carbon capture journal

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CO2CRC H3 capture project
- investigating capture technology with Australian brown coal

Doosan Babcock OxyCoal test

CO2 compressors Special Edition
- GE Oil & Gas
- MAN Turbo
- Ramgen Power Systems
- Siemens

Accelerating CCS implementation in Alberta

TUV NEL report - flow measurement of CO2 will be challenging

CO2 Capture Project 'definitive' CO2 geological storage report

Scotland - Europe's CO2 storage solution?

Low-cost, high-efficiency CO2 compressors

Ramgen Power Systems is developing a unique shockwave compression technology for use on high molecular weight gases like CO2. The primary goal is a low-cost, high-efficiency CO2 compressor that will significantly reduce the overall capital and operating costs of CCS.

By Peter Baldwin, President, Ramgen Power Systems

CO2 compressors represent approximately 1/3 of the significant capital and operating cost of a post-combustion, amine-based CCS system. The CO2 compressor power required for a pulverized coal power plant is 8-12% of the plant rating, depending largely on the suction pressure.

A 1,000 MW PC plant would require 100 MW, or 134,000 hp for CO2 compression at an estimated $150 million equipment cost for today's 3 x 50% configuration. Installation costs at $75-100 million would be in addition.

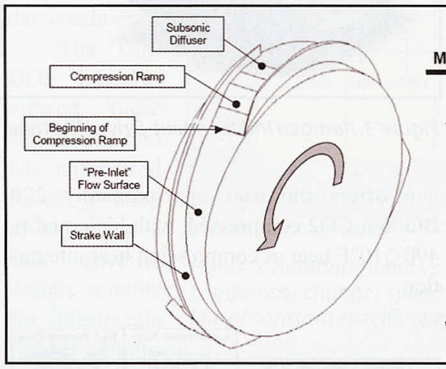


Figure 1. Supersonic compression stage rotor

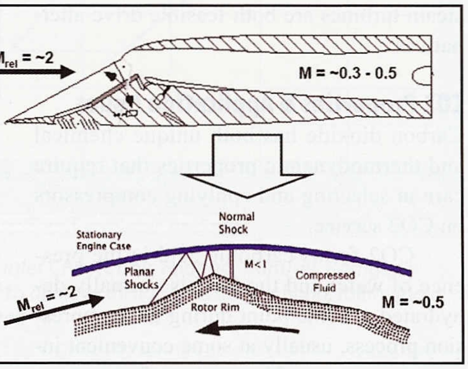


Figure 2. Shock structure and comparison to flight inlet

Ramgen Technology

Ramgen's shock compression technology is expected to represent a significant advancement in the state of the art for many compressor applications, and specifically for CO2 compression.

The principal advantage of Ramgen's shock compression, based on proven supersonic aircraft inlet design and shown "inverted" below, is that it can achieve exceptionally high compression efficiency at very high single stage compression ratios, resulting in a product simplicity and size that will lower both capital and operating costs.

The Ramgen Technology concept addresses the two key objectives identified by the U.S. Department of Energy for the Capture and Storage of CO2 – lower costs and improved efficiency.

The reason that existing CO2 compressor designs are so expensive is, in part, because the overall pressure ratio is anywhere between 100:1 and 200:1, and, in part, because CO2 requires stainless steel construction in the presence of water vapor. The most significant impact on cost however, is an aerodynamic design practice that limits the stage pressure ratio on heavier gases such as CO2.

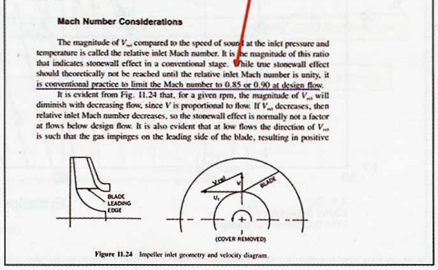
The Importance of Mach#

Standard turbomachinery design practice is to limit the inlet flow Mach# to less than 0.90 at the inducer blade tip to avoid generating shock waves in the blade passages and the accompanying losses that they would generate.

Designers typically do this by adjusting the stage speed and/or diameter.

