Compression options for carbon capture

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The promise and potential of hydrogen as key to a carbon free energy economy has generated significant development of technologies to efficiently produce, transport, store, and utilise hydrogen. Because of cost and logistical advantages, most hydrogen entering the market over the next 15 - 20 years will be blue hydrogen derived from fossil fuels such as natural gas, as opposed to green hydrogen derived from alternative energy sources.

For every kilogram of blue hydrogen produced through steam reforming or partial oxidation gasification, or derived from power plant post-combustion flue gas separation or other industrial processes, about 10 kg of CO_2 is also produced. This CO_2 needs to be compressed from near atmospheric conditions to pipeline operating transport pressure, and then to geological formation storage pressure for long-term sequestration. Consequently, the race toward a low-carbon economy has fuelled the need for added new CO_2 compression capacity for separation, pipeline transport, and storage injection.

Although CO_2 compression has been successfully performed for many years in the oil and gas industry's enhanced oil recovery projects and acid/sour gas injection, the quantity scale of compression required for carbon separation, transport, and sequestration challenges the current state-of-the art.

One promising technology for these applications is a hybrid combination of a centrifugal compressor to compress the gas slightly above its critical point, in series with a dense-phase pump to reach the desired process discharge pressure. Both low-pressure CO_2 compressors and dense-phase pumps are proven technologies, but their hybrid combination has not yet seen significant service in the industry.

Power generation

CO_2 is generated by the combustion or burning of fossil fuels including coal, oil, and natural gas in order to produce electricity. Power generation is responsible for over 40% of all energy-related emissions. Worldwide emissions of carbon dioxide from burning fossil fuels total about 33 billion tpy. About 44% of this is from coal, about 34% from oil and about 21% from natural gas.

Natural gas power plants produce about 1 lb of CO_2/kWhr of electricity, while coal plants produce about 2.5 lbs of CO_2/kWhr (EPA, 2019). These numbers can vary significantly based on an individual plant's efficiency. Thus, a typical 500 MW natural gas combined cycle power plant will usually produce 1 - 2 million tpy of CO_2, depending on its duty cycle (equivalent full load running hours per year) and efficiency.

Technologies and processes exist to capture the CO_2 from the power generation flue gas, which is currently separated and released as a pure stream into the atmosphere (Figure 1).

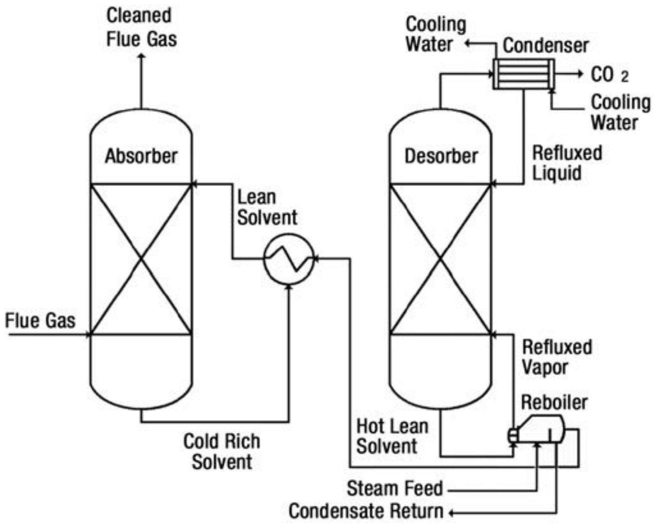

Figure 1. Flue gas separation.

Hydrogen production

The majority of hydrogen (95%) is produced from fossil fuels by steam reforming of natural gas, other light hydrocarbons, and coal gasification. In the steam reforming process, natural gas is reacted with steam at an elevated temperature to produce carbon monoxide and hydrogen. A subsequent reaction – the water gas shift reaction – then reacts additional steam with the carbon monoxide to produce additional hydrogen and carbon dioxide.

- $CH_4 + H_2O \rightarrow CO + 3\ H_2$
- $CO + H_2O \rightarrow CO_2 + H_2$

The CO_2 that results from the steam reforming process is currently vented to the atmosphere.

CO_2 safety issues

CO_2 is an inert gas and is generally considered non-toxic. However, CO_2 is heavier than air and poses an asphyxiation risk. Figure 2 shows human exposure limits for CO_2. Oxygen detectors are required when working with CO_2 compression systems. Although CO_2 is non-toxic, its safe exposure limits may be governed by other impurities in the process mixture. In acid and sour gas applications, H_2S and SO_2 limits are regulated at ppm limits, and exposure limits may be in the order of seconds. For these cases, a special flaring capability may also be required.

