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CENTRIFUGAL COMPRESSOR DESIGN CHALLENGES FOR CO_2 AND OTHER ACID GAS INJECTION SERVICES

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ABSTRACT

Centrifugal compressors are the preferred compression equipment for its higher reliability. However, when centrifugal compressors are designed to handle high CO_2 and other acid gases such as H_2S, special challenges must be addressed. Some of the key challenges are thermodynamic performance, materials selection, phase changes, hydrate formation, stability, and sealing. This paper presents how centrifugal compressors can be designed to meet these challenges.

[*Keywords*: CO_2 Compressor, Acid Gas Injection, CCS, Reinjection compressor]

INTRODUCTION

Oil and gas reserves contain variable amounts of carbon dioxide (CO_2), hydrogen sulfide (H_2S), nitrogen, and water vapor. Both H_2S and CO_2 are soluble in water and form an acidic solution that is highly corrosive. Since H_2S is also poisonous, it is removed from the natural gas for meeting the pipeline export quality. CO_2 in the natural gas reduces heating value and may present challenges in pipeline export. Therefore acid gases such as H_2S and CO_2 must be removed to meet export quality gas. This is typically done by aqueous amine solution to absorb acid gases [1]. If nitrogen is present in significant amount, it is separated by expensive cryogenic process. In recent years the use of membrane technology, that works on permeating acid gases and water vapor faster than natural gas molecules, is gaining momentum to separate the acid gases [2]. Once acid gases are separated from the natural gas, these must be disposed in a safe manner. H_2S is flared in low concentrations or sent to sulfur recovery. CO_2 with natural gas mixture is vented to the atmosphere, flared, or injected for enhanced oil recovery. With the growing concerns for greenhouse gases and the emissions control requirements, many companies have started exploring the feasibility of acid gas reinjection. Wong et al. [3] discuss the economics of Alberta acid gas reinjection projects relative to sulfur recovery and CO_2 mitigation. IEA estimates current cost of carbon capture and storage in power plants range from \$35-\$80 per tonne of CO_2 [4], which means 2.3 billion metric tons of current annual CO_2 emission in U.S from electricity generation alone will cost \$92 billion for CCS at \$40/TCO_2. CO_2 compression total cost are in the range of \$8-\$14/TCO_2 for power generation [4]. Currently most of the acid gas reinjection occurs in the enhanced oil recovery (EOR), where it is naturally more profitable to inject than to flare. EOR helps in additional 20%-30% oil recovery as acid gases help reduce oil viscosity and can easily permeate through rocks. For reliable and optimum reinjection compressor design, it is important to address several key concerns such as acid gas thermodynamics, materials, sealing, and rotordynamics. All these challenges are better explained by using a 310 bar high-pressure CO_2 reinjection compressor that was recently successfully tested at the author's factory.

NOMENCLATURE

CCS =Carbon Capture and Storage
TCO_2 = Tonne of CO_2
EOR = Enhanced Oil Recovery
LP = Low Pressure
FPSO = Floating Production, Storage and Offloading
NACE = National Association of Corrosion Engineers

RE-INJECTION SERVICE

The reinjection service in current discussion is for a FPSO project where it is required to compress the CO_2 rich hydrocarbon mix gas from 3 bar to 310 bar. A schematic of the compression process used in this oil and gas production is shown in Fig 1. The gas from the primary LP compressor goes through gas treatment and then to CO_2 membrane which separates the mixture of CO_2 and hydrocarbon gases into natural gas rich mixture, and CO_2 rich mixture. The CO_2 rich mixture is then compressed to 310 bar in four sections of compression. It is important to note that the CO_2 rich mixture from the membrane may contain more than 15% of hydrocarbons by volume. The effectiveness of the membrane-based separation improves with the increasing content of CO_2 in the produced gas. Therefore the reinjection gas composition changes both due to variation in produced gas, and due to membrane separation efficiency.

