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INTEGRALLY GEARED COMPRESSORS FOR SUPERCRITICAL CO2

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ABSTRACT

This paper is giving an overview of advanced and proven technologies for CO2 compression. These include reciprocating and centrifugal compression - with focus on modern integrally geared designs for CO2 applications. A short overview about the processes that require high-pressure CO2, Enhanced Oil Recovery (EOR), Carbon Capture & Storage (CCS) and Coal Gasification (IGCC, Oxyfuel), will be given. Traditional and advanced compression technologies will be compared and benefits of integrally geared compressors will be discussed. Design challenges concerning thermodynamical and mechanical design will be pointed out with special regard to topics arising when compressing CO2 in the supercritical region. These topics include the pronounced real gas behavior of supercritical CO2 and the close-coupled design process of integrally geared compressors.

INTRODUCTION

CO2 has a long tradition in modern industrial processes and furthermore plays an increasing role in the present discussion of the world wide climate change. It is used in refinery, chemical and food industry applications as well as for fire extinguishers or as a solvent. Today many industrial processes require CO2 not in a gaseous but in a compressed state at a specific pressure and temperature.

The traditional approach for compressing CO2 is by using high-speed reciprocating compressors. Nevertheless this technology is limited in several ways – e.g. the flow capacity has strong restrictions due to the mechanical design.

For this reason centrifugal type compressor systems are now state of the art and a promising solution for future CO2 projects. Centrifugal compressors generally can be split into two major types which are distinguished by their design namely single-shaft (inline, between bearings) centrifugals and multi-shaft integrally geared centrifugals. This paper will focus mainly on integrally geared centrifugal compressors.

MAN Diesel & Turbo has manufactured reciprocating compressors in the past and still is manufacturing both types of centrifugal technologies (inline and integrally geared type, according to API 617 as stated by MACEYKA, PICKEREL (2007)) for CO2-services. We therefore feel confident and in a position to give a comprehensive overview and comparison of all technologies.

OVERVIEW OF CO2 RELATED APPLICATIONS AND PROCESSES

Before we step into compression technology some explanations concerning CCS and EOR are given:

Carbon Capture and Storage (CCS)

A steeply rising demand for energy world-wide, combined with increasingly strict environmental regulations have created the need for new technologies for the clean and sustainable generation of power. Carbon Capture and Storage labels a group of technologies which all have one aim: To separate carbon dioxide in the process of conventional thermal power generation.

Whether the method by which CO2 is separated is IGCC, Oxyfuel or Post-Combustion: Every one of these processes requires the compression of CO2 for transport and storage for future use. The process paths of different approaches can be seen in Figure 1.

