Compression Technology for the Next Generation

SwRI engineers develop new tools to enhance gas transmission

By Danny M. Deffenbaugh, Klaus Brun, Ph.D. and Ralph E. Harris, Ph.D.

The natural gas industry's transmission system remains one of the vital energy infrastructures in the United States. This industry operates pipelines throughout the country, with compressor stations at regular intervals of 30 to 100 miles to help ensure a steady flow of gas. More than 70 percent of the compressor fleet, or approximately 4,000 units, are reciprocating-piston compressors.

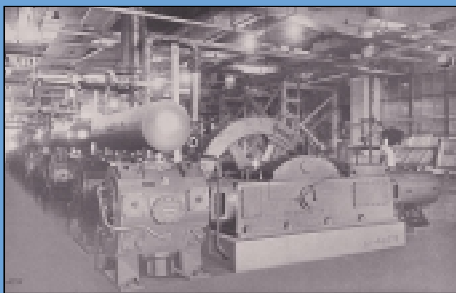
Advances in compression technology helped the U.S. gas industry expand after World War II. The original, first-generation compression technology consisted of many small (500 to 750 horsepower) slow-speed (180 rpm) compressors to move gas from producing regions to markets. To provide the necessary expansion, a developmental second generation of larger, higher-speed machines promised significant reductions in installed costs. However, as industry installed the first of these machines they experienced many reliability and operational problems involving flow pulsations and mechanical vibrations that resulted in piping failures.

To address these problems, the pipeline industry in 1952 formed what is now the Gas Machinery Research Council (GMRC), which contracted with Southwest Research Institute (SwRI). As a result of this initial collaboration, SwRI developed pulsation control systems that combined acoustic filters and dampers with effective mechanical restraints. SwRI has continuously operated the GMRC pulsation design service for decades, generating royalties that have funded GMRC research since 1955.

This second generation of compression technology has since become known as "slow-speed integral" compression. This equipment has nominally three times the horsepower, running at twice the speed (at less than 300 rpm in the 1,500 to 2,500 hp range) of the equipment it replaced. These slow-speed integral machines have been the U.S. pipeline industry's compression workhorses.

The promise of dramatic cost reductions has driven the industry toward even higher-speed, larger-horsepower reciprocating compression, powered by efficient, separate, modern gas engines or large electric motors. Within the past few years, the first iteration of this new class of machines has been installed. This third generation of equipment has three times the power of the prior generation and is now running at two to three times the speed (500 to 1,000 rpm; 4,000 to 8,000 hp). With this technology have come new vibration and pulsation problems. The pipeline industry faces a technology transition similar to that of 50 years ago. As a few large machines replace many small ones, each must provide a wider flow-rate capacity range with increased reliability. Wider variations in speed complicate pulsation control, and higher speeds have resulted in significant losses in compressor efficiency, contributed to in part by both pulsation control and conventional valve technology.

Slow-speed, integral machines are generally no longer commercially available because they are cost-prohibitive to manufacture and install. While affordable, the current high-horsepower, high-speed compressors require advancements in technology to meet



Slow-Speed Compression
180 rpm, 500 to 750 hp

Slow-Speed Integral Compression
300 rpm, 1,500 to 2,500 hp

High-Speed Separable Compression
500 to 1,000 rpm, 4,000 to 8,000 hp

Compression technology has advanced since World War II from small, slow-speed compressors (left), to the faster integral compressors developed in the mid 1950s (center) to today's high-speed, high-horsepower machines (right).

their full potential to address the pipeline industry's compression needs.

Advanced Reciprocating Compression Technology (ARCT) program

To meet growing demands for energy, the U.S. Department of Energy initiated a Natural Gas Infrastructure program with the goal of increasing capacity of the current pipeline infrastructure by 10 percent and reducing operational costs by 50 percent. Under funding from the DOE Office of Fossil Energy, National Energy Technology Laboratory-Delivery Reliability Program, SwRI led an effort in conjunction with the GMRC to formulate a research program for DOE to address this challenge. The objective of the ARCT program is to create the next generation of reciprocating compressor technology to enhance the flexibility, efficiency, reliability and integrity of pipeline operations. The suite of technologies developed during this program will not only provide pipeline operators with improved, affordable choices for new compression, but will also provide innovative solutions that can be retrofitted to existing machines to substantially improve current reciprocating compression.

