

ADVANCEMENTS IN PULSATION CONTROL TECHNOLOGY

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INTRODUCTION

Historically, the advancement of reciprocating gas compressor technology has been made possible through the effectiveness of the compressor pulsation control system. In the 1940's and early 1950's, low speed (180 RPM) integral machines were developed as the first generation of reciprocating compressors. These early slow speed machines did not require pulsation control systems because the compressor pulsations associated with the low horsepower operation were minimal. As the compressor technology advanced and speed and horsepower increased, the need for more extensive pulsation control systems became a requirement for efficient operation. Many of the first pulsation filters were designed using the Southwest Research Institute (SwRI) Analog Design tool. With the capability for a well-designed pulsation control system, a second generation of mid-range integral machines (operating at ~300 RPM) emerged. This new class of integral machines was enabled by the advancements in pulsation control technology through the SwRI Analog Design Tool. The design tool led to better methods for filtering pulsations, resulting in reduced system vibrations, increased system reliability, and improved compressor efficiency.

The recent advent of high speed (500-1000 RPM), separable reciprocating compressors has created a new set of challenges for compressor pulsation control technology. Compared to the second generation (~ 300 RPM) integral compressors, the vast majority of current high speed compressors operates less efficiently and is more susceptible to mechanical vibrations. Coupled with the higher speeds, the transition to variable speed operation has changed the strategies for pulsation control because the pulsation filters must be designed to filter pulsations over a broad range of operational speeds. The existing compressor manifold designs are challenged to meet requirements for adequate pulsation control and system efficiency over a large operating flow range.

Advanced pulsation control techniques are needed to accommodate the increase in compressor running speed, the variation in operations, and the inherently higher pulsation amplitudes. New pulsation control concepts are being developed to accommodate more flexible, higher speed compressors. These concepts will enable this third generation of reciprocating compressors to advance beyond the current systems - to meet the operator efficiency, flexibility and reliability needs for the future. In addition to new pulsation control technologies, improved design tools are required to more accurately predict pulsations in the compressor manifold systems.

In 2005, the Department of Energy (DOE) and the Gas Machinery Research Council (GMRC) sponsored the first step in the advancement of new pulsation control technologies for modern high speed reciprocating compressors, termed the Advanced Reciprocating Compressor Technology (ARCT) program. The ARCT program fueled the development of new concepts for pulsation control and, equally as important, established the framework for the growth of a pulsation control research program. The recent advances in the 2006-2007 GMRC pulsation control research are discussed in the present paper. In addition, this paper presents a vision for the next generation of pulsation control technologies, which will enable further development of the modern high speed reciprocating compressor.

PULSATION CONTROL RESEARCH PROGRAM

The GMRC pulsation control technology research program at SwRI may be viewed in terms of two key areas: (1) Nozzle Solutions: Technologies aimed at reducing nozzle pulsations and controlling nozzle resonance; and (2) System / Lateral Solutions: Technologies for improved system or lateral pulsations. Both the nozzle and the system technology solutions should function to reduce pulsation amplitudes *and* improve efficiency of the compressor. By targeting both of these key areas where a significant amount of the losses take place (nozzles / valve losses and pulsation filter system losses), the new technologies will help to improve the current high speed compressor efficiencies. One of the goals of this effort is to restore the high speed compressor *system* efficiency to a level similar to the second generation of low speed integral machines (~ 82-87% efficiency).

The GMRC research program is currently developing pulsation control technology solutions in both of the areas where high speed compressors suffer the highest pulsation induced reliability issues and efficiency losses. The current research program is shown in Figure 1 below. The nozzle solutions technology includes four key concepts – the Tapered Cylinder Nozzle, Infinite Length Nozzle, Virtual Orifice and Compact Nozzle Pulsation Absorber. Each of these technologies offers distinct advantages for various high speed compressor installations. The nozzle solutions reduce pulsation levels in the nozzle and valve interaction area through two means: improved dissipation of the dynamic pressures (through more efficient methods) and shifting of the nozzle resonant frequency.

For the system solutions, the Tunable Side Branch Absorber and the Tunable Filter Bottle technology are presently being developed to minimize pulsations at the station level and function over a broad range of compressor speeds. The technologies are system solutions capable of filtering pulsations more efficiently, within and beyond the traditional compressor manifold system. These technologies will be designed to accommodate the variable speed range of modern high speed compressors.

