SECTION 2: COMPRESSORS IN AGI PERFORMANCE – SELECTION – DESIGN – MATERIALS - CONTROL

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Introduction

Acid Gas Injection (AGI) involves disposal of a mixture of different gases with two bulk constituents; carbon dioxide (CO_2) and hydrogen sulfide (H_2S). The ratio of these gases that are present will vary from one facility to another depending on how sour the natural gas entering the processing facility is and how much of the acid gas needs to be removed to make a saleable product or a product that meets downstream treating specifications. Acid gas from natural gas processing facilities is a byproduct stream that:

- Usually has little or no economic value, although there is a growing market for capturing CO_2 that is dependent upon oil, gas, dry ice and other industrial market conditions, government incentives, or corporate initiatives.
- Cannot be vented or flared in large quantities due to environmental regulations.
- Usually is saturated with water from upstream processes and flows out of the vent stack at low temperature and low pressure (typically slightly above atmospheric pressure).

Injecting the acid gas stream into a nearby injection well for permanent underground storage is an attractive means of disposal since it disposes of the entire stream, is not subject to market conditions, does not generate SO_2, H_2SO_4, elemental sulfur, or other sulfur compounds, does not require third parties to come to the facility to remove and transport large quantities of sulfur, and is generally regarded as an environmentally responsible practice.

The heart of the acid gas injection system is the acid gas compressor. Many acid gas injection (AGI) system processes share some similar characteristics:

- The quantity of acid gas to be injected is usually small, i.e. less than 10 MMSCFD.
- The gas is produced by the upstream acid gas removal unit saturated with water at a low pressure, i.e. less than 10 psig.
- The required injection pressure is high, i.e. greater than 1,000 psig.
- Dehydration of acid gas is common with H_2S fractions < 30 vol. % (mol. %), but above 30 vol. % H_2S, the compression and cooling steps are typically sufficient to remove enough water prior to sending the acid gas to the injection well.

These flow rate and suction and discharge pressure characteristics make reciprocating compressors an ideal AGI compression technology, and specifically packaged reciprocating compressors are widely used for AGI throughout the gas treating industry. This section of the fundamentals of AGI will use an example acid gas injection system based on the following conditions:

- Feed flow rate of 6 MMSCFD on a wet basis.
- Gas composition on a dry basis of 95 vol. % CO_2 and 5 vol. % H_2S, saturated with water at the feed pressure and temperature.
- Feed conditions of 10 psig and 120 °F at the compressor package inlet flange.
- Discharge conditions of 2,500 psig at the compressor discharge flange and (assumed nearby) injection wellhead inlet.
- Air cooling of the compressor is required and during summer can cool to 120 °F.

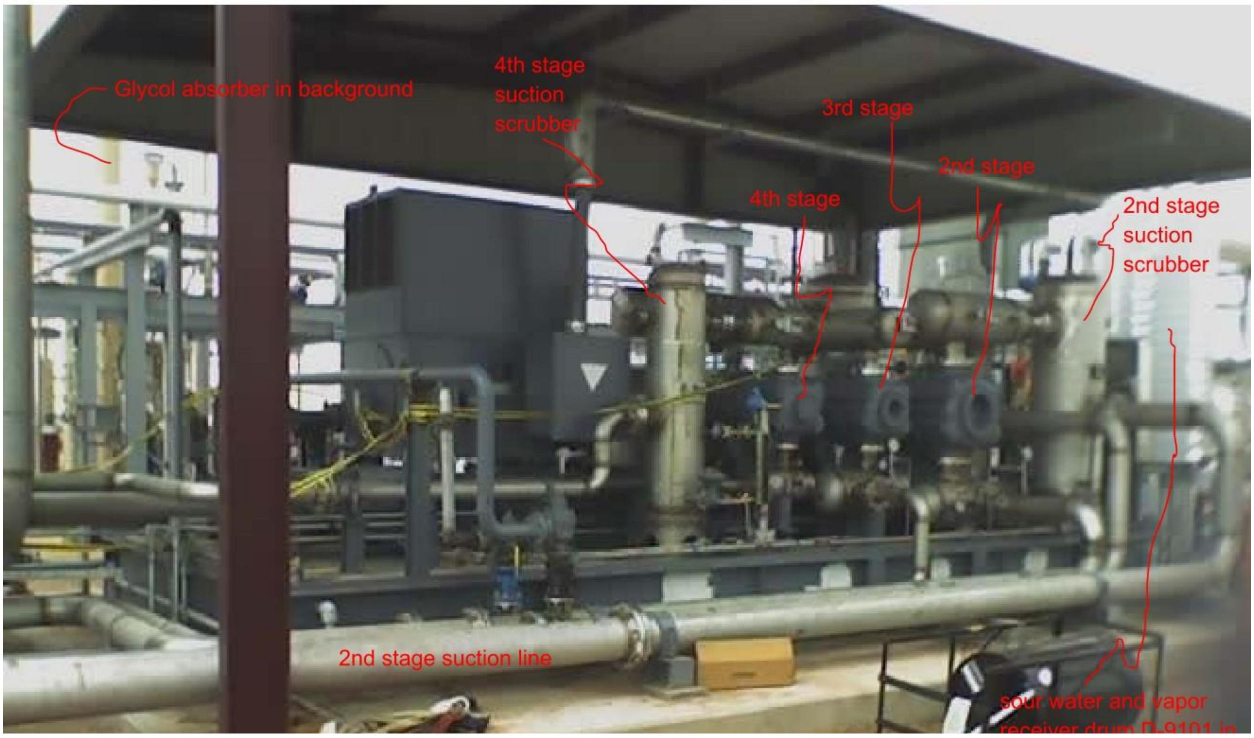
Figure 1 and Figure 2 are photographs taken from AGI Compressor sites that Trimeric designed.

Compressor Performance & Selection Considerations

The previous section of this fundamentals paper dealt with the physical properties of acid gas mixtures and the importance of knowing the properties of the acid gas across the entire range of operating conditions. This is true when specifying an acid gas compressor, especially one that compresses acid gas to a pressure higher than the critical pressure. The critical pressure of a mixture of H_2S and CO_2 falls between the pure component critical pressures as a function of the H_2S fraction. The critical pressure for pure H_2S is 1,300 psia and it is 1,071 psia for pure CO_2. Compressor manufacturers usually maintain their own modeling programs that are either used internally or also made available to external users. As part of the selection process, independent confirmation of the accuracy of the physical property package used to specify and design the compressor is recommended.

Suction and discharge conditions are set by the system designer and need to encompass the entire operating window of the acid gas system. Some important things to consider when defining the suction and discharge conditions include:

1. The entire range of possible acid gas flow rates. The upstream acid gas removal unit may be built to operate on a defined inlet gas specification, but in practice receive gas that has far less acid gas in it than the specification allows. As a result, the total acid gas flow rate may be less than what the acid gas removal unit was designed to remove. A maximum, minimum, and normal flow condition should be provided to the compressor designer.



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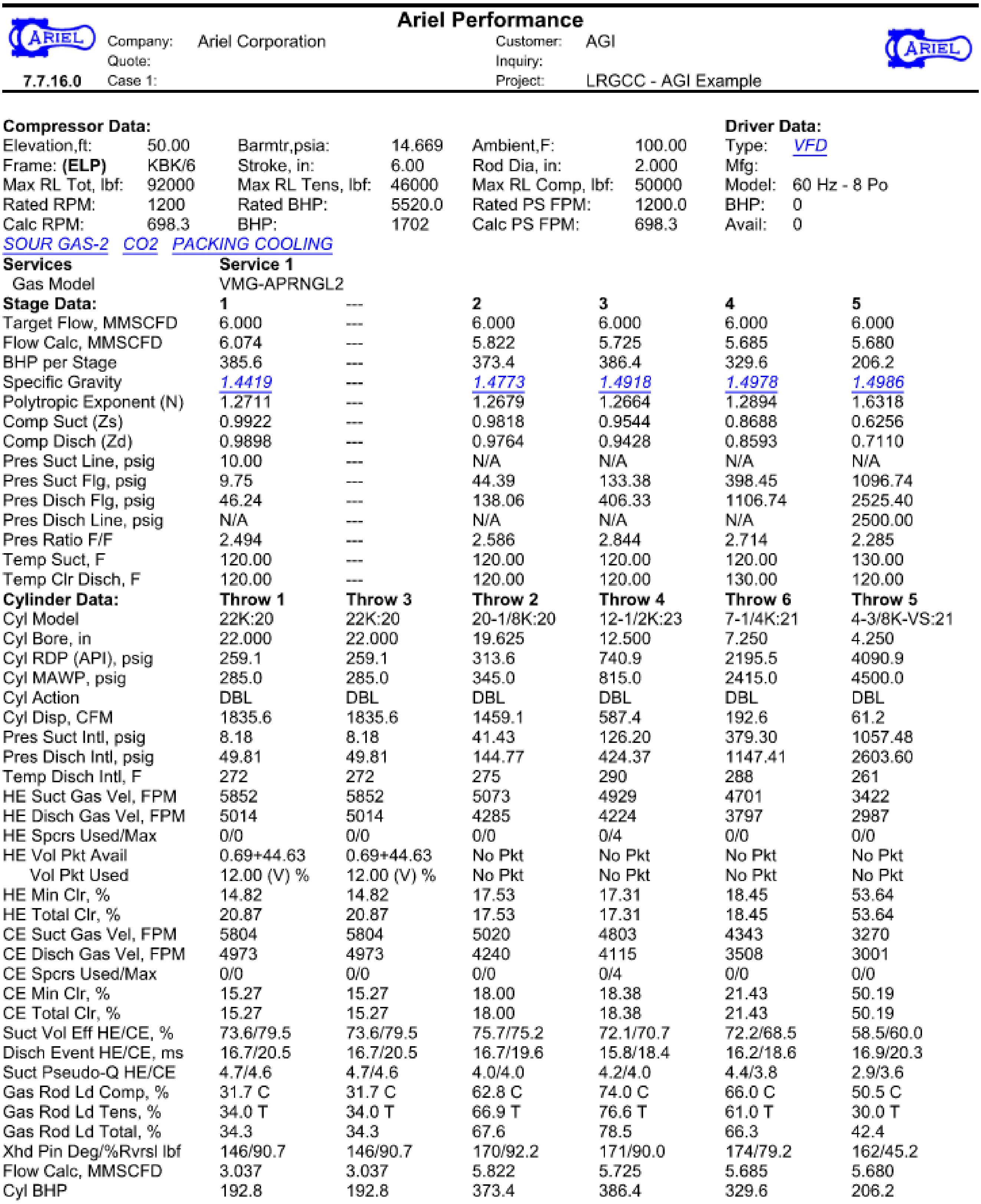
2. Discharge pressure conditions may not be well known if the acid gas injection well is not already designed or if it is being drilled into a formation with few existing wells in it. If the acid gas compressor needs to be ordered before the well is fully characterized, it may be prudent to design the acid gas compressor for a lower discharge pressure than the maximum and allow for a downstream boosting unit, like a dense phase pump to be installed in the future if necessary.
3. Winter conditions and summer conditions will also have a larger impact on the acid gas compressor design than on some other gases. The interstage coolers of the acid gas compressor will most likely be air-cooled and therefore the acid gas temperatures will be subject to diurnal temperature swings unless the system is designed to maintain temperatures in the compressor. Hydrate formation considerations, liquefaction of the acid gas at moderate pressures, and different gas densities at compressor stages are all things that have to be considered in the compressor system design.