The primary challenges for the slow-speed, integral fleet are limited flexibility, large range of thermal performance, and significant operating and maintenance costs. The primary challenges for the new, high-speed compressors are cylinder nozzle pulsations, mechanical cylinder vibrations, short valve life and even lower thermal efficiency. The goals for next-generation compression are improved flexibility (50 percent turndown in flow rate), improved efficiency (more than 90 percent), improved reliability and maintenance (increase valve life by a factor of 10 with half the pressure loss) and improved integrity (vibration levels less than 0.75 inches per second).

The initial ARCT program was a five-year, three-phase program, which began in October 2004. Many promising technologies were developed at SwRI during the first phase of the program, completed in October 2005. Two particularly significant ones were a tapered nozzle pulsation control device and a semi-active electromagnetic valve.

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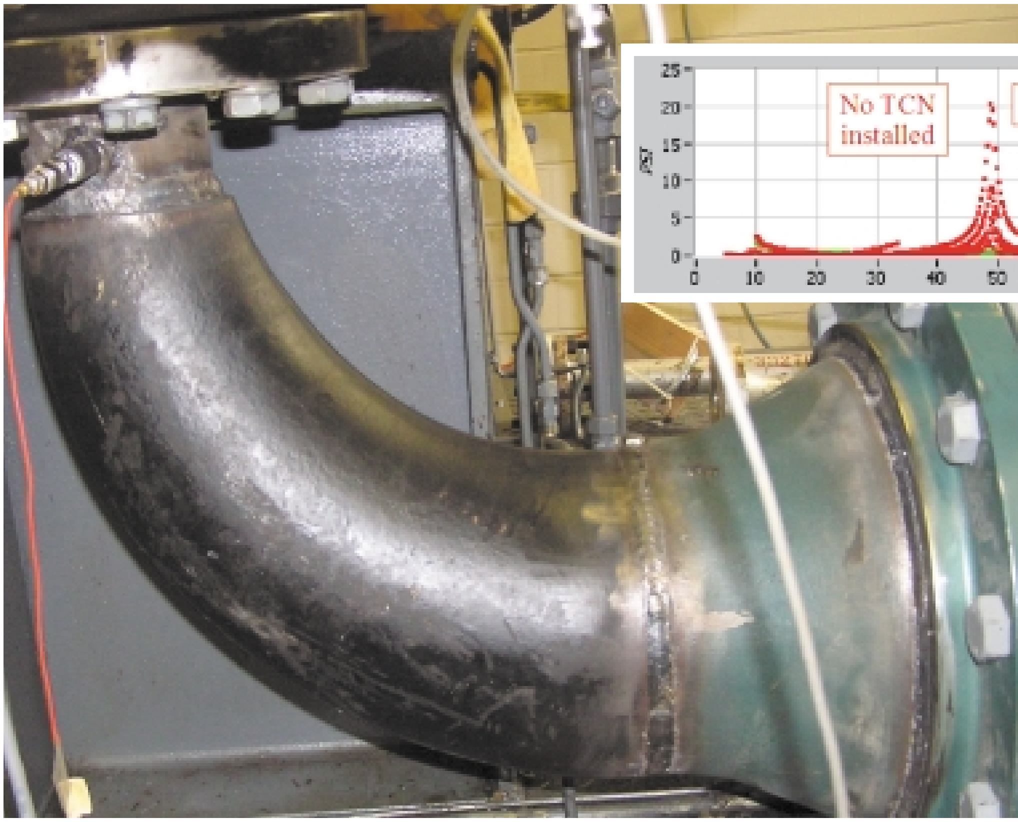
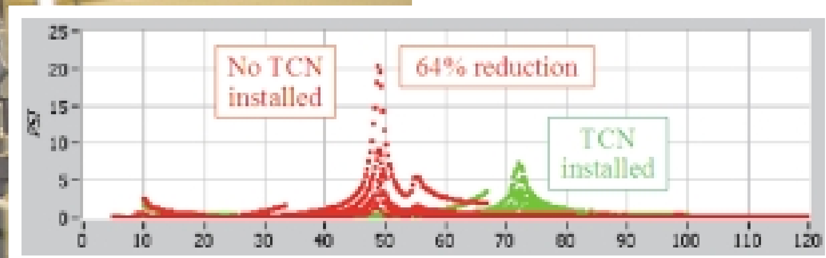
Danny Deffenbaugh (left), director of SwRI's Mechanical and Fluids Engineering Department in SwRI's Mechanical and Materials Engineering Division, manages the Advanced Reciprocating Compression Technology program. Program Manager Dr. Klaus Brun (center) is the principal developer of the semi-active electromagnetic plate valve for the ARCT program, and Staff Engineer Dr. Ralph Harris (right), conceived of the tapered cylinder nozzle design. Brun and Harris are also staff members in the Mechanical and Fluids Engineering Department.



