PAN HI-PERFORMANCE COMPRESSOR MANIFOLDS

MAJOR EFFICIENCY GAINS ACHIEVED BY ADAPTING HIGH-PERFORMANCE ENGINE TECHNOLOGY TO RECIPROCATING COMPRESSORS

BY JOHN J. BAZAAR, W. NORM SHADE, GLEN F. CHATFIELD, AND DALE WELLS

EDITOR'S NOTE

This is part two of a series of technical papers on PAN technology. Part one – "New Paradigms For Pulsation Attenuation, Compression Efficiency, And Increased Gas Flow" – appears in the July 2016 issue of Gas Compression Magazine*, p. 26, and online at www.gascompressionmagazine.com.*

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INTRODUCTION

Since 2006, ACI Services Inc. (ACI) and OPTIMUM Pumping Technology (OPT) have been collaborating to develop and apply finite amplitude unsteady gas dynamic wave modeling technology to reciprocating gas compressors.[1] This quickly led to inventing several new patent-pending devices that the companies termed "PAN." The first prototype used tuned loops to create a very efficient filter, called a "Pulsation Attenuation Network," that canceled pulsations with little or no pressure drop penalty. This evolved into a product that is now called a PAN Filter.

With further research and development, beginning in 2008, the companies created tuned compressor manifolds. These are similar to high-performance engine intake and exhaust manifolds, which provided a boost to compressor performance in the form of lower specific power (bhp/MMscfd) and/or more flow for the same power input. This device was referred to as a "Performance Augmentation Network." It provides pulsation cancellation similar to the PAN Filter, but goes much further by interleaving cylinder pulsations and timing the reflection of pressure waves back to the compressor cylinder suction and discharge valves during the time that they are open. With careful optimization, it controls line-side pulsations while simultaneously reducing the required adiabatic work and power and/or increasing the cylinder's mass flow rate or capacity.[2,3] This technology has evolved into a product that is now called a PAN Hi-Performance Compressor Manifold.

The technology behind these products is explained in more detail in Part 1 of this series.[4] OPT's development of finite amplitude wave simulation and design technology for reciprocating engines dates back to 1994 with work that they sponsored at The Queens University of Belfast (QUB). In 2005, at the encouragement of a well-known compressor reliability engineer, Randall R. Raymer, OPT started to model reciprocating compressor cylinders and their connected piping systems. This soon led to collaboration with ACI to leverage that company's considerable reciprocating compressor optimization experience.

VALIDATION OF PAN TECHNOLOGY FOR PULSATION CONTROL AND PERFORMANCE ENHANCEMENT

The pressure drop and power penalties that can occur with conventional volume-choke-volume and restrictive orifice pulsation control methods on high-speed reciprocating compressors has been well documented, especially at high flows and low-pressure ratios.[5,6]

Many years of significant developmental effort resulted in OPT's Virtual Pumping Station (VPS) software, which is a robust modeling and design tool that uses accurate real gas thermodynamic properties. The use of this system to design and model several large, single-stage reciprocating compressor systems showed the potential for double-digit improvements in compressor efficiency and specific power (bhp/MMscfd). For example, simulations in 2011 showed that a PAN Hi-Performance Compressor Manifold would reduce the bhp/MMscfd by an average of 12% across a speed range of 580 to 720 rpm on a 6-throw, 8000-hp (5968-kW) compressor operating at a design pressure ratio of 1.20, including a 15% reduction at the 720 rpm rated speed.[2,3] Among the best improvements predicted from several extensive investigations of optimized PAN Manifolds potentially applied to existing compressors was a 31% bhp/MMscfd reduction at a 1.12 pressure ratio on a 4800-hp (3580-kW), 1000-rpm, 6-throw, single-stage compressor.

LABORATORY TESTING

Prior to full-scale field testing of PAN technology, laboratory tests were conducted to validate the pulsation cancellation predicted by VPS simulations of a compressor test rig. In 2008, an industrial compressor rig was configured as two double-acting, 4-in. (101-mm) bore diameter x 3-in. (76-mm) stroke cylinders operating in parallel. A PAN Filter was designed and fabricated for the discharge side of this compressor and tests were conducted from 700 to 1050 rpm using atmospheric air.[7] With a straight pipe and no pulsation control system, the pulsation was highest at 850 rpm and 35 psig (2.41 bar) discharge pressure. Replacement of the straight pipe with a single-loop PAN Filter showed a pulsation reduction of 61.4% at that condition. The PAN Filter accomplished this with a pressure drop that was only 0.4% higher than what was measured with the straight pipe. Further experimentation with a PAN Filter having two loops in series showed a 93.9% pulsation reduction at the same operating condition, with a pressure drop penalty of only 0.7%. The testing further confirmed that the 2-loop PAN filter effectively controlled pulsations as well as an orifice plate over the full speed range of 700 to 1050 rpm, while having much less pressure drop penalty than the orifice plate.