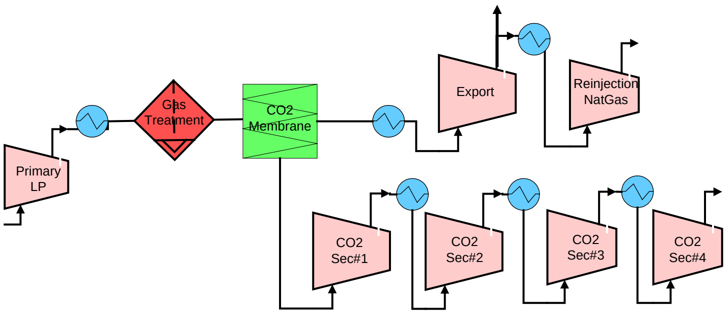

Fig. 1 Compression process for FPSO

Two operating conditions (A, B) based on the varying CO_2 content for the reinjection service are selected to study the effect of changing compositions. Mole weight has the biggest impact on the head requirements for a fixed pressure ratio and fixed inlet temperature compressor. Therefore a hypothetical operating condition (C) is added to demonstrate the effect of mole weight change. These three conditions are shown in Table 1. Since the permeate gas pressure from the membrane governs the suction pressure of the reinjection compressor, the suction pressure is optimized between compressor size and membrane efficiency. It is important to note that at this low suction pressure, any further drop in permeate pressure results in significantly higher compressor inlet volume which can result in bigger compressor frame size.

Table 1. Operating Conditions for 310 bar reinjection

	Cond A	Cond B	Cond C
Mole Weight	39.4	41.4	34.5
% CO2	83%	90%	60%
Psuct (Bar A)	3	3	3
Pdisch(Bar A)	310	310	310
Temp (Deg C)	40	28.3	40
Std Vol Flow (MMsm³/d)	0.5	0.49	0.48

PHASE CHANGES

For safe reliable operation of the compressor, it is important to know the thermodynamic properties of the gas handled in the machine. Centrifugal compressors are designed to run in the single-phase region and multiphase region is avoided. CO_2 has a critical pressure of 73.8 bar and high critical temperature of 31 deg C, and is known to easily form dry ice below a certain pressure and temperature. It is therefore a major concern in designing high-pressure centrifugal compressors, which may be subjected to rapid depressurization. Donnelly and Katz [5] carried out experiments to understand carbon dioxide and methane phase equilibrium. Their phase map for various compositions of CO_2 and methane are shown in Fig 2. As seen in Fig 2, phase envelope for CO2 and methane can vary significantly depending on the amount of methane present. The three-phase locus in figure 2 shows that when CO2-methane mixture is cooled below –70 Deg F, then solid carbon dioxide can form. Since solid carbon dioxide can plug and damage rotating equipment, care must be taken to predict pressure and temperature conditions that may be favorable in formation of CO2 frost. Therefore pumping acid gas hydrocarbon mixture using refrigeration system can be difficult and sub-optimal if the gas composition changes were significant.

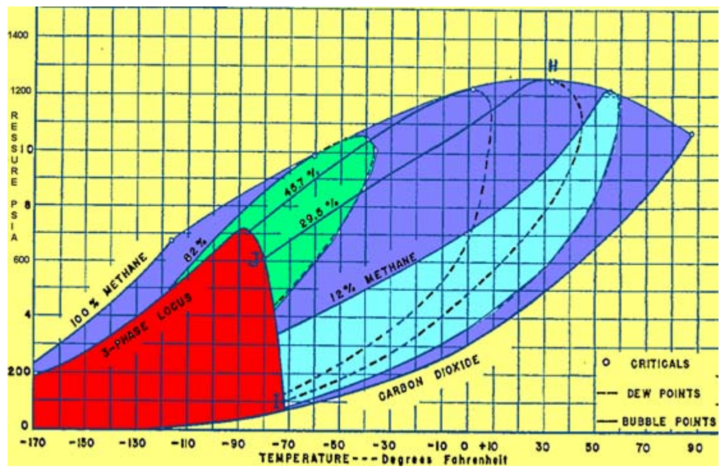

Fig. 2 Phase map of Carbon-dioxide and methane mixtures [4]

