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TESTING OF GAS-LIQUID CENTRIFUGAL SEPARATION AND COMPRESSION TECHNOLOGY AT DEMANDING OPERATING CONDITIONS

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Mr. Maier has co-authored and presented papers at numerous technical conferences including SYMCOM, ASME IGTI, and TAMU Turbo-Symposium and currently holds thirty six US Utility Patents. He received a B.Sc. degree from Rochester Institute of Technology in Mechanical Engineering in 1981. He is a member of ASME, ΤΒΠ, and ΦΚΦ.

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Dr. Gilarranz actively participates in new project development and serves as the main technical and commercial contact between Dresser-Rand and its clients in the area of compact compression systems. Previously, Dr. Gilarranz was a Senior Aero/Thermo Engineer and was heavily involved in the design, specification and use of advanced instrumentation for development testing. He has also been engaged in shop and on-site testing of centrifugal compression packages for both dry and wet gas applications.

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ABSTRACT

This paper describes experimental testing of a Rotating Centrifugal Separator (RCS) integrated within the casing of a centrifugal compressor. This unique combination of rotary gas-liquid separation and centrifugal compression technologies represents a new class of turbomachinery and leads to increased system compactness by eliminating the need for large external gravity based separation/scrubbing vessels often used on traditional compressor trains. The OEM's closed-loop, multiphase flow test facility was used for measuring aero/thermodynamic and liquid separation performance of the system. The test loop utilized inert gas as the vapor phase component and a commercially available, stabilized liquid hydrocarbon based solvent as the liquid phase component. The phase of the test program discussed in the paper extends the separation performance data previously obtained for the RCS stage to more challenging separation conditions. The paper also discusses the application of this technology in two production type machines, and illustrates the intimate relationship that can exist between the processing side and the rotating equipment side of the oil and gas business.

INTRODUCTION

Conventional floating production storage and offloading (FPSO) systems are usually designed with all the equipment required to support the oil and gas activities arranged in modules (see Figure 1).

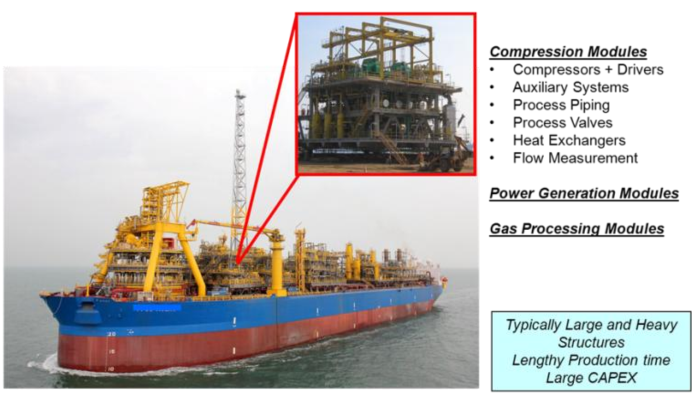

Figure 1. Typical FPSO Arrangement Using Conventional Compression Modules.

Typically several of these modules accommodate the compression and associated process equipment, while others accommodate power generation equipment, gas and liquid processing facilities, and liquid handling and boosting systems. The modules that accommodate the compression equipment include gas/liquid scrubbing equipment, compression trains, process piping, valves instrumentation and control devices, heat exchangers, flow measurement systems as well as the auxiliary equipment required to support the rotating equipment (lube oil system, seal gas systems, etc.). Several aspects of current design practices contribute to large module sizes. These include specified minimum straight upstream and downstream piping lengths between conventional gravity based gas/liquid separation and scrubbing equipment, heat exchangers and flow measurement devices. Further, the superposition of conservative sizing rules applied to individual components results in larger and heavier modules and support structures.

In recent years there has been an interest in reducing the size and weight of the compression modules by the application of novel technology and/or the implementation of new design rules that have emerged in the market place. Some examples are the compact, printed circuit heat exchangers, advanced multi-hole, pressure balanced flow meters, and high speed motors and magnetic bearings to eliminate the need for gear boxes and bulky lubricating oil systems. In addition, the use of hermetically sealed motor/compression systems, available from several compressor OEMs, often allows for the elimination of the gas conditioning system and dry gas seals.

Another target component in the size reduction efforts applied to conventional gas compression modules is the gas/liquid scrubbing equipment. Historically, gas dominated compression services have used static gas/liquid scrubbers composed of large vertical pressure vessels containing separation enhancing internals. These scrubbers are designed to protect the compression equipment from potentially damaging effects of liquids and suspended solids that can be part of the incoming gas stream (e.g. erosion, fouling, etc.). Combinations of various static scrubbing technologies are used in the internal components in these vessels. The choice of one technology over another may be based on the expected liquid loading of the gas entering the scrubber, the composition of the liquid and vapor stream entering the scrubber, the pressure at which the scrubber is operating, as well as the end-user preference. The selection of separator vessel diameter also plays a key role in overall separation efficiency (Campbell 2004). Scrubbers with larger vessel diameter generally have better separation efficiency. This of course means that effective gravity based scrubbers tend to project a relatively large footprint within the compression module. In general, for scrubbers operating at a pressure above 500 psia (35 Bara), the length-to-diameter ratio (L/D) of the scrubber vessel is usually set at a value of 5. The height of these vessels often extends vertically upwards to an extent that prohibits the installation of other equipment directly above them in typical multi-deck offshore modules. As process pressures increase, liquids become harder to separate, requiring further increases in scrubber vessel diameters. This increase in diameter compounds into even further increases in module weight and size due to required thickening of pressure vessel walls.

To address this key aspect of compression module size, a compressor OEM has developed a rotating centrifugal separator (RCS) that can be integrated within the casing of centrifugal compressors to provide the compressor stages with scrubber quality gas. The rotary drum of the RCS, directly mounted on the compressor shaft upstream of the first impeller, uses density-based separation of liquids and gases, enhanced by centripetal acceleration, similar to traditional static cyclonic separation devices. A major difference between the rotary separator and static cyclones is the magnitude of centripetal body forces used in the separation process. With a rotating drum, the RCS can achieve "G" forces that are an order of magnitude larger than static cyclones, making the separation system significantly more compact and capable of being integrated within the compressor casing. This potential difference in size is quantified in Figure 2 with a plot of characteristic volume versus Souders-Brown gas loading K factor for various separation technologies.

Thus, the integrated separator facilitates a significant reduction in the size and footprint of the overall compression train and associated gas/liquid separation equipment, while still providing sufficient protection to the compressor flow path. Details describing the technology and its development may be found in the works of Maier et al. (2010), Griffin and Maier (2011).

