Benefits of the Virtual Orifice: Pulsations and Vibrations Reduced, Performance Improved

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ABSTRACT

Controlling cylinder nozzle resonant pulsations while maintaining acceptable compressor performance has been an issue in reciprocating compressors for the last 50 years or more. The common solution to reduce vibrations and pulsations in the cylinder nozzle is the installation of an orifice plate at the compressor cylinder nozzle flange or welded into the nozzle near the nozzle-to-bottle acoustic junction. Lower efficiencies and higher pulsations are more evident for high speed, high horsepower machines due in-part to the higher mean flows and coincidence of the cylinder nozzle acoustic response with lower compressor orders. The GMRC pulsation research program at Southwest Research Institute has developed a pulsation control device as a replacement and improvement upon the commonly installed cylinder nozzle orifice plate solution. The new device is termed the Virtual Orifice. The Virtual Orifice (VO) has recently been installed at El Paso's Baxter compressor station. Measured field data has shown that the installation of the VO resulted in a significant reduction in pulsations and vibrations related to the cylinder nozzle resonance while noticeably improving the compressor efficiency.

This paper will discuss the fundamental issues that the Virtual Orifice is designed to address. It includes data (vibration, pulsation, and performance) from a field compressor before and after Virtual Orifices were installed. The paper will explain and demonstrate the results from the field test of the installation of a Virtual Orifice on each cylinder of a high speed reciprocating compressor. The field test results will include summaries of the data that describe the vibration, pulsation, and performance improvements that were observed. This paper demonstrates the benefits of properly applied Virtual Orifices.

Introduction:

Pulsations associated with the cylinder nozzle response have created an ongoing pulsation control challenge that is generally tackled through frequency avoidance or by pressure drop damping. Resonance avoidance is not normally possible with the wide speed ranges and/or large variations in operating conditions (temperatures and pressures) that are associated with most reciprocating compressors. As a result of the common need to manage resonance rather than avoid it, orifice plates are commonly installed at or near the cylinder nozzle flange connection of most high-speed and many low-speed reciprocating compressors. A continuing need for increased operational flexibility with lower losses drives today's pulsation control research.

"Cylinder nozzle resonance" is a phrase that refers to an excited acoustic response associated with the lengths and diameters of the cylinder gas passage, cylinder nozzle, and filter bottle volume. When the frequency of the pulsations that are inherently generated by reciprocating compressors coincides with or is near the acoustic natural frequency of the cylinder nozzle response, the pulsation amplitudes are significantly amplified.

A primary goal of the Gas Machinery Research Council (GMRC) sponsored pulsation control research program at Southwest Research Institute (SwRI) is to develop a low pressure drop method of controlling the cylinder nozzle resonance, thus eliminating the need for orifices in the cylinder nozzle region. In 2007, the GMRC sponsored pulsation control program built and field tested a device that showed exceptional ability to control the cylinder nozzle resonant pulsations during laboratory type tests. Because the novel application of the side branch absorber (SBA) near the cylinder nozzle was meant to replace the typical orifice plate, the device was named the Virtual Orifice (VO).

Evolution of the Virtual Orifice

Side Branch Absorber (SBA) or side branch resonator or Helmholtz resonator technology has been used for many years to alter acoustic responses in compressor piping systems. Side branch absorbers are well established pulsation and vibration control devices that have been used to reduce pulsations, and therefore vibrations, in compressor piping systems, typically for lateral resonances and acoustic filter responses. An example of the results that can be achieved with the proper installation of an SBA is depicted in Figure 1. For the fixed speed (400 RPM) compressor piping system, the acoustic filter frequency was not adequately placed to limit pulsations in the adjacent centrifugal compressor piping to acceptable levels. Additional pulsation control in the form of an SBA attached to the piping lateral resulted in significant reduction of the pulsations at one times the compressor running speed (1x). Since the VO is an SBA applied in the compressor cylinder nozzle region, the VO has a similar impact on pulsations at the cylinder nozzle resonance frequency. For optimum pulsations reduction, the VO should be located as close as possible to the compressor cylinder valves (i.e., at the pulsation maximum of the cylinder nozzle quarter wave response).