FIRST PROOF-OF-CONCEPT FIELD EXPERIENCE

Following successful laboratory results, collaboration with a major gas transmission company led to installation of a proof-of-concept PAN system on a compressor at a gas storage site in Northern-Central Pennsylvania in 2009.[8,9,10] Due to limited space and budget, a PAN was designed and retrofitted to the discharge of one side of a 4-throw, single-stage Superior MH64 compressor having 9.5-in. (241-mm) cylinders. The 6-in. (152-mm) stroke compressor operated from 750 to 1000 rpm, and the existing system used a volume-choke-volume pulsation control system that also included multiple orifice plates. At low-pressure ratios, pressure drop in the existing system was excessive, but at high-pressure ratios, the pulsation control was not sufficiently effective over at least some of the operating range.

The primary objective of the PAN system was to eliminate the excessive pressure drop associated with effective pulsation control. The resulting PAN system for this application combined a simple early version of a PAN Manifold and a 2-loop PAN Filter operating in series as shown in Figure

1. The end user's requirement to minimize changes to the package skid and to make the PAN system removable in case it did not meet expectations led to mounting the PAN Filter in a stacked arrangement in a pre-fabricated steel frame that was lagged to a 4-in.- (101-mm-) thick concrete floor, i.e., no foundation under it, as shown in Figure 2. Removal of the existing bottles and installation of the PAN system, including grouting under the PAN frame, was accomplished in less than five days.

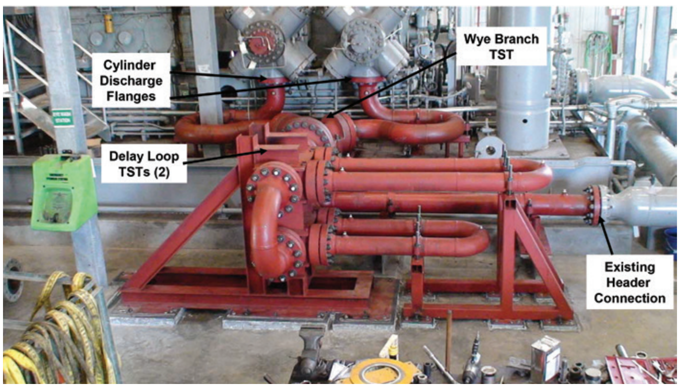

Figure 1: Proof-of-concept PAN system installed on discharge of one 2-throw side of a field compressor in 2009.

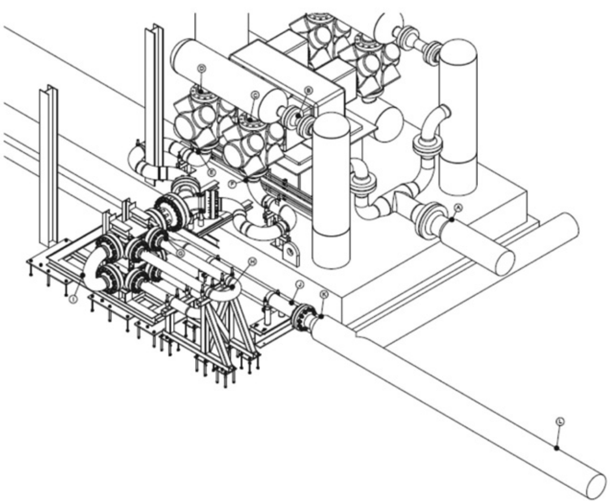

Figure 2: Proof-of-concept PAN installation and measurement locations.

During the field testing, gas conditions permitted operation with various load steps over a speed range of 860 to1000 rpm. Figure 3 summarizes the effectiveness of the PAN Manifold and the combined effects of the PAN Manifold and 2-loop PAN Filter at an average discharge pressure of 886 psig (61 bar) and a constant pressure ratio of 1.35. The very simple PAN Manifold, by itself, reduced pulsations by 47 to 79% over the speed range. Addition of the PAN Filter in series further reduced pulsations by 88 to 93% over the speed range, which equates to pulsation levels of only 0.4 to 0.6% of discharge line pressure. This test data confirmed the simulation predictions that a properly designed PAN system effectively controls pulsations over a wide range of operating speeds.