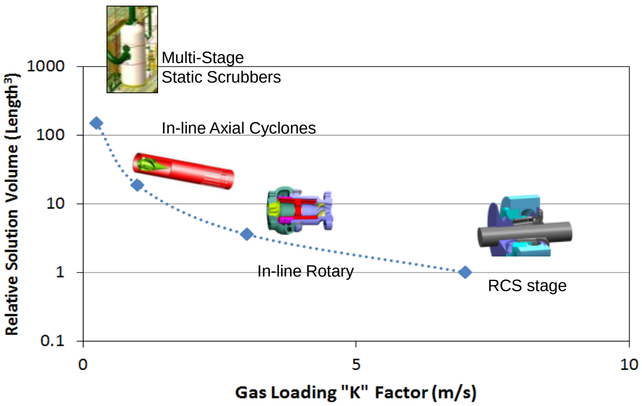

Figure 2. Comparison of Various Separation Technologies.

The elimination and/or size reduction of the process scrubber has also been considered for subsea compression applications. Figure 3 shows a traditional subsea compression process arrangement. In this system, a conventional, high efficiency gravity based scrubber is combined with the slug catching function and placed upstream of a motor/compressor system. The compressor boosts the vapor phase of the wet gas stream while the liquids removed by the scrubber are boosted by a subsea pump and recombined with the gas downstream of the compressor. As mentioned above for the case of topside equipment, sizing of the scrubber vessel to optimize the separation performance may result in a large vessel. For subsea applications, the compression and processing equipment has to be designed not only to safely contain the internal pressure of the process fluids, but also to accommodate the external hydrostatic forces acting on the outside of the components. For deep water applications, the external pressure can be as large (or even larger) than the process fluid pressures. The combination of large vessel size and the need to withstand both internal and external forces often results in very large and heavy vessels, which may be unattractive due to the problematic installation or intervention operations required.

Two alternative solutions have been developed to overcome this issue. The first solution is based on the removal of the scrubber/slug catcher vessel and subsequent use of a fluid pressure boosting system that can handle a multiphase fluid (Figure 4). This solution has the drawback of limited slug handling capability and reliance on problematic multiphase compression equipment. The second alternative is to retain a smaller primary separation and slug catching vessel and to use a wet gas tolerant compressor to boost the vapor dominant stream and a liquid boosting system (subsea pump, or pneumatic boosting system) to handle the liquid (Figure 5). For this OEM, the liquid tolerant compressor will include the integrated separator to perform the scrubbing function inside the compressor casing. When compared to alternate configurations that are intended to compress the wet gas directly, the integrated separator coupled with subsequent handling (or boosting) of the vapor and the liquid phases as separate streams allows for a reduction in the overall power consumption of the wet stream boosting system. Also, keeping the liquids out of the compressor flowpath allows for an increase in the availability and reliability of the compressor as it reduces the potential fouling and erosive agents that may enter the unit.

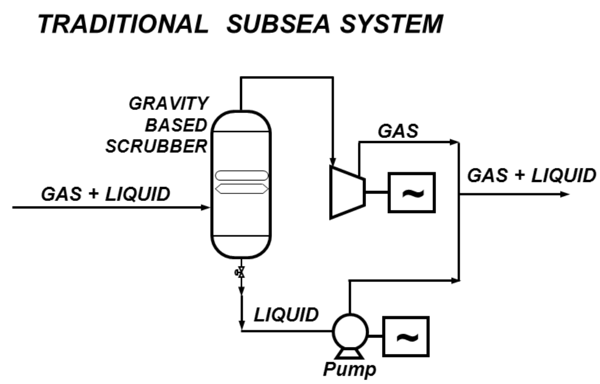

Figure 3. Typical Subsea Compression Process Arrangement.

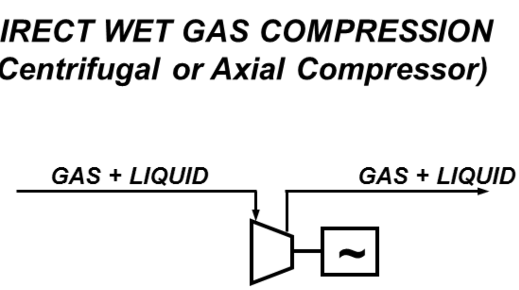

Figure 4. Subsea Direct Wet Compression Process Arrangement.

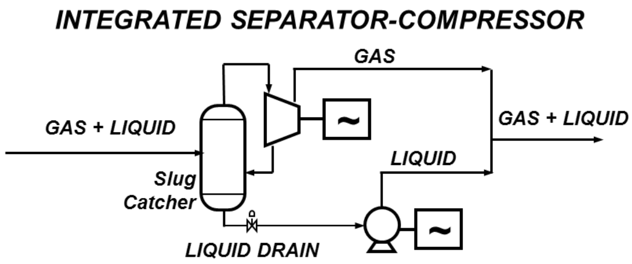

Figure 5. Subsea Compact Compression Process Arrangement.

Brownfields are another field of application where significant benefits can be realized through size and weight reduction of compression systems and associated process equipment. Here the operator needs to increase the compression capacity of the facility by installing additional compression trains. Brownfield facilities may have space and weight constraints as well as locational constraints due to the position of existing structures and modules. Often, there is barely enough space for a compressor and driver in one location and the scrubber must be located remotely requiring problematic piping routing. The RCS system solution favorably addresses these issues with only a minimal space and weight increase over a conventional compressor and driver alone.

TESTING BACKGROUND

Previous technical papers by Maier et al. (2010), Maier and Biba (2010), Griffin and Maier (2011) describing the development of the RCS stage have presented initial phases of combined analytical design and test campaigns executed on a scaled test rig (see Figure 6). This testing was used to optimize the separator stage geometry with an emphasis on maximizing separation efficiency while minimizing axial space claim of the separator. These previous tests series were performed at pressure levels between 40 psia (3 Bara) and 300 psia (20 Bara). This pressure limit was due to limitations of special flow visualization sight glasses in the inlet and discharge piping and to drive power limitations. The sight glasses were subsequently replaced with blind flanges and an alternate driver was installed to allow for the higher pressure testing, up to 550 psia (38 Bara), reported in the present paper.

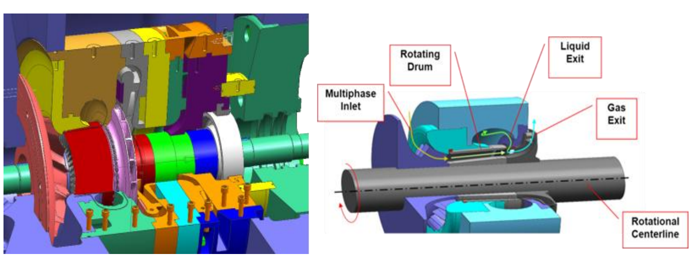

Figure 6. Solid Rendering of Separator Laboratory Test Rig.

Higher pressure testing extended the testing to higher ranges of Separation Parameter (SP′). This non-dimensional parameter was developed by the OEM (Maier et al. 2010) as a way to characterize the degree of difficulty of separation for rotating separator technology. SP′ is a primary parameter used by the OEM to screen potential applications of this technology. In addition to covering higher pressure testing, additional testing was done to further characterize the capabilities of the separator stage under both steady state conditions and under conditions that were intended to simulate sudden liquid ingress.