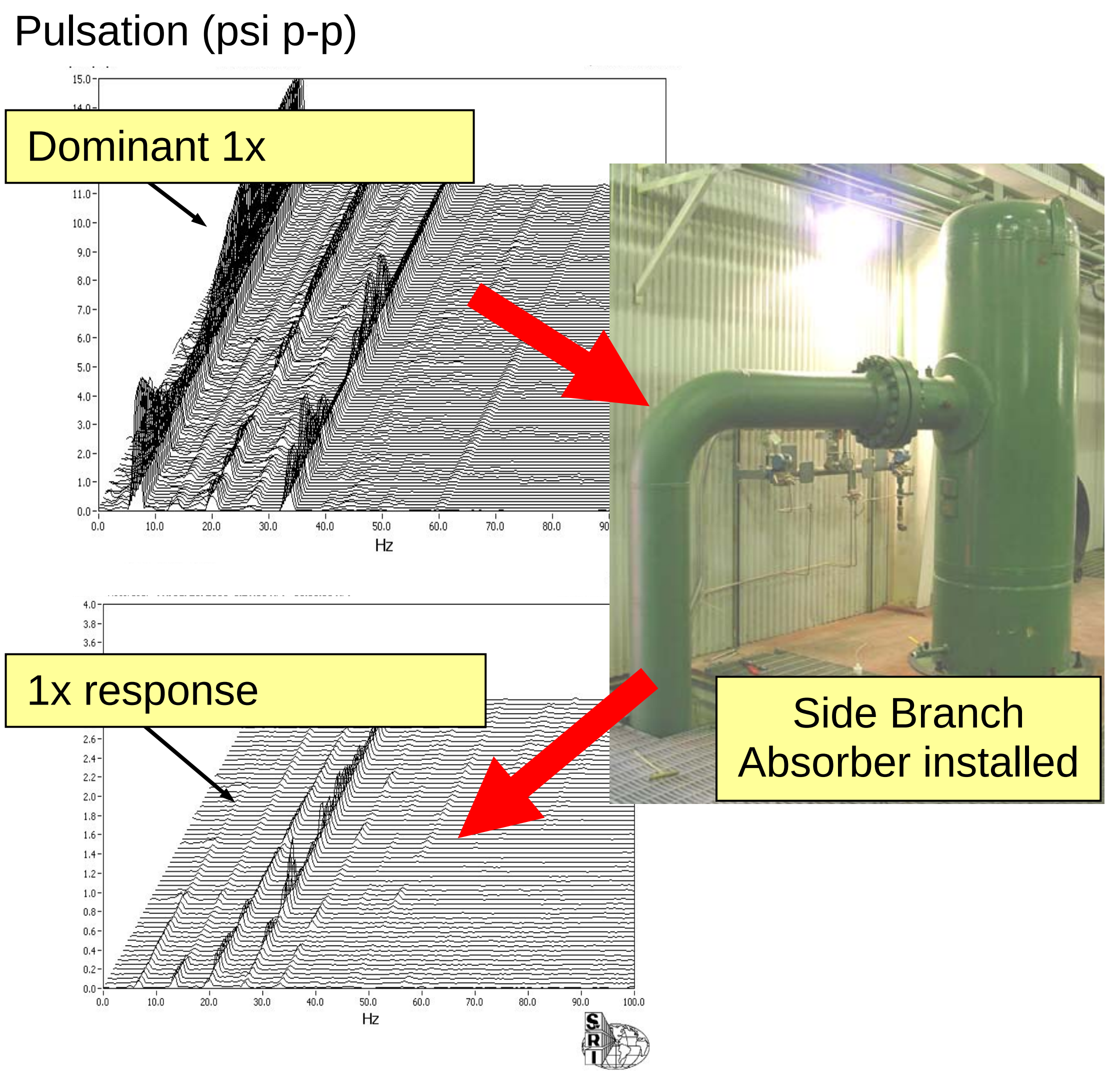

Figure 1: Effectiveness of a Side Branch Absorber

As is the case with the SBA, the VO is comprised of a choke tube (relatively small piping) that connects a volume to the main piping. Initial sizing of the VO choke tube and volume is determined using the well-documented equation for the Helmholtz resonator. Frequency placement and effectiveness of the VO are then fine tuned by modeling the piping system using proven acoustic modeling tool. This sizing method has been successfully used throughout the developmental stages of the VO.

VO Field Testing

Field testing of the VO was necessary to further validate the design. At El Paso Western Pipeline's Baxter Station they had experienced excessive vibrations and cylinder nozzle failures as a result of uncontrolled cylinder nozzle pulsations generated by the two-throw reciprocating compressor. As a result of the nozzle failures, fairly restrictive cylinder nozzle orifice plates were installed in the suction and discharge side of the cylinder. Installation of the orifices reduced the vibrations and eliminated the nozzle failures; however, installation of the orifices also resulted in loss of throughput. Therefore, representatives from El Paso Western Pipelines welcomed the opportunity to install the VO with the hope that the unit efficiency would improve.