Applying the PAN system to only one side of the compressor had the advantage of simultaneously measuring the effectiveness of the PAN system and the existing pulsation control system at all operating conditions. Figure 4 compares the PAN and existing bottle systems over the 860- to 1000-rpm speed range operating at 896 psig (61 bar) average discharge pressure and a pressure ratio of 1.1 across the unit. The PAN system's pressure drop averaged 5 to 6 psig less than the bottle system's pressure drop across the entire speed range. To quantify this benefit, at 860 rpm, the PAN system discharge pressure loss was only 19% of the bottle system's loss. At 1000 rpm, it was 38%. This reduced discharge pressure loss resulted in approximately 7% lower pressure differential on the cylinders having to move gas at this low pressure ratio condition, reducing the required power. Simulations predict that a similar benefit would occur by deploying a PAN system on the suction side, which would translate to an efficiency gain and power savings of about 15% at this condition. It is important to note that, since pulsation cancellation was the goal of this particular PAN system, not wave reflections for performance enhancement, this improvement is solely the result of the substantial reduction of pressure drop in the pulsation control system. Further efficiency gains would be expected with an optimized PAN Hi-Performance Compressor Manifold.

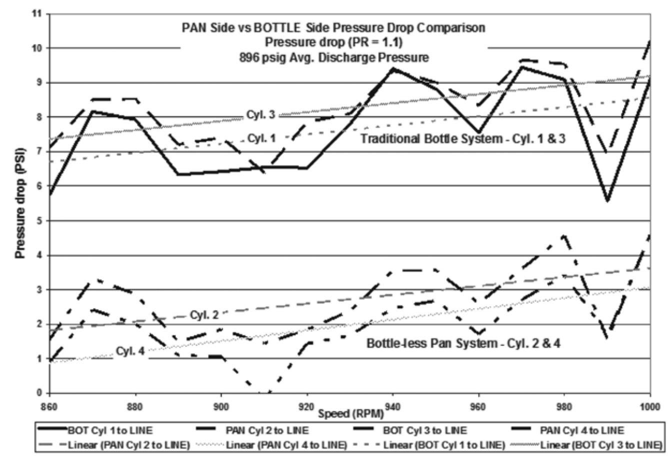

Figure 4: Comparison of pressure loss from cylinder discharge flange to header for proof-of-concept PAN and existing bottle systems.

FULL-SCALE COMPLETE PAN COMPRESSOR MANIFOLD FIELD EXPERIENCE

In 2014 and 2015, two compressor packages were configured with PAN Hi-Performance Compressor Manifolds and installed at two central gas-gathering booster stations in Northeast Pennsylvania. The identical units included 4-throw, single-stage Ariel JGT/4 compressors with 6.75-in. (171.45-mm) cylinders. The 4.5-in.- (114.3-mm-) stroke compressors were driven by 1380-hp (1029-kW) gas engine drivers at a design speed of 1400 rpm. The required operating range was very broad with suction pressures from 450 to 900 psig (31 to 62 bar) and discharge pressures from 1000 to 1200 psig (68 to 82 bar). The end user preferred to operate at 1400 rpm, relying on manual head end variable volume clearance pockets, rather than variable speed, for capacity control.

Speed (rpm)	Pulsation at Compressor Discharge Flange (P/P psi)	Pulsation after Manifold PAN Y-Junction (P/P psi)	Pulsation Reduction after PAN Manifold Y-Junction (%)	Pulsation after PAN Filter (P/P psi)	Total Pulsation Reduction (%)	Pulsation of Line Pressure (%)
860	46.4	9.8	79	4.8	90	0.5
900	50.8	27.0	47	3.6	93	0.4
950	43.9	14.8	66	4.0	91	0.4
980	43.5	20.6	53	4.8	89	0.5
1000	44.5	20.8	53	5.3	88	0.6

Figure 3: Proof-of-concept discharge PAN pulsation measurements at 886 psig (61 bar) average discharge pressure and 1.35 pressure ratio.

Nevertheless, to demonstrate the ability of a PAN Manifold to perform over a range of speeds, a design range of 1300 to 1400 rpm was selected.