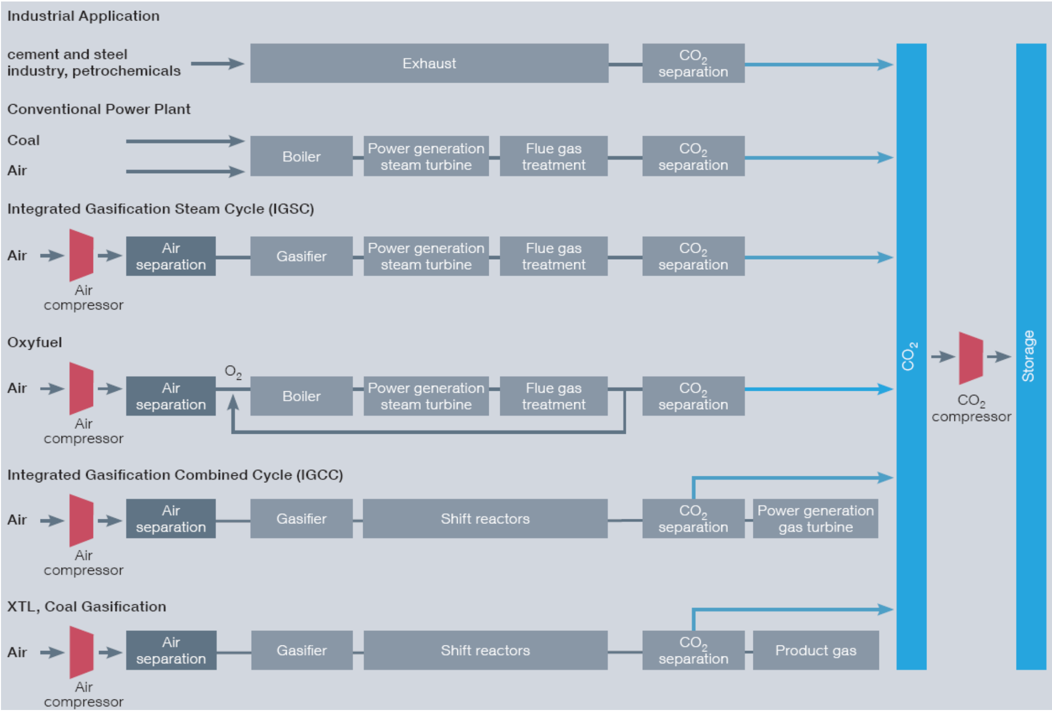

Figure 1: General process overview

CO2 Separation/Gasification

Before CO2 can be compressed for storage and EOR applications it has to be separated. This happens in different processes, which are briefly explained below.

Oxyfuel:

The combustion of fossil fuels with almost pure oxygen is an effective method for CO2 capture. The concentration of the CO2 in the exhaust gas is about five times higher than produced when combusting with air. The lighter and the heavier gas components are separated from the CO2 stream in different stages of a cryogenic purification process.

Pre-Combustion:

Integrated Gasification Combined Cycle (IGCC) converts fossil fuels such as coal to synthetic gas at elevated pressures. After the conversion of carbon monoxide to carbon dioxide in shift reactors, the CO2 can be separated from the syngas. Due to the elevated partial pressure of the CO2 in the gas stream, this is mainly achieved by absorption processes employing physical solvents. The captured CO2 can then be released from the solvent by simple depressurization.

Post-Combustion:

In post-combustion CO2 capture, the exhaust gas of a conventional power plant or other processes in which fuel is burned at atmospheric pressure is treated with a chemical solvent to dissolve the carbon dioxide. The CO2 is then released by thermal regeneration of the solvent.

CO2 Storage

If there is no economically feasible use for the separated carbon dioxide, it needs to be safely removed to avoid negative environmental impact. The safest option is to store CO2 underground. The gas is compressed to a supercritical fluid state and passed into deep geological formations. Different physical and chemical mechanisms prevent it from moving back into the atmosphere: Usually, an impermeable layer of rock provides a natural seal for the gas. Additionally, the CO2 can dissolve in existing water reservoirs or react with minerals to firm immobilized carbonate binds.

Enhanced oil and gas recovery (EOR, EGR)

Enhanced Oil Recovery (EOR) techniques are applied when the amount of oil in a field has decreased to a level where no more can be recovered with conventional extraction methods like water injection. Oil and water do not mix. When water is used to push oil through a reservoir, it leaves a significant residue behind. Instead, flooding with CH4 – gases or CO2 is a significantly more effective method. CO2 and oil mixes above a pressure known as the minimum miscibility pressure (MMP). At or above the MMP, CO2 acts as solvent, cleanly sweeping the reservoir, leaving only very little residue behind. At pressure below the MMP, CO2 also assists oil production by swelling the oil and reducing its viscosity. This technique can also be used in natural gas fields to recover additional gas from exploited fields. The elimination of CO2 from the atmosphere is a welcome side effect. The estimated development of the yield of oil fields with EOR can be seen in Figure 2.