Baxter Compressor Station operates the two-throw 1,200 BHP compressor in a single stage natural gas transmission service over a 1,050 to 1,150 RPM speed range. Each cylinder has a 7.5-inch [191 mm] bore and a 6.0-inch [152 mm] stroke. Operating pressures are 780 psi [5378 kPa] suction pressure and 1030 psia [7102 kPa] discharge pressure. Figure 2 shows the VO installed at the suction valve cap on one side of the compressor.

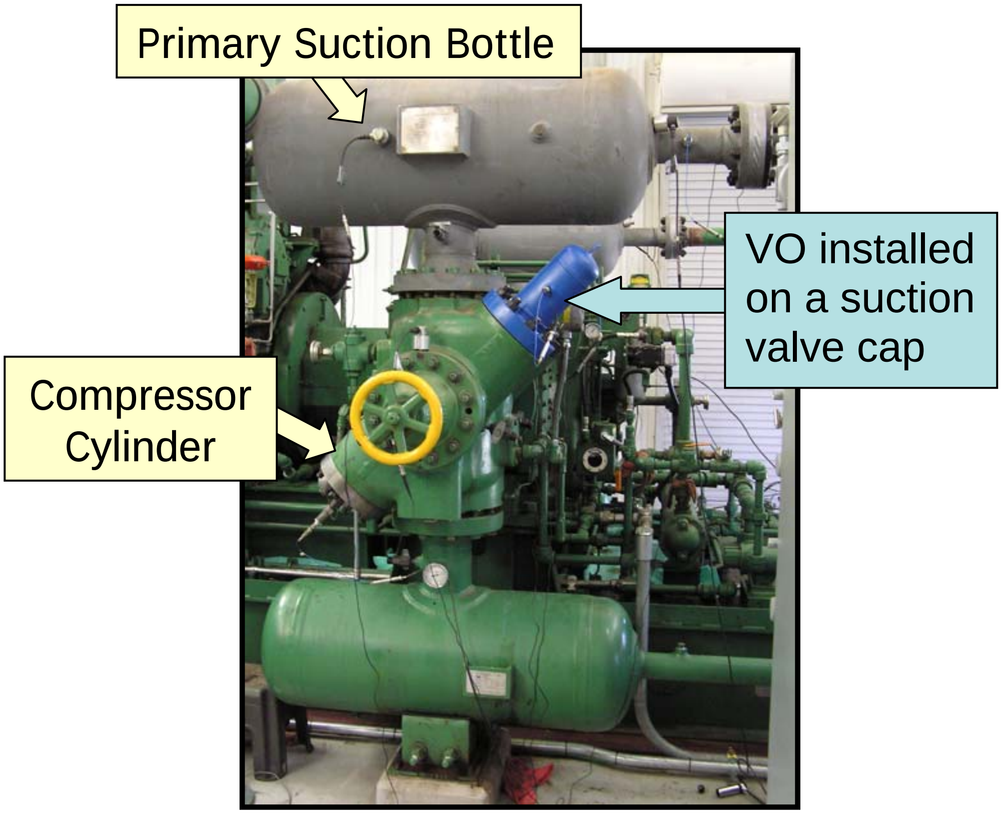

Figure 2: VO installed at GMRC Member Company Station (El Paso's Baxter Station in Wyoming)

To validate the SwRI natural gas laboratory data, a smaller, more compact VO design was developed and installed on the suction side of each of the two natural gas pipeline compressor cylinders to absorb the suction cylinder nozzle resonance associated with each cylinder. Figure 3 portrays two 3-D images of the improved VO design. In this figure, the VO volumes are transparent to show the internal details. The design incorporates the VO into the valve cap such that the valve cap and VO became one assembly. Field test measurements of the compressor pulsation, vibration, and performance were acquired in July 2007 and are summarized in the following sections.