A similar engine and compressor package equipped with a traditional pulsation control system was available at one of the two stations for comparative testing with the PAN unit. In addition to the extensive support of the end user, a number of companies and the Gas Machinery Research Council were involved in sharing the development cost and supporting the testing and evaluation of the first of these two PAN Manifold units.[11]

The shift of the project away from (originally) a mainline transmission to a midstream natural gas-gathering application posed several new project and design challenges. The higher operating speed and comparatively lighter engine and compressor posed design challenges in avoiding mechanical natural frequencies of the machinery, skid, and support structure. In addition, the fact that the compressors required a wide operating range with pressure ratios that vary from very low ratios to ratios that are much higher than gas transmission applications posed several new design challenges. One was that the generally higher pressure ratios dictate the use of cylinders with low volumetric clearance and smaller valves.

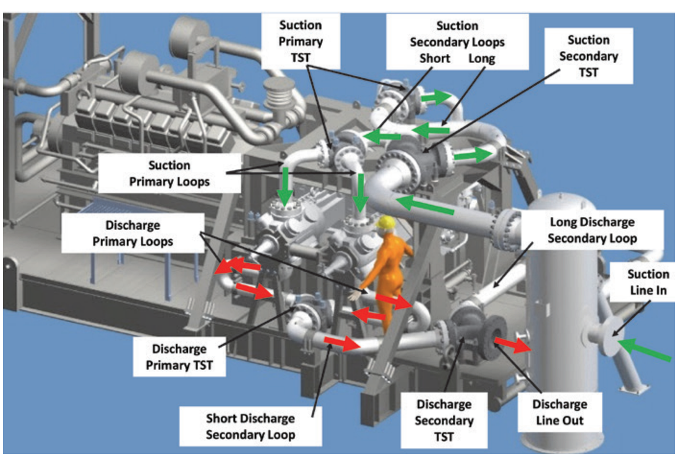

Figure 5: PAN Manifold CAD model – left side view.

The end user's desire to take full advantage of the driver power rating to maximize capacity with the PAN Manifold's higher efficiency required changing to larger 6.75-in. (171.45-mm) bore diameter cylinders than the 6.0-in. (152.4-mm) bore diameter cylinders on the existing comparative unit equipped with traditional pulsation bottles and orifice plates. Analytical assessment of the existing bottle-equipped unit showed that the engine driver would be overloaded at some of the required operating conditions with the larger compressor cylinders that the PAN Manifold unit could accommodate. This complicated the direct comparison, requiring that the bottle-equipped unit test results be adjusted for the effects of larger cylinders using agreed-upon corrections developed jointly with the compressor original equipment manufacturer (OEM) prior to the test.

Although both PAN packages were new, they were reconfigured from packages that were originally built as bottle-equipped units. Therefore, some design compromises were required to retrofit them with PAN Manifolds. The end user also required that the entire PAN Manifold be pre-packaged on the skid to minimize field installation time and expense. A complete 3-D computer-aided design (CAD) model was developed for the PAN Manifold and the design modifications required for the package. This was also used in a comprehensive finite element analysis (FEA) to evaluate mechanical responses and natural frequencies of the entire system prior to starting fabrication.[11]

The resulting package design is shown in Figures 5 and 6, which also show the direction of flow and some of the typical terminology used for the PAN Manifold. Care was taken to ensure that the compressor could be reasonably accessed for routine maintenance, and the package was designed to easily remove and reassemble outrigger extensions that exceeded normal permitted shipping width. Best industry practices[12] were used in the design where applicable.

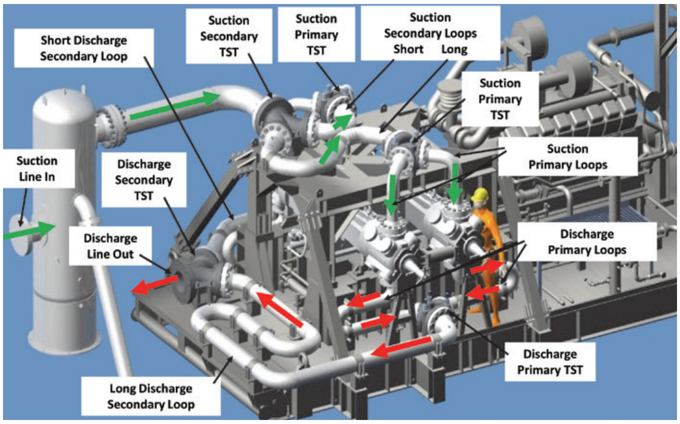

Figure 6: PAN CAD model – right side view.