HYDRATE FORMATION

Gas hydrates are ice-like crystalline material, which are formed when gas molecules smaller than n-butane react with liquid or free water. Smaller natural gas molecules such as methane, ethane, hydrogen sulfide, and carbon dioxide form more stable hydrates. Hydrates cause partial or complete blocking of flowlines, fouling, plugging, and erosion [1]. Therefore, water vapor must be removed to reduce both the corrosion and the hydrate formations. Hydrates reduce pipeline efficiency. Inter-cooling between the compression section reduces the amount of water present in the injection gas. But it is still important to predict hydrate formation conditions and not to cross the hydrate line. Therefore any J-T effect that can result in crossing the phase map or the hydrate line should be avoided. For the 310 bar reinjection service, phase maps and hydrate lines are plotted for all three conditions A, B, and C as shown in Fig 3. Also plotted are the isenthalpic expansion lines for Cond A discharge pressure at two different temperatures of 194 Deg C and 150 Deg C. These expansion and J-T cooling effect would be representative of the primary seal gas expansion when process gas is used as primary sealing gas. At 150 Deg C, there is a possibility that the seal gas can pass through the mixed phase. Therefore a gas seal heater may be required to maintain a 20 Deg F superheat. However, at 194

Deg C, primary seal gas supply has enough superheat and does not enter the mixed phase region.

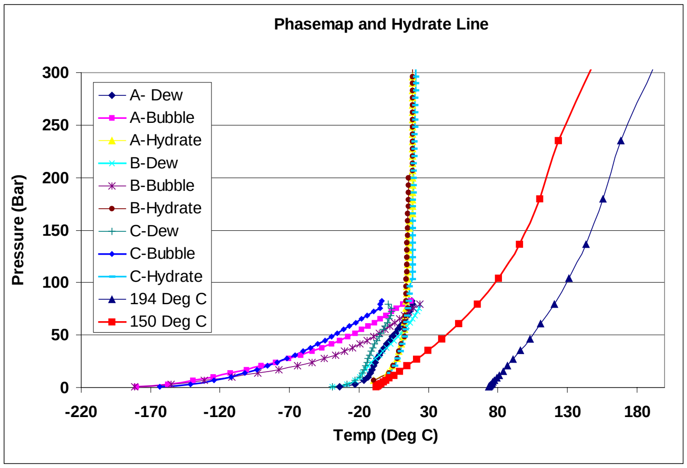

Fig. 3 Phasemap and Hydrate Line prediction for conditions A, B, and C.

The path of the acid gas compression from 3 bar to 310 bar is shown in Fig 4. Note that the compression path avoids the two-phase region and is designed not to run into hydrate formation temperature of 19 deg C and below. The total compression is done in 4 sections and inter-cooling is employed to reduce power consumption.

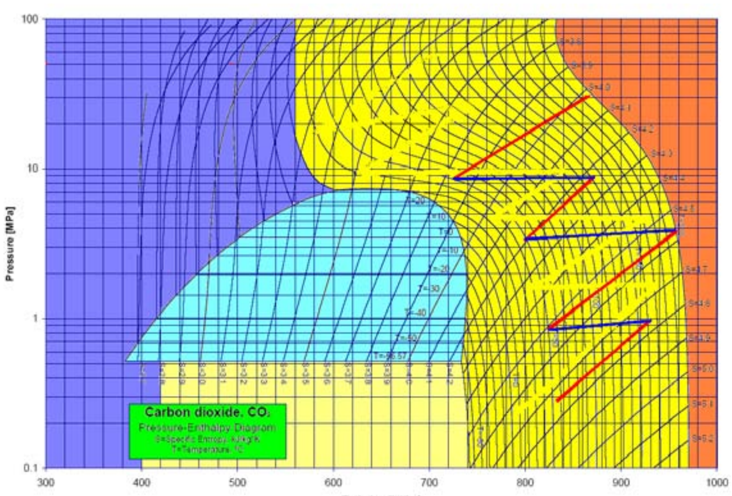

Fig. 4 Path of the CO2 compression

EQUATION OF STATE:

To predict thermodynamic properties of the acid gases, different equations of state (EOS) are used depending upon the gas composition, and pressure & temperature conditions. Peng-Robinson EOS works better in critical region and is preferred for acid gas mixtures. Peng-Robinson EOS is also a good starting point for gas hydrate and CO2-frost predictions. LKP and extended LKP EOS work better in the supercritical region. However, OEMs should always use their own test data from their extensive experience to validate the predictions.