SwRI engineers developed a tapered cylinder nozzle for high-speed compressors that decreases both pulsation amplitude and pressure loss.



This comparison of a standard nozzle (red) and the tapered cylinder nozzle design (green) documents a 64 percent reduction in pulsation amplitude and a shift in frequency from 48 to 72 Hz.

Pulsation Control

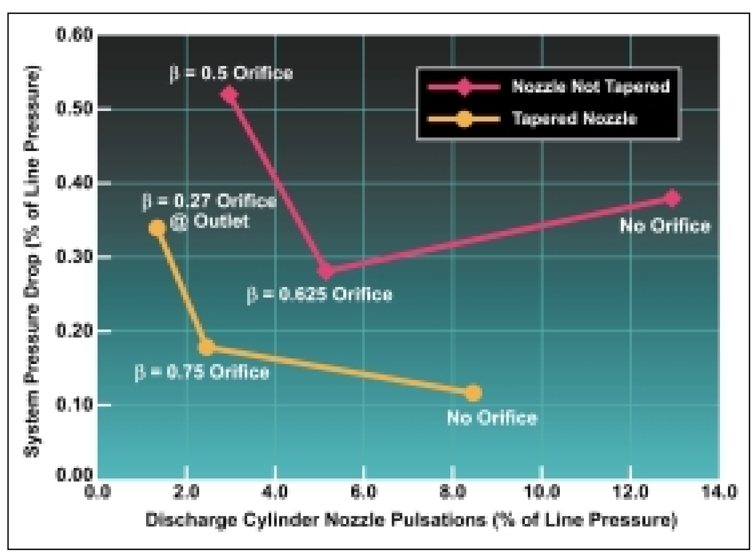
The state of the art in pulsation design and control technology has evolved as compressor technology installed by industry has changed. Designs for low-speed compressors are more mature, with fewer critical issues. However, relatively recent high-speed, high-horsepower compressor designs are placing significant challenges on the pulsation control designer.

Cylinder nozzle response represents the single most important challenge to high-horsepower, high-speed, variable-speed units. Significant reductions in unit efficiency and capacity occur through use of pressure drop elements required to control pulsation amplitudes. Technology is required to allow control of the nozzle response without significantly lowering cylinder performance. This is particularly important if compressor flexibility (in turndown ratio) is required, or if the trend toward higher speed continues.

For high-speed compressors, there is a need to lengthen the cylinder nozzles (to reduce mechanical coupling), raise the resonance frequency and reduce pulsations at the cylinder nozzle resonance frequency. SwRI engineers formulated a concept to replace conventional, straight compressor cylinder nozzles with tapered cylinder nozzles. The tapered cylinder nozzle concept lowers the effective acoustic resistance, thereby reducing the acoustic reflection, decreasing both the resultant pulsation amplitude and the pressure loss through the nozzle. Benefits associated with this concept include significant increase in the cylinder nozzle resonant frequency and lower amplitudes of excitation. Also, it allows for lengthening the cylinder nozzle such that mechanical coupling between the cylinder and the rest of the piping is reduced.

Simulation and experimental data of the tapered cylinder nozzle show both a significant shift in the cylinder nozzle resonant frequency and reduced amplitude of the cylinder nozzle pulsations. At the same time, the associated thermal efficiency is improved due to the reduced parasitic pressure loss through the nozzles.