Further extension of the SP′ experience range and additional full scale separator test programs are currently underway as part of a joint industry program between the OEM and an oil and gas operator. This demonstration program includes testing of a 10 MW, hermetically sealed, motor/compressor for topside and subsea applications. This pilot test unit has nine stages arranged in two back to back sections of compression within a single body (intercooled). Figure 7 shows the compressor bundle and the rotor for the above referenced pilot unit during assembly. This image, showing the separator drums on each end of the rotor, clearly illustrates the compactness of an RCS solution relative to the conventional static scrubber technologies.

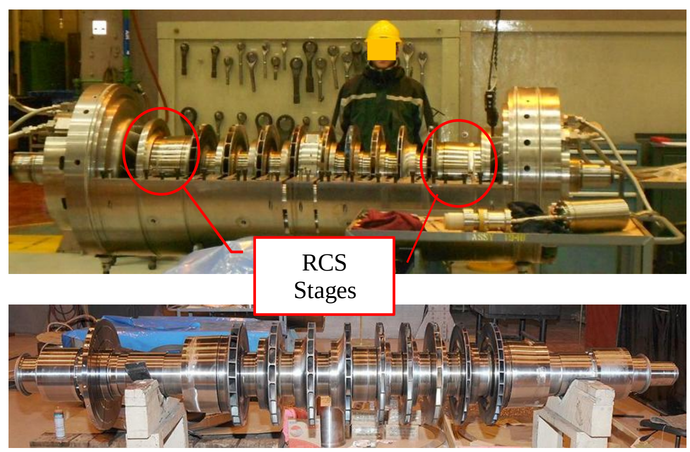

Figure 7. Pilot Unit Compressor Bundle and Rotor.

In addition to these test programs, the OEM has been selectively introducing integrated, centrifugal separation technology into the market. Figures 8a and 8b show a 3D model and the actual hardware built for a centrifugal compressor that incorporates the rotating centrifugal separator. This unit, completed in 2014 for an oil and gas operator, will be installed on an offshore platform in the Gulf of Mexico. The compressor designed for discharge pressure 1120 psia (77 Bara) and capacity 119 MMSCFD (3.36 MMSCMD) has seven stages of compression arranged in a straight through configuration with the first being an RCS stage. Separated liquids exit the casing via the liquid drain nozzle (Figure 8a). This unit was subjected to a factory acceptance test as part of the client's acceptance test requirements. The results of this testing and a comparison with analytical predictions are also presented in this paper.

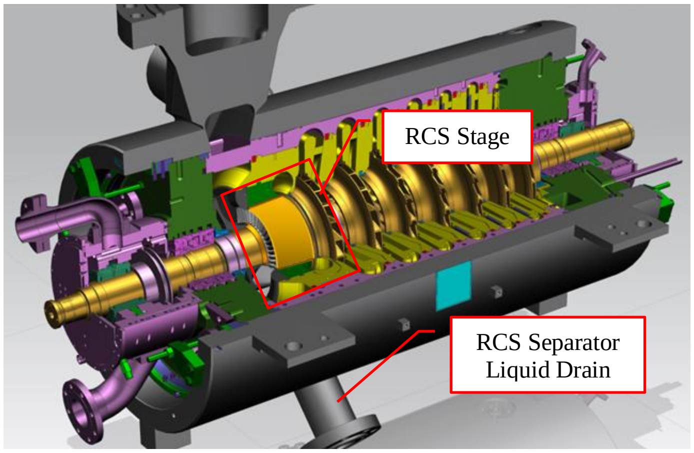

Figure 8a. 3-D Rendering of an RCS Integrated Stage for a Production, Offshore, GT Driven Compression Train.

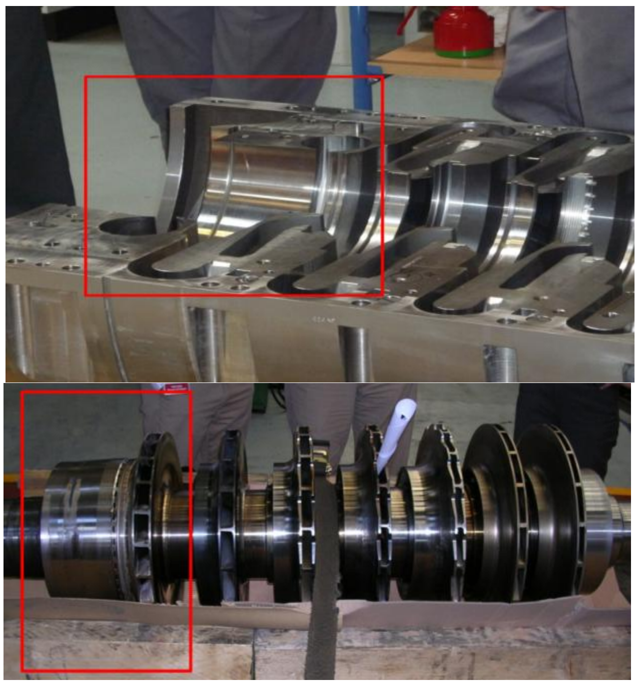

Figure 8b. Internal Components of RCS Integrated Separator for an Offshore, GT Driven Compression Train.

Table 1 summarizes information about the two test units covered in this paper.

Table 1. Test Unit Summary.

Test Name	Laboratory Test	Commercial Unit FAT
Dry (Type 2) Compression Performance Test	Yes	Yes
Separator Recycle On	Yes	Yes
Liquid Injection Test	Yes	No
Number of Compression Stages in the Unit	1	7
Driver	Steam Turbine	Test Driver
Average Impeller Diameter, inch (mm)	13 (330)	19 (483)
Nominal Sectional Power- Test Conditions, HP (MW)	1560 (1.15)	1448 (1.07)
Maximum Sectional Power- Field Conditions HP(MW)	N/A	14800 (11.0)

LABORATORY UNIT TESTING

Multi-phase Test Set-up

The laboratory testing reported on in this paper was done in the OEM's wet compression 2950 HP (2.2 MW) demonstration test rig previously described by Maier and Biba (2010). The test rig was instrumented to measure required process flow and thermodynamic parameters. A major change to the test loop was the use of two guard separators connected in series to reduce uncertainty of separation performance measurements. They are of a novel in-house axial swirl tube design where the main gas flow is directed downward. Other upgrades included a torque-meter for direct mechanical power measurement, and additional pressure and temperature measurements in the drain/ vent line of the separator. These changes can be seen highlighted in yellow in the test loop process flow diagram of Figure 9.

A torque meter allowed evaluating the impact of liquid content on the power consumed by the unit. Separation efficiency was measured with a mass balance on the liquid stream, comparing the amount of liquid introduced into the loop to the amount of liquid carryover. Liquid-related equipment includes a supply/receiver tank, a delivery pump, an injection port, flow meters, and secondary separators. The liquid injection port utilized an array of misting nozzles and was designed to provide dispersed atomized liquid flow with droplet size 100 micro inches. Further details of instrumentation placement around the RCS stage are shown in Figure 10.