COMPRESSOR PERFORMANCE:

The 310 bar high-pressure reinjection compression is done in two back-to-back inter-cooled compressors driven by a motor. A picture of the bundle assembly of the 310 bar back-to-back high-pressure centrifugal compressor is shown in Fig 5. The center division wall seal is a damper seal (hole pattern seal). The compressor has tilting-pad radial journal bearings in series with squeeze film dampers, a tilting-pad thrust bearing, and dry gas seals. The advantages of using a back-to-back machine for high-pressure re-injection applications have been mainly better thrust balance ability especially at off-design conditions, elimination of a large diameter balance piston results in less leakage, and higher effective damping because of the optimum location of the hole pattern seal.

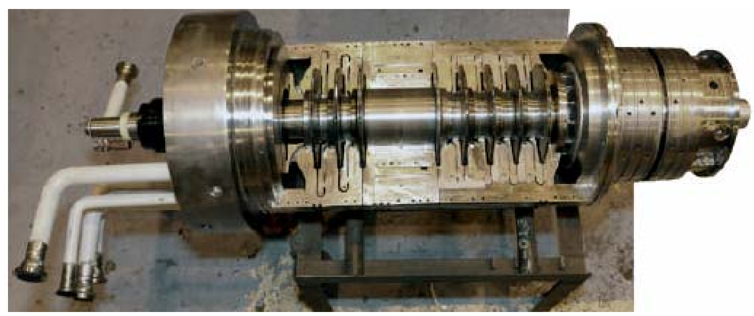

Fig 5 Bundle assembly of the 310 Bar back-to-back compressor

This reinjection compression train is a fixed speed motor driven train. Fixed speed motor driven solution, preferred on FPSOs for lower CAPEX, weight and footprint, is the most economical solution when power and performance are within acceptable numbers. But when gas composition changes are significant, a fixed speed solution can cut operating range and result in higher power consumption. Fixed speed motors also present challenges in compressor start-up. To handle the same pressure ratio requirements with changing mole weight as given in Table 1, the compressor is suction throttled. With suction throttling at low pressure, the first section of the train is most impacted due to volume increase. Fig. 6 shows the polytropic head requirements of the 1st section for the three operating conditions A, B and C when only variable speed configuration is considered. When the low mole weight condition C is introduced, it requires higher polytropic head and thus results in increased speed of the compression train.

The fixed speed suction throttled configuration's polytropic head requirements are also plotted in Fig.6. Suction throttling results in cutting the operating range of conditions A and B when this hypothetical low mole weight condition C fixes the speed of compression train. In this fixed speed configuration, operating conditions A and B will operate close to their overload margin. This is expected since for the same machine speed, the high mole weight case will have a smaller operating range due to mach effect.

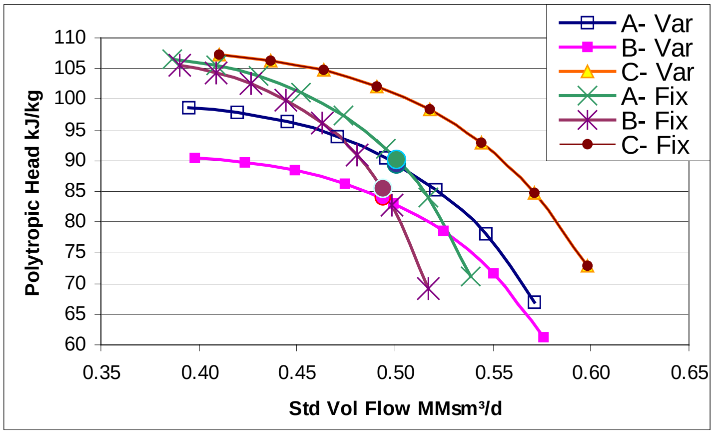

Fig 6 Polytropic head requirements for fixed speed suction throttled

When challenges of handling a wide mole weight swing are considered, the optimal configuration may be variable speed option, and in some cases a combination of both variable speed and suction throttled.