The reliability of the acid gas compressor is critical for the gas treating facility to be able to operate normally. When the compressor shuts down, upstream operations may need to be curtailed or flaring of the acid gas may be necessary, which can have a substantial financial penalty associated with it. Maintaining an acid gas compressor is also difficult; each shut down requires a blow down and purge of the compressor system. The compressor is specified to minimize the chances of unintended maintenance, and the system designer should include reliability requirements in the request for bid package that is sent to compressor designers. Compressor packagers operate in a competitive business environment with tight margins and in the absence of clear reliability and performance requirements, they may design a lower capital cost compressor that has a higher overall cost of ownership with more downtime for scheduled and unscheduled maintenance. Some specifications to include on the compressor design and bid request are as follows:

1. Limiting piston speed to less than 850 ft/min. Piston speed is set by the RPM of the compressor, multiplied by the stroke length, and multiplied by 2.
2. Lower RPM speed compressors will reduce the total cycles of the compressor valves proportionally and thereby increase their lifespan. Acid gas is a high molecular weight gas and high molecular weight gases are more likely to cause suction valves in the compressor to stay open past the end of the suction stroke of the piston and then the valves are slammed closed as the compression stroke starts. This can lead to premature valve failure and is more likely in high RPM compressors.
3. Lower discharge temperatures on each stage will increase the reliability of compressor valves. Discharge temperature is largely set by the compression ratio across a given stage, which also sets the rod load of the compressor. The speed of the compressor will also have an impact on the discharge temperature of the gas; slower machines will have a lower discharge temperature for the same gas flow rate, but this is a lower impact than the compression ratio. Discharge temperatures should always be kept below 300 °F and ideally even below 280 °F.

For the example listed above, the compressor selected for this service is a six cylinder, five stage compressor. The first stage of compression has the highest volumetric flow rate and this sets the processing capacity of the compressor, is made up of two cylinders operating in parallel, and each subsequent stage of compression is done with one cylinder. Figure 3 shows a run sheet for the selected compressor.



Ariel Performance

Company: Ariel Corporation
Quote:
7.7.16.0 Case 1:

Customer: AGI
Inquiry:
Project: LRGCC - AGI Example

Compressor Data:						**Driver Data:**	
Elevation,ft:	50.00	Barmtr,psia:	14.669	Ambient,F:	100.00	Type:	*VFD*
Frame: **(ELP)**	KBK/6	Stroke, in:	6.00	Rod Dia, in:	2.000	Mfg:	
Max RL Tot, lbf:	92000	Max RL Tens, lbf:	46000	Max RL Comp, lbf:	50000	Model:	60 Hz - 8 Po
Rated RPM:	1200	Rated BHP:	5520.0	Rated PS FPM:	1200.0	BHP:	0
Calc RPM:	698.3	BHP:	1702	Calc PS FPM:	698.3	Avail:	0

SOUR GAS-2 *CO2* *PACKING COOLING*

Services	**Service 1**					
Gas Model	VMG-APRNGL2					
Stage Data:	**1**	---	**2**	**3**	**4**	**5**
Target Flow, MMSCFD	6.000	---	6.000	6.000	6.000	6.000
Flow Calc, MMSCFD	6.074	---	5.822	5.725	5.685	5.680
BHP per Stage	385.6	---	373.4	386.4	329.6	206.2
Specific Gravity	*1.4419*	---	*1.4773*	*1.4918*	*1.4978*	*1.4986*
Polytropic Exponent (N)	1.2711	---	1.2679	1.2664	1.2894	1.6318
Comp Suct (Zs)	0.9922	---	0.9818	0.9544	0.8688	0.6256
Comp Disch (Zd)	0.9898	---	0.9764	0.9428	0.8593	0.7110
Pres Suct Line, psig	10.00	---	N/A	N/A	N/A	N/A
Pres Suct Flg, psig	9.75	---	44.39	133.38	398.45	1096.74
Pres Disch Flg, psig	46.24	---	138.06	406.33	1106.74	2525.40
Pres Disch Line, psig	N/A	---	N/A	N/A	N/A	2500.00
Pres Ratio F/F	2.494	---	2.586	2.844	2.714	2.285
Temp Suct, F	120.00	---	120.00	120.00	120.00	130.00
Temp Clr Disch, F	120.00	---	120.00	120.00	130.00	120.00
Cylinder Data:	**Throw 1**	**Throw 3**	**Throw 2**	**Throw 4**	**Throw 6**	**Throw 5**
Cyl Model	22K:20	22K:20	20-1/8K:20	12-1/2K:23	7-1/4K:21	4-3/8K-VS:21
Cyl Bore, in	22.000	22.000	19.625	12.500	7.250	4.250
Cyl RDP (API), psig	259.1	259.1	313.6	740.9	2195.5	4090.9
Cyl MAWP, psig	285.0	285.0	345.0	815.0	2415.0	4500.0
Cyl Action	DBL	DBL	DBL	DBL	DBL	DBL
Cyl Disp, CFM	1835.6	1835.6	1459.1	587.4	192.6	61.2
Pres Suct Intl, psig	8.18	8.18	41.43	126.20	379.30	1057.48
Pres Disch Intl, psig	49.81	49.81	144.77	424.37	1147.41	2603.60
Temp Disch Intl, F	272	272	275	290	288	261
HE Suct Gas Vel, FPM	5852	5852	5073	4929	4701	3422
HE Disch Gas Vel, FPM	5014	5014	4285	4224	3797	2987
HE Spcrs Used/Max	0/0	0/0	0/0	0/4	0/0	0/0
HE Vol Pkt Avail	0.69+44.63	0.69+44.63	No Pkt	No Pkt	No Pkt	No Pkt
Vol Pkt Used	12.00 (V) %	12.00 (V) %	No Pkt	No Pkt	No Pkt	No Pkt
HE Min Clr, %	14.82	14.82	17.53	17.31	18.45	53.64
HE Total Clr, %	20.87	20.87	17.53	17.31	18.45	53.64
CE Suct Gas Vel, FPM	5804	5804	5020	4803	4343	3270
CE Disch Gas Vel, FPM	4973	4973	4240	4115	3508	3001
CE Spcrs Used/Max	0/0	0/0	0/0	0/4	0/0	0/0
CE Min Clr, %	15.27	15.27	18.00	18.38	21.43	50.19
CE Total Clr, %	15.27	15.27	18.00	18.38	21.43	50.19
Suct Vol Eff HE/CE, %	73.6/79.5	73.6/79.5	75.7/75.2	72.1/70.7	72.2/68.5	58.5/60.0
Disch Event HE/CE, ms	16.7/20.5	16.7/20.5	16.7/19.6	15.8/18.4	16.2/18.6	16.9/20.3
Suct Pseudo-Q HE/CE	4.7/4.6	4.7/4.6	4.0/4.0	4.2/4.0	4.4/3.8	2.9/3.6
Gas Rod Ld Comp, %	31.7 C	31.7 C	62.8 C	74.0 C	66.0 C	50.5 C
Gas Rod Ld Tens, %	34.0 T	34.0 T	66.9 T	76.6 T	61.0 T	30.0 T
Gas Rod Ld Total, %	34.3	34.3	67.6	78.5	66.3	42.4
Xhd Pin Deg/%Rvrsl lbf	146/90.7	146/90.7	170/92.2	171/90.0	174/79.2	162/45.2
Flow Calc, MMSCFD	3.037	3.037	5.822	5.725	5.685	5.680
Cyl BHP	192.8	192.8	373.4	386.4	329.6	206.2

Figure 3. Example Acid Gas Compressor Run Sheet.

To stay close to the parameters for reliability, while allowing for some additional capacity in the acid gas system, the compressor motor has a maximum rotational speed of 891 RPM, but will be driven by a variable frequency drive so that it normally operates at a slower speed. This also allows for a further reduction in capacity that will be discussed later in this section of the fundamentals.

The compression process mapped out on a pressure vs. enthalpy diagram is shown in Figure 4.

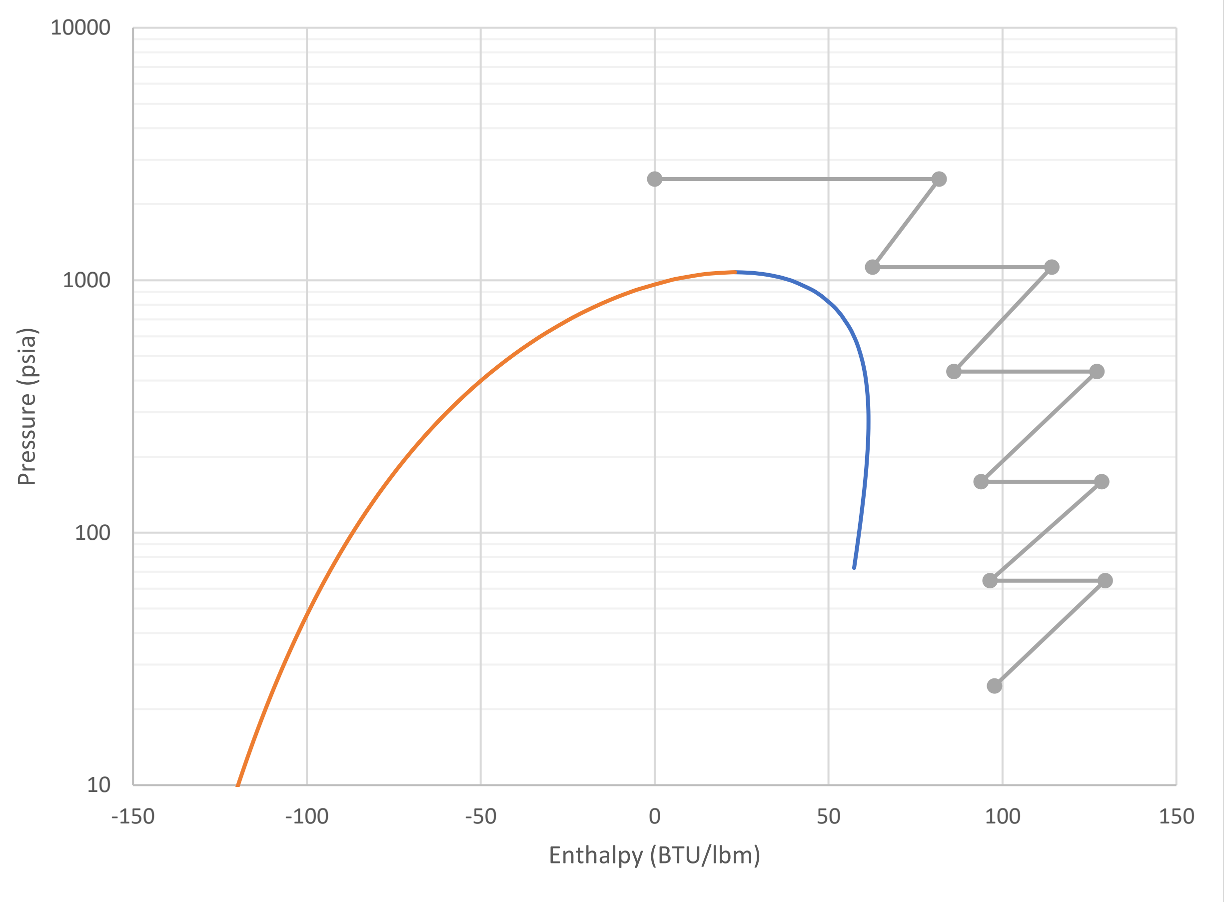


Figure 4. Pressure vs. Enthalpy (PH) Diagram of Acid Gas Compression Process.