The pulsation control technologies are shown in the context of their developmental stages in Figure 2. The SwRI GMRC research program classifies technologies into four basic technical stages of maturity - (i) *Proof of Concept*: The concept and technology benefit has been proven through modeling or experimental testing; (ii) *Breadboard Design*: The design has been built into a basic implementation that can be tested experimentally; (iii) *Prototype*: The matured design is fabricated and installed to be tested in various field trials; (iv) *Commercialization*: The

pulsation control technology is an integral part of pulsation control systems and produced as a commercial product for reciprocating gas compressor installations.

The research program has recently developed several technologies that are being evaluated in the initial proof of concept testing phase, such as the Compact Nozzle Absorber (a variation on the virtual orifice technology) and the Tunable Filter Bottle. Other technologies which originated in the DOE / GMRC ARCT program are currently in a prototype stage and will be commercially ready in the next two years. The recent prototype test results from the 2007 research program and the new technology concepts will be discussed in the present paper.

In addition to new pulsation control technologies, SwRI is also developing an enhanced pulsation modeling software, capable of determining compressor system pulsations more thoroughly than previous acoustic methods. Similar to the need for the Analog Design Tool of the 1950's, a new design tool is needed for modern high speed compressor systems to accurately predict pulsations and understand the pulsating flow field. The new SwRI software termed the Transient Analysis Pipe Solver (TAPS) is a numerical solution to the one-dimensional Navier Stokes equations and fully accounts for non-linear flow effects. The recent modeling results using TAPS in the prediction of compressor pulsations are discussed in the 2007 GMC paper by Brun [1].