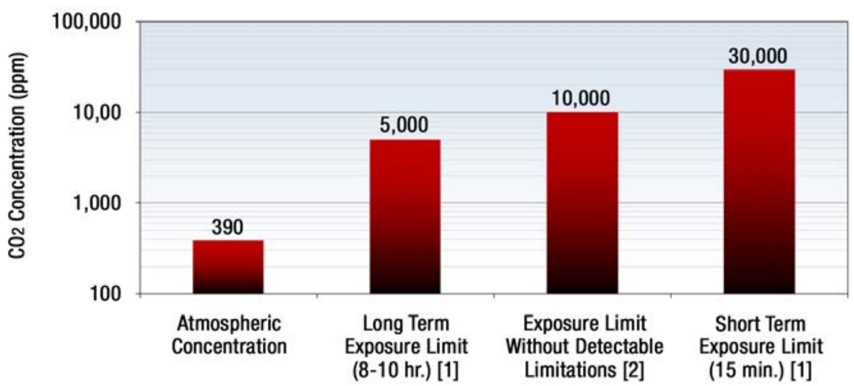

Figure 2. Human CO_2 exposure limits (Source: Brun et al., 2017).

CO_2 regulatory framework, codes, and standards

Beyond health and safety standards, there are several relevant codes and standards to consider when transporting carbon dioxide in a pipeline:

- Title 49 of the US Code of Federal Regulations Part 195 for pipelines transporting hazardous liquids.
- DNV-RP-J202, Recommended Practice on Design and Operation of CO_2 Pipelines.
- ISO 13623:2009, Petroleum and Natural Gas Industries – Pipeline Transportation Systems.
- DNV-OS-F101, Offshore Standard on Submarine Pipeline Systems.
- ASME B31.4, Code for Pressure Piping – Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids.

- ANSI B31.8 for gas transmission lines.
- API and ISO codes for machinery such as API 617, 618, etc.

This is not a complete list, but these items are a good starting point for relevant standards for CO_2 transport and compression.

A path forward

To reduce carbon emissions, the CO_2 generated from power plant applications and industrial processes such as acid gas reinjection, enhanced oil recovery and the production of natural gas, cement and fertilizer must be separated and captured either pre-combustion, or from the exhaust flue gas via a post-combustion process, and then transported and sequestered, or repurposed.

CO_2 is a heavy gas that is relatively easy to compress from a thermodynamic perspective. Power plant applications and industrial processes that generate CO_2 utilise some of the following compression duties:

- Pipeline header injection and re-compression transport.
- Injection into geological storage reservoirs for sequestration.
- Separation processes (membrane, thermal or chemical).
- Compression from the separation processes to pipeline pressure.
- Power plant cycle compression (Oxy and sCO_2 cycles).
- Pipeline boost compression.

These technologies provide important practical experience that can be extended to capture, transport, and store a significant fraction of the CO_2 generated from the combustion of fossil fuels. It is also important to recognise that CO_2 compression comes with technical challenges that must be individually addressed in the design process for large-scale industrial carbon capture and sequestration technologies.

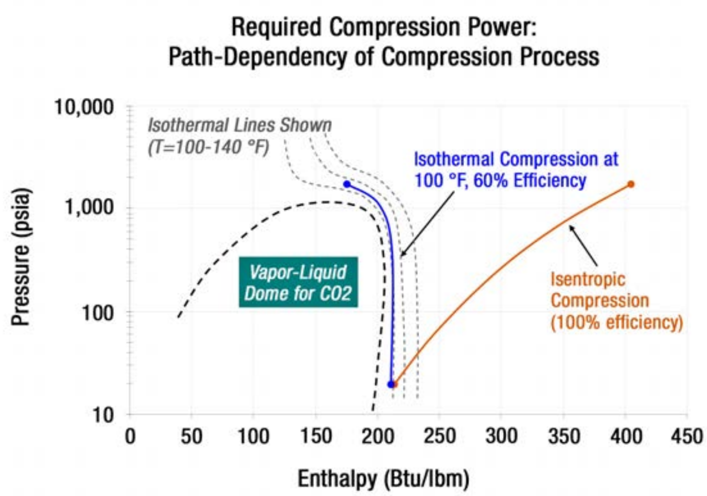

Figure 3. Isothermal vs isentropic compression.