The Mach number itself is a function of molecular weight and therefore this effect occurs at lower tip speeds and becomes more pronounced on the "heavier than air" CO2. The resulting lower inducer tip speed limit results in a pressure ratio per stage limit of approximately 1.7 to 2.0:1 on CO2. At these stage pressure ratios, eight stages of compression are typically required to reach an overall pressure ratio of 100-140:1, and ten stages up to 200:1.

Furthermore, conventional integrally geared designs need to be intercooled between each compression stage. The heat of compression discharge temperature associated with these very low stage pressure ratios is approximately 200°F, which, as an inlet to the next stage, is too hot to achieve good efficiency, but lacks the thermal driving force for cost-effective heat exchanger selection. This heat is also of insufficient quality to be of practical use elsewhere in the process. The only option is to reject virtually all the compressor electrical input power to the coolant through heat exchangers and supporting cooling towers or fin-fan radiators, themselves a significant capital and installation expense.


effect is normally controlled by impeller-inlet vector geometry. In Fig. 11.24, vector U_1 may be drawn to represent the tangential velocity of the leading edge of the blade similar to ... of the in... radially (... relative to ... V. At de... shown.

...it is conventional practice to limit the Mach# to 0.85 or 0.90 at design flow.

Mach Number Considerations

The magnitude of V_{rel} compared to the speed of sound at the inlet pressure and temperature is called the relative inlet Mach number. It is the magnitude of this ratio that indicates stonewall effect in a conventional stage. While true stonewall effect should theoretically not be reached until the relative inlet Mach number is unity, it is conventional practice to limit the Mach number to 0.85 or 0.90 at design flow.

It is evident from Fig. 11.24 that, for a given rpm, the magnitude of V_{rel} will diminish with decreasing flow, since V is proportional to flow. If V_{rel} decreases, then relative inlet Mach number decreases, so the stonewall effect is normally not a factor at flows below design flow. It is also evident that at low flows the direction of V_{rel} is such that the gas impinges on the leading side of the blade, resulting in positive

Figure 11.24 Impeller inlet geometry and velocity diagram.

Source: Compressed Air & Gas Handbook

The actual intercooler selection is made even more difficult by the need for low-pressure drop designs and the requirement to use low heat transfer effectiveness corrosion-resistant stainless steel construction. Air-cooled heat exchangers, often required in cold or arid climates, exacerbate the problem with their generally lower approach temperatures and require substantial fan horsepower, often overlooked in the "compressor" power evaluation.

The Ramgen concept offers matched sets of independent-drive, single-stage compressors instead of a conventional integral gear compressor configuration with a common bull gear drive. Each of the stages can achieve a 10+:1 pressure ratio. An intercooler is used between the LP and HP Stages and an aftercooler is used after the HP Stage. The high-pressure stage is shown in Fig. 3 along with a typical T-s diagram for a two-stage configuration.

These stage discharge coolers can be the CCS process itself. Cost effective heat integration, enabled by the high quality heat of compression associated with the 10:1 compression ratio, can substantially improve the economics of CCS. The Ramgen LP and HP Stages can provide approximately 270 Btu/lbm- CO2 for a variety of heat integration options.

At a minimum, this independent-drive approach allows better matching of each stage to its specific process flow, including side-streams. In addition, this drive configuration approach lends itself to a variable speed capability that can provide desirable operational flexibility.

The Ramgen baseline drive utilizes a conventional low-speed motor and simple, single-step external speed-increasing gearbox, with other variations available to suit customer and contract requirements. High-speed permanent magnet motor drives or steam turbines are both feasible drive alternatives.

CO2 Properties & Application Issues

Carbon dioxide has both unique chemical and thermodynamic properties that require care in selecting and applying compressors on CO2 service.

CO2 forms carbonic acid in the presence of water and the CO2 is normally dehydrated at some point during the compression process, usually at some convenient interstage pressure. The amount of water considered acceptable is subject to some debate, but current system guidelines issued by the U.S. Department of Energy call for -40°F dew point. Stainless steel construction is typically required in the presence of water.