ROTORDYNAMICS

Rotordynamic modeling of this eight-stage, back-to-back, 310 bar high-pressure re-injection compressor is done to determine the stability of the machine. For the complete lateral analysis of this compressor, the following components are modeled: tilt-pad journal bearings in series with squeeze film dampers, hole pattern division wall seal, impeller eye and inter-stage stationary tooth labyrinth seals, second-section gas balance stationary tooth labyrinth seal, and all eight impeller stages.

The traditional industry belief is to associate high density and high pressure with potential instability due to higher aero cross-coupling excitations. However the OEM has extensive test experience that shows that rotordynamic stability improves with increasing pressure, mainly due to the use of hole pattern seals [6]. On the 310 bar CO_2 machine, the OEM carried a magnetic bearing exciter test at full load full pressure Type 1 test to measure log dec, an indication of rotordynamic stability. The results of measured log dec and analytically predicted log dec for the final discharge pressure of 310 bar are shown in Fig 7. Note the measured log dec for the final discharge pressure is very close to the analytically predicted log dec value. Consistent with OEM's prior experience, log dec increased with increased discharge pressure as shown in Fig 7. However, it is important to note that for the same discharge pressure, log dec also increases with increasing density. Analytical predictions of log dec for all three operating conditions A, B, and C are shown in Fig 8. The higher density conditions A and B have higher predicted log dec than the lower density condition C, which has lower predicted log dec. Both minimum and maximum predicted log dec values which occur due to minimum and maximum seal clearances are plotted in Fig 8. Therefore higher density helps in increasing the stability of the machine when hole pattern seal is used. This is a favorable aspect when using centrifugal compressor with a hole pattern seal in CO_2 and H_2S injection services.