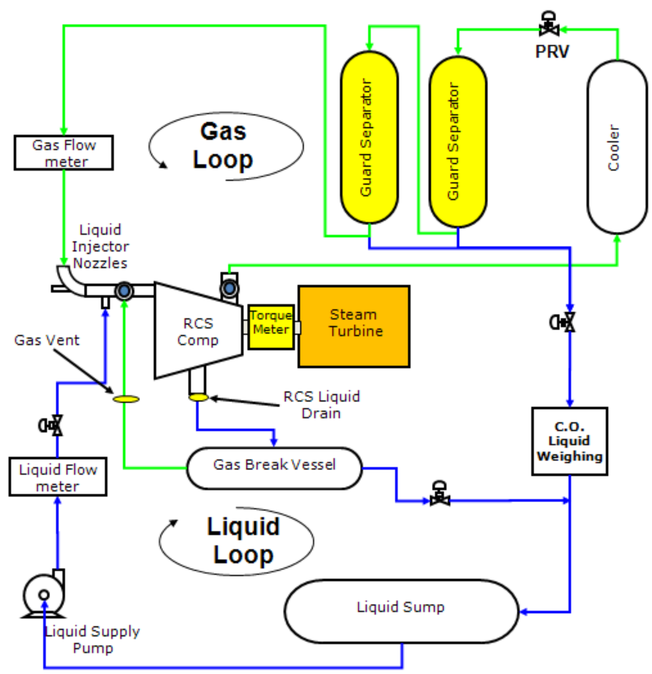

Figure 9. Process Flow Diagram of Experimental Test Set-up.

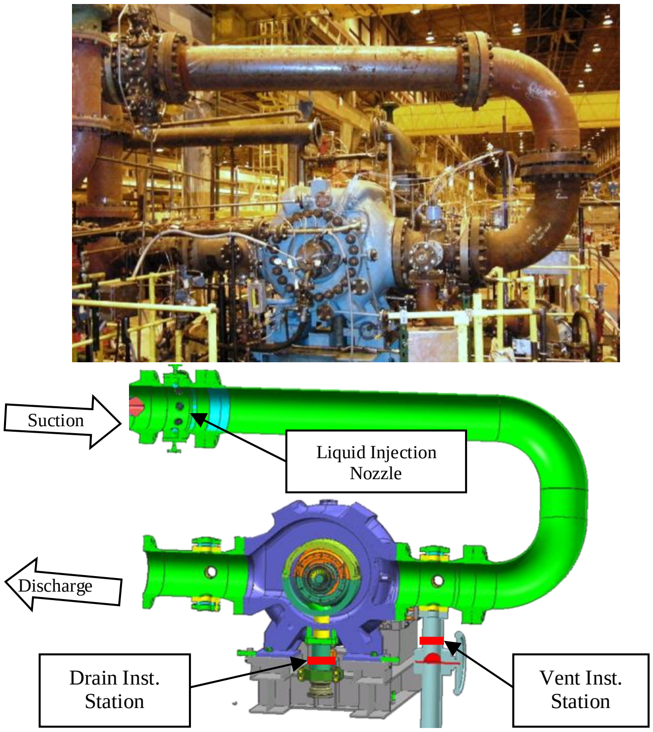

Figure 10. RCS Compressor Test Set-up.

Multi-phase Test Conditions

Multiphase testing was done over a range of rotational speeds and fluid flowrates at the highest attainable suction pressure (Table 2). Ultimate pressure limits were set by the capability of the legacy compressor casing used to house the test RCS internals. Testing fluids included industrial nitrogen gas and Exxsol D60™ a commercially available, stabilized, liquid hydrocarbon based solvent representing wellhead condensate liquids.

Table 2. Laboratory Test Conditions.

Speed Curve #	Suction Pressure	Volume Flow	Speed	Max. Brake Power	Max. LMR
	psia (Bara)	*ACFM*	*RPM*	*kW*	
1	550 (38)	Range	9000	410	Dry
2	550 (38)	Range	12000	1022	Dry
3	550 (38)	Range	9000	531	0.40
4	550 (38)	Range	12000	1318	0.40

As with previous multiphase test series, the testing was first conducted without liquid injection ("dry" speed lines 1 and 2) and then with liquid injection ("wet" speed lines 3 and 4). Gas flow rates for wet speed lines were set at fixed values determined during dry test runs. At each gas flow point the liquid injection rate was set to discrete test points, gradually increasing to the maximum desired liquid flow, allowing sufficient time to settle the system between each wet point. Before moving to the next gas flow point the liquid injection was stopped; returning the loop to the dry baseline condition. Performance and vibration spectrum data were recorded for each dry and wet point.

Dry Compression Test Results

The results of dry Type 2 (per ASME PTC 10, 1997) performance testing at higher pressure on the laboratory unit are compared with earlier lower pressure data of Maier and Biba (2010), Figures 11 and 12. Shown are normalized polytropic head, efficiency, and work input versus the normalized flow coefficient. The change in performance between the two operating conditions is caused not only by the difference in suction pressure but also by the amount of gas recycling between the RCS rotating drum and the compressor inlet through the liquid drain/ vent loop. While this recycle was closed during previous low pressure dry testing, it was open for the present tests, resulting in an effective flow capacity shift of the performance curves. The nominal recycle flow was set to 5 percent of the main gas flow at the design point. The work input characteristics for both conditions are linear and the variation between them is less at lower speed.

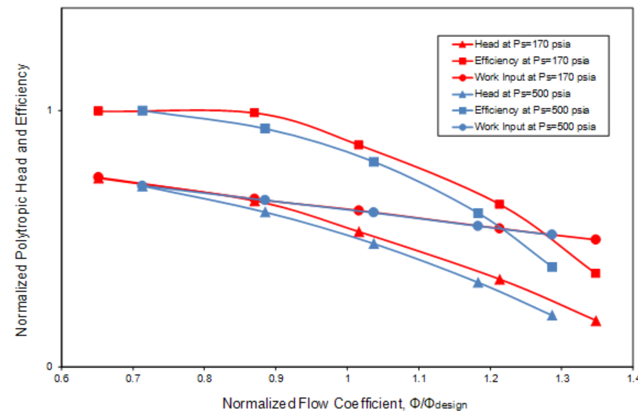

Figure 11. Dry Compression Performance at 9000 rpm.

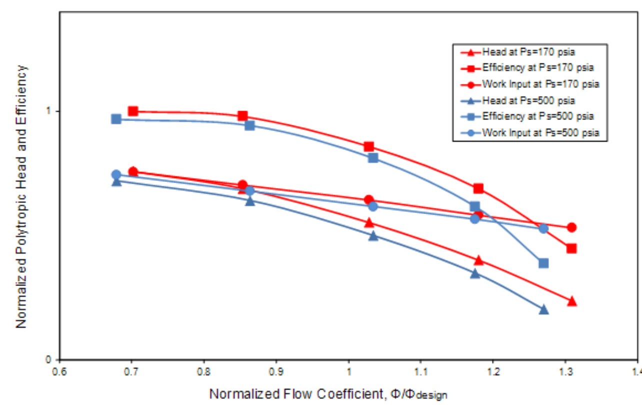

Figure 12. Dry Compression Performance at 12000 rpm.