Figure 4 shows several key considerations for the acid gas compression process. The compression process happens well-away from the two-phase region of the fluid so there is little or no chance for liquids to form in the process as long as interstage temperatures are properly controlled. Staying away from the right side of the dome (or the dew point of the gas) also reduces the risk of solid hydrates forming as these usually in a gas temperature range between 32 and 60 °F. Temperature is not shown in Figure 4, but cooling after Stages 1 through 3 is done to 120 °F in this example. The inlet to Stage 5 is at or near the critical pressure of the fluid, which by itself is not a major issue but as the fluid approaches the critical point (i.e. the critical pressure and critical temperature), the physical properties of the fluid can change substantially and this may cause the compressor to operate differently or even cause damage to the compressor. As a result, it is important to operate the compressor away from the critical point and in this example, the Stage 4 discharge gas is not cooled all the way to 120 °F but instead just to 130 °F, so that the compression process maintains an adequate margin away from the critical point. Some compressor manufacturers recommend staying 40-50 °F above the critical temperature to ensure stable physical properties. Compressor system designers often design the transition through the critical pressure to occur midway through a compression step, so that the suction scrubber and pulsation bottle and the discharge pulsation bottle will not be subject to large changes in volumetric flow rate that can occur with small changes in temperature or pressure near the critical point. That would be another concern with cooling the Stage 4 discharge / Stage 5 suction gas closer to its critical temperature. It is also important to maintain the fluid's compressibility above 0.5 for the compressor to be able to compress the fluid (Ariel Corporation, 2025).

Compressor Design and Materials

Reciprocating compressors are well known in the oil and gas industry. Their function and general makeup are well understood. However, it is the application in which the compressor is applied in that defines most of its enigmatic internal processes. AGI applications are one of the most demanding. Compressing a corrosive, toxic gas composed mostly of hydrogen sulfide and carbon dioxide, from relatively low suction pressures to discharge pressures up to 3000 psig, requires significant attention to materials of construction and system design. There are industry standards such as API 618 and NACE MR0175/ISO 15156 that provide guidance on the shall/shall nots, however, it is the field experience that ultimately proves success.

As with any piece of rotating machinery, there is a source of power and a source consuming that power. A reciprocating compressor is the consumer. A driver provides torque as well as the rate the torque is applied, horsepower. The driver in AGI applications is almost always an electric motor with variable frequency drive (VFD). The horsepower required mostly depends on the flow requirement and compression ratio. AGI applications tend to have flow requirements of approximately 0.5 10 MMSCFD and a total compression ratio exceeding 100, requiring about 250 to 2500 HP. Lastly, a compressor's cylinder configuration and frame size are also determined based on this flow, power, and compression ratio.

The running gear of a reciprocating compressor will remain much the same regardless of the application, as depicted below in

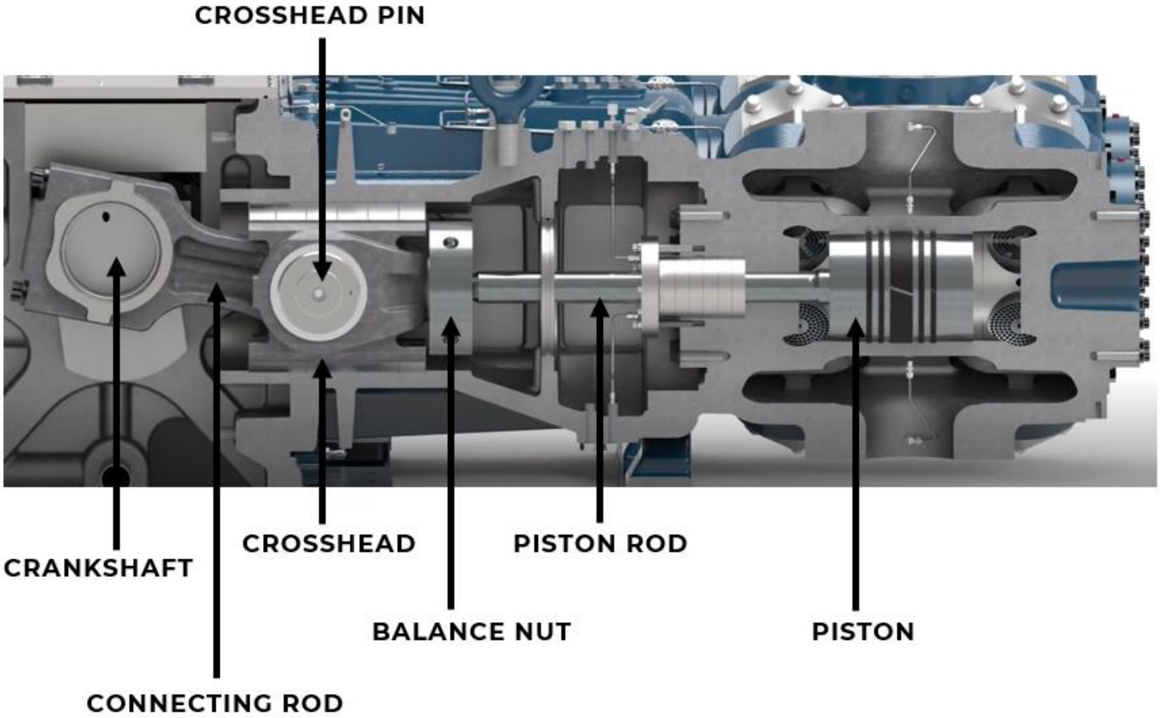


Figure 5. Utilizing a slider-crank mechanism, composed of a crankshaft, connecting rod, and crosshead, the rotational motion of the driver provides a torque which is then translated into a linear motion and force. The resultant force is composed of the inertia of the reciprocating components (crosshead, balance nut, piston rod assembly) and the gas force due to compression, referred to as crosshead pin load per API 618. The crankshaft will dictate the stroke of the piston and the speed of the driver will determine the piston speed (2 x stroke x RPM). The lower the piston speed, the lower the wear rate on consumable components such as seals/bearings, increasing reliability which is paramount in AGI applications. However, reduced speed inherently reduces throughput or capacity. Lower piston speeds also provide better flow dynamics of the heavy gas within a compressor cylinder, this will be discussed later.

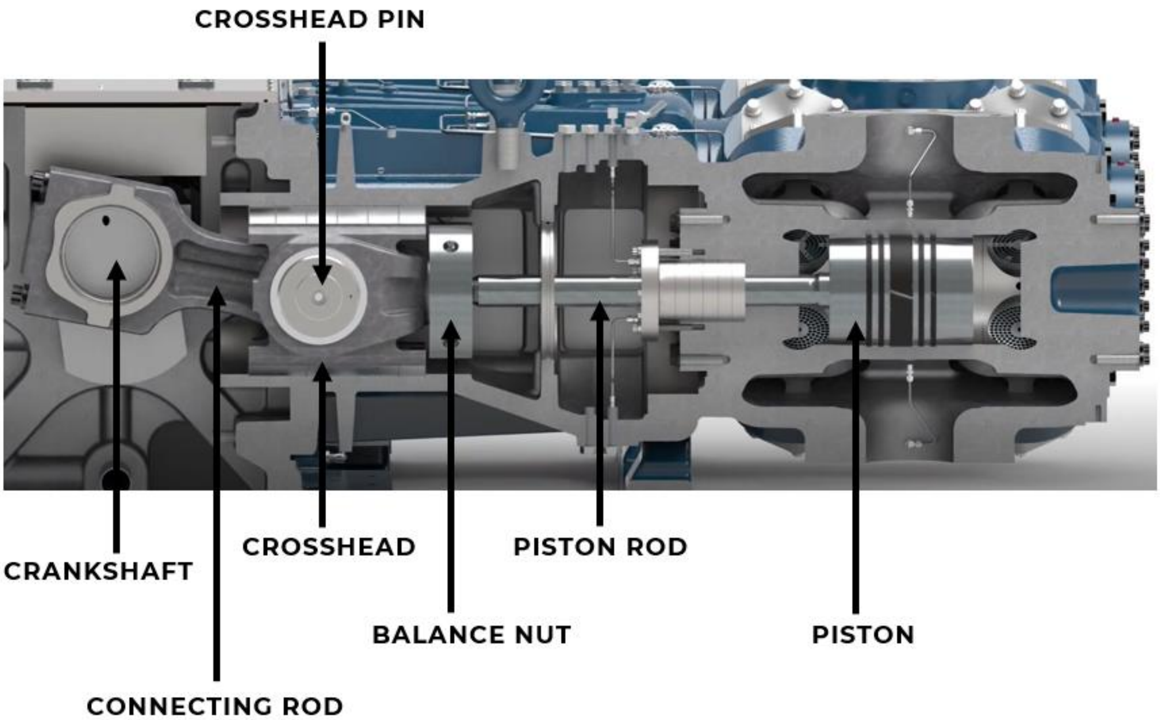


Figure 5: Reciprocating Compressor Running Gear.

There appears to be a generational influence, as well as recommendations from industry standards, demanding no yellow metals within the frame, or crankcase of the compressor, for AGI applications due to the high concentration of hydrogen sulfide in the process gas. Yellow metals (copper alloys) are found in the half-shell bearings of the frame mains and big-end of the connect rods, as well as the bushings within the small-end of the connecting rods and crossheads. Hydrogen sulfide will react with the copper alloys creating a black surface layer of copper sulfide. Applying no yellow metals requirements means bearings/bushings made of aluminum. Furthermore, aluminum is not as robust as the tri-metal bearings or the bronze bushings it replaces, and thus, derates of the compressor and increased service intervals may follow. Also, larger frames rated at higher rod loads may not allow the use of aluminum bearings altogether. In a properly designed system, no process gas will be exposed to the crankcase and yellow metals may still be used.

Safety moment: If process gas enters the crankcase of a reciprocating compressor, it will ultimately be exposed to the external environment surrounding the compressor as the crankcase contains a breather vent and crankshaft dust seal. Neither are designed to hold pressure. A hydrogen sulfide concentration of 500 ppm is enough to be deadly within minutes.

One also has to consider, if process gas enters the crankcase, then it will be exposed to the compressor’s lube oil, the life blood for the running gear. Unless the oil is formulated to handle such situations, oil contamination and degradation may follow, potentially leading to a breakdown in oil viscosity which spells disaster for bearings/bushings.

So, what is a properly designed system to prevent process gas from entering the crankcase for AGI applications with high concentrations of hydrogen sulfide and carbon dioxide? It is applying two compartment distance pieces with nitrogen or sweet natural gas purge at positive pressure to the piston rod seals, applying the latest technology in piston rod seals, routing distance piece vents/drains into individual manifolds with little-to-no backpressure and piping them to a collection system for further disposal. Each of these will be discussed in detail below but first, one has to consider where the main source of process gas leakage occurs and how it can enter the frame.

Regardless of the compressor application, the main seal to prevent process gas leakage into the crankcase is the packing depicted as item 5 in Figure 6. The packing is a dynamic seal comparable in nature to that of a mechanical seal of a rotating pump, but rather, instead of sealing a rotating shaft, it is sealing a reciprocating shaft or piston rod. Typically lubricated, and most certainly in AGI applications, a packing case is composed of a number of single acting seal ring sets that are meant to seal in one direction (towards the cylinder), incrementally breaking down the pressure. The last ring set in the packing is a double-acting ring that seals in both directions. The double-acting ring encourages any remaining gas from the cylinder to enter the packing vent/drain and prevents intrusion of gas from the distance piece in the event of back pressure. For AGI applications, this last seal ring set must have a positive pressure purge gas applied to enhance its sealing capability.