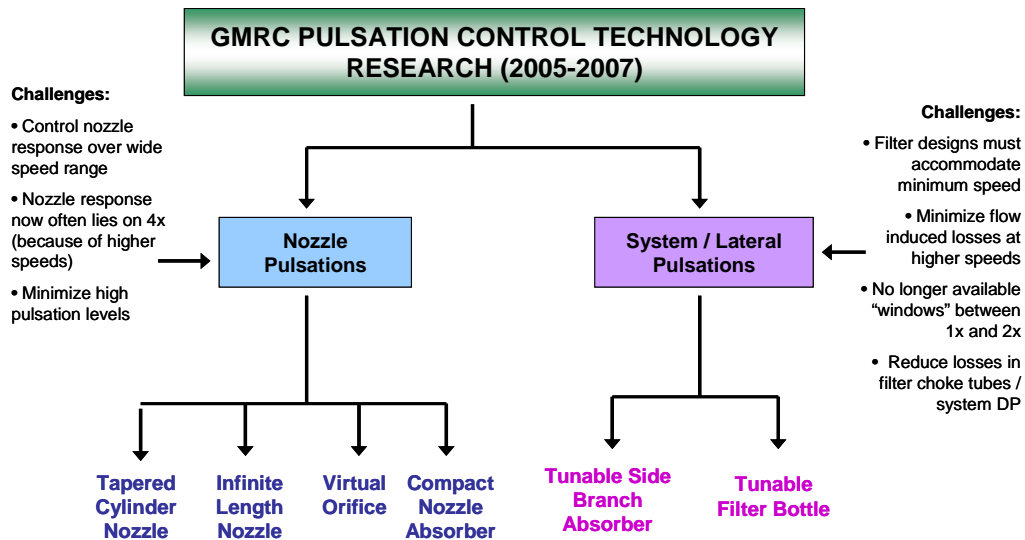


Figure 1. Classification of GMRC Pulsation Control Technologies

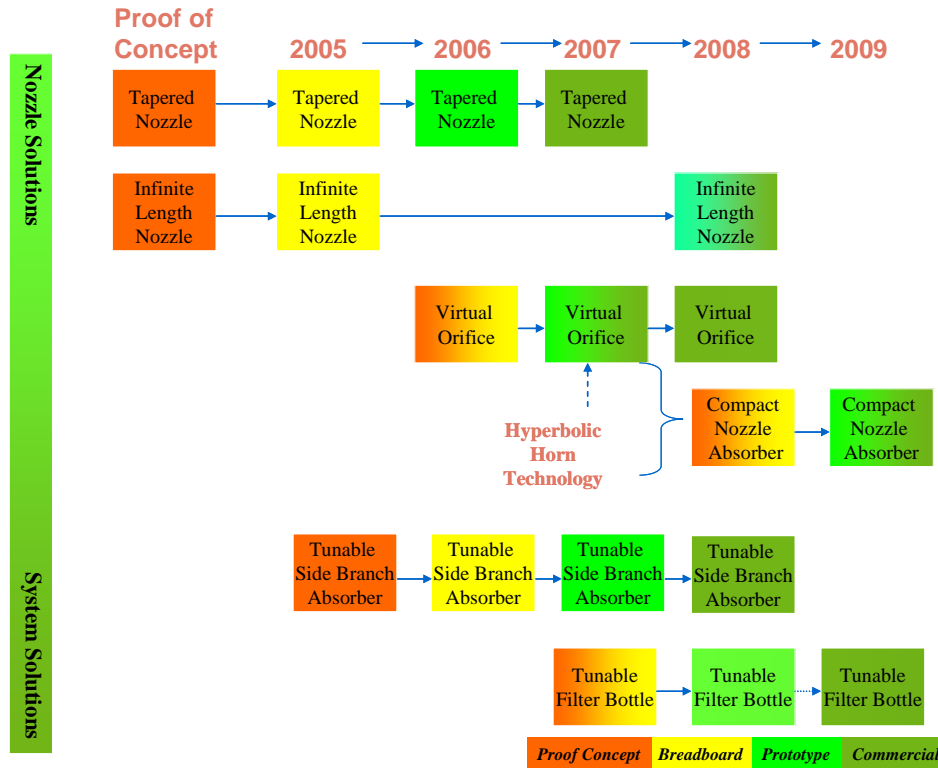


Figure 2. Pulsation Control Technology Development under GMRC Research Program

NOZZLE SOLUTIONS

The compressor cylinder nozzle area can contain excessively high dynamic pressures, which can contribute significantly to compressor inefficiency. Several pulsation control technologies have been developed to reduce the losses in the compressor nozzle area and minimize the cylinder nozzle resonance. The nozzle technologies each work to reduce the pulsation amplitudes more effectively and with less pressure drop than using a traditional orifice plate, which is typically used to reduce pulsations through its inherent pressure losses. The prototypes of the Tapered Cylinder Nozzle (TCN), the Infinite Length Nozzle (ILN), and the Virtual Orifice (VO) are shown in Figure 3.

Tapered Cylinder Nozzle (TCN)

The Tapered Cylinder Nozzle prototype has been tested at the SwRI Reciprocating Compressor Test Facility (RCTF) and the Advanced Reciprocating Compressor Technology (ARCT) test bed. When installed in place of a traditional nozzle, the TCN shifts the nozzle resonance to a higher frequency and thus reduces the level of acoustic excitation. On modern high speed compressors, the resonant frequency of the nozzle often corresponds to 4x the compressor running speed, causing an acoustic response that amplifies the compressor generated pulsations at 40-55 Hz. Moving the resonance to above 4x running speed is advantageous because this design strategy will reduce pulsations significantly without any additional loss in pressure. This strategy will improve efficiency. When installed at the RCTF in place of a traditional nozzle, the

TCN increased the resonant frequency of the nozzle from 50 Hz to 75 Hz, well above 4x running speed, for variable speed compressors operating at 800-1000 RPM.



Figure 3. Prototype Pulsation Control Technologies

The TCN prototype was tested extensively at the SwRI ARCT test bed and the RCTF in place of a traditional nozzle, for comparison purposes. At the ARCT test bed, the cylinder nozzle pulsation amplitudes were reduced by approximately 34%. In the RCTF testing, the pressure drop utilizing the TCN was 33 to 68% less than a traditional compressor cylinder nozzle, depending on operating conditions. The amount of pressure drop reduction with the TCN installed is dependent on whether the system is operating on or off the nozzle resonance based on the compressor running speed.

For compressor systems with particularly high pressure losses in the compressor nozzle due to the coincidence of the acoustic response with a high amplitude order of running speed, the TCN is particularly beneficial. The TCN prototype also offers the capability of using a traditional orifice plate at the cylinder nozzle flange to reduce pulsations further but with less pressure drop because the orifice is at a more effective location in the mode shape where a larger bore orifice can be installed and thereby increase compressor efficiency.

Infinite Length Nozzle (ILN)

Another nozzle control technology in its prototype stage is the Infinite Length Nozzle (ILN). The ILN technology is a device added to the end of an existing compressor cylinder nozzle (internal to the pulsation bottle). The concept behind the ILN is to transform the acoustic characteristics of the cylinder nozzle-bottle junction to a more gradual change in diameter, instead of the abrupt impedance change which typically occurs. The ILN reduces the pulsations in the nozzle through effectively reflecting the pressure wave at each of the ILN perforations. The distribution and shape of the perforations affect the pulsation amplitude reduction and nozzle resonant response (see photograph of prototype in Figure 3).