Separation Test Results

The results of high pressure tests on the laboratory unit are compared to previous lower pressure results in a plot of separation efficiency versus SP′ (Figure 13). Increasing fluid pressure changes the gas to liquid density ratio and surface tension, both leading to increasing liquid separation difficulty. Both of these effects contribute to higher separation parameter for higher pressure operation. The higher pressure separation results are similar to previous low pressure results, maintaining the expected linear relationship between separation efficiency and SP′. However, a small degradation in separation efficiency is seen with the higher pressure results at the same SP′. These data suggest that all effects of pressure are not fully modeled by the current separation parameter.

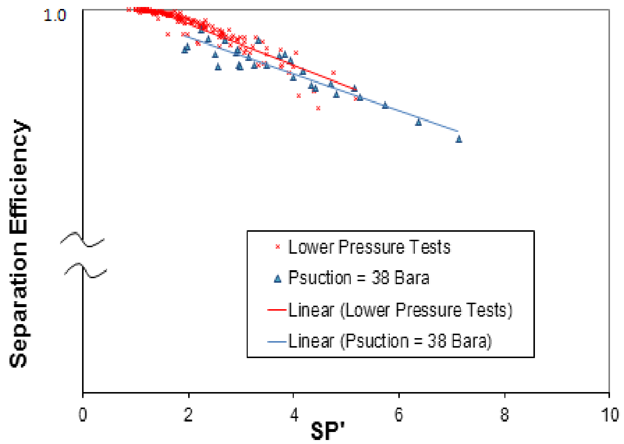

Figure 13. Measured Effect of Pressure on Separation Efficiency.

The capacity of the RCS to protect downstream components is illustrated in Figure 14. Here downstream liquid carryover (CO), expressed as a fraction of gas mass flowrate, is shown as a function of liquid loading and gas flow rate. For all test points the amount of liquid reaching downstream components was below 6% of the gas mass flow. Although a small increase in CO at the highest liquid loadings is seen, virtually no change in CO is detected over the complete range of gas flows.

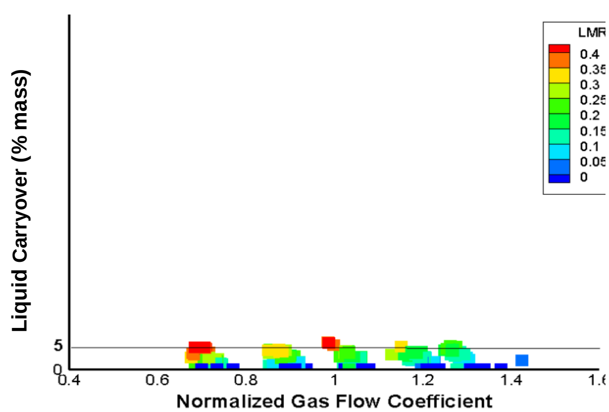

Figure 14. Liquid Carryover as a Function of Gas and Liquid Loading.

Wet Compression Test Results

Wet compression performance of the laboratory unit was calculated from measured parameters using the heterogeneous model described by Brenne et al. (2005). Stage performance values were calculated using measured values at the compressor inlet and outlet. Performance for the separator drum used the values measured at the separator drain line in the proximity of the drum discharge. Figures 15, 16, 17, and 18 show pressure ratio and two-phase polytropic efficiency for stage and drum, respectively.

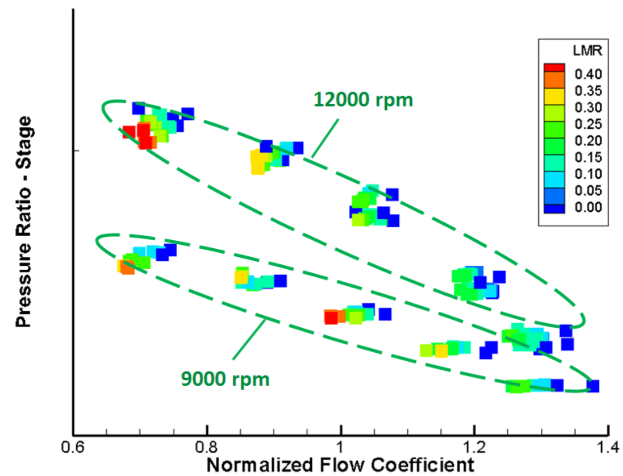

Figure 15. Stage Pressure Ratio

The measured stage performance results of Figure 17 show that increases in liquid injection rate negatively impact overall two-phase RCS stage compression efficiency. The results for the drum component of the RCS shown in Figure 18 are more complex. The drum maintains relatively high compression efficiency at lower gas flowrates; even with high liquid injection rates. At high gas flow values its performance is reduced with increasing liquid flow.

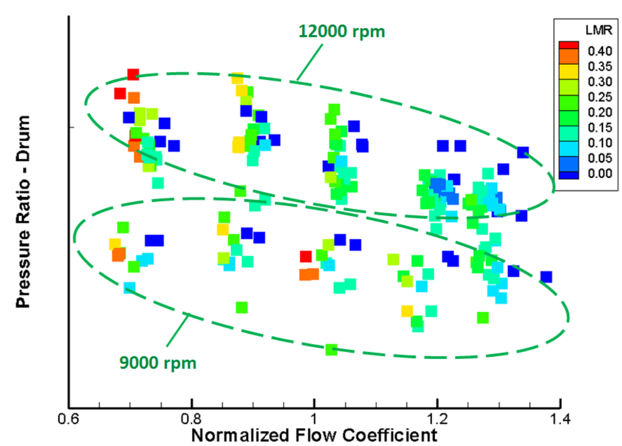

Figure 16. Drum Pressure Ratio.

The observed effect of liquid loading on the separator drum's performance appears counter to the negative influences shown in the overall separator stage efficiency of Figure 17. However, this is simply a result of the assumed definition of two-phase heterogeneous polytropic efficiency as defined by Brenne et al. (2005). In the heterogeneous model, polytropic work contains a term proportional to the mass of liquid handled and to the pressure rise in the device (the RCS drum in this case). Additionally, work input attributable to the drum is affected by heat transfer between gas and cooler liquid. Thus, the indicated drum compression efficiency is higher at larger liquid injection rates, especially at lower gas flow rates.

In case of extreme liquid injection load or/and unlikely event of RCS separation performance deterioration, unexpectedly large liquid carryover may occur. In such circumstances compressor operator would notice increased power consumption due to two-phase stage efficiency decrease, as Figure 17 illustrates.