CO2 can also infiltrate elastomers, which then suffer decompression damage from incomplete out gassing analogous to divers getting "the bends". Suitable seal, gasket and o-ring materials are available and have been applied successfully.

Intercooler selection and operation require great care. Good design practice maintains a minimum 20°F superheat at the inlet of each compression stage to avoid the CO2 two-phase region, or that of the impurities within it. In practice, experienced operators maintain stage inlet temperatures between 95°F and 100°F, and 1600 psia is considered to be the minimum discharge pressures to insure that all impurities are above their critical pressure.

Eight or ten-stage designs are particularly sensitive to this two-phasing effect because the margin between the compressor-stage discharge pressure and the two-phase region in and around the critical point, shown in red, is both small and somewhat unpredictable, depending on impurities.

The proximity of the line of constant 100°F temperature to the CO2 vapor dome in the pressure-enthalpy diagram show in green (Fig. 4) illustrates the challenge of fully intercooling the later stages of multi-stage designs. Ramgen, on the other hand and shown in blue, operates in regions very much removed from the critical point.

At the same time, the enthalpy associated with these CO2 state points does offer a significant opportunity for heat recovery on both the Ramgen LP and HP stages. Ramgen offers the user approximately 270 Btu/lbm-CO2 compressed, with high quality 490-510°F heat of compression heat integration.

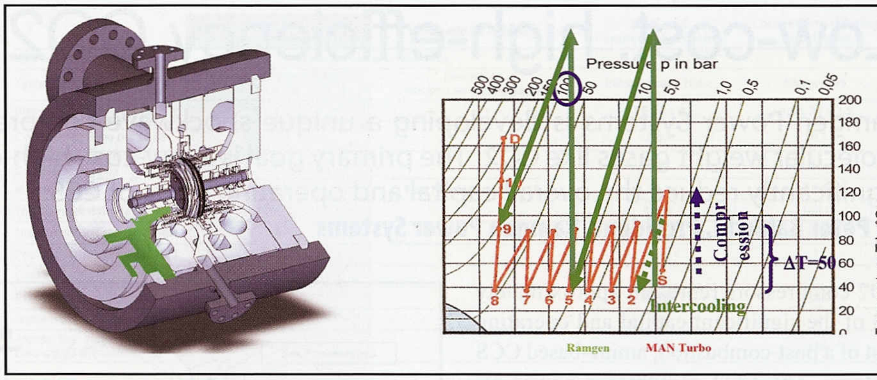


Figure 3. Ramgen Independent-Drive HP Stage

	Low Pressure Stage 22 - 220 psia	High Pressure Stage 220 - 2200 psia
Compressor Shaft Input Work	90.6 Btu/lbm	87.0 Btu/lbm
Discharge Temperature	489 °F	509 °F
Lower Recovery Temperature	100 °F	100 °F
Recovered Heat	92.4 Btu/lbm	178.8 Btu/lbm
Recovered Heat/Compression Work	102%	205%

Compressor Performance Issues & Assumptions

Compressor performance calculations are relatively straightforward. The assumptions behind them are not.

The specification generally provides the basic input of mass flow, gas composition, inlet pressure and temperature, and discharge pressure, but invariably overlooked are the cooling medium available and its temperature. The CCS process itself only controls the first stage suction conditions; the cooling medium controls the others.

A good assumption for pressure drop is , but not to exceed 5 psi. Coolant temperature is only relevant to determining subsequent stage inlet temperatures and coolant flow rates. In the case of CO2, experienced operators generally assume interstage temperatures of 100°F to avoid the two-phase regions and control it at that level.

Configuration assumptions are required beyond these generic values and include sparing philosophy, or stated differently, how many units are required to meet the mass flow specified.

Ramgen will develop a series of LP and HP frame sizes to support both amine-based and the ammonia-based capture technologies, as well as any capture technologies that might emerge. The planned LP and HP sizes would be able to support the full capacity 800MW unit in a single set of units.

Ramgen's Competitive Advantage

Ramgen's technology has both capital and operating cost advantages.