Multiple prototypes were produced over the course of the ILN design development to determine the ideal perforation pattern. Similar to the TCN results, the ILN performance showed a dramatic pulsation reduction when fourth order was coincident with the baseline compressor nozzle response. Recent testing has determined the optimal perforation pattern for the prototype ILN. For the four ILN prototype designs, the on-resonance pressure losses were one-tenth to one-third lower when an ILN was installed as compared to the pressure losses in the baseline system (no ILN installed).

As shown in Figure 4, the pulsation levels in the nozzle were reduced by 66% compared to the baseline “on resonance” system for all of the ILN designs. The ILN can significantly damp the cylinder nozzle resonance without creating increased pressure loss or high pulsations at other frequencies. As a somewhat “insertable” device, the ILN offers a good option for retrofit designs of existing installations requiring a reduction in compressor nozzle pulsations.

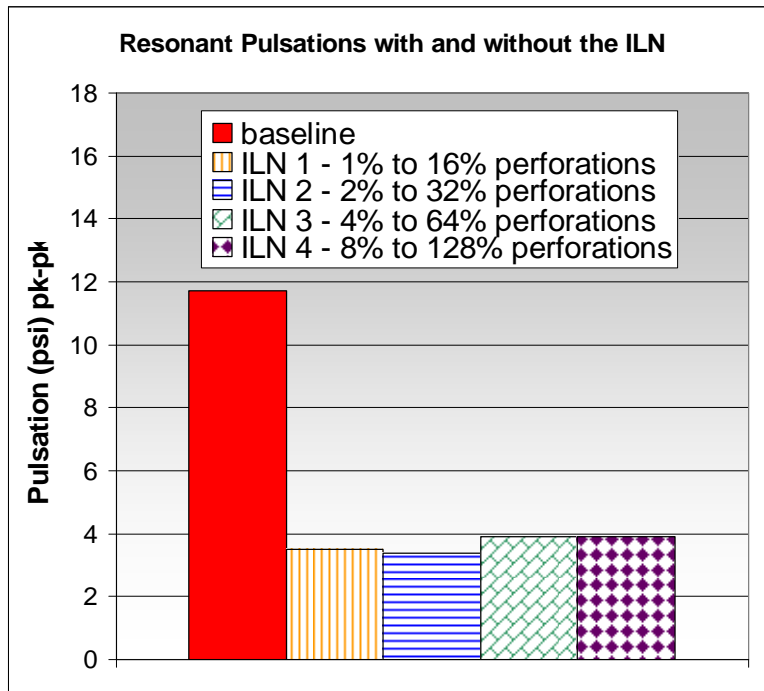


Figure 4. ILN Test Results from the SwRI Advanced Reciprocating Compressor Test Bed

Virtual Orifice (VO)

The third nozzle technology under development is the Virtual Orifice (VO) technology. As the least intrusive of the three nozzle pulsation controls, the VO absorbs the cylinder nozzle pulsations and minimizes the losses due to the nozzle resonance. The VO can be designed for any compressor speed and placed on the valve cap or the cylinder nozzle. Recent testing of the VO prototype at the SwRI ARCT test bed showed the effectiveness of this technology over a large speed range.

Compared to a traditional orifice plate installed in the cylinder nozzle (see Figure 5), the VO absorbs the nozzle pulsations and results in a higher compressor efficiency over the entire speed range of the compressor. The VO technology, demonstrated through the recent experimental testing, improves the compressor efficiency and reduces pulsation amplitudes on and near resonance. As shown in Figure 5, the Virtual Orifice is equally beneficial to the compressor system, on or off resonance. Field trials of the VO are planned for the 2007 research program to demonstrate the effectiveness of the technology on existing compressor systems with high cylinder and valve losses.