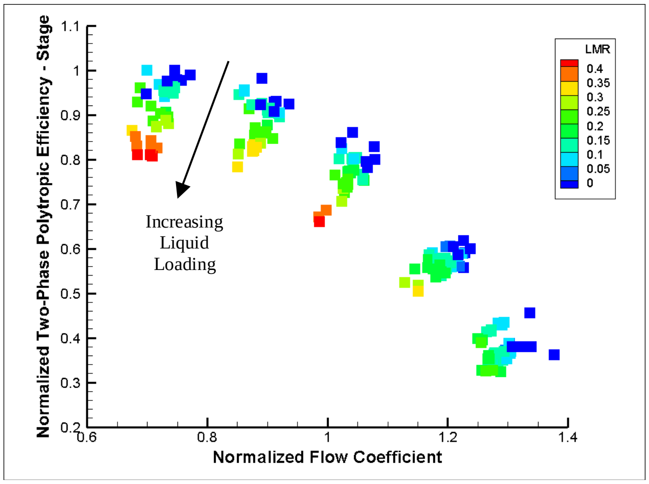

Figure 17. Stage Two-Phase Polytropic Efficiency.

Stability margin may be also affected at increased carryover, as its impact on compressor performance is greater at low flow values, which is noticeable in Figure 15. Attempts to increase rotational speed in order to maintain desired discharge pressure may lead to approaching stability limit.

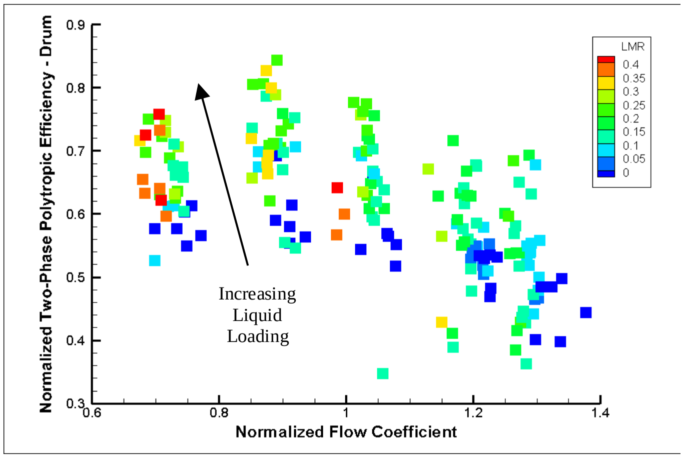

Figure 18. Drum Two-Phase Polytropic Efficiency.

Another particularly interesting effect is illustrated in Figure 19 where pressure ratio curves for drum and stage converge and cross near a normalized flow coefficient of 1.3. This cross-over implies that under these conditions the downstream RCS stage components are absorbing gas power and therefore not contributing positively to stage compression.

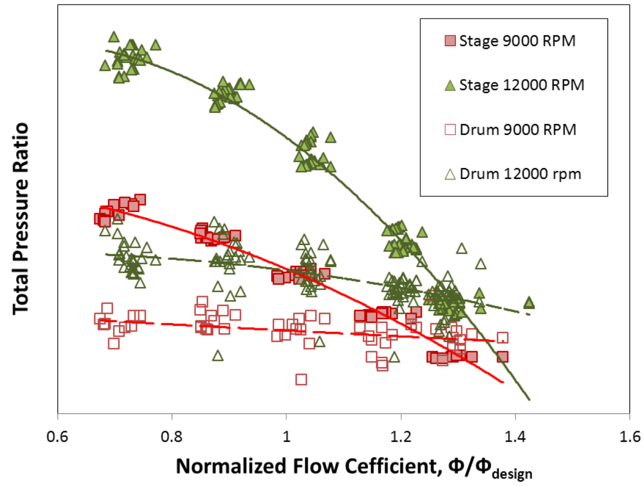

Figure 19. Pressure Ratio: Drum and Stage.

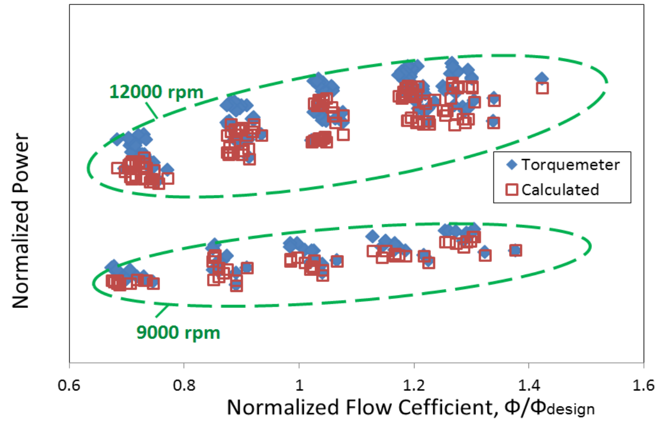

Figure 20. Measured and Calculated Power for Multi-phase Tests.

The ability to accurately predict RCS power consumption at different liquid injection rates is important for design and operation of two-phase compression units. To help achieve accurate prediction, the heterogeneous model was enhanced to account for secondary heat transfer effects in the liquid drain/ vent recycle path of the RCS stage. These effects were experimentally measured during testing. Additionally, an extra tuning parameter for drum liquid work in the stage power balance was established. This parameter was adjusted to best match the calculated power consumption with global torquemeter measurements. Figure 20, a comparison of measured versus calculated stage power after tuning, shows generally good agreement between calculation and measurement. However, some measured values remain higher than calculated values for some test points.

COMMERCIAL UNIT FACTORY ACCEPTANCE TEST

Test Set-up

The general layout and the instrumentation chart for the test setup of the commercial multistage compressor described earlier is shown in Figure 21. Additional instrumentation included pressure and temperature probes at the return bend of the RCS stage, and static pressure and temperature probes and a flow meter in the RCS drain vent line.

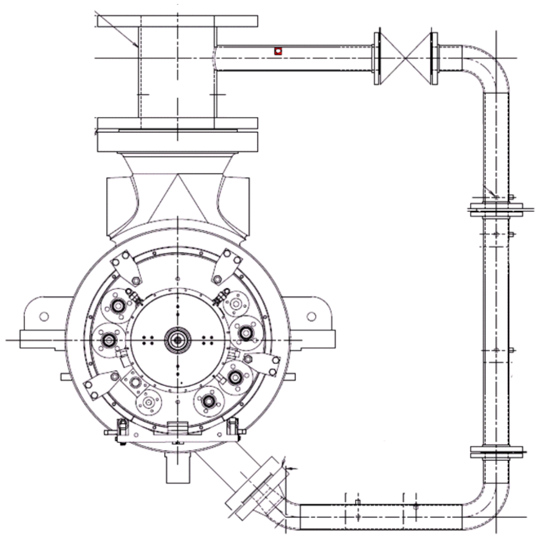

Figure 21a. Factory Test Piping Shown in Front Elevation View.