- Ramgen expects to be 50-60% of the conventional integrally-geared centrifugal compressor on an installed cost basis.
- The Ramgen two-stage configuration will require approximately the same shaft in-

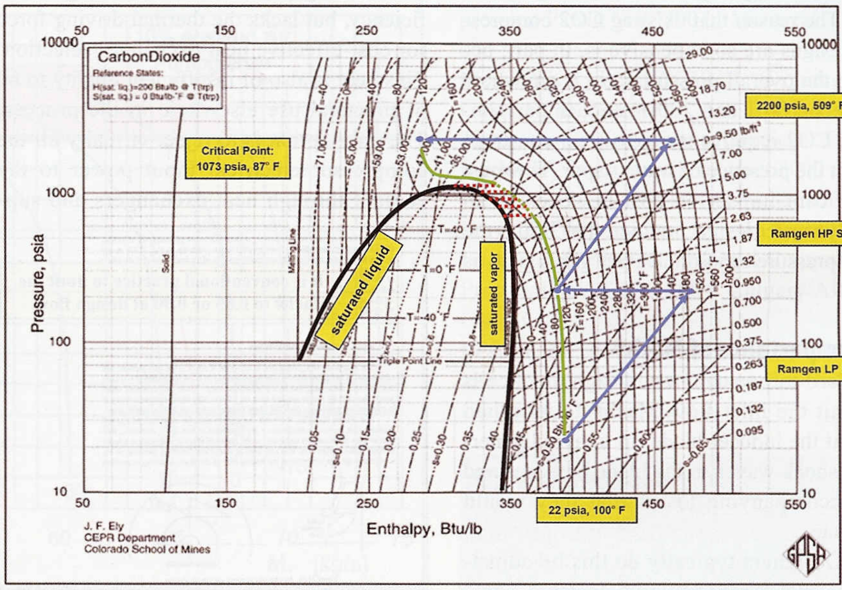


Figure 4. Pressure-enthalpy diagram

put power as the eight or ten-stage equivalent when realistic interstage temperatures are considered and realistic pressure drops associated with intercooler are included.

• Heat recovery can be of significant value when fully integrated at scale. The Ramgen two-stage configuration has a nominal discharge temperature of 500°F vs. conventional integrally-geared designs of only 200°F.

• The Ramgen design can actually take advantage of colder inlet temperatures and resulting lower power consumption, if available. The Ramgen interstage pressures are nowhere near the critical point and the associated two-phase concerns. Ramgen may be able to run on colder interstage temperatures, which could further enhance its efficiencies.

• Shock compression is a near-instantaneous phenomenon. As long as the discharge pressure is above of the critical point of all the constituents in the gas mix, concerns over two-phase flow should be minimized.

• The two-stage intercooled log mean temperature difference (LMTD), a key determinant of surface area required, will be 3x that of the integral gear designs resulting is coolers that require 1/3 the surface area to achieve the same cooling effect.

• Ramgen should be substantially smaller footprint

• High power drives are of limited availability and are expensive. Ramgen's independent drive configuration should allow for improved motor selection options.

Technology Status

The company completed its Rampressor-2 effort, a definitive aero test program where it demonstrated world-record level performance of a single-stage rotor, validating our advanced Computational Flow Dynamics (CFD) analysis and design tools on air, and proving a flow path directly traceable to the intended CO2 compressor.

The "as-built" rotor was predicted to produce a pressure ratio of 8.1:1. The test resulted in a measured value of 7.8:1, and the CFD correlated almost exactly to the test day conditions.

The U.S. DOE has reviewed these test results and has authorized Phase II work to begin on a CO2 specific design, suitable for pilot-scale field demonstration.