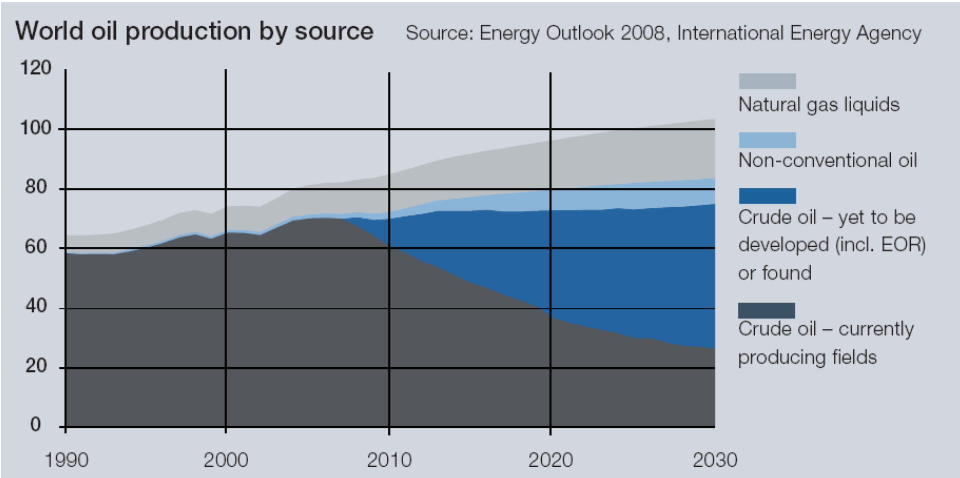

Figure 2: Development of oil yield with EOR

CONVENTIONAL CO2 TECHNOLOGY (RECIPROCATING AND CENTRIFUGAL COMPRESSORS)

or Food Industry, Refineries, Sequestration (CCS) or Enhanced Oil Recovery (EOR), the traditional approach to CO2 compression has been to use high-speed reciprocating compressors. The main reasons for this are:

- Short delivery times, since many manufacturers select from a line-up of frames and cylinders on stock, and can assemble a package in a few months
- Flexibility with regards to pressure ratio, and capacity (if equipped with variable speed drive or valve unloaders)
- Light-weight skid-mounted units can be relocated at will
- Familiarity of the field operators with these machines and their suppliers

A number of factors however favor using centrifugal compressors for such application, see BOVON & HABEL (2007):

- Reciprocating compressors are maintenance intensive
- The capacity of most CO_2 recovery schemes today exceeds the range of reciprocating compressors (max. 12 kg/s)
- The high density of CO_2 may cause problems with high velocities (valves)
- Slow speed recips. require massive foundations - resulting in high capital and operating costs

By comparison, centrifugal compressors offer:

- Higher capacity, up to ~ 100 kg/s is possible
- Superior efficiency
- Oil-free compression
- Higher speed, better matched to the high-speed driver (electric motors or steam turbines) commonly used in the 10-40 MW range
- By design, they are less maintenance-intensive, leading to considerably extended intervals between overhauls

PROVEN INTEGRALLY GEARED TECHNOLOGY FOR CO2 PRJECTS (EOR & CCS)

Within the centrifugal compressor markets, there are still two technologies, namely single-shaft (inline, between bearings) centrifugals and multi-shaft integrally geared centrifugals. It is the author's opinion that for most high flow CO2 applications, the multi-shaft integrally geared design offers undeniable advantages:

Higher pressure ratio per machine (up to ~ 200 is possible depending on the required flow rate) due to:

- Possible use of shrouded or unshrouded impellers
- High circumferential speeds, especially with unshrouded impellers
- Multiple intercooling lowers required compression head, see Figure 4

Higher efficiency, thanks to:

- Optimum impeller flow coefficient, due to the fact that optimum speed can be selected for each pair of impellers, see Figure 3
- Axial in-flow to each stage
- Small hub/tip ratio leading to low inlet mach numbers
- Intercooling possible after each stage (impeller), quasi isothermal compression, see Figure 4.

External connection after each stage gives more flexibility for integrating process equipment

- Process pressure levels can be selected freely with regard to process equipment size and cost
- All kinds of process related equipment can be integrated, e.g. sidestreams, extractions, dryers, reactors
- Since every stage has its own casing no cross contamination of process gases can occur

Small footprint due to

- Pinions arranged around the bullgear, stages arranged on both sides of gear box, see Figure 5
- No separate speed increaser gearbox necessary
- Can be driven directly by electric motor via bullgear or by turbine via integrated drive pinion.
- Intercoolers arranged below compressor

Figure 3 shows a comparison of inline and integrally geared compressors for a compression of CO2 from 1 bara to 150 bara. In the left graph of Figure 3 pressure and speed of the two compressors are shown for each stage and the discharge (labeled stage 9 for the integrally geared compressor and 16 for the inline compressor), in the right graph the volume flow and volume flow coefficients are shown. The inline compressor is comprised of a low-pressure casing with eight stages and a high-pressure casing with seven stages. Each casing features one intercooler with a third intercooler between the casings. A gearbox between the casings increases the speed of the high-pressure casing with respect to the low pressure casing. The integrally geared compressor is an 8-stage machine with six intercoolers.