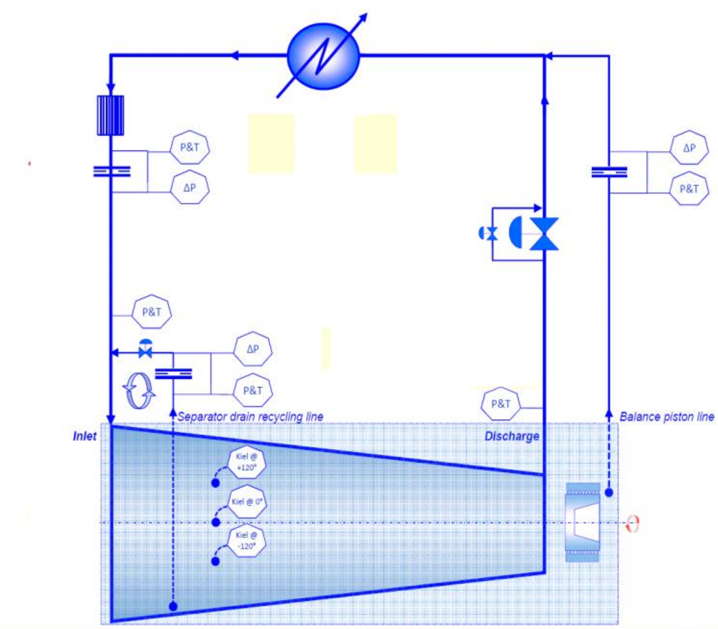

Figure 21b. Factory Test Instrumentation.

Only dry testing was performed on this unit. Although no separation performance could be obtained, this testing did allow the validation of the RCS design and the OEM's prediction of its dry compression performance.

Performance Prediction

The results of dry performance testing on the RCS stage of this compressor are compared to a CFD stage model. Several views of the fluid volume for this model are shown in Figure 22. As shown in the figure, a full stage model of the separator stage was used including complete inlet plenum and inlet guide vane volumes, an arc segment model of the drum and diffuser domains, and a full liquid collector volume. A hybrid mesh system was used with TET/prism meshes for the Inlet plenum, IGV vane, and liquid collector domains, and block structured meshes for the drum, diffuser, and return channel domains. Fillets were not included in the drum and diffuser, blade passages models. The process fluid, CO_2, was modeled as ideal gas.

ANSYS CFX version 15.0 was used as the flow solver with k-epsilon turbulence modeling and scalable wall functions. Wall boundaries were modeled as adiabatic using no-slip boundary condition with surface roughness. Circumferentially averaging "stage" interfaces were applied between the IGV and drum domains, the drum and rotating diffuser domains, the stationary diffuser and return channel domains, and at the inlet of the liquid collector. Inlet total pressure boundary conditions were applied at the inlet of the inlet plenum and mass flow outlet boundary conditions applied at the collector outlet and return channel outlet boundaries. A mass flow inlet boundary condition was applied at the drain vent recycle inlet boundary. Actual test mass flow rate, total temperature, and total pressure conditions were modeled.

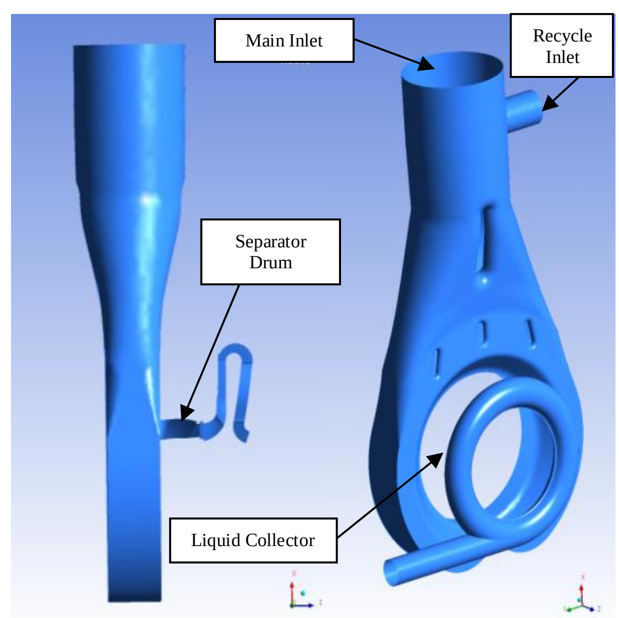

Figure 22. RCS Stage CFD Model Gas Volume.

Test Results and Comparison

Compression performance results of the Type 2 (ASME PTC 10, 1997) test for the commercial unit incorporating an RCS stage are shown in Figure 23. Generally good agreement is seen between prediction and test results. Figure 24 displays spectral results of the API 617 (2009) mechanical test for this unit. The small sub-synchronous component evident in the results was attributed to the test stand gear box used to drive the compressor. The production train gearbox will not affect the compressor train mechanical behavior. It is important to state that the unit successfully passed the factory test program, meeting all contractual requirements. The unit is on route to its Gulf of Mexico installation site at the time of this paper's writing.

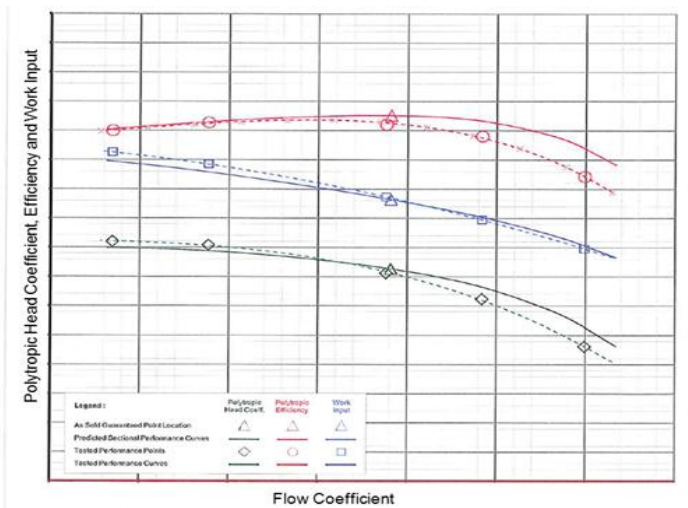

Figure 23. Flange to Flange Performance Results of Factory Acceptance Test of a Commercial Unit with Integrated RCS Stage.

The dry test data are compared with numerical results of Computational Fluid Dynamics (CFD) modeling. Figures 25 and 26 show a comparison of normalized total pressure and total temperature ratio with CFD predictions over the range of gas flows tested.

The red curves in these figures represent the range of pressure ratio and temperature ratio measured at various circumferential stations around the return channel. Predicted pressure ratio and temperature ratio follow the same functional trend as the test results versus gas flow, but are generally higher. The CFD model also predicts the onset of stall at a larger gas flow than measured results indicate.

Some simplifications in the CFD model may have contributed to the general over prediction of these parameters including lack of fillet modeling, uncertainty in actual surface roughness, simplified model flow network (i.e. no secondary flow systems) and the lack of wall heat transfer.