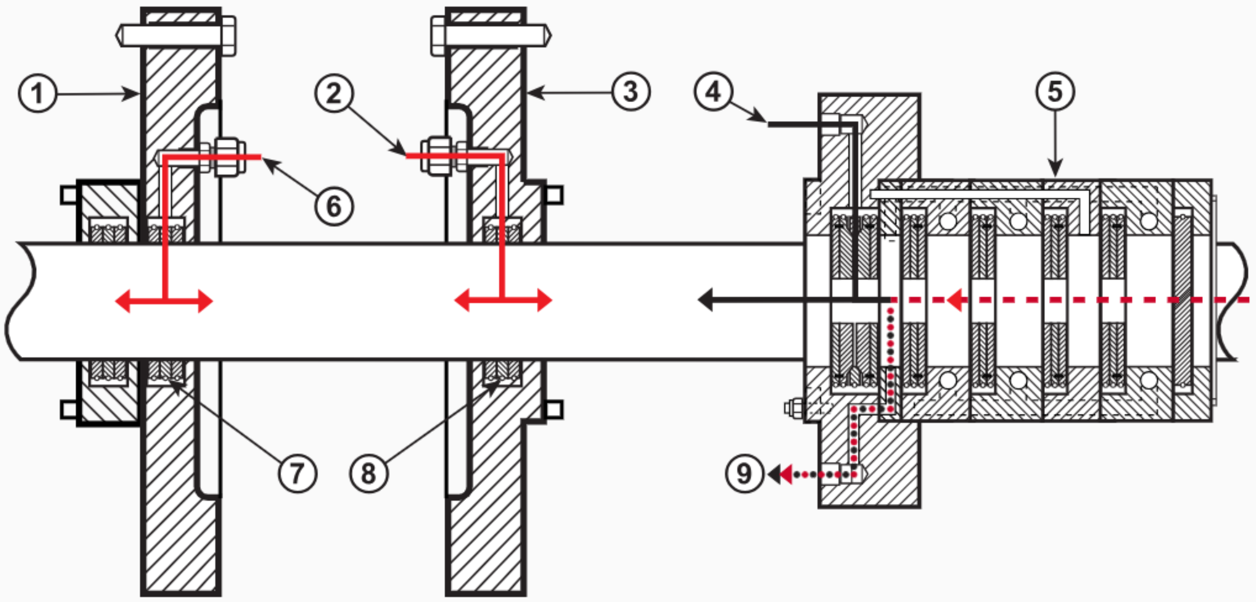


Figure: Typical Purge & Vent Packing

1 Purged Wiper Seal (L2 Compartment or KBK:T:C:D:F:Z:U L1 Compartment
2 Intermediate Packing Purge Connection
3 Purged Intermediate Packing (L2 compartment only)
4 Pressure Packing Purge Connection
5 Pressure Packing
6 Wiper Purge Connection
7 Purged Wiper Seal
8 Purged Intermediate (partition) Packing
9 Packing Vent/Drain

Figure 6: Typical Purge & Vent Packing Configuration in a Long Two Compartment Distance Piece.

<u>Side Note</u>: Regulatory agencies, most notably the EPA, call out leakage thresholds and service intervals on the packing as it is the primary source of emissions for reciprocating compressors, aside from blow down events. The seals within the case

are typically spring energized, non-metallic, although a combination of metallic/non-metallic is also common. Most packing seals still reflect early 20th century designs, however, spurred by increased regulatory pressure and advancements in material science, the design and performance of these seals have improved drastically in recent years. In some applications, achieving near-zero emissions. The seals will eventually wear and will need to be replaced, although lower piston speeds will prolong the wear life of the seals.

In addition to the main packing seal, a two-compartment distance piece arrangement has additional barriers to further prevent process gas leakage into the crankcase. The additional barriers are an intermediate packing and wiper gland, both having purge capabilities, depicted as item 1 and 3 of Figure 6. The intermediate packing seals between the outboard and inboard compartment while the wiper gland wipes frame oil off the rod, preventing oil migration from the frame to the inboard compartment. There is also a seal ring set located in the wiper gland to help prevent back pressure in the compartment from entering the frame. This is a likely source if process gas leakage is observed in the crankcase. Legacy style sealing technology in the wiper was not designed to seal against much back pressure, however, advancements in sealing technology have been applied successfully in this area.

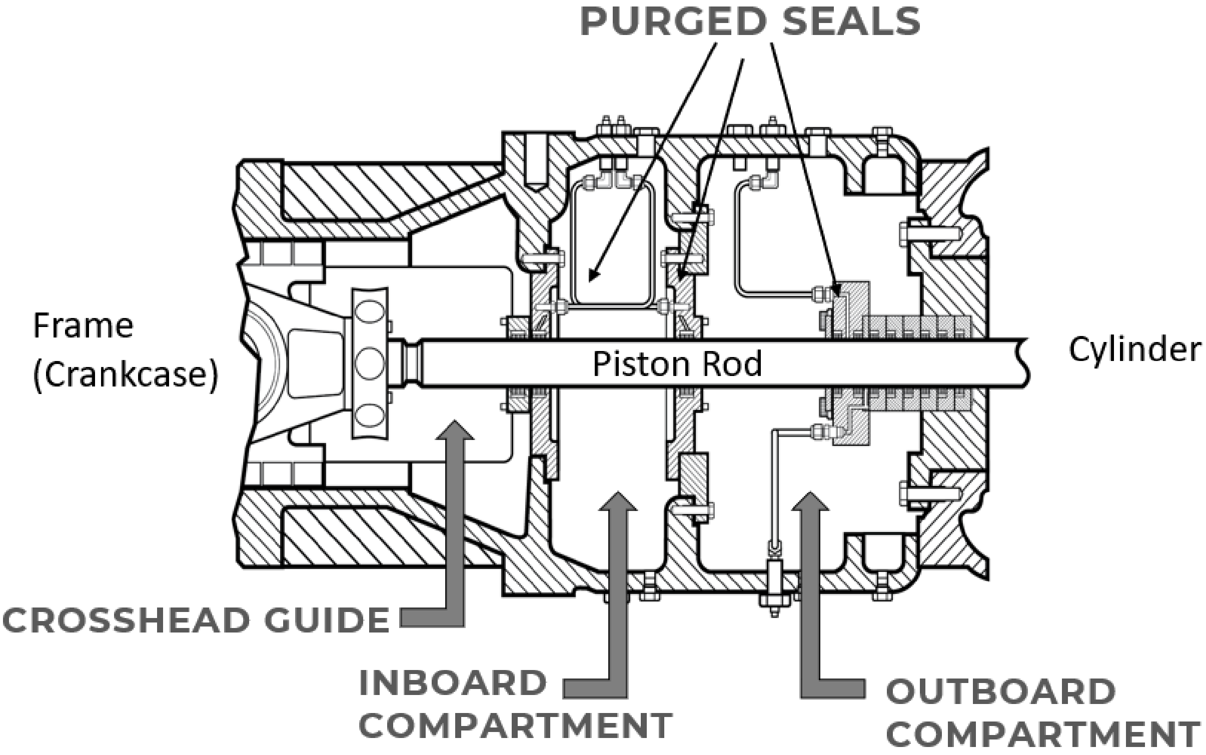


Figure 7: Two Compartment Distance Piece, Type 3 ISO 13631, Type C API 618.

The purge gas to the packing, intermediate packing, and wiper gland is supplied at a pressure of 5-10 psi above the back pressure of the vent/drain system. Each compartment has a vent at the top and a drain at the bottom. The packing case has its own dedicated vent/drain line (seen in Figure 7 as the tube to the bottom of the outboard compartment or item 9 in Figure 6). These three areas are the beginning of the vent/drain system. This system is ideally at atmospheric pressure, or as low as possible, simply to encourage any process gas leakage to enter the system. Or else, it may find the path of least resistance elsewhere.

Each of these vent/drains must be manifolded separately to prevent cross communication with one another. Connecting them together in any way defeats the purpose of a two-compartment distance piece as it allows gas to flow between compartments. The combined line size should equal the added areas of the incoming two lines. For example, if two 3/4-inch lines meet, a 1-inch line is appropriate after the connection. Lines need to be appropriately sized to prevent restrictions to drain both oil and gas, such as increasing to minimum 3/8-inch tubing from 1/4-inch NPT connections that are provided on the bottom of the distance piece by the OEM. It is common to join the vent and drain of the same compartment to a manifold as the source of these two lines are the same. Internal/external tubing for vent/drains, and lubrication lines, are typically 304 stainless materials although 316 stainless tubing/fittings is commonly applied as an option due to the corrosive process gas. Figure 8 depicts a properly configured vent/drain system with separate manifolding that collectively leads to a separation pot.

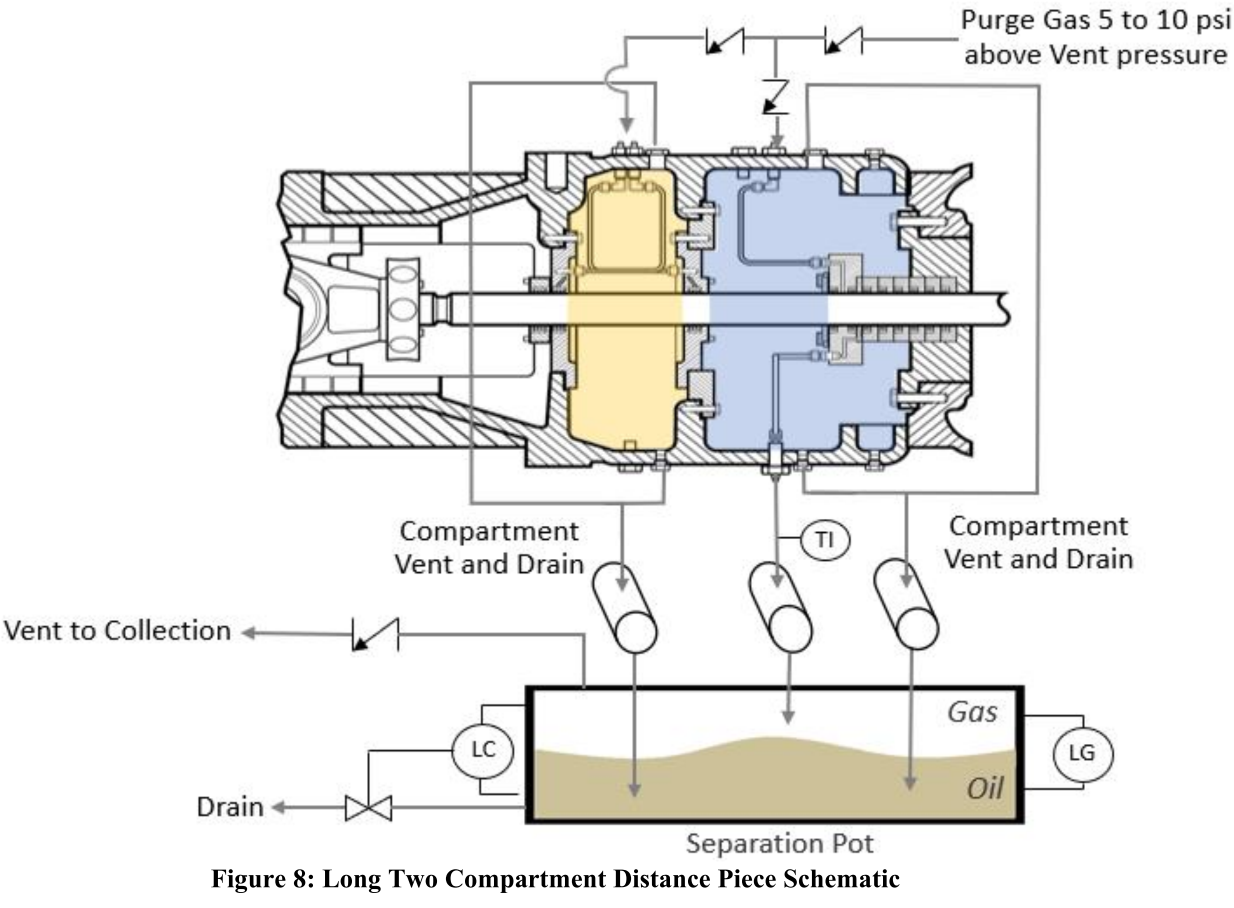


Figure 8: Long Two Compartment Distance Piece Schematic

The separation pot separates lubricating oil and process gas for further disposal to a collection system. Its design is important such that no three manifolds cross communicate with one another. As shown in Figure 8, a liquid level is utilized as a liquid check valve for the compartment manifolds as their lines enter the separation pot and conclude below the liquid level. Oil level is maintained/verified with a controller/gauge and a drain is present to take away excess. Lastly, process gas leakage is vented to its own collection system. This may be to a plant vent system leading to flare or reinjected into the process by means of a small emission recovery unit (ERU) compressor.