As can be seen in the left graph the stage pressure rise of the integrally geared compressor is much higher than the inline compressor's. Also shown is the increasing compressor speed after each two stages for the integrally geared compressor and the speed increase between the casings for the inline compressor. In the right graph the decreasing volume flow is clearly visible leading to decreasing volume flow coefficients for the inline compressor. Due to the high compressibility of CO2 after the fifth stage the volume flow coefficients get very unfavorable with respect to stage efficiency. By introducing a speed increasing gearbox between the low-pressure casing and the high-pressure casing this effect can be somewhat mitigated but nevertheless all stages of the high pressure casing feature unfavorable flow coefficients as well. With the integrally geared compressor, however, the volume flow coefficients stay well within the desirable range due to the speed increase after every two stages.

The use of an integrally geared compressor for the compression task mentioned in this example leads to a reduction in power consumption of 18%. One part of this overall reduction is due to the closer approach to an isothermal compression resulting in a necessary head which is 13% smaller than for the inline compressor. The other part of the overall reduction in power consumption is related to the increased stage efficiency due to higher volume flow coefficients.

Figure 4 shows an existing 10-stage compression process (1 bara to 200 bara) realized with the world's first 10-stage integrally geared compressor. The left graph shows the representation of the compression process in the T-s-diagram, the right graph shows selected design parameters. The approach to an isothermal compression by means of multiple intercooling can be clearly seen in the left graph, in the right graph the increasing speed can be seen as well as the decreasing compressibility factor Zs which is limited only by omitting the intercoolers after stages 8 and 9.