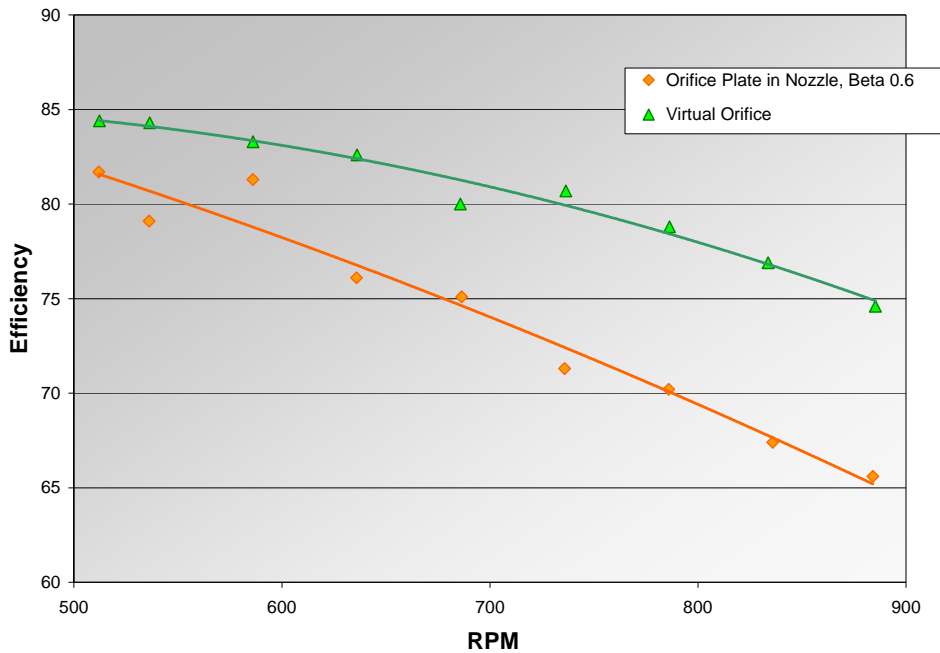


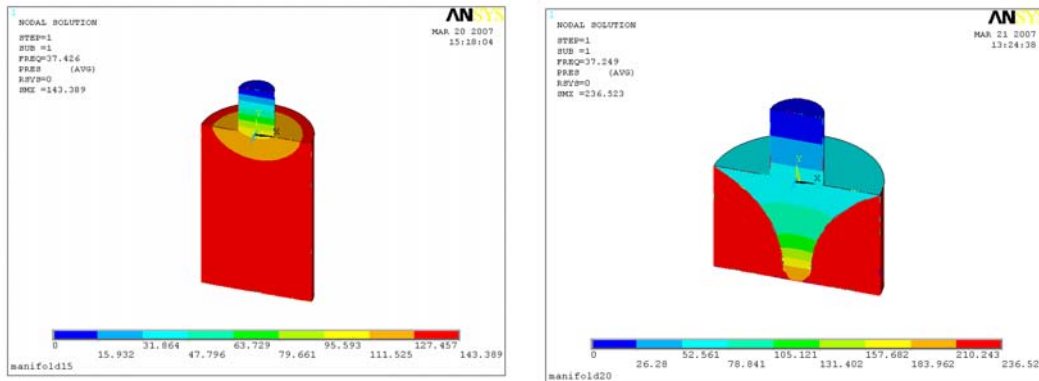
Figure 5. Comparison of Isentropic Efficiency using VO compared to Traditional Orifice

Compact Nozzle Pulsation Absorber (CNPA)

In addition to the three nozzle solutions, a new concept is being developed for use in pulsation control applications requiring a more compact size. A new technology - termed the hyperbolic horn – can be applied to a standard resonator to change its effective length and maintain the same acoustic resonance characteristics. The hyperbolic horn is an efficient technique to generating

mass reactance without resorting to a long inlet throat [2]. For example, incorporating the hyperbolic horn design into a typical side branch resonator with a 36" length reduces the physical length to 14 inches, while maintaining an equivalent resonant frequency of 37 Hz.

The basic hyperbolic horn design (shown in Figure 6) may be incorporated into the Virtual Orifice technology to reduce the size and better adapt the pulsation control technology to existing compressor nozzles. This new concept of a more compact VO using the hyperbolic horn technology is termed the Compact Nozzle Pulsation Absorber (CNPA). The initial experimental validation of this concept will utilize a breadboard design for the CNPA. The testing of this technology is expected to be performed in July 2007.



*Traditional Resonator Design,
Frequency @ 37.4 Hz, L=36"*

*Hyperbolic Horn Design,
Frequency @ 37.2 Hz, L=14"*

Figure 6. Hyperbolic Horn Technology Compared to Typical Resonator

SYSTEM / LATERAL SOLUTIONS

The other area of pulsation control research is the system and lateral solutions. The present compressor manifold system experiences significant losses, which typically increase with compressor speed and loading (flow rate through the pulsation filter bottles).

Tunable Side Branch Absorber (TSBA)

One of the system / lateral pulsation technologies which originated from the ARCT program is the Tunable Side Branch Absorber (TSBA). The general Side Branch Absorber (SBA) technology has been used previously to control pulsations and works as a Helmholtz resonator with a volume connected to the main system piping through a choke tube. This technology was designed to reduce pulsations in the lateral leg connecting the compressor manifold to the header piping. Often times, low frequency pulsations (at 1x or 2x compressor running speed) are not completely filtered by the compressor manifold pulsation controls. This situation is especially common when the pulsation filter Helmholtz response is designed to lie between 1x and 2x and the compressor operates with single-acting cylinders (which produces a stronger, unfiltered 1x response).