Although the distance piece vent/drains are necessary to collect process gas and lube oil leakage, the goal is to minimize or prevent this leakage in the first place. Steps to prevent this are lower piston speeds, applying appropriate materials of construction to piston rods, applying OEM specified lube oil grade in the cylinders/packing, and water cooling in the packing which will depend on mean cylinder pressure and piston speed.

Due to the corrosive nature of high concentrations of hydrogen sulfide and carbon dioxide, at high partial pressures, stainless steel piston rods may be required. NACE MR0175 defines acceptable materials of construction, for example, a 17-4PH material for piston rods in the double H1150 condition, UNS S17400, Rc 33 maximum. Other grades of stainless may also be acceptable. The piston rod will be exposed to the process gas as it enters into the cylinder on the suction stroke of the crank end side of the cylinder. In addition to surface hardening by means of heat treating, such as ion nitriding, a surface coating of the piston rod is commonly applied in the packing travel region as this is the section of the rod that the seal rings are energized. If a coating is not applied, accelerated wear of the piston rod is likely. Tungsten carbide and chromium nitride coatings are common. To prolong the life of the seal rings and piston rod, a lube oil is injected into the packing case. Ideally, the oil will coat the surface of the rod so the rings will seal along a film of oil, increasing sealing effectiveness and wear life. The lube oil will be exposed to the process gas so it is of the utmost importance to adhere to OEM specifications on lube oil grade. It is not uncommon to see an ISO 220 or ISO 460 grade oil applied. These grades are too heavy to be utilized in the frame lube oil system, so an independent oil supply is required, as seen in Figure 9 below.

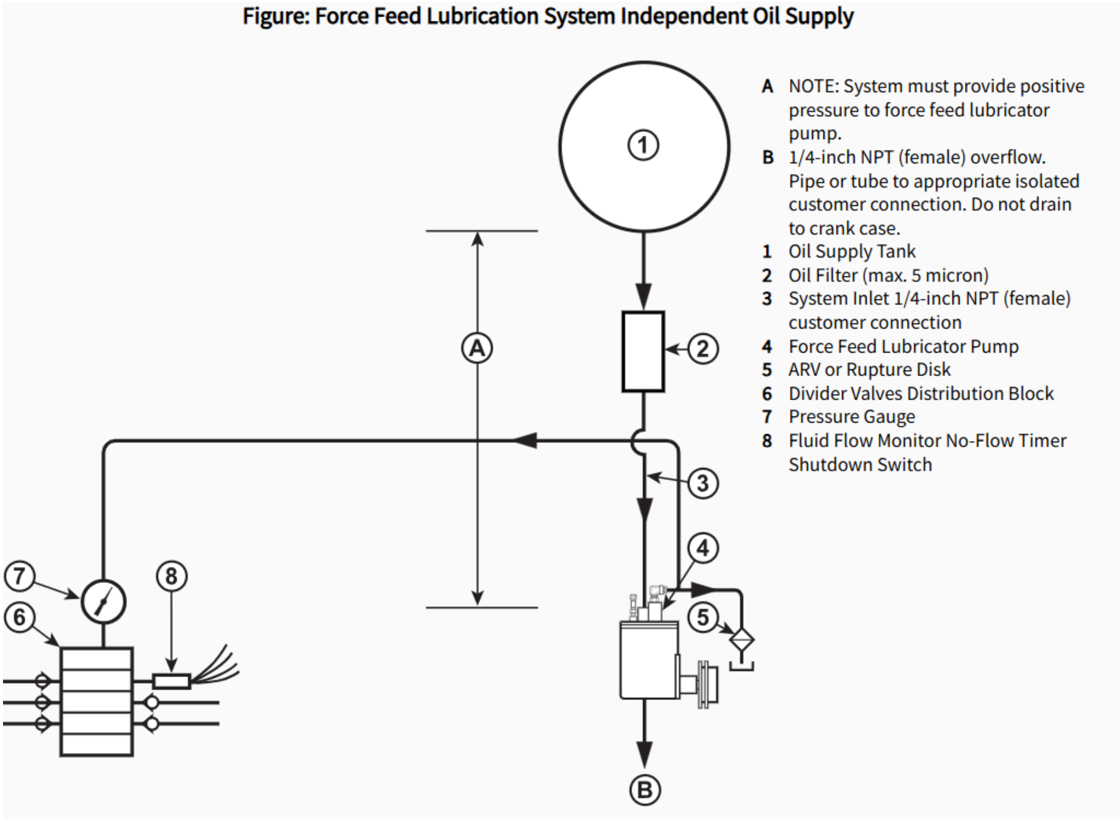


Figure: Force Feed Lubrication System Independent Oil Supply

A NOTE: System must provide positive pressure to force feed lubricator pump.
B 1/4-inch NPT (female) overflow. Pipe or tube to appropriate isolated customer connection. Do not drain to crank case.
1 Oil Supply Tank
2 Oil Filter (max. 5 micron)
3 System Inlet 1/4-inch NPT (female) customer connection
4 Force Feed Lubricator Pump
5 ARV or Rupture Disk
6 Divider Valves Distribution Block
7 Pressure Gauge
8 Fluid Flow Monitor No-Flow Timer Shutdown Switch

Figure 9: Force Feed Lubrication System Independent Oil Supply

Oil provided by the independent supply lubricates both the packings and cylinder bores. The rate of oil delivery will be specified by the OEM. A newly commissioned compressor will typically be set to a “break in” oil delivery rate of 1.5x the normal lube rate. After a set number of operating hours, usually ~200 hours, the oil delivery is adjusted back to the normal lube rate. The break in period is just that, sealing components will wear to conform to the surface they are sealing against.

Reciprocating compressor cylinders for AGI applications are commonly double-acting, compression occurs on both ends of the cylinder, and made of ductile iron of ASTM A395 grade 60-40-18 suitable per NACE standards. The OEM and/or end user may take exception to NACE standards in the grade of cast iron for AGI applications as field experience would take precedence. The last stage of compression may require the use of forged steel, or block-style, cylinders. The maximum allow working pressure (MAWP) of ductile cylinders is limited to about 2500psi. AGI applications typically operate at or above pressures in which forged steel is then necessary to achieve higher MAWP. For example, forged steel of AISI 4340 softened to 22 RC or a 17-4PH stainless steel material, as defined in NACE MR0175. Stainless bolting is option that may be applied external to the cylinder at the flanges, valve caps and heads, however, these surfaces are not “wetted” or exposed to the process gas directly at operating pressures, so standard bolt materials of a grade 8 material might be applied, depending on the compressor OEM.

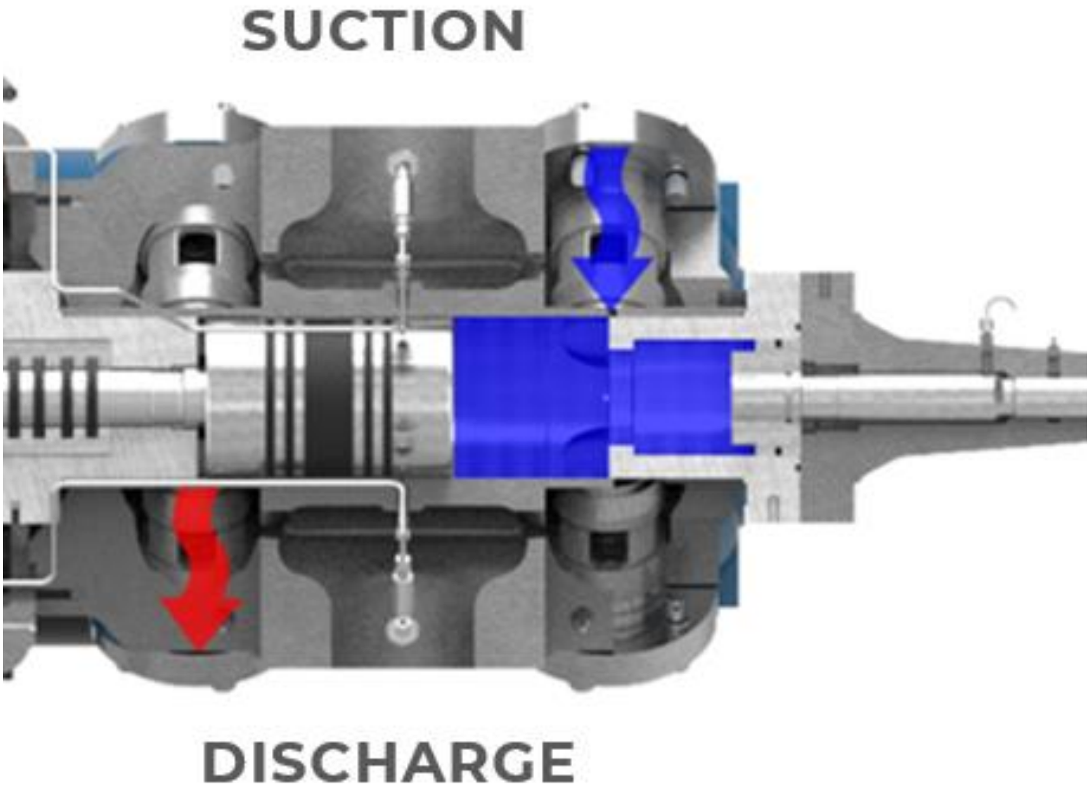


Figure 10: Compression Process of a Double-Acting Cylinder

Cylinders are typically orientated with suction on the top and discharge on the bottom. As seen in Figure 10, when one end of the piston is compressing, the other end is intaking a fresh charge of gas. This process will repeat on both ends as the piston reciprocates back and forth, at the piston speed determined by stroke and operating RPM. It may seem like a continuous flow of gas but the cylinder actually “burps” gas out in pulses at a high frequency.

Process gas can only flow in one direction due to the plate-style valves that act similarly to check valves. Valve body material will be directly influenced by the process gas similarly to piston rods, so a 17-4PH material is commonly applied in AGI applications and meets NACE specifications, though there is field experience suggesting a 400 series stainless material is suitable. Valve plates are mostly non-metallic PEEK material, blending rigidity with a touch of conformability. However, depending on operating pressures of the valve, alternative valve plate materials may be required to maintain sealing effectiveness. Also, valve timing, or the closing event of the valve plate, is thoroughly reviewed for each stage of compression to further confirm valve performance and reliability. The valve timing is adjusted by the use of springs of different stiffness.

Side Note: A flushing lube may be applied to the inlet nozzle on the suction side of the cylinder as a means to coat the valve in oil to prevent corrosion due to the high concentrations of hydrogen sulfide and carbon dioxide. The thought process behind applying flushing lube is the discharge valves will inherently be coated due to cylinder lube by the flow of gas and suction valves miss out on that opportunity. However, there is a sizable sentiment from end users suggesting flushing lube is the cause of decreased valve reliability due to stiction of the valve plate. Similarly to lifting a cold beverage with its coaster still attached, the valve plate may delay opening during the intake stroke due to it sticking to the seat and causing it to slam open.