The first PAN Manifold unit was installed in October 2014. Figures 7 and 8 show the first package installed and operating, prior to the installation of work platforms. After commissioning and vibration testing, rigorous thermodynamic performance tests were conducted on it (Figure 9), as well as on the bottle-equipped comparative unit. Both packages were extensively instrumented with pressure and temperature instrumentation as well as American Gas Association (AGA) flow meters in the suction lines. The flow meter for the PAN Manifold unit is shown in Figure 10.


Figure 7: First PAN Manifold unit installed (without work platforms) – left side view.

By the time the first PAN Manifold unit was installed, local gas conditions were different than anticipated and specified at the time of project specification and used in the design process. Limited gas flows from the producer's field prevented operation at the upper end of the specified suction pressure range, but the unit was operated and tested successfully over a suction pressure range of 442 to 648 psig (30 to 44 bar) and a discharge pressure range of 1000 to 1300 psig (69 to 89 bar) at 1400 rpm.

The following is a brief overview of significant test results[13,14] and conclusions.

A capacity increase of 15.4 to 19.6% was measured for the PAN Manifold unit compared to the existing bottle-equipped unit over the range of conditions tested, well within the objective of maximizing capacity for the 1380-hp (1029-kW) driver's rating. Most of this increase resulted from being able to use larger bore diameter cylinders on the PAN Manifold unit because of its higher efficiency.

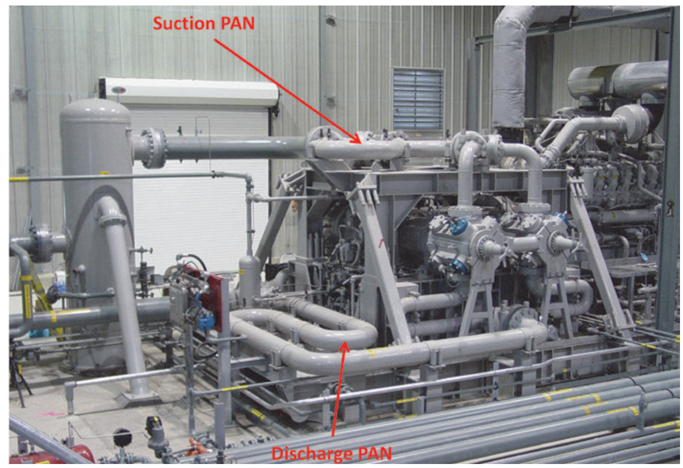

Figure 8: First PAN Manifold unit installed (without work platforms) – right side view.

Total PAN Manifold system (suction and discharge combined) pressure drop averaged 0.3 psi (2.06 kPa) over the range of conditions tested, well within the objective of 2.0 psig (0.13 bar) maximum. Pressure drop from the inlet scrubber to the compressor cylinder suction flanges averaged zero. Pressure drop from the cylinder discharge flanges to the off-skid discharge piping immediately downstream of the PAN Manifold averaged 0.3 psi (2.06 kPa). Both of these pressure drops were much less than the bottle-equipped system across the range of pressure ratios tested, even though the PAN Manifold system flows were much higher.


Figure 9: First PAN Manifold unit undergoing extensive thermodynamic performance testing.

Figure 10: AGA flow meter in suction line to PAN Manifold unit, used for performance testing.

Line side peak-to-peak pulsation in the suction header upstream of the PAN Manifold at 1400 rpm ranged from 0.5 to 1.0% of line pressure over the range of conditions tested and well under the design goal of <1.5% over the entire 1300- to 1400-rpm speed range. Line side peak-to-peak pulsation in the discharge header downstream of the PAN Manifold at 1400 rpm met the design goal of <1.5% of line pressure within the range of conditions tested as well as through a speed range of 1350 to 1400 rpm.

The bottle-equipped unit manifold power ranged from about 30% (45 hp) higher than the PAN Manifold unit at the highest (2.65) pressure ratio tested to almost 100% (102 hp) higher at the low-pressure ratio (1.65) tested. This measurement included all cylinder plenum and all pulsation system losses other than the valve losses. In addition, the measurements showed that the PAN Manifold unit required 8% less bhp/MMscfd than the existing bottle-equipped unit at the 2.65 pressure ratio and 18% less bhp/MMscfd at the 1.65 pressure ratio.