An SBA designed by SwRI reduced lateral pulsations significantly over a narrow speed range (270-330 RPM). The fixed geometry design of an SBA limits the Helmholtz resonator response absorption to a small speed range.

In 2005, the design of an SBA was adapted to varying speeds and operating conditions in a prototype termed the Tunable Side Branch Absorber (TSBA). The tunability of the design is achieved through varying the gas volume in the TSBA with a piston – increasing the gas volume causes the resonant frequency to decrease to correspond with a reduction in compressor operating speed. The TSBA was further refined to automate the “tuner” through direct measurements of the compressor speed and temperature.

In 2006-2007, a TSBA prototype was designed and installed at the ARCT test bed. The resulting performance of the TSBA is compared to the baseline system with high lateral pulsations in Figure 7. The data shown in Figure 7 represents the versatility of this technology over a large speed range – 600 to 900 RPM. The pulsation reduction for the 1x residual pulsations with the TSBA installed on the system lateral line was greater than 80% (TSBA tuned to running speed). Other implementations shown in this figure include a damped SBA and a TSBA tuned to a specific operating speed (780 RPM). As shown, the greatest reduction in pulsations is achieved when the TSBA is tuned to match the running speed for the compressor. The Tunable Side Branch Absorber is a significant advancement in designing pulsation control technology to suit a variable speed compressor.

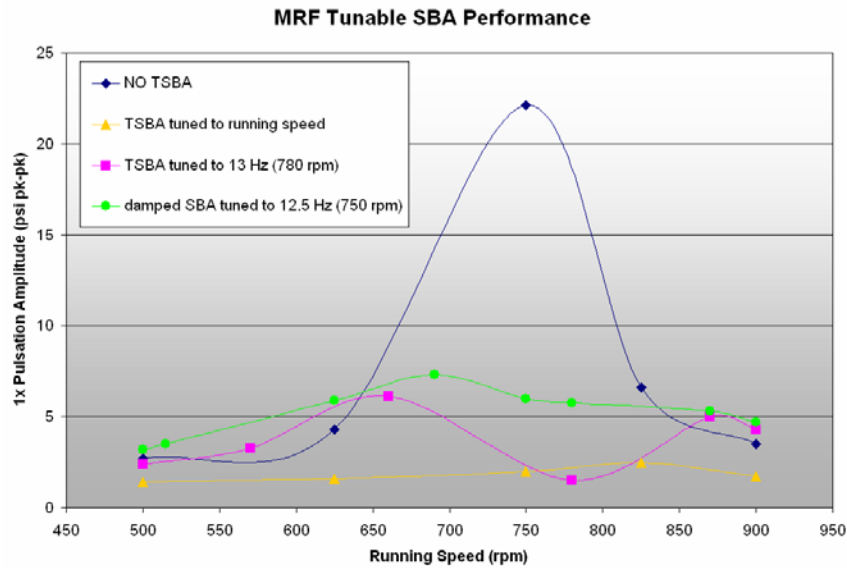


Figure 7. Tunable Side Branch Absorber Pulsation Amplitude Reduction of 1x Pulsations

Tunable Filter Bottle

For optimal performance and efficiency, the compressor filter system should also be capable of accommodating variable speed compressors by shifting its Helmholtz response according to the

compressor speed. Over the last year, a new system technology concept has been developed as part of the GMRC research program, aimed at making the compressor manifold system capable of adapting to the compressor operating speed. This concept is represented by the Tunable Filter Bottle (noted in the research program plan in Figure 2), which can vary its Helmholtz frequency according to the compressor speed variation.

The Tunable Filter Bottle can be designed (conceptually) by varying the Helmholtz response through one of the four parameters: bottle diameter, bottle (volume) length, choke tube length or choke tube diameter. A trade-off study was completed to examine which of these parameters is the most effective method for “tuning” the filter. The study considered a compressor operating over a broad speed range of 450-900 RPM. Typically for this operation, the pulsation filter is designed to meet the low end of the compressor speed range, with a Helmholtz response of less than 7 Hz. The filter design is also constrained by a minimum pressure loss requirement imposed by the high flow rates at 900 RPM (the maximum speed of the compressor).