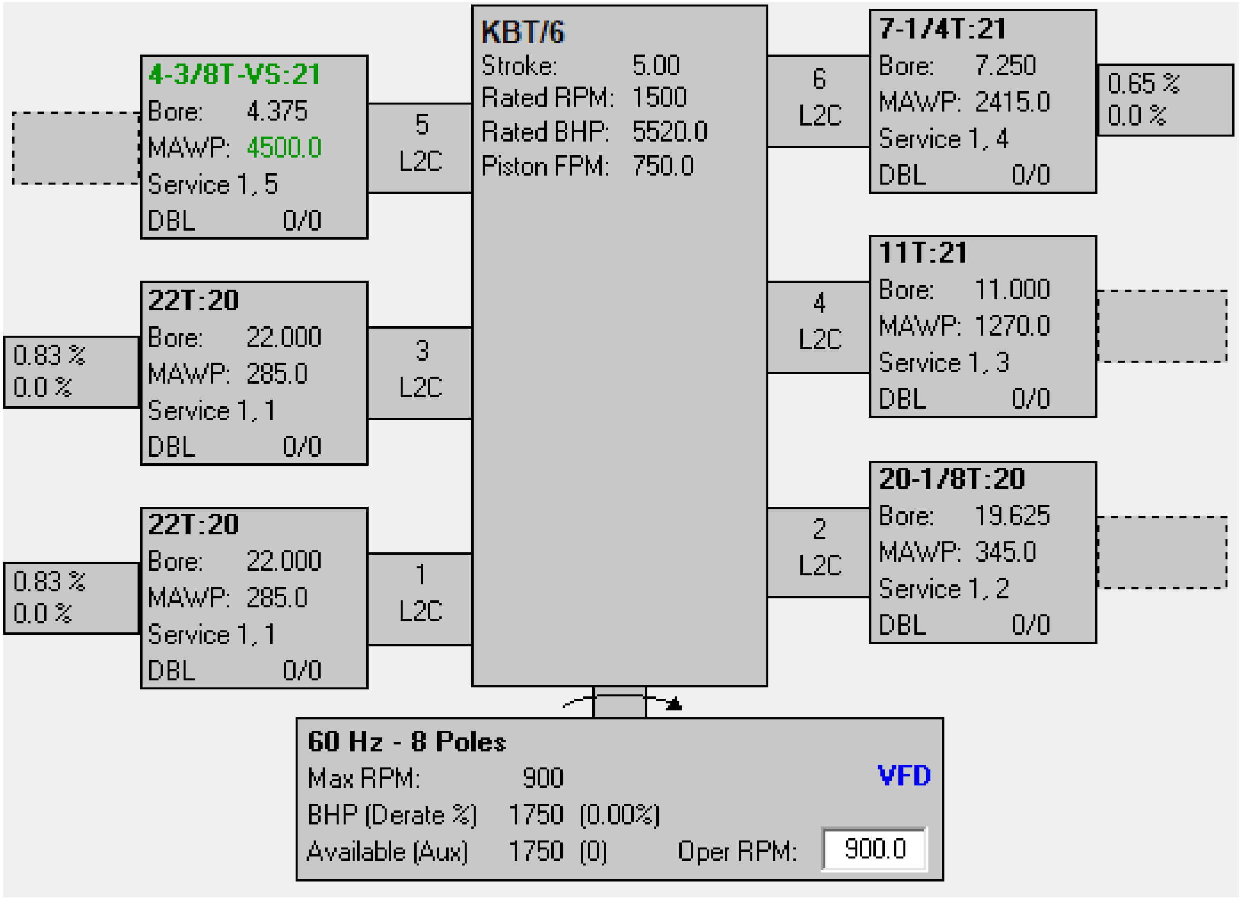
Valves operate based on differential pressure. On the suction stroke, the piston retracts and any remaining gas inside the cylinder expands. Eventually the pressure internal to the bore reduces below suction pressure and gas is drawn into the cylinder by the opening of the suction valves (the blue portion of Figure 10). Discharge pressure will hold the discharge valves closed at that time. When the piston reverses, compression will begin forcing the suction valves closed. Once internal bore pressure meets and exceeds discharge pressure, the discharge valves will open and gas will exit the cylinder.

In AGI applications, the heavy gas, typically 1.2 – 1.5 specific gravity, may struggle to exhaust from large bore cylinders due to tight internal clearances and the long distance between suction/discharge valves. Essentially, the compressed gas is not given enough time for it to travel across the face of the piston and out the cylinder. This phenomenon coined by an OEM is called “Instationary Flow”. What ensues is decreased capacity and efficiency. The legacy style solution was to reduce operating RPM and/or reduce stroke (not an easy task if an existing unit). However, there have been recent improvements to large bore cylinder designs to remedy this phenomenon.

Figure 11 is a real-world example of a 1750 hp six throw 5 stage acid gas injection unit. The configuration displayed has two first stage cylinders and one cylinder for each of the remaining stages. The first 4 stages utilize ductile iron A395 cylinders while the 5th stage utilizes AISI 4140, 22 Rc forged steel. The gas analysis mainly contains hydrogen sulfide and carbon dioxide with specific gravity of 1.4. Inlet pressure is 6 psig with a discharge pressure range of 2400-3700 psig. Required flow is 4 MMSCFD.

The reason for many stages, and thus many throws, is partly due to the high compression ratio of 120-180 (discharge pressure absolute / suction pressure absolute) and due to the required flow rate. As the old saying goes, “there’s no replacement for displacement,” when discussing power for an engine. This saying can also be applied to reciprocating compressors, as flow and power are proportional to an extent. To achieve more flow, then any of the following are required: longer stroke, larger cylinders, more cylinders, increased speed, increased inlet pressure, and sometimes, more stages. In AGI applications, longer stroke, increased speed, and increased inlet pressure have traditionally not been easily achieved. This is in part due to the source of the acid gas and the acid gas properties. That leaves larger cylinders, more cylinders, and more stages as the main solution, although as mentioned above, recent changes to an OEM’s cylinder designs may unlock higher piston speeds.

Each stage then takes a bite out of the total compression ratio, at most around 4 ratio per stage. This limit exists so discharge temperatures, suction volumetric efficiency, and gas rod load remain within compressor limits. The process gas will be cooled on the interstage, to some degree, before being introduced into the next stage. The intricacies of interstage cooling of acid gas injection applications will not be discussed here and are discussed elsewhere in the document.


KBT/6
Stroke: 5.00
Rated RPM: 1500
Rated BHP: 5520.0
Piston FPM: 750.0

4-3/8T-VS:21
Bore: 4.375
MAWP: 4500.0
Service 1, 5
DBL 0/0

5
L2C

22T:20
Bore: 22.000
MAWP: 285.0
Service 1, 1
DBL 0/0

0.83 %
0.0 %

3
L2C

22T:20
Bore: 22.000
MAWP: 285.0
Service 1, 1
DBL 0/0

0.83 %
0.0 %

1
L2C

6
L2C

7-1/4T:21
Bore: 7.250
MAWP: 2415.0
Service 1, 4
DBL 0/0

0.65 %
0.0 %

4
L2C

11T:21
Bore: 11.000
MAWP: 1270.0
Service 1, 3
DBL 0/0

2
L2C

20-1/8T:20
Bore: 19.625
MAWP: 345.0
Service 1, 2
DBL 0/0

60 Hz - 8 Poles
Max RPM: 900
VFD
BHP (Derate %) 1750 (0.00%)
Available (Aux) 1750 (0)
Oper RPM: 900.0

Figure 11: Example of an Acid Gas Injection Unit.

Compressor Package Design and Materials

Packaging of acid gas compressors requires that special attention be paid to material selections, components and design features.

Material Selections

Acid gas coming to the compressor is typically saturated with water by the upstream acid gas removal unit. As the acid gas is compressed and cooled downstream of each compressor stage, the ability of the gas to hold water is reduced and water condenses. At higher pressures above the critical pressure, acid gas regains capacity to hold more water as the pressure is increased. The pressure of minimum water content varies with the gas mixture and is the subject of various papers previously presented at LRGCC and will not be repeated here. The condensed water contains hydrogen sulfide and carbon dioxide and is acidic and corrosive. It is removed from the gas stream in the inlet separator for the next compressor stage.

For many years, the industry standard for acid gas compressors was to utilize austenitic stainless steel (304L, 316L, etc.) on the cold side or suction of each compressor stage and carbon steel on the hot side, or discharge. Cooler tubes, piping to the next stage, suction separator, inlet pulsation drum would all be fabricated from stainless steel materials. Discharge pulsation drum and piping to the cooler would be carbon steel because the gas is well above its water dew point (superheated) during operation. Cooler headers are the same material as the cooler tubes. This met the requirements of older versions of NACE MR-0175. Subsequent editions of NACE MR-0175 limit the use of 304L and 316L materials to the extent that, in practice, they cannot be used in an acid gas application except for the first stage. However, there are many successful installations using the above materials and some purchasers continue to specify these materials instead of defaulting to compliance with the latest edition of NACE MR-0175. Note that austenitic stainless steel not typically suitable if there are chlorides present in the gas stream.

If compliance with the latest edition of NACE is required, the cold side piping and vessels can be made from carbon steel (see below) or high nickel alloys such as Alloy 825 or Super Duplex. Even if carbon steel is resistant to sulfide stress cracking and hydrogen induced cracking, it is still subject to corrosion from acidic condensation. The addition of an inhibition system or using coated carbon steel can control this corrosion and permit the use of carbon steel. Purchasers who do not have the experience to support going against the latest NACE recommendations, and do not want the added operational cost of a corrosion inhibition system or coated piping, are specifying the more exotic materials. Not only are these materials expensive and require long lead times, but the specialized weld procedures needed are slow when compared to more conventional materials. Additionally, many compressor packagers do not have approved weld procedures for these materials and so they need to develop them or subcontract this work out to a specialist. Either way, equipment deliveries are much longer and the cost of the compressor package is greatly increased.

When carbon steel materials are used, it is important to keep stresses low and hardness below Rockwell C 22. Hardness should be checked in the base metal, Heat Affected Zone and weld metal. Carbon steels should have a uniform and fine grain structure. For large diameter vessels, use HIC tested ASTM 516-60 or 516-70 normalized plate. For smaller diameter vessels and nozzles, use A-333 Grade 6 seamless pipe. Pipefittings should be ASTM A-350 LF2 or ASTM A-420 WPL6. Note that some clients specify 516-60N plate, based on internal research that shows it is less susceptible to stress corrosion cracking than 516-70N under the same conditions. Post-weld heat treatment is required for all carbon steel to eliminate localized stresses caused by welding. A minimum of 1/8” (3 mm) corrosion allowance should be included, but the purchaser should specify what is required based on their experience. Note that if more than ¼” (6mm) corrosion allowance is specified, drain lines and other small-bore connections may have to be made from corrosion resistant material. Alternatively, they could be made larger in order to have sufficient wall thickness after the corrosion allowance to withstand the design pressure.

100% radiography of all butt welds and UT examination of other pressure retaining welds, is normally specified to ensure the weld integrity no matter what materials are selected.

Hydrogen sulfide reacts with the iron in steel to produce iron sulfide (FeS), and carbon dioxide reacts in a similar way to form iron carbonate ($FeCO_3$). Both of these form a barrier that actually helps protect the steel from further corrosion. Add to this the thin coating of oil that comes from the cylinder lubrication being carried by the gas stream and in practice the corrosion rates on carbon steel vessels and piping in compressor packages are not as high as predicted by most corrosion prediction software programs. This is helped if gas velocities are reduced from the normal rule of thumb of 3000 feet per minute (15 m/s) for natural gas applications to 2000 feet per minute (10 m/s). These lower velocities reduce erosion of the protective layer and also ensure that pressure drops are similar to natural gas applications.

The traditional cooler material selection is carbon or stainless steel headers and stainless steel tubes, and coolers are still being purchased this way. For latest NACE compliance, if carbon steel is acceptable, the headers can be fabricated from HIC tested ASTM 516-70N plate with SA 179 seamless carbon steel tubes. Since it is not practical to include a corrosion allowance in the cooler tubes, some purchasers use the less expensive carbon steel headers, with a corrosion allowance and Super Duplex or Alloy 825 tubes.

As can be seen from the above discussion, there are many different opinions on the best material selections. There is no industry standard or theory as good as practical experience with like gas under like conditions. Experienced end-user input is essential in order to come up with a practical, reliable, and safe solution.

When using austenitic stainless steel, it is essential to ensure that no chlorides are present in the hydrotest water. Distilled water should be used. There are recorded cases of chloride stress cracking of stainless steel vessels in which the root cause of the failure was traced back to using tap water for hydro test purposes.