To be completely objective, the performance of the existing bottle-equipped unit was theoretically adjusted for the effect of larger cylinders. A conservative comparison of this adjustment indicated that the PAN Manifold unit required 2.7% less bhp/MMscfd at the high ratio (2.65) test point and 6.2% less at the low ratio (1.65) test point. As predicted by simulations, the PAN Manifold power savings and efficiency, consistent with the pressure drop trend, increased as pressure ratio decreased, becoming very pronounced at low ratios. Unfortunately, the limited gas flow to the station precluded operation at the lowest pressure ratios where the efficiency benefits of the PAN Manifold would be most pronounced. Extrapolation of measured specific power efficiency (bhp/MMscfd expenditure) data to the minimum specified design pressure ratio of 1.11 indicated that the PAN Manifold unit would require 16.6% less bhp/MMscfd than the bottle-equipped unit, even after adjusting the bottle-equipped unit for the cylinder differences. This improvement is more than what would result from simply eliminating the system pressure drop losses, which confirms that the PAN Manifold's performance augmentation (from properly timing the suction and discharge pressure waves when the cylinder valves are open) further reduces the adiabatic power required for compression.

The PAN Manifold system met the objective of acceptable vibration at the design speed of 1400 rpm, as well as over the speed range of 1350 to 1400 rpm over the range of conditions tested. However, being the first, full-scale implementation of a PAN Manifold, a significant step in development, not everything turned out to be perfect. In the evolution of the design optimization process that determines if a PAN Manifold operates safely, effectively, and efficiently for a very broad range of speeds, pressures, pressure ratios, temperatures, and load steps, a procedural error (that has since been eliminated via automatic checking routines added to the VPS design and simulation software) went undetected until the unit was installed and operating. An acoustic resonance in the PAN Manifold discharge secondary piping loops was present at a frequency that caused higher discharge pulsations, which, in turn, caused unacceptable vibration levels in the discharge side of the PAN Manifold and off-skid piping below about 1340 rpm. Further simulations after this was encountered indicated that, without degrading other aspects of performance, the resonance could be safely moved out of the operating range by lengthening each of the PAN Manifold secondary loop pipes by 20 in. (508 mm). Since the end user only operates the compressor at 1400 rpm, the reduced speed range did not pose an operational problem; therefore, the user did not elect to have any physical changes made to the system to extend the operating speed range below 1350 rpm.

Figure 11: Second PAN Manifold unit installed (with work platforms) – left side view.

Figure 12: Second PAN Manifold unit installed (with work platforms) – right side view.

Except for planned engine and compressor maintenance and performance test instrumentation installation and removal, the unit ran 24/7 over the first 10 weeks, from late September through early December 2014, accumulating 1240 hours of operating time with no problems. Although low gas prices have limited volumes and therefore the running time on all units at the station after that, the PAN Manifold unit has continued to perform reliably whenever needed. The operators reported that of eight units at the station, the PAN Manifold unit is the one that they prefer to operate because it performs reliably and delivers the most flow for its horsepower.

A second identical PAN Manifold unit was installed at another station in the same region, becoming operational in September 2015. Interestingly, conditions at this station were significantly different than originally specified in the design. Prior to operation, the new operating conditions and load steps were simulated using the VPS software and confirmed to be acceptable. In the first eight months of operation, the unit has subsequently demonstrated similar performance and reliability to the first unit. Figures 11 and 12 show the second unit. These units include work platforms that had not yet been added to the first units when they were photographed in Figures 7 and 8.

NEXT-GENERATION PAN MANIFOLD TECHNOLOGY

ACI's and OPT's commitment to advancing PAN technology continues, and several significant improvements have been developed for the next generation of PAN Manifold units. Additional modeling and simulation has led to an additional simple and cost-effective technique that can be incorporated in PAN Manifold systems to effectively eliminate pipe resonances in compressor systems. This technique was field-tested on the aforementioned second PAN Manifold field unit, validating the concept and the simulations of it. More information about this proprietary development can be made available under confidential disclosure protection.

Additional development work has also been focused on improving the mechanical design of the PAN Manifold and its integration into a more cost-competitive compressor package. An example of a next-generation design for a 4800-hp (3580-kW), 1000-rpm, 6-throw, single-stage compressor is shown in Figures 13 and 14. One goal was to improve access to the compressor for maintenance. Another was to reduce the number of 90° bends in the manifold piping to reduce pulsation-related shaking forces and therefore reduce the complexity of the structural framework required for supporting the PAN manifold. The Next-Generation PAN Manifold accomplishes both, applicable to 2-throw, 4-throw, and 6-throw single-stage reciprocating compressors as well as to multi-stage compressors having 2 throws or 3 throws per stage.