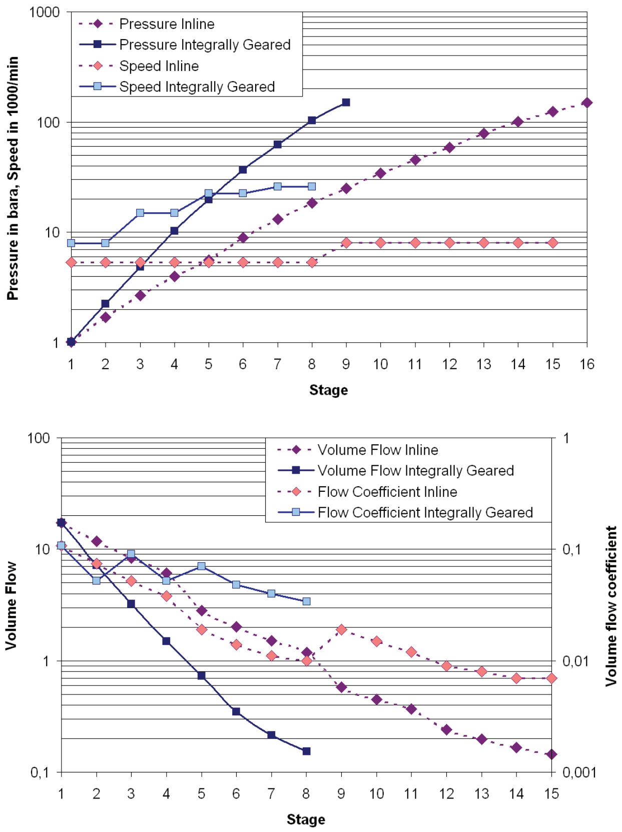

Figure 3: Comparison of inline and integrally geared compressors for CO2-service

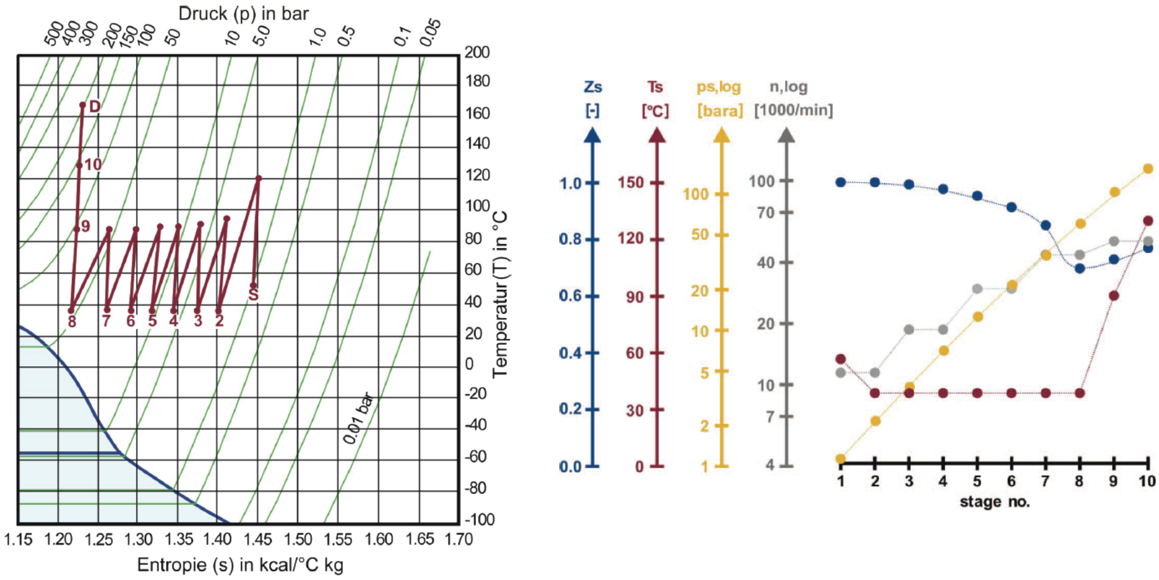

Figure 4: T-s-diagram of 10-stage compression process with intercooling

All the features of integrally geared machines are well-proven and many references exist in various frame sizes, both for the classical markets for integrally geared compressors, e.g. air separation as well as for diverse process gas applications.

- Design is existing for more than 30 years
- Engineered units can be built up to ten stages (five pinions). Unit power range up to 30 MW is commonly used, for instance in air separation plants
- Can be equipped with all the current range of sealing systems
- Integral-gear compressors now recognized by API 617
- Reliability and interval between overhaul considered comparable to inline design

In Figure 5 a typical design of a 4-stage integrally geared compressor is shown. In Figure 6 a typical performance curve of an integrally geared compressor for CO2-service is displayed:

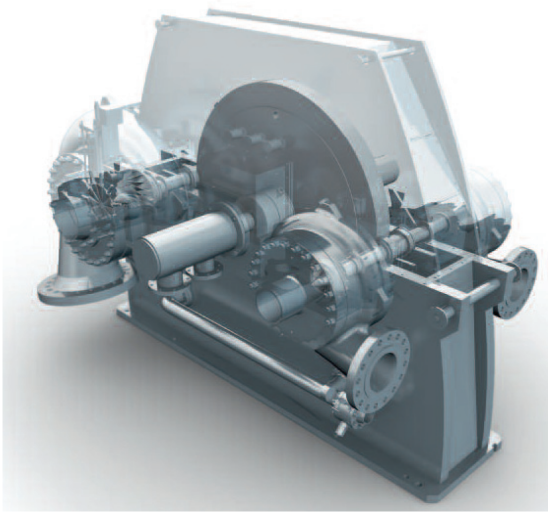
Figure 5: Typical setup of a 4-stage integrally geared compressor

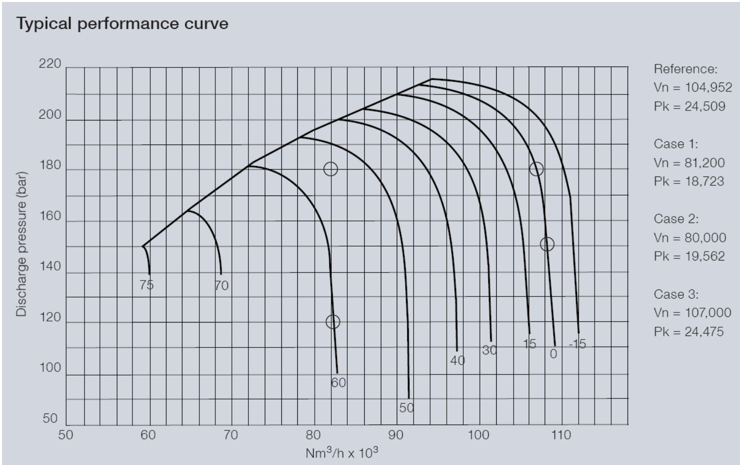

Figure 6: Typical performance curve for an 8-stage integrally geared compressor for CO_2-service