Low stress stamps should always be used for identifying purposes on sour gas vessels and piping.

Threaded connections in the process system should be minimized. All lines 1.5” NPS and larger should be flanged and welded. 1” and smaller lines can utilize stainless steel tubing with stainless steel fittings in lieu of screwed piping. ½” and ¾” threaded instrument connections are generally acceptable, although some customer specifications require all flanged connections on the pressure vessels.

All scrubbers should be equipped with bottom drains to allow complete draining of liquids during a shutdown. Drain valves should be installed on all discharge pulsation bottles and low points for the same reason. Most reputable compressor packagers design suction pulsation bottles to be self-draining to the cylinder nozzle as standard. This is especially important on an acid gas compressor where you want to be able to drain out all liquids after shutting the unit down.

Relief valve discharge headers are required. The compressor blowdown valve should be connected to this same header.

The purchaser should specify the number, size and type of corrosion coupons and/or corrosion monitoring points that are required, to ensure uniformity with the balance of plant. The compressor packager should select the locations where corrosion is likely to be the highest, such as a low point where liquid might collect, or a region of high velocity.

Proper handling of the fluids from the packing and distance piece vents and drains is essential. Figure 12 shows a typical set up, which includes a purge and vacuum pump. This push–pull approach is the best solution, even though each manufacturer has a slightly different recommendation. The purge gas pushes any potential leak towards a vent where it can be safely handled. The vacuum pump on the drain tank helps pull leaking gas into the vent system and is essential any time there is more than 5 psig (0.3 barg) back pressure on the vent system, such as when it is connected to a flare that has other sources attached to it. Using a liquid seal in the drain tank prevents excess packing leakage blowing back into the distance piece.

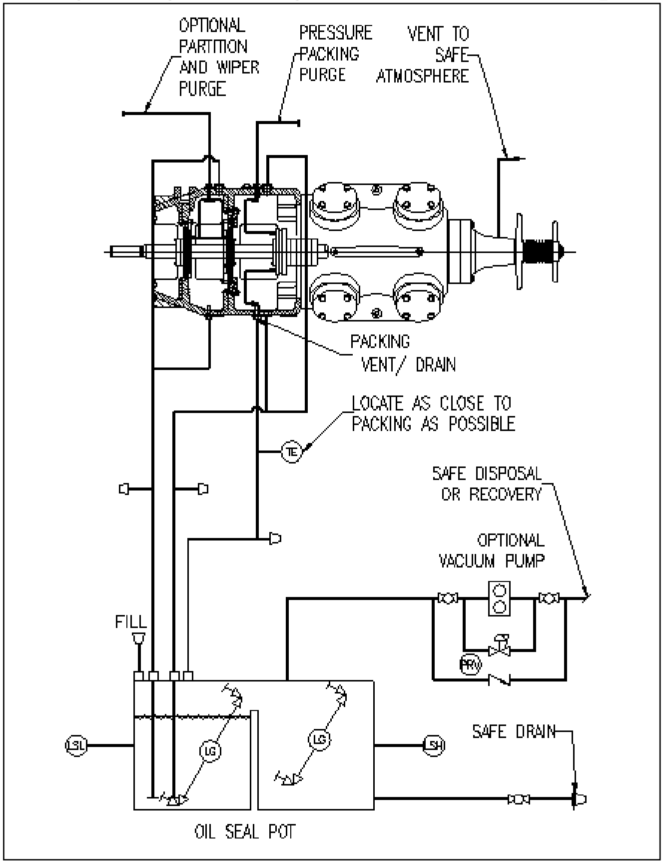


Figure 12. Diagram of Distance Piece Vent and Drain Handling System.

The compressor crankcase vent or breather should be piped away to a safe area to reduce acid gas fumes getting into the crankcase.

To provide maximum flexibility, drivers for acid gas compressors are typically variable speed. Some are gas engine drive, but the desire for reliability results in most being variable speed electric drive. To ensure the maximum operating speed range, it is often necessary to operate the compressor below its normal minimum speed. The minimum operating speed of a reciprocating compressor is set based on the crankshaft driven oil pump design. In order to operate below the minimum speed an external, electric motor driven, full capacity lube oil pump is added. Speed limitation is then only a matter of any torsional limitations. A detailed torsional analysis should be performed on all electric motor driven reciprocating compressors but it is even more critical with a variable speed application.

Compressor Controls

The controls around the acid gas compressor are similar to controls that might be found in other compressor applications, but there are some additional concerns that come with acid gas compression. The controls can broadly be broken into three different categories; start up and shut down control, capacity and pressure control, and temperature control.

Start Up and Shut Down Control

As discussed above, carbon steel is susceptible to corrosion when acid gas and liquid water are present on the steel surface. This corrosion may occur rapidly and lead to substantial wall loss in the affected area of the system so it is important to minimize the chances for corrosion to occur in carbon steel parts of the compressor system. This is commonly accomplished using automated valving around the compressor system. On shut down of the compressor system, the compressor is isolated by closing automated valves on the inlet and outlet of the compressor.

After isolation, the compressor should be blown down by a different automated valve that can route the venting acid gas to a safe location. The blown down acid gas will be extremely cold (potentially below -100 °F) at the start of the blow down operation and a safe location should be carefully vetted to be sure that there is no potential for the gas blowing down to freeze water unintentionally or vent in low-lying areas. After blow down is complete, the compressor should be purged with a dry gas, such as fuel gas or nitrogen, to further reduce the potential for a liquid water phase to form in an acid gas atmosphere.

Settle out pressure is also important in this application. The very high compression ratio across the entire compressor means that there is a large mass of compressed gas (or fluid in the case of the supercritical stage) that, if allowed to equalize across the entire compressor, can overpressure vessels and cause relief valves to lift on every shut down. The acid gas system designer needs to calculate the settle out pressure of the compressor and determine if it will be below the maximum allowed working pressure (MAWP) of all vessels in the entire compressor system. If the settle out pressure is above the MAWP of any of the vessels, the compressor should be blown down on a shut down before opening the recycle valves or start up bypass valves.

Capacity and Pressure Control

The amount of acid gas produced by the upstream acid gas removal unit will vary as the incoming gas flow rate changes, as the fraction of CO_2 and H_2S coming into the acid gas removal unit changes, and as the performance of the acid gas removal unit changes. The acid gas compressor system needs to be able to respond to all of these different scenarios by controlling the suction pressure to the compressor. Capacity control on reciprocating compressors can be done in a number of different ways; the compressor motor or engine can be slowed down to rotate the compressor more slowly, pockets can be opened on the compressor cylinders or entire cylinder head ends can be deactivated by unloaders that are actuated automatically or manually, or acid gas can be recycled around the compressor.

An engine will usually have a minimum speed of 70-80% of the design speed of the engine, while a variable frequency drive (VFD) will be able to operate the compressor at a much slower speed, perhaps as low as 20-25%. It may be difficult for the compressor to operate at that low of a speed due to lubrication system limits of crankshaft driven oil pumps and there can also be natural frequencies at different speeds (critical speeds) that can cause very high vibrations in the compressor that need to be avoided. Pulsation studies also need to be completed across the entire speed range of the compressor. A common minimum limit on compressor speed is 50% of the rated speed of the compressor frame to be sure that the crankshaft driven oil pump can still operate correctly. Lower speeds may require the installation of an electric motor driven auxiliary oil pump.

Head end deactivation is accomplished by either opening a port on the compressor cylinder to return gas to the suction passage or suction pulsation bottle or by holding the compressor suction valves open during the compression stroke of the piston. Head end deactivation is most commonly done on the first stage cylinder(s) of the acid gas compressor and effectively reduces the cylinder capacity to 50%. Fixed volume head end pockets will open to increase the clearance volume of the head end of the compressor cylinder so that less gas is compressed per stroke of the compressor. On large compressor cylinders, more than one pocket can be installed and together the pockets can reduce the capacity of the head end of the compressor to less than 60% of design. Fixed volume pockets are normally actuated pneumatically. Variable volume clearance pockets (VVCPs) are also installed on the head end of the cylinder and are turned manually by personnel to open or close the pockets as needed to adjust capacity. VVCPs are only adjusted while the compressor is offline though, so the ability to make adjustments quickly is limited. All of these devices have packing that can leak to atmosphere, so there is some potential for an unwanted leak to atmosphere with these devices.

Recycle around the acid gas compressor is possible and done routinely, but it needs to be carefully engineered to avoid the formation of hydrates, liquid formation from condensed acid gas, or very cold and dense gas at the inlet of a compression stage. Acid gas from the discharge of a cooler expanding from a high pressure to a low pressure will result in cold temperatures (the Joule-Thompson Effect), which can lead to phase changes in the acid gas or the formation of hydrates. The Pressure Enthalpy (PH) diagram of the compression process in Figure 13 illustrates this phenomenon well when considering recycling gas from the discharge of the compressor to the inlet of the fourth stage of the compressor.

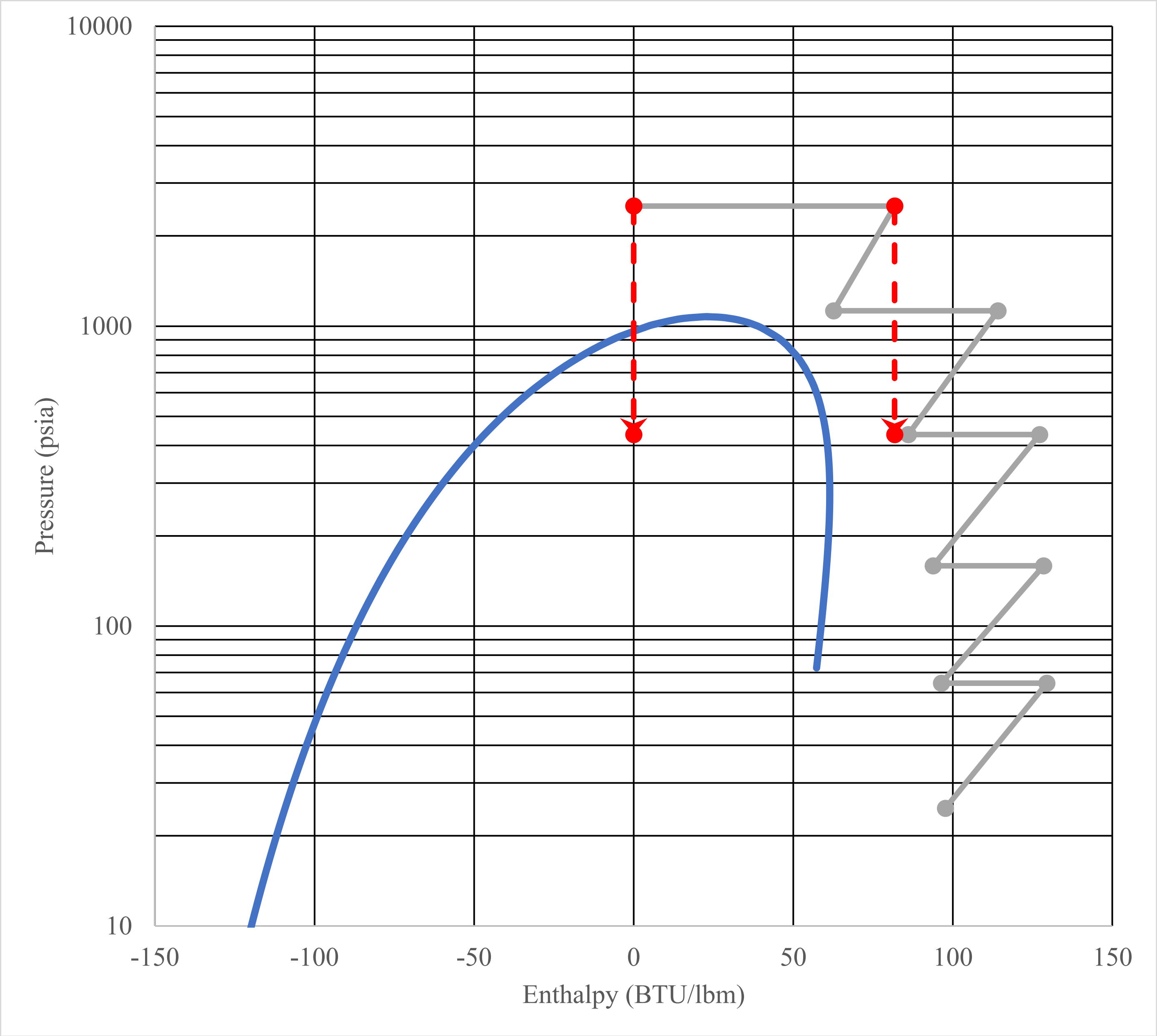


Figure 13. Pressure vs. Enthalpy (PH) Diagram of Recycle Around Acid Gas Compressor.