Results demonstrated that the cylinder nozzle resonant frequency shifted above the fourth order of running speed or 24 to 26 Hz frequency, which is a 50-percent increase. The maximum nozzle pulsation amplitudes were reduced by 34 to 35 percent, and the pressure drop was reduced by one-third. The tapered cylinder nozzle results showed fewer pulsations (below 3 percent of line pressure) with less pressure drop than would be required in a traditional system with a straight nozzle installed. (The



The tapered cylinder nozzle reduces pulsation level and parasitic pressure loss. The top curve shows pulsation response and pressure loss for a standard nozzle, while the bottom curve shows the reduced pulsation level and pressure loss for the tapered nozzle.

American Petroleum Institute pulsations guideline is 7 percent of line pressure for these operating conditions.)

SwRI researchers concluded that the tapered cylinder nozzle is a viable concept that warrants further development. This concept has demonstrated the potential to resolve the critical cylinder nozzle problem experienced in modern high-speed compression and may very well be the needed enabling technology for next-generation compression.

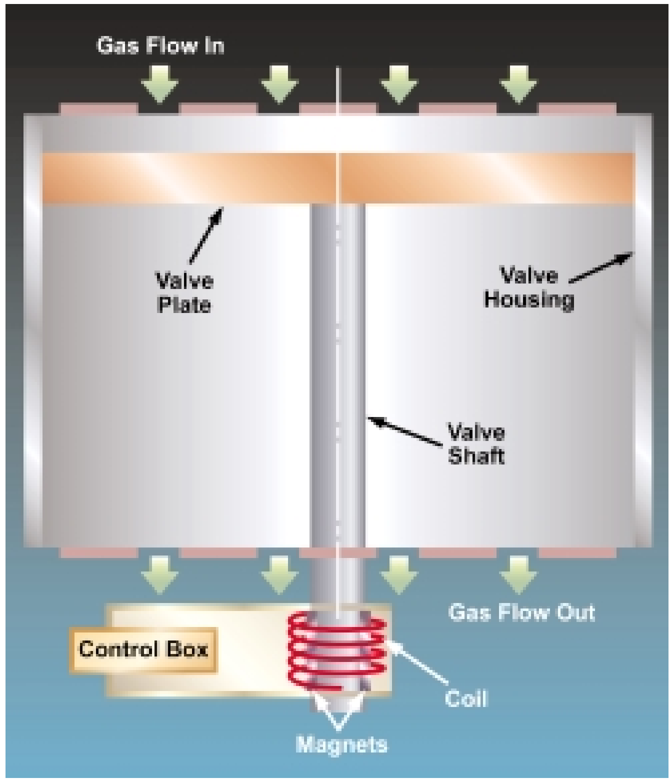
The financial benefit to reducing pressure loss in these nozzles can be realized either in terms of improved thermal efficiency or in expanding the flow through the station. At a current cost of natural gas of $9 per thousand cubic feet, a 6 percent improvement in overall thermal efficiency would result in a cost savings of $50,000 per year per compressor.

The second approach to realizing financial benefit from an improvement in efficiency is to increase gas flow throughput and avoid the need to install new compression. The estimated capital cost reduction can vary over a large range. A conservative estimate is to assume a $1,000 per horsepower benefit and calculate a simple capital cost savings. The same 6 percent efficiency improvement for a slow-speed integral would recover $120,000 in capital cost.

While this technology development has undergone a proof-of-concept experiment, additional development is required before full-scale acceptance by the industry can be expected. Laboratory testing of the technology, along with development of design tools, is under way, and will be followed by prototype demonstration in an actual pipeline under realistic conditions. SwRI engineers can then incorporate the proven technology in the designs of advanced pulsation control systems.