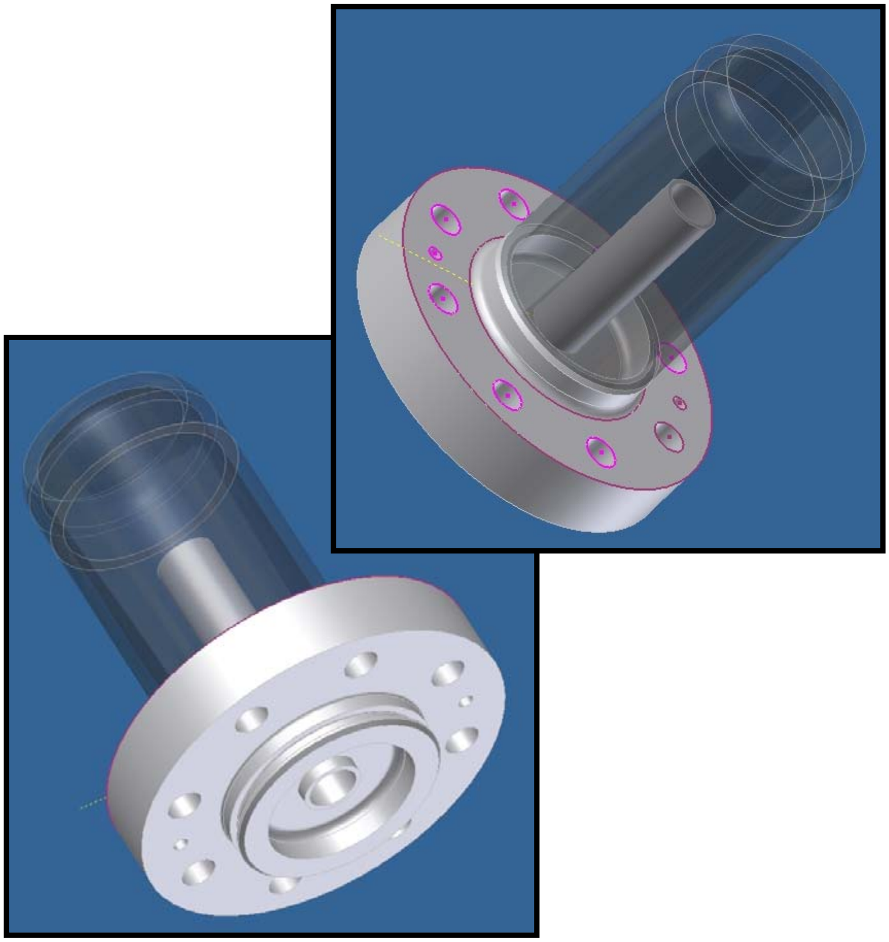

Figure 3: 3-D Model of the Field Tested VO

Pulsations Improvement

Pulsation measurements were obtained at a single cylinder valve cap for each cylinder. Data were measured for the following configurations:

1) with neither the orifice nor the VO installed,
2) with only the orifice installed, and
3) with only the VO installed.

A summary chart of the pulsation measurements resulting from testing each of the three configurations described above reveals the benefits of installing the VO (see Figure 4). For configuration 1 (neither device installed), the cylinder nozzle response was just above four times compressor running speed (4^{th} order or 4x), and the maximum pulsations resulting from that response placement peaked out at 52 psi [359 kPa]. Pulsation amplitudes at 2x increased significantly when the orifice was installed (configuration 2), resulting in a maximum pulsation amplitude of 30 psi [207 kPa]. The large increase in 2x pulsations is indicative of an undersized orifice. With the VO installed, maximum pulsation amplitudes over the entire 0 to 200 Hz frequency range were reduced to 15 psi [103 kPa]; therefore, the maximum pulsation amplitudes over the 0 to 200 Hz frequency range were reduced by 71 percent with the VO installed. Overall pulsations were approximately 50 percent lower with the VO installed as compared with that of the orifice. Pulsation improvements also resulted in vibration and efficiency improvements as described in the following sections.