CO_2 pipeline transport

For long distances, it is generally accepted that CO_2 should be transported as a supercritical fluid above 2100 psi in pipelines. At 2100 psi, CO_2 is well above its critical point in a supercritical (dense phase) state for almost all ambient temperatures. Fluids in a dense phase share some physical properties of liquids, such that they have a very low compressibility, and also some of gases, in that they will expand in space to fill voids. The advantage of transporting CO_2 at supercritical pressures is that its density does not change much with pressure, and from a thermodynamic perspective, it is basically pumped rather than compressed. The disadvantages of operating at these high pressures are the added injection compression ratio required at the pipeline header station and the significantly higher costs for materials to build a pipeline designed for maximum allowable operating pressures well above 2100 psi.

However, transport at 2100 psi is not required for all applications, and the actual transport pressure very much depends on the starting pressure at the separation process outlet, the distance the CO_2 must be transported, and the geologic sequestration injection pressure, which is often well below 2100 psi. Since the CO_2 available from separation is usually at low, near atmospheric pressures (<100 psia), the pipeline header station must always use a compressor.

A 2100 psi CO_2 pipeline requires a high-pressure ratio header compressor with many intercooled states that can handle the significant volume reduction. The gas is transported in dense phase, either by pump or by compressor in the pipeline beyond the header station. Conversely, if a lower-pressure CO_2 pipeline is used, conventional compressors are preferred for the header station, with recompression stations along the line. Clearly, selection of transport pressure depends on the carbon sequestration application, but it is not always advantageous to go to the pressure needed for a supercritical CO_2 pipeline.

Operating conditions for carbon sequestration

The pressure of the CO_2 gas from the separation process is strongly dependent on the type of separation process utilised, and can vary from slightly above atmospheric to several hundred psi. For example, CO_2 from a methane steam reforming process is produced near 30 psia, whereas from a gasification process, it is likely to be at pressures well above 150 psia. Flue gas separation is usually near atmospheric but can be as high as 20 psia. While there is a wide range of possible compressor suction pressures for a CO_2 compressor, most of the commercially viable industrial applications produce CO_2 somewhere between atmospheric and 50 psia.

There is also significant uncertainty about the compressor discharge pressure since it depends on whether the CO_2 will be transported as a gas or dense phase, or will be directly injected into a geological formation. Furthermore, the geological formation injection pressure strongly depends on the type of formation and its drilled depth of injection. For every mile of depth of injection, it is generally accepted that about

1800 psi of gas pressure is required. Since many of the geological formations being considered are relatively shallow, injection pressures well below 2000 psi are often the case. Nonetheless, a typical carbon separation and storage pressure application usually requires CO_2 to be compressed from below 50 psia to above 2100 psia. This assumes that most separation processes will produce CO_2 somewhere near or slightly above atmospheric pressure. For purposes of simplicity, a 30 - 2100 psia assumption will be used as a basis for a CO_2 transport compressor. This assumption may not be valid for all cases and is application specific.

Path dependence

Many viable thermodynamic path options exist to get from the start to the end point in this compression process, including near-isothermal, refrigeration and liquid pumping, and high-pressure ratio compression. Basically, one can compress the CO_2 and stay in the gas state on the right side of the vapour dome, refrigerate the CO_2, and pump it in the liquid state on the left side of the dome, or one can utilise a hybrid combination of the above two options.

Figure 3 shows this from an energy perspective. The total energy required for the compression process is simply the enthalpy difference (compressor head) multiplied by the mass flow. Clearly, an isothermal process (i.e. a process at constant temperature) will require significantly less power than an isentropic process (i.e. a process at constant entropy) since the enthalpy difference is drastically lower.

Turbomachinery design for carbon capture

Turbomachinery for carbon capture applications must satisfy many operational and performance requirements. These are primarily driven by the type of application, the service duty, and the plant's commercial and operational design requirements. Fundamentally, most carbon capture applications aim for low capital cost, wide operating range, frequent starts and stops, and a very high availability. Some of these requirements are inherently contradictory and require compromise design decisions.

A variety of compression paths and technologies for large-scale carbon storage applications exist. Some are commercially available, while others are still in development. One promising technology is a hybrid combination of a centrifugal compressor to compress the gas to slightly above its critical point, in series with a dense-phase pump to reach the desired process discharge pressure.

Conclusion

Part I of this article has addressed some of the challenges of CO_2 compression. Part II will present the use of a hybrid compressor and pump system for carbon sequestration and transport applications. This solution provides for significantly reduced power consumptions while maintaining the reliability and flexibility of barrel type machinery. Part II will be published in an upcoming issue of *World Pipelines*.

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