DESIGN CHALLENGES FOR HIGH PRESSURE CO2 COMPRESSION

There are several design challenges for CO2 compression systems which have been successfully mastered by the author's employer. Some of them which are especially important for integrally geared compressors are listed below.

- Very high pressure levels with respect to:
  - Real gas behavior of CO_2
  - High density of supercritical CO_2
  - Rotordynamic behavior
- Compressibility of CO_2, range of impeller diameters and pinion speeds
- Interaction between thermodynamical design and mechanical design

Very High pressure levels:

The use of CO2 for EOR, gas injection is leading to a request of very high pressure levels together with special gas properties.

Real gas behavior of CO_2

The overall compression process is characterized by the non-ideal gas behavior of CO2. Figure 7 shows a T-s-diagram of CO2 with marked pressure lines for 100 and 220 bara. The area above the critical point (light blue circle in Figure 7) is called "supercritical region" or "dense phase" as opposed to "liquid" or "gaseous". In this region the fluid has properties of liquid and gas at the same time. Nevertheless fluids and fluid mixtures can be further compressed in the supercritical region. The integrally geared CO2-compressor described by OLSON, AMMERMANN, HAGE (2004) has a discharge pressure Pd = 187 bara with a suction pressure Ps = 1.1 bara within one 8-stage machine. Knowledge of real gas behavior in the supercritical region is a key factor to designing compressions systems serving discharge pressures above the critical pressure (73.8 bara). As has been shown in Figure 4 especially in the high-pressure stages the compressibility factors can drop considerably, in some cases even below 0.6. To describe the behavior of CO2 or CO2-mixtures in this regime different equations of state may be used. It is the author's experience that the equation of state acc. to Lee-Kessler-Plöcker (LKP) gives a good representation of reality for the operating envelope served today. Extension of the operating envelope may require additional, more detailed insight into the behavior of CO2.

High density of supercritical CO_2

In conjunction with the pronounced real gas behavior of carbon dioxide high densities result due to the high molecular weight. While the high molecular weight enables very high compression ratios with a comparatively low stage count and power consumption, the density has an important influence on rotordynamic behavior and thus stable operation of the compressor. The CO2 compressor operated in the Russian federation is reaching a density of approx. 500 kg/m3 at a discharge pressure of 200 bara, see HABEL & WACKER (2009). Figure 8 shows a comparison of densities between Methane and CO2. It can be seen that the density of CO2 at 140 bara is equal to the density of Methane at app. 700 bara. This poses new challenges in terms of stability as will be addressed in the next paragraph.