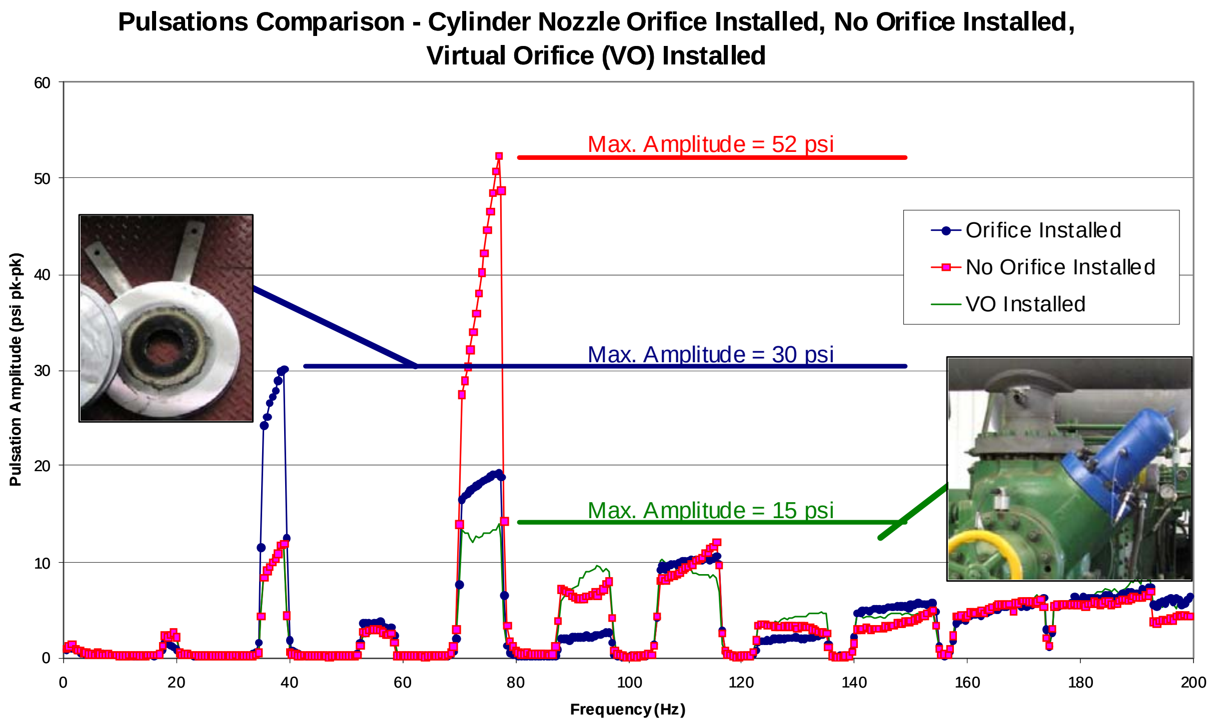

Figure 4. Field Data Show Reduced Pulsations with VO Installed

Vibrations Improvement

Vertical cylinder vibration was measured for the three configurations described in the previous section. After review of the vibration and pulsation data, it was clear that a large portion of the 4x vibrations are directly related to the pulsations associated with the cylinder nozzle response. Pulsations at 4x were approximately 0.8 ips [20 mm/s] when there was no orifice and no VO installed (configuration 1). With either the orifice or the VO was installed, pulsations at the bottom end of 4x were reduced down to 0.6 ips [15 mm/s] and down to 0.3 ips [8 mm/s] at the top end of 4x. The vibration data acquired at the Baxter Station are summarized in Figure 5. Maximum vibration amplitudes at the second (2x) and third (3x) orders were not affected by the system configuration changes. It was determined from the field test results that 2x and 3x vibrations were not pulsation driven and that vibration reduction at these frequencies would require modifications to the mechanical system. In this field test case, the VO did not significantly improve vibration compared to that of the orifice; however, because the improvements were similar to that of the orifice, these data provide further evidence that the VO could potentially replace the orifice.

