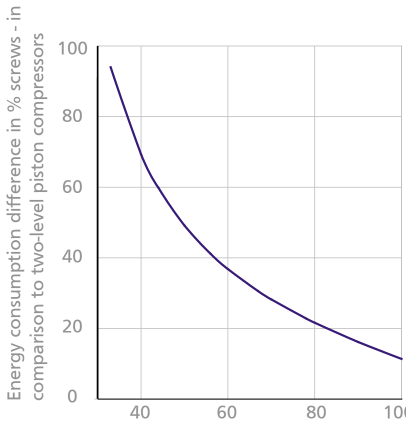


Figure 7

3. The oil usage of a standard 2-Stage piston compressor package (< 4 ppm) is significantly lower than that of standard screw compressor package (approx. 15 ppm). This results in less clogging and therefore a higher output of the installation.

4. The buying price of a screw package with economizer up to a suction swept volume of approx.. 1200 m³/h is 45% higher than a piston package with System B Interstage cooling. Above this swept volume the difference decreases up to approx. 1800 m³/h when several piston units must be installed to meet the duty.

5. The maintenance intervals of a piston compressor are indeed more frequent but the effective costs are much lower.

6. For capacity regulation of a piston compressor a frequency converter is an excellent solution. The investment cost for a frequency converter will be rapidly repaid. This will be commented on more closely in a following article.

Next month we look in more detail to the selection of the correct 2-Stage compressor for the installation and explain the Grasso Interstage cooling System B. Should you have comments regarding the coming article, or observations concerning this one then can you get in touch with:

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