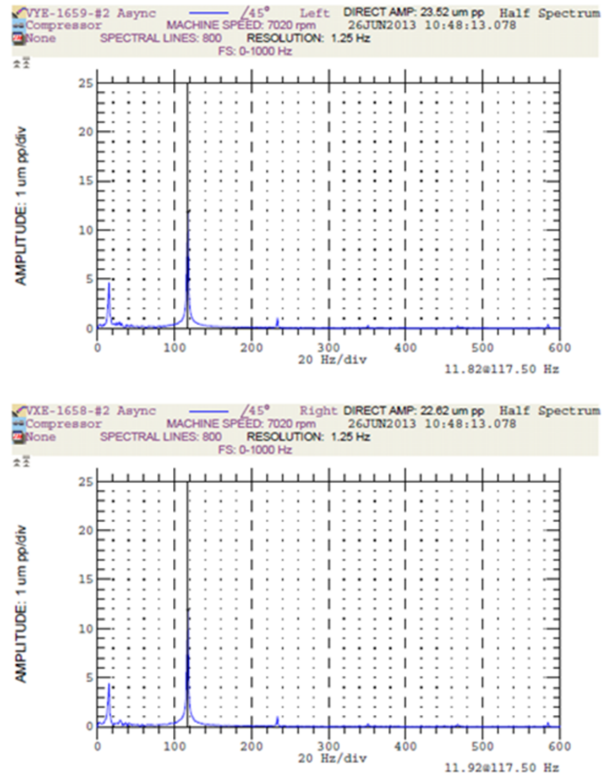

Figure 24. Spectral Results of Mechanical Factory Acceptance Test of a Commercial Unit with Integral RCS stage.

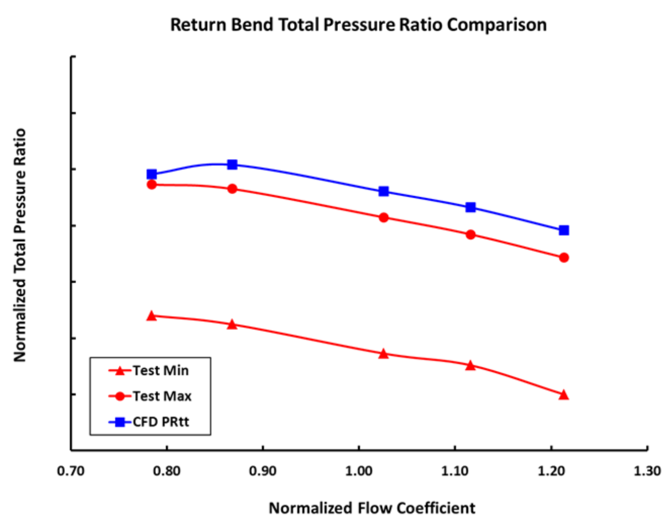

Figure 25. Total Pressure Ratio versus Flow Rate.

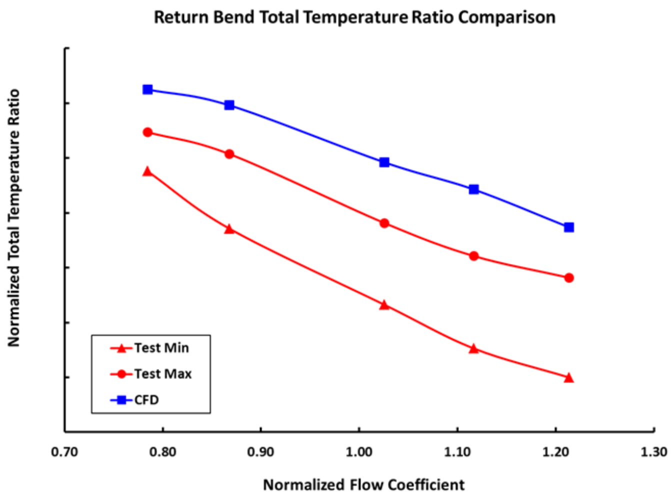

Figure 26. Total Temperature Ratio Versus Flow Rate.

CONCLUSIONS

The rotating centrifugal separator stage is a compact separation device that has been successfully integrated within a centrifugal compressor. This combination offers an attractive alternative to traditional, gravity based gas/liquid scrubbers, through significant reduction in size and weight of the total compression module.

Compact separator technology has been extensively tested since 2006 by the OEM and has proven appropriate for providing adequate protection for compressor internals. No erosion effects could be discerned on any flow path surfaces after hundreds of hours of liquid testing. In most cases a regular compressor maintenance schedule is expected to apply. However, the OEM recommendations could be tailored to user's specific operating conditions and gas/liquid content.

For subsea gas boosting applications, the integrated separator can facilitate simplification and reduction in size of protective inlet slug handling vessels. A reduction in this vessel diameter/size is a key advantage for deepwater applications.

Space and weight savings depend on the type of driver that is used for the compression train, and on the type of process components (heat exchangers, flow measurement elements, etc.) that are used in the packaging of the compression module. Based on different studies that have been made by the OEM, the use of the integrated separator, and the application of novel, compact packaging techniques to create a single lift compact compression module, can offer space savings between 35% and 55% and associated weight savings between 40 and 60%.

The test program that has been continuing since 2009 extends the range of separation and compression performance data previously obtained for the RCS to higher suction pressure levels reaching 550 psia (38 Bara). The test allowed better understanding of the aero- and thermodynamic behavior of the RCS and validated both compression and separation performance at demanding operating conditions.

To conduct the program the test facility was upgraded by enhanced secondary separator in the closed loop, higher powered driver at 2950 HP (2.2 MW), and added torquemeter.

Dry performance testing validated the results of the previous lower pressure test series while also showing the effects of RCS drain vent recycle flow between the RCS drum and compressor inlet. Nominal recycle flow was set to 5 percent of the main gas flow at design point.

At given pressure conditions and variable liquid injection rates the unit was tested for LMR $\leq$ 0.4. As LMR depends on pressure, it can vary with application. At field conditions it is expected to correspond to gas volume fractions between 97 and 100 percent.

Several conclusions can be drawn from the liquid separation results of the laboratory unit:

- The separation performance of an RCS stage is generally well characterized by the non-dimensional separation parameter, SP′.
- The separation parameter as currently defined appears to slightly under estimate the deleterious effects of increased pressure on separation performance within the SP′ range between 2 and 7.5. This may be due to shortcomings in calculated liquid droplet size characterization within the model.
- The RCS demonstrated its ability to limit liquid egress to downstream components over a wide range of liquid loading and gas flows at these more demanding operating conditions.

Multiphase compression testing demonstrated that:

- Calculated compressor power consumption correlates well with torquemeter measurements. The obtained data can be used to further tune the meanline two-phase performance model for RCS selection and sizing.
- Overall stage compression performance deteriorates with increasing liquid loading while component performance of the RCS drum remains relatively high, especially at low gas flow rates. Peculiarities of the RCS blading cause downstream flowpath components to "turbine" at overload conditions.

Examples of recent production units incorporating RCS technology were presented including compressor performance testing on one of these units. Both the development and commercial unit dry performance tests satisfied API 617 (2009) requirements on power tolerances.

As-tested RCS stage performance of the commercial unit was compared with CFD results showing similar trends across the range of gas flow rates. Over-predicting performance is attributed to simplifying assumptions in CFD modeling, a subject to be considered in future work.

NOMENCLATURE

CO	-	Carryover, mass ratio of liquid to gas flow downstream of separation device
LMR	-	Liquid to gas mass ratio
RCS	-	Rotary Centrifugal Separator
SP′	-	Separation parameter, non-dimensional parameter defining degree of separation difficulty for RCS

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