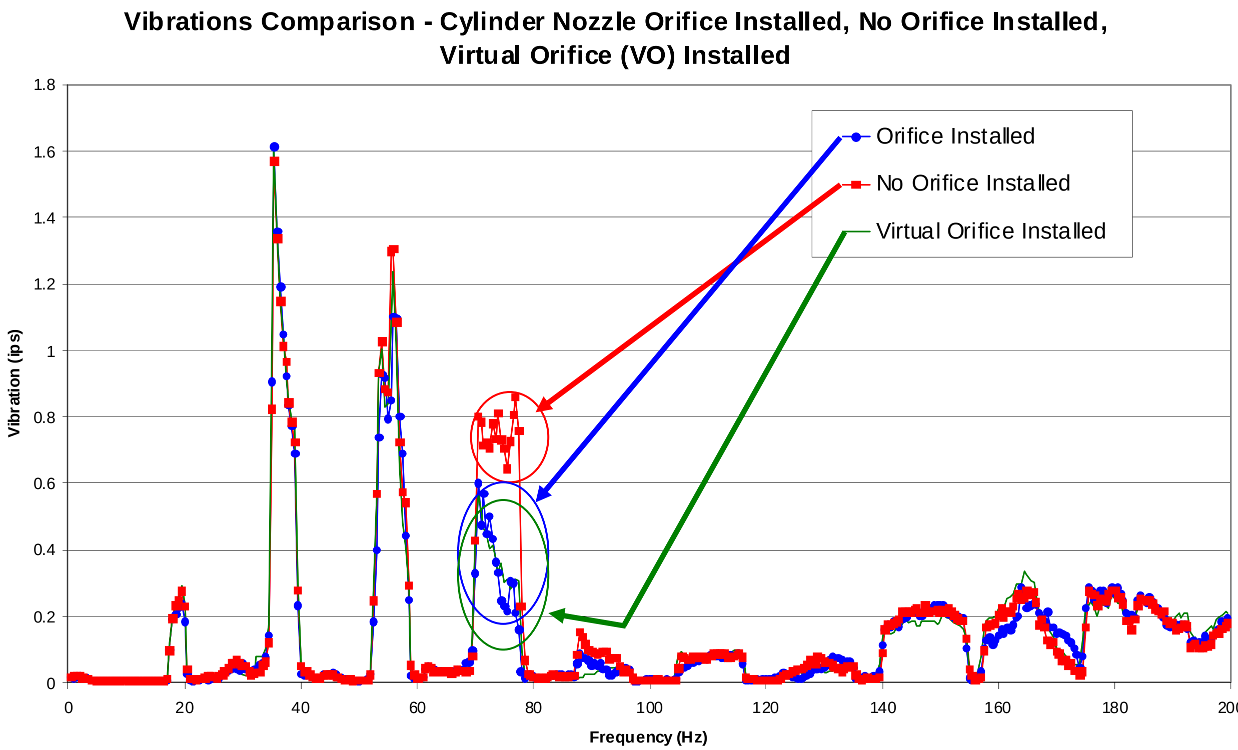

Figure 5: Field Data Show Reduced Vibrations with VO Installed

Valve Cap Bolt Loading

Valve cap bolt loading was reviewed due to some potential concerns regarding the installation of the VO as a replacement of compressor cylinder valve caps. Figures 6 and 7 show the free body diagrams of the typical valve cap and VO. The simplified free body diagrams summarize the different bolt loading forces that should be considered when reviewing the valve cap bolt loads. The following forces have been included on the free body diagram:

- Fsp = Force due to static pressure
- Fdp = Force due to dynamic pressure
- Fva = Force due to acceleration resulting from the vertical vibration of the compressor cylinder
- Fcage = Force due to pressure build-up that occurs within the cylinder prior to the valve opening event
- Fb = Force applied to each bolt due to the above loads

Fsp and Fcage remain approximately the same whether a valve cap or VO is installed. The Fva is expected to increase when a VO is installed in place of a valve cap due to the increased mass. The increase in Fva is related to the square root of the ratio of the change in mass; therefore, Fva for the Baxter installation was estimated to increase by approximately 22%. The Fdp is expected to decrease when a VO is installed in place of a valve cap due to the reduced dynamic pressure pulsation amplitudes in the cylinder. The Fdp is directly related to the ratio of the change in 0-peak dynamic pressure pulsation amplitudes. As stated in the Pulsations Improvement section, installation of the VO (configuration 3) reduced the maximum dynamic pressure pulsations in the cylinder gas passage by approximately 50% as compared with the pulsations when the orifice was installed. The forces due to dynamic internal pressures acting on the internal surface of the VO volume partially cancel. The forces do not perfectly cancel due to the area difference associated with the choke tube. Therefore, the Fdp decreased by approximately 26%. When the Fva and Fdp were calculated for the Baxter Station installation, the increase in Fva and the decrease in Fdp resulted in an overall increase of approximately 130 lbs on each bolt. That increase in force is less than 4% of the total load on each bolt prior to the installation of the VO. Valve cap bolt strain measurements will be obtained whenever the next virtual orifices are installed. The bolt strain measurements will be obtained for the valve cap bolts before and after the VOs are installed.