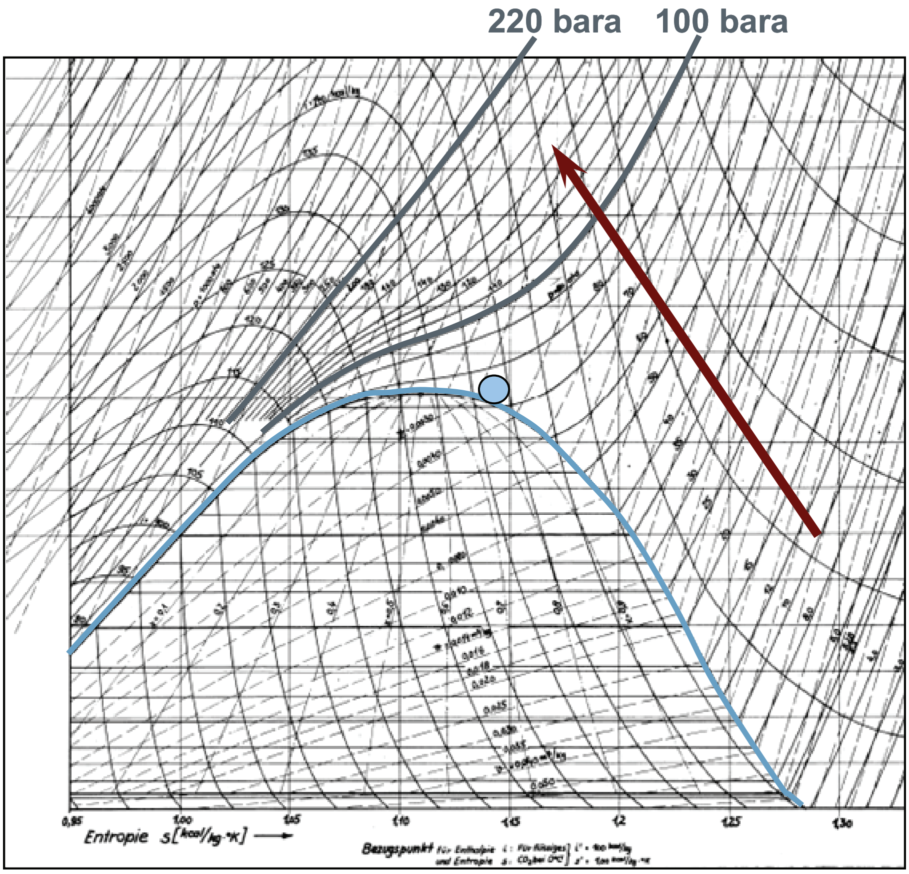

Figure 7: T-s-Diagram for CO_2 with marked pressure lines for 100 bara and 220 bara

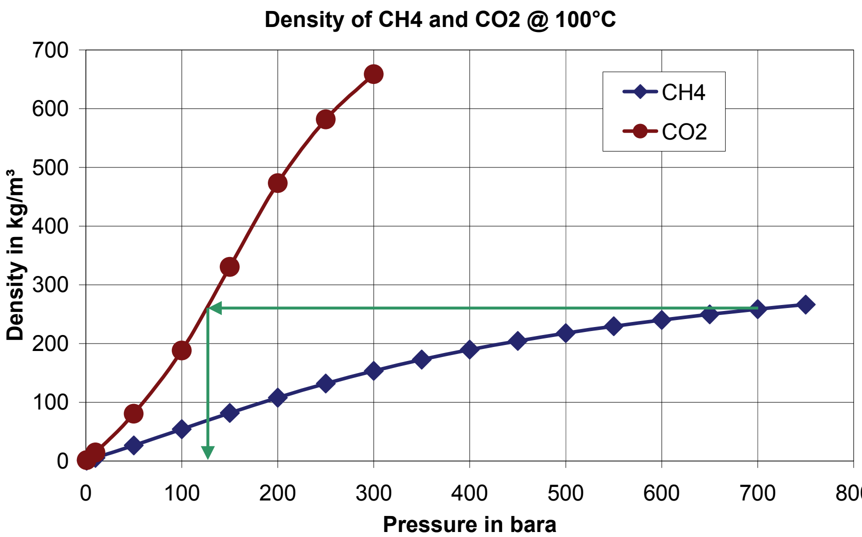

Figure 8: Comparison of densities of CO_2 and Methane

Rotordynamic behavior

For turbo machinery engineers, the rotordynamic behavior and stability is always a challenge especially for high speed, high pressure applications with high gas density. For this reason BAUMANN (1999) has conducted rotordynamic stability tests on high pressure radial inline compressors. He investigated configurations with standard labyrinths, swirl brakes and comb-grooved labyrinths. Based on this work further studies with alternative seal systems have been conducted. In one of them BIDAUT & BAUMANN (2010) improved the design of a high pressure casing with the help of finite element analysis to ensure the rotor dynamic stability of a high pressure centrifugal compressor equipped with a hole pattern seal. Stability measurements during full load full pressure test have been carried out for 390 bar and 655 bar (9500 psi) discharge pressure.