The trade-off study resulted in determining how the four parameters must be varied to change the filter frequency over the range of 450-900 RPM. Both the bottle length and the choke tube length parameters required changing the length over a 7:1 ratio. The bottle diameter change was equally as demanding, requiring a bottle ID change from 8” to 24” (3:1 ratio). The fourth parameter - choke tube diameter - only required changing the choke tube from slightly less than a 2” ID to a 4” ID (2:1 ratio) to shift the Helmholtz response from 7 to 13.5 Hz. In addition, the choke tube diameter can be expanded as the compressor speed (and flow) increase – resulting in a filter pressure drop that stays constant (or declines) with increasing compressor speed. This effect is described in Figure 8, which compares the pressure drop associated with the four filter design parameters over the compressor speed range.

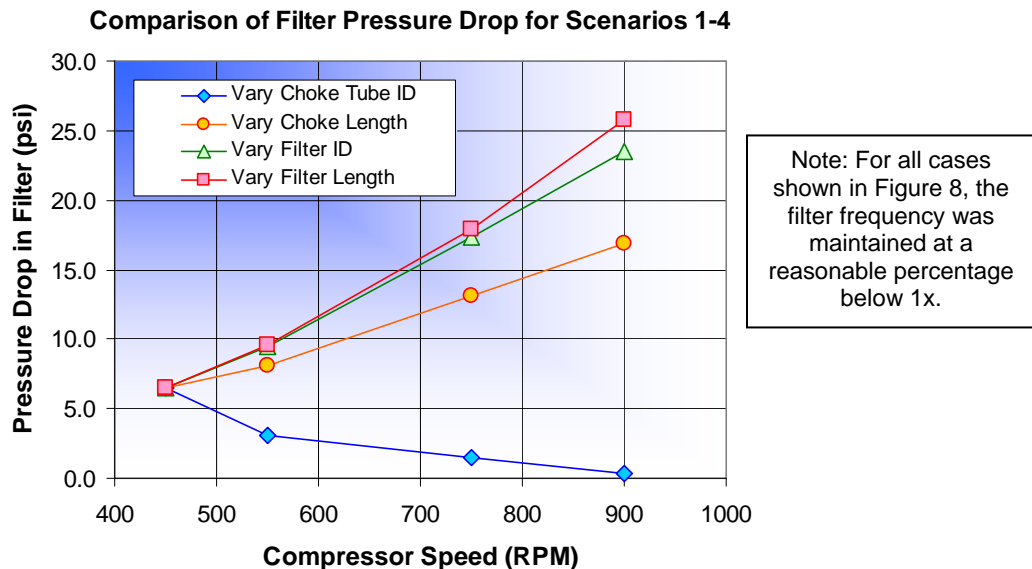


Figure 8. Pressure Drop for Variation in Filter Parameters Over Variable Speed Range

The Tunable Filter Bottle concept was modeled to determine the benefit of using this pulsation control technology on a typical two-cylinder, variable speed machine (450-900 RPM). A

traditional filter for this machine would utilize a 7' bottle (22.5" ID) and a 6' choke tube (2.323" ID). Two design methods for the Tunable Filter Bottle were considered. This first method tried to optimize reduction in pressure drop by varying the choke tube diameter, using the same size pulsation bottle as the traditional filter. The second method considered reducing the bottle diameter to an 18.5" bottle ID – and varying the choke tube diameter to maintain a somewhat constant pressure drop over the speed range.

The resulting pressure loss predicted by the model for the two Tunable Filter Bottle designs is shown in Figures 9-10. The curves show the pressure drop for various choke tube diameters for the minimum flow rate (at 450 RPM) and the maximum flow rate (at 900 RPM). Increasing the choke tube diameter as the flow rate increases (proportional to compressor speed) allows the pressure drop to be reduced as compressor speed increases – instead of the significant increase in pressure drop resulting from keeping the choke tube diameter constant, as in the traditional filter design. This result indicates the possibility of achieving a significant increase in compressor efficiency using the Tunable Filter Bottle concept. Additionally, the initial models of the Tunable Filter Bottle indicate that the traditional filter bottle design could be reduced in size, which would better control vibrations and mechanical responses of the system.

The Tunable Filter Bottle concept is presently being developed through a more extensive design effort. These design iterations are examining methods of changing the choke tube diameter for one and two bottle pulsation filter systems. In addition, the research effort is considering methods of automating the tunable filter to passively determine the appropriate choke tube diameter to meet the compressor operation. Since many embodiments of the design concept are possible, experimental testing is necessary to determine an optimal design for the tunable choke tube. Testing of a simple breadboard design to vary choke tube diameter is currently underway at the SwRI RCTF. Results of this initial breadboard testing are expected in July 2007.