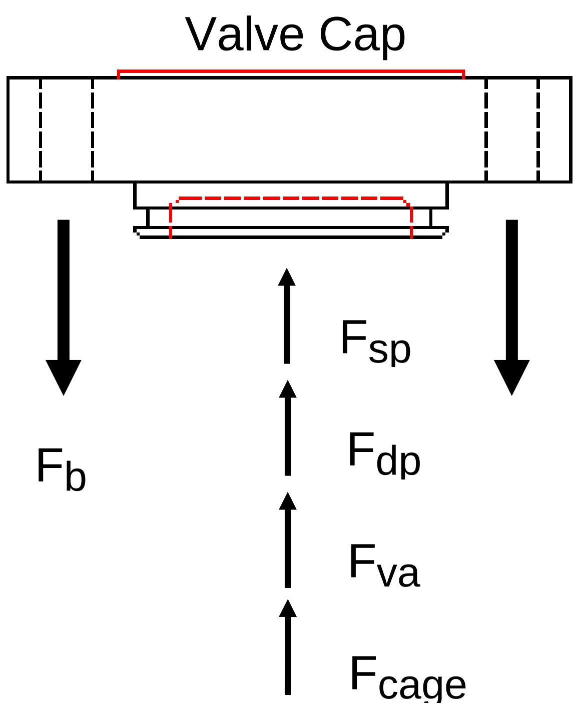

Figure 6: Valve Cap Free Body Diagram

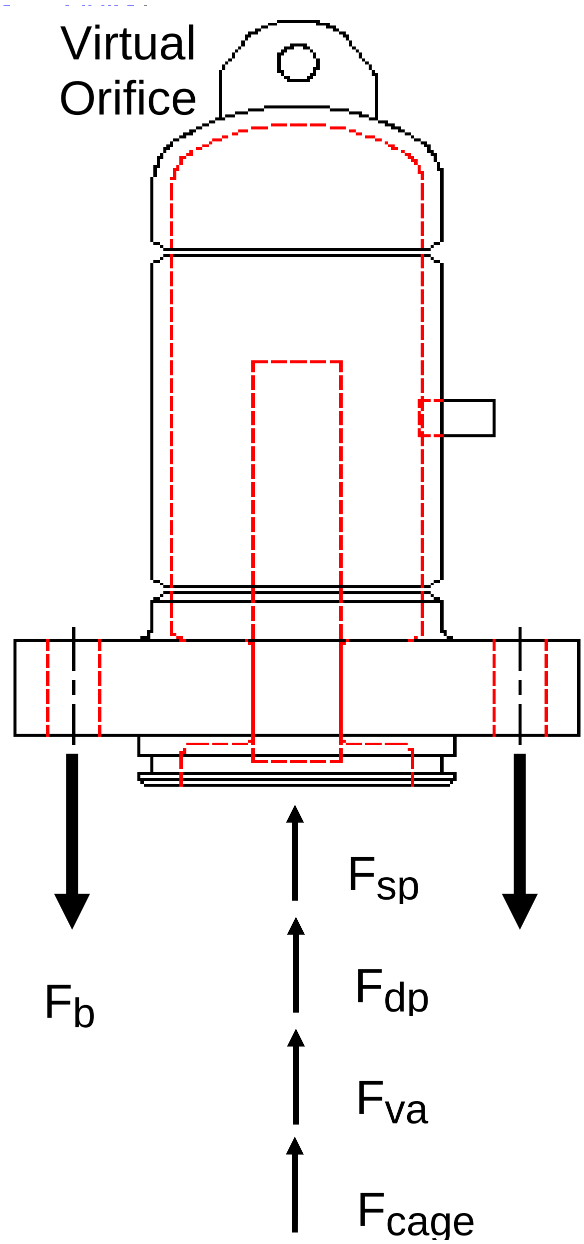

Figure 7: Virtual Orifice (VO) Free Body Diagram

Efficiency Improvement

After observing pulsation and vibration improvements, further analyses were performed to determine the effect on compressor cylinder efficiency that would result from the installation of the VO. Overall thermodynamic efficiency and power per unit flow were calculated based on the measured Pressure-Volume (PV) cards. The efficiency values were calculated to determine the relative changes in cylinder efficiency when an orifice or VO is installed. Efficiency changes are summarized in Figure 8. With the installation of the virtual orifice on only the suction side of each compressor cylinder, compressor efficiency improved by 2.5 to 4.0 percent as noted in the upper plot. The lower plot depicts a 1.7 HP/MMSCFD [1416 kW/(Nm^3/hr)] reduction in power per unit flow with the VO installed. Based on the fuel savings generated by installing the two VOs on the test compressor, a payback time of less than two years is estimated.