Compressibility of CO2, range of impeller diameters and pinion speeds:

Due to the high compressibility of CO2 a very pronounced reduction in volume occurs in conjunction with the increasing pressure. In the example shown in Figure 3 the suction volume flow of the eighth stage is less than 1% of the suction volume flow of the first stage. Figure 9 shows the line-up of impellers for an 8-stage integrally geared compressor from 1.1 bara to 187 bara. Three of these machines, mentioned by OLSON, AMMERMANN, HAGE (2004) as well as PERRY, ELIASON (2004) are in operation in North Dakota. The impeller size decreases from 840 mm in the first stage to 145 mm in the eighth stage, combined with an increase in rotational speed from 7400 1/min to 26400 1/min. For smaller volume flows MAN Diesel & Turbo's references exist for impeller diameters down to 90 mm and to pinion speeds up to 48000 1/min.

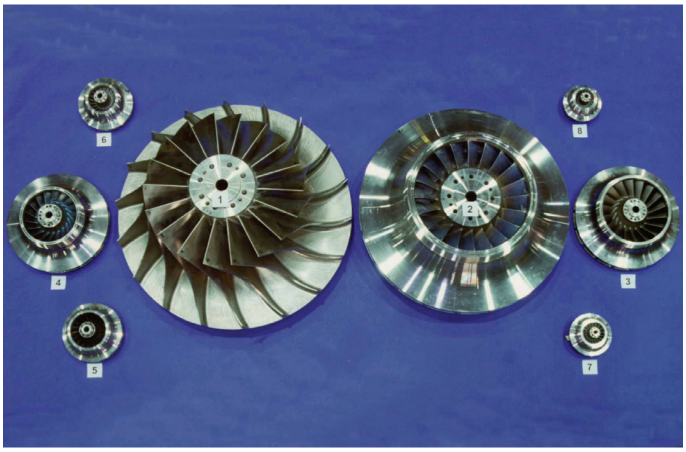

Figure 9: Line-up of impellers of an 8-stage integrally geared compressor for CO_2

Interaction between thermodynamical design and mechanical design:

The power consumed by the impellers on one pinion must be transmitted via the gear mesh. The resulting tangential tooth force has to be taken by the radial journal bearings of each pinion. The capabilities of these bearings are determined by the bearing area (bearing diameter and bearing aspect ratio) and the permissible bearing load. The bearing diameter is limited by the permissible bearing speed and the rotational speed of the respective pinion. This means that the bearing area has to decrease with increasing pinion speed. This in turn leads to a decreasing permissible bearing force and thus to decreasing tooth forces and pinion powers.

The axial thrust generated by the impellers and the helical toothing of the gear has to be taken by the thrust collars which axially position the pinions relative to the bullgear. The thrust collar capabilities are again dependant on the geometry and rotational speeds. Since the axial thrust of the impellers is generated symmetrically to the axis of rotation and the counterforce exerted by the thrust collar is generated with a certain offset to the axis of rotation a resulting torque is created orthogonal to the axis of rotation. This torque has to be taken by the journal bearings in addition to the forces caused by the gear mesh.

The stiffness and damping properties of the hydrodynamic journal bearings change with bearing load. This means that the rotordynamics of the pinions is dependant on the operating point of the compressor. Compliance to applicable industry standards has to be ensured for the specified operating envelope by way of rotordynamic analysis.

In the previous paragraph it has been shown that a large range of pinion speeds must be accommodated in one single gear. Also the high pinion speeds especially for smaller machines call for very high gear ratios. These facts in conjunction with the dependencies mentioned above make it absolutely necessary that the design of integrally geared compressors focuses not only on thermodynamics but is handled as a multidisciplinary process. In-depth knowledge of all involved aspects is a key factor for successful design.

CONCLUSION

In conclusion and based on our experience, for volume flows greater than 12 kg/s and pressures up to 250 bar integrally geared compressors have definite advantages over other compression technologies in most CO2 service. Above 250 bar inline compressors are considered to be state of the art.

- Integrally geared compression is more efficient than other compression technologies
- Inline compressors require approx. twice the number of stages than integral-gear compressors, leading to one or two additional casings
- Integral-gear compressors have comparable maintenance requirements as inline compressors
- Inline barrel type design is better referenced for pressures > 250 bar

Based on the individual project demands a proven, reliable, and cost effective solution for advanced CO_2 compression can be chosen.

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