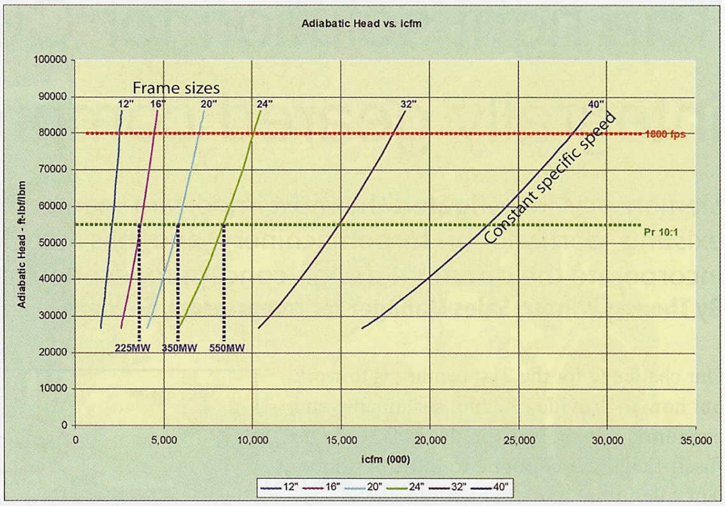


Figure 5. Adiabatic head vs inlet CFM (Cubic Foot per Minute). Ramgen's compressor changes speed to achieve design pressure or head, following a line of constant specific speed

Of considerable importance is that the design tip speed of the 10:1 pressure ratio CO2 compressor rotor is only ~1500 ft/s and sufficiently low to allow for a shrouded rotor design concept. A shrouded rotor will be used to eliminate tip clearance issues, associated tip leakage effects, and greatly simplifies the mechanical design.

Ramgen is currently planning to demonstrate its HP Stage at a commercial size of 8-10MW. This unit would be suitable for ~200MW coal-fired power plant. That program is scheduled for completion in 2012. We anticipate that by year end 2011, we will be able to make firm commitments for projects with commercial operating dates scheduled for the 2014/2015 timeframe.

We have investigated single train LP and HP Stages for 800MW coal-fired power plants and consider them both feasible and within our capabilities to scale and deliver.

Commercialization Plan

On November 10, 2008, Dresser-Rand Group Inc. ("Dresser-Rand") (NYSE: DRC) announced that it had made an investment in Ramgen Power Systems, LLC, and further expects to support Ramgen's ongoing development work. Dresser-Rand's funding helped satisfy Ramgen's requirement with the Department of Energy's National Energy Technology Lab to obtain private matching funds for development.

Dresser-Rand is recognized as a leading compression technology company in the world and they are the ideal partner for Ramgen in completing the development of its supersonic shock wave compression. Dresser-Rand has the credibility and capability required for the scale of rollout that will be necessary to make a difference with CO2 emissions, widely recognized as the major contributing factor to Climate Change.

Dresser-Rand will bring its considerable resources to bear on commercializing the Ramgen technology. Of particular interest is that Dresser-Rand does have a large-scale test capability that could support testing of a commercial scale unit. D-R is also a world leader in the supply of steam turbine drives, which are of considerable interest as prime movers for the CCS compressor application.

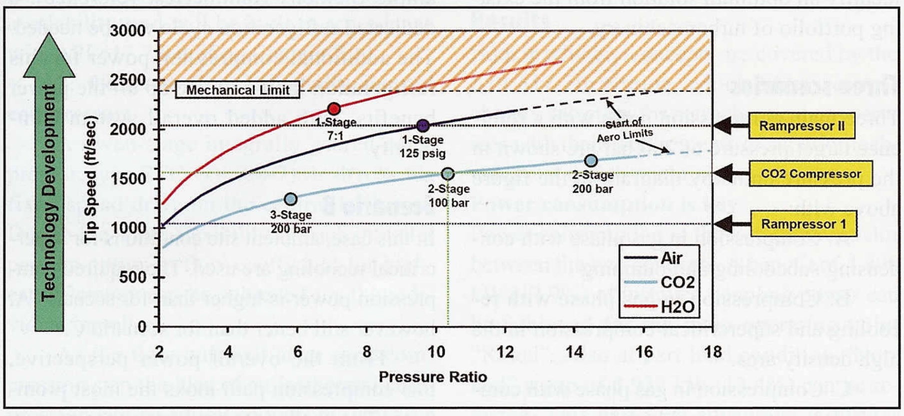


Figure 6. Technology development

More information

Ramgen's business is based on the application of supersonic aircraft engine inlet concepts and methods to ground-based air and gas compression applications.

www.ramgen.com
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