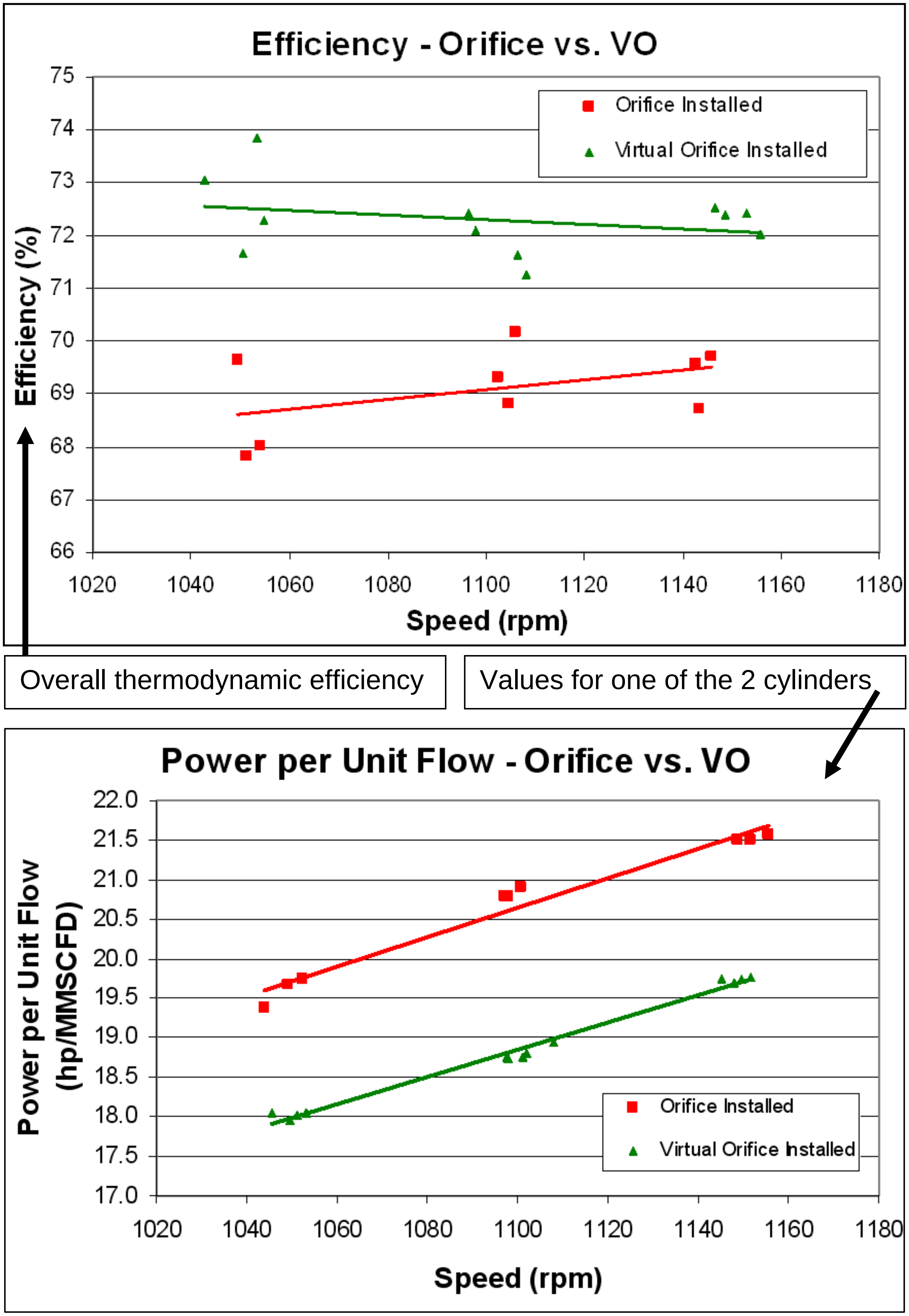

Figure 8: Field Data Show Improved Efficiency with VO Installed

Summary

The more than 50 year search for a device that would control the cylinder nozzle pulsations, while maintaining acceptable compressor performance, appears to have come to a successful conclusion. Through the GMRC research program, the Side Branch Absorber (SBA), an industry proven pulsation control device, was adapted for use at a novel location in the piping system. Efforts to control cylinder nozzle pulsations with minimal losses resulted in a very useful device called the Virtual Orifice (VO). Data summarized in this paper suggests that the VO is an effective device for tackling the problem of high amplitude compressor cylinder pulsations that are typically associated by the cylinder nozzle response. The VO can be installed on both low-speed and high-speed compressors to replace any cylinder nozzle orifices that are consuming large amounts of horsepower as long as one compressor cylinder valve cap is unoccupied per suction and/or discharge side of each cylinder. The VO can be installed on either the suction or discharge side of the cylinder or both side of the cylinder, depending on the need to control suction or discharge cylinder nozzle resonances. Installation of the VO on a gas transmission compressor has shown significant pulsation reduction and improved efficiency. Vibration reduction achieved with a VO installed was similar to that achieved with an orifice installed, but with less pressure drop. Reciprocating compressor installations require a balance between pulsation control, compressor performance, and mechanical vibration. The VO offers a solution that manages the cylinder nozzle resonance more effectively and more efficiently, thereby achieving an improved system balance.

Acknowledgements

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