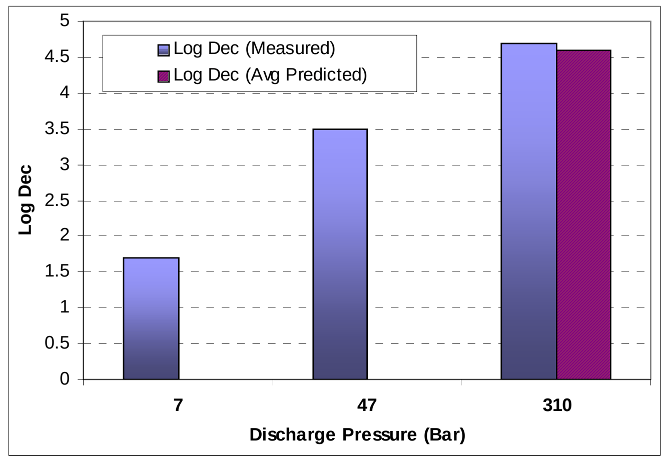

Fig 7 Discharge Pressure vs Log Dec for 310 Bar CO2

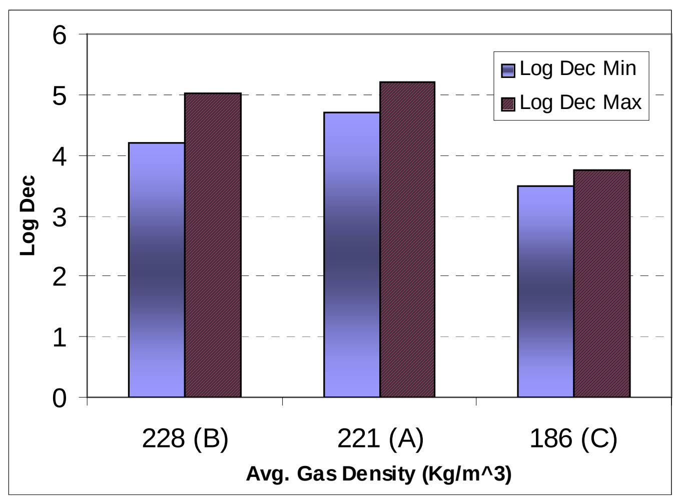

Fig 8 Average Gas Density vs Log Dec for 310 Bar CO2

MATERIALS

Wet CO_2 is highly corrosive and therefore the 1st stage impeller in a compressor section should be considered wet and stainless steel impeller should therefore be used. If the application has considerable amount of H_2S, then NACE criteria should be used to prevent sulfide stress cracking. High CO_2 and water content may require kanigen (catalytic nickel generation) method of electroless nickel alloy plating or stainless steel weld build-up for corrosion protection. Another concern with high CO_2 is the o-ring material. Materials should be selected based on the possibility of explosive decompression. High pressure may drive CO_2 gas to permeate the o-rings and upon quick release of the pressure, o-rings may be permanently damaged. Carbon steel cannot be used for piping and valves, if the gas has free water. Rapid expansion of the gas from 310 bar to near atmospheric condition can also result in very low cryogenic temperatures, and therefore materials for valves should be carefully considered.

SEALING

Dry gas seals in acid gas reinjection service are susceptible to the exposure to multi-phase fluids when acid gas is used as the primary seal gas. Acid gases are polar and thus have higher water retention ability than hydrocarbons. Water retention capability of acid gas increases with increasing temperature and with increasing pressure beyond a specific pressure as shown in Fig 9. Therefore if acid gas is not dehydrated at its optimal temperature and pressure, then the gas may be saturated with water. Upon J-T expansion of the acid gas in the gas seal system, this may result in free water if the acid gas is cooled below its saturation point. This can be avoided by providing sufficient superheat to the sealing gas.

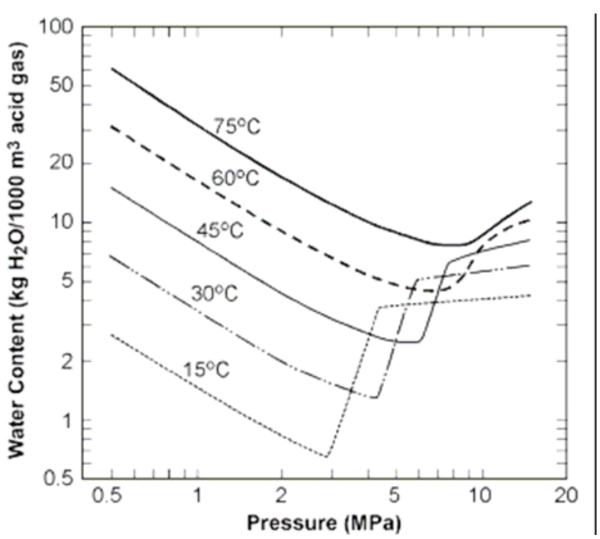

Fig 9 Water retention capability of acid gas as a function of pressure and temperature [2]

Another challenge in the acid gas system is the presence of oxygen, which even at ppm levels can result in the formation of solid elemental sulfur [2] as given in equation (1) and (2).

$$H_2S + 1^1/_2\, O_2 \text{-->} SO_2 + H_20 \qquad (1)$$
$$2H_2S + SO_2 \text{<-->} 3/n\, S_n + 2H_2O \qquad (2)$$

Oxygen in the system may be introduced from nitrogen based buffer gas seal system. Designers should therefore consider the possibility of elemental sulfur formations and reduce the possibility of oxygen entering the system.

SUMMARY, DISCUSSSION, AND CONCLUSIONS

Designing acid gas injection service using centrifugal compression equipment involves several challenges that must be addressed early in the design phase to improve the machine reliability. Apart from aerodynamic and rotordynamic challenges, careful consideration should be given to predicting the two-phase region and the hydrate formation conditions. Wet acid gas injection is highly corrosive and the right materials should be selected for the application. Dynamic simulation should also be considered as part of the design to size and rate the motors, valves, and piping accurately.

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