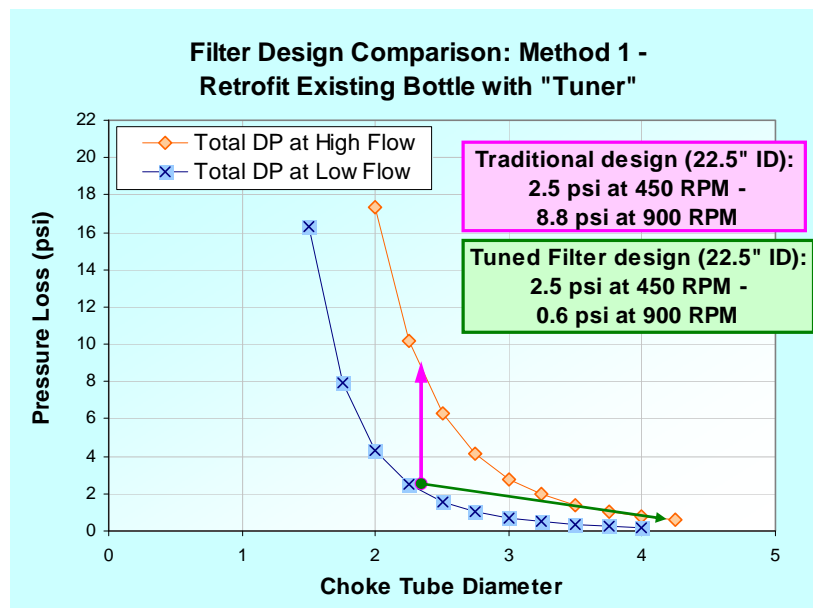


Figure 9. Comparison of Filter Pressure Loss as a Function of Choke Tube Diameter for High and Low Flow Rates – Method 1 Design

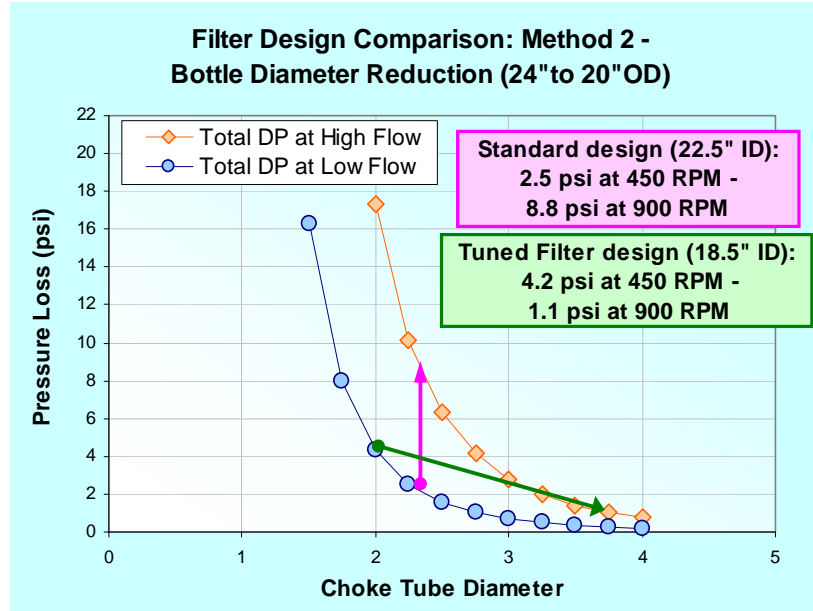


Figure 10. Comparison of Filter Pressure Loss as a Function of Choke Tube Diameter for High and Low Flow Rates – Method 2 Design

SUMMARY: ENABLING HIGH SPEED COMPRESSORS

The modern high speed compressor suffers from inefficiencies produced in two key areas: dynamic pressures in the valve / cylinder nozzle area and high differential pressures (produced by high flow rates) in the compressor manifold system. The GMRC pulsation control research program is developing technologies to reduce pulsations and thereby improve the compressor system losses in these two areas. The pulsation control technologies must be viewed collectively as advancements to the entire compressor system. The technologies for cylinder nozzles and the compressor manifold system (when combined with improvements to valve technology) should result in significant savings in horsepower and increased efficiency.

The need for a “rubber” compressor station arose in the deregulated gas industry with the operator’s need for more flexible operation, an operation which is more tolerant of changes in flow and more adaptable to a wider range of pressure ratios across the compressor. Though many advances in compressor technology have provided the roadmap to a rubber compressor station, the pulsation control technology must also adapt to become more versatile and accommodating of operational changes. Advanced pulsation controls are being developed for the next generation of pulsation control, in essence, a “rubber” pulsation control system. The advancements in pulsation control technology represented in the GMRC research program will enable a more efficient high speed compressor.

ACKNOWLEDGEMENTS

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