Recycling gas from the discharge of the Aftercooler down to the inlet of the fourth stage pressure results in a two-phase mixture of liquid and gas at 24 °F, which cannot flow through the compressor without risking damage to the machine. Recycling gas from the discharge of the fifth stage before the Aftercooler to the inlet of the fourth stage will result in a single phase gas stream at 105 °F, which is very near the design inlet temperature of the stage and is the appropriate source for recycle gas.

Recycle must be done across the entire compressor though, and recycling gas from the third stage discharge to the inlet of the compressor also needs to be checked to be sure that the recycled gas is at an appropriate temperature. Again, the PH diagram in **Figure 14** shows this graphically.

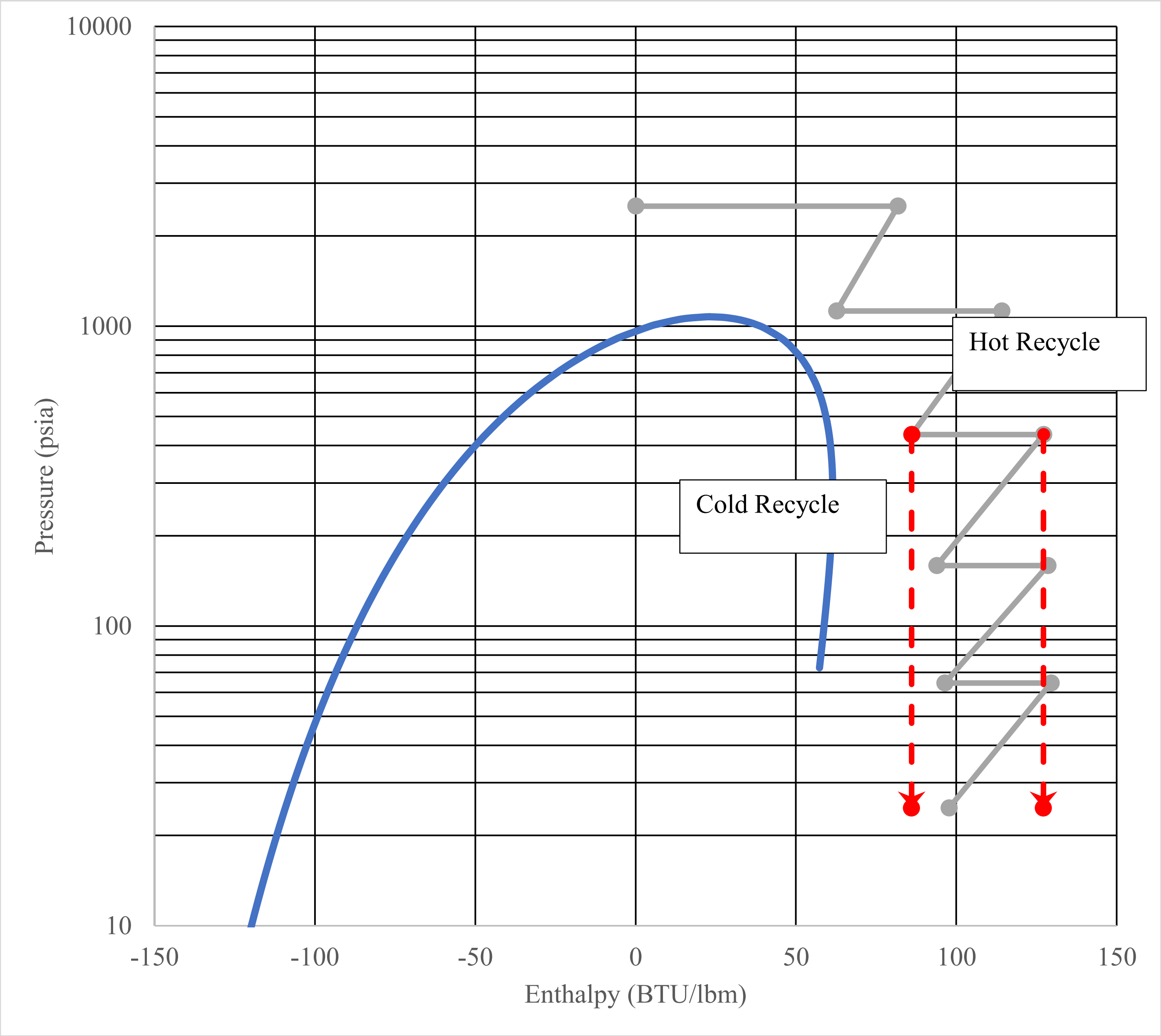


Figure 14. Pressure vs. Enthalpy (PH) Diagram of Recycle Around the Compressor.

Recycling from the fourth stage inlet of the compressor to the inlet of the compressor results in a gas flowing back to the compressor at 65 °F, which may or may not be acceptable for the compressor. Recycling gas from the discharge of the 3rd stage before the interstage cooler will result in a gas flowing back to the compressor at 259 °F, which is too hot for the compressor. If 65 °F is too cold for the compressor, some alternate methods may be utilized to achieve a more suitable recycle temperature.

1. Hot gas upstream of the compressor cooler may be blended with cold gas from downstream of the compressor cooler. This is usually accomplished with two control valves on either side of the compressor cooler blending gas together upstream of a final control valve. The temperature blending valves have a low differential pressure across them and the large pressure drop is taken across the final control valve.
2. Hot gas can be recycled through a control valve and then a cooler to get the gas closer to ambient temperature.

Either of the methods outlined above can work; the gas blending operation requires tight temperature control on the intercooler even in winter operation while the recycle cooling option requires extra capital investment. The system designer needs to weigh the benefits and drawbacks of each option.

Temperature Control

Reciprocating compressors in acid gas service are multiple stage compressors. Compression through each stage increases the temperature of the gas and it is necessary to cool the gas before it flows to the next stage to protect the soft parts of the compressor and to maximize the efficiency of the compression process. In acid gas compressors, it is possible to over-cool the gas in the interstage coolers, which can lead to the formation of hydrates or even partial liquefaction of the gas. Many acid gas compressors use air coolers as the interstage heat exchangers. The exchangers are normally mounted in the same air cooler bay and cooled by the same fans. Extensive controls are required in order to keep the acid gas warm enough, but not too warm, throughout the compression process. Temperature control is accomplished with variable speed fans, automated louvers over each gas cooler, and hot air recycle in colder climates. In addition to preventing hydrate formation and gas liquefaction, maintaining temperatures in the compressor system will provide for reliable recycle operation as noted above.

Operation and Maintenance Concerns

Generally, expected uptime for a reciprocating compressor is 98% or higher. The main culprit making this statistic not fully 100% is the driver of the equipment. Engines may be sensitive to their surrounding environment, such as encountering large temperature swings from day-to-night during seasonal changes, as well as other variables such as fuel gas, combustion/exhaust tuning, and others. Compressors used in AGI applications are mostly driven by electric motors. Motors tend to be sensitive to over-horsepower events due to off-design conditions. It is important to consider off design conditions during the initial stages of the project and to establish an expected operating envelope of suction/discharge pressures and temperatures for the compressor, so the motor can be sized properly. Best practice and industry standard is to apply a 10% margin over the greatest compressor power demand for the driver selection. For electric motor drivers, this 10% margin can be applied to the motor rated horsepower, or to the Service Factor. If applied to the Service Factor, a specific review is required with the motor and motor controller suppliers to ensure continuous operation within Service Factor can be allowed. This 10% margin is a selection criterion to account for the variables affecting power demand and power supply. This is not meant to limit the use of the available driver power.

Reciprocating compressors must undergo periodic maintenance just like any other piece of rotating machinery. The maintenance intervals will depend on if the compressor is intermittent duty or continuous duty, meaning if the compressor starts/stops frequently or if it runs without stopping for long periods of time. AGI applications are almost always continuous duty. Typical maintenance intervals for continuous duty are every 4,000 hours or 6 months. This is to change compressor frame lube oil. An engine will typically follow this same maintenance interval. At 8,000 hours piston rings, packing, and valves are suggested to be inspected and at 16,000 hours they are usually replaced. At 32,000 hours, inspection of the crosshead/conrod bushings and of the piston ring grooves is necessary. Lastly, the major maintenance interval to overhaul the compressor is 48,000 hours (24,000 hours for aluminum bearings/bushings depending on the compressor OEM). This is to replace main/connecting rod bearings, connecting rod/crosshead bushings, auxiliary end torsional damper (if applicable), and lubricator distributor blocks. There are many other important checks to perform at these maintenance intervals, such as frame oil sampling. The ones mentioned are just the highlights. Refer to OEM maintenance and repair manuals for frame specific guidelines.

Example Installation

For the example case followed throughout this paper the final installed AGI compressor system is capable of compressing 6 MMSCFD of acid gas from a suction pressure of 10 psig up to a discharge pressure of 2,500 psig. To accomplish this, the entire AGI compressor system will consist of:

- A six-cylinder, five stage reciprocating compressor.
    - The first stage will be two of the cylinders working in parallel and each subsequent stage will be a single cylinder.
    - Piston rod and valve materials will be upgraded metallurgy to reduce corrosion.
    - The compressor will have separate frame and cylinder oil systems and the cylinder oil will be compatible with the acid gas stream. It is likely that the cylinder oil will be a full synthetic oil.
    - The compressor will use long two-chamber distance pieces with purged seals to maintain separation between the frame the cylinders to minimize the potential for acid gas leakage into the non-pressurized parts of the compressor.
    - Yellow metals will be allowed in the frame.
    - The compressor will come with manual variable volume clearance pockets (VVCPs) on the stage 1 cylinders.
- An 8-pole electric motor driven by a VFD.
    - At full speed, the compressor will rotate at 891 RPM and be capable of compressing 7.77 MMSCFD of acid gas. This will be at a slightly higher piston speed (891 ft/min) than the specification of 850 ft/min, but for the initial design case, the compressor will rotate at a slower speed.
    - At a flow rate of 6 MMSCFD, the compressor will rotate at 689 RPM with a piston speed of 689 ft/min.

    - At a minimum speed of 600 RPM with the stage 1 VVCPs open, the compressor will process 4.4 MMSCFD.
- An air-cooler bay with heat exchangers downstream of each stage of compression.
    - Fan motors powered by VFD.
    - Exchanger tubes and header boxes constructed of stainless steel or other alloy piping.
    - Automated louvers on each exchanger bundle.
    - Hot air recycle system.
- Recycle valve system with a single valve from the fifth stage discharge (hot side) to the fourth stage inlet and then a temperature blending system supplying hot gas from the third stage discharge and supplying cold gas from the 4th stage inlet to a final control valve that lets gas down to the first stage inlet of the compressor.
- Stainless steel or other alloy piping on all cold piping and vessels within the compressor system. Carbon steel piping and vessels on the hot side of the compressor system.