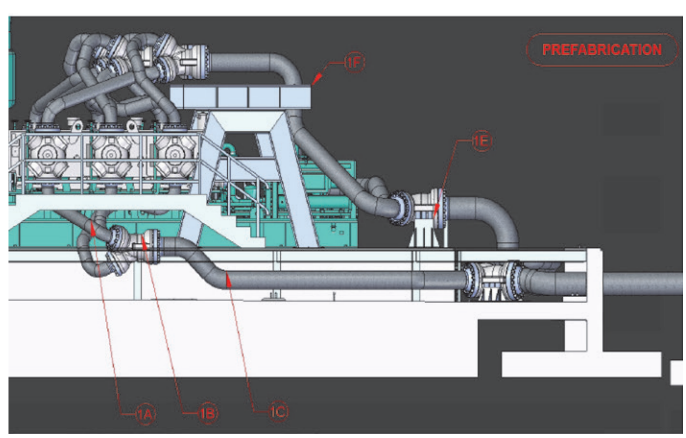

Figure 13: Example of Next-Generation PAN Manifold (for 6-throw compressor).

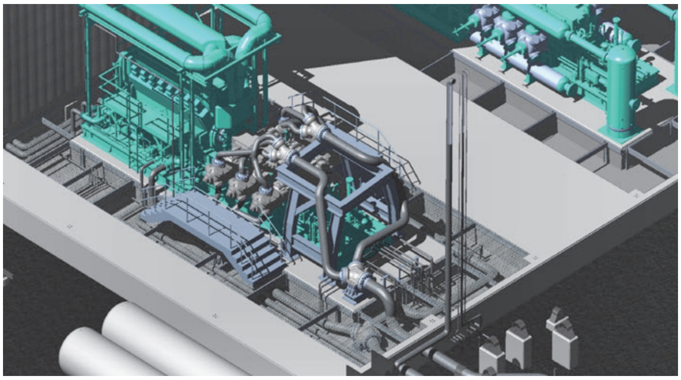

Figure 14: Next-Generation PAN Manifold (for 6-throw compressor) compared to a pulsation bottle-equipped unit.

The initial PAN Manifold package concepts that have been applied in the field tend to add about 6% to the packaged cost for an 8000 hp (5968 kW) unit and as much as 14% to the packaged cost for a 1380 hp (1029 kW) unit. The goal of the new design, together with leveraging the experience gained in the early designs, is to reduce the cost premium to 4% and 9%, respectively. Economic analyses[13,14] show that the increased flow from PAN Manifold units and the potential capital savings from requiring fewer units in multiple train plants recover the incremental cost in less than one year. Further, the higher efficiency and associated smaller environmental footprint are important benefits that will be viewed favorable by government regulatory agencies.

An additional goal has been to integrate efficiency and capacity improvements that result from the PAN Manifold into the performance predicted by the compressor manufacturer's performance program. A previously developed methodology,[15] adapted and calibrated with test results from the first two PAN Manifold units, can be applied to provide predicted performance, operating maps and optimal load steps for any point or range of points within the specified range of operating conditions.

SUMMARY

Lab testing and field installations have successfully demonstrated that PAN Hi-Performance Compressor Manifolds effectively control pulsations while significantly increasing reciprocating compressor system efficiency and capacity. Using advanced VPS simulation software, optimal PAN Manifold systems can be designed and the performance reliably predicted for the wide range of operating conditions that are typical of most reciprocating compressor applications.

Several key advantages have driven end users' interest and commitment toward the successful introduction of PAN technology in actual field applications. In addition to a fundamental interest in supporting the advancement of new compression technology, the end users saw the potential for significant commercial benefit by delivering more flow from compressors for a given driver size and energy input. The potential increases in flow and efficiency expected from the PAN system reduce fuel cost and exhaust emissions on a specific power basis. Such advancements may soon become mandatory as new regulations emerge from recently announced government initiatives to increase natural gas compressor efficiency and reduce greenhouse gas emissions. In cases where multiple units are paralleled in a station, the PAN technology offers the potential to reduce capital cost by reducing the number and/or size of the required drivers and compressors.

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