Compressor Valves

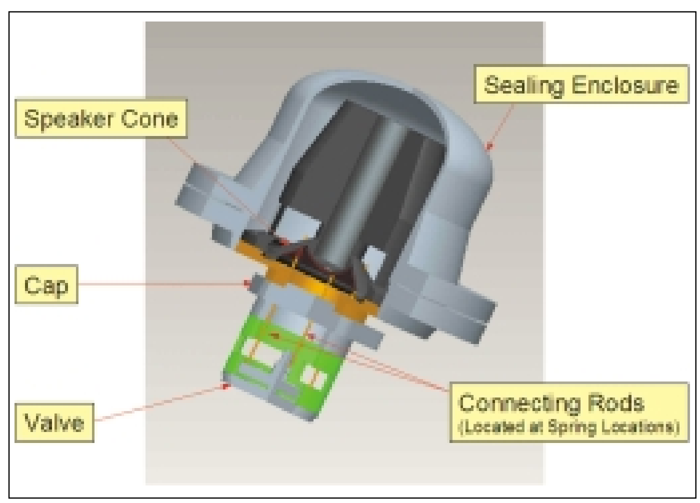
The single largest maintenance cost for a reciprocating compressor is compressor valves. Valve failures can primarily be attributed to high-cycle fatigue, sticking of the valve, accumulation of dirt and debris, improper lubrication and liquid slugs in the gas. Valves are designed for an optimal operation point; hence, valve operation is impaired when the operating conditions deviate significantly from the design point. In the traditional compressor valve design, an increase in valve life (reliability) directly relates to a decrease in valve efficiency. This relationship is due to an increase in valve lift (and flow-through area) being limited by the corresponding increase in the valve impact force. Above a certain impact velocity, valve plate failure is attributable to plastic deformation of the valve springs. These springs fail to provide adequate damping for the plate. The design of the valve springs is a major weakness in the valves currently in use. A lack of durability and low efficiency of the passive valve design demonstrates the need to control valve motion.



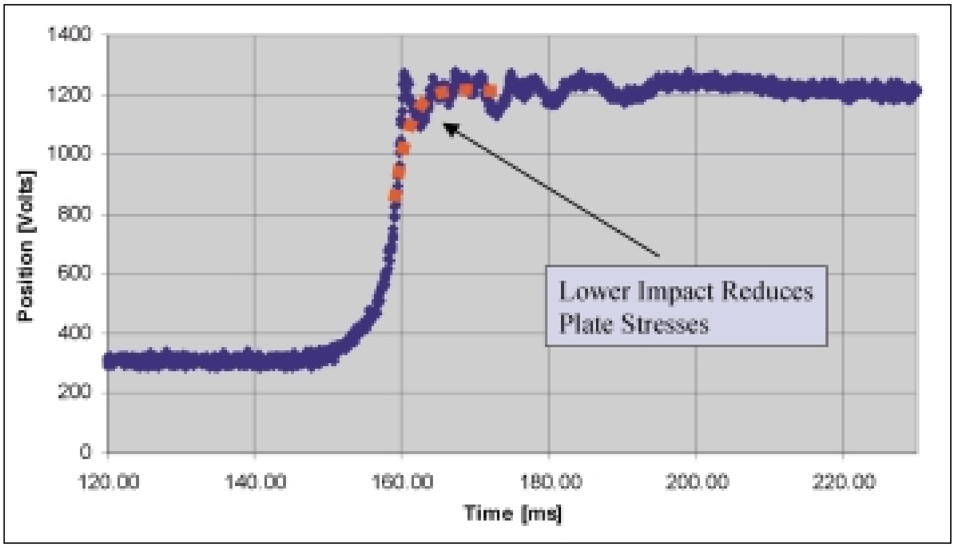
The semi-active electromagnetic plate valve is a relatively simple modification to a standard plate valve, with the addition of a center shaft and a speaker voice coil.

Reducing impact velocity can greatly increase the life of a valve. SwRI engineers have developed a new valve concept that could create a soft landing at both the valve seat on closing and at the valve guard on opening. The concept is to effectively replace the valve spring with an electromagnetic coil that senses position and provides an opposing force prior to impact. This concept is referred to as a "semi-active electromagnetic plate valve" because it is still activated by gas pressure and only controlled prior to impact. This new valve concept was initially tested using a single impact shock tube. During this testing, a valve element was coupled to the voice coil of a speaker to provide a variable reaction force. The reaction force applied by the coil was able to measurably reduce the impact velocities of the valve plate. The reduction in impact velocities resulted in a relative life gain of 3 to 11 times that of a standard valve experiencing the same forces. Engineers designed and implemented a full-scale test breadboard in a reciprocating compressor located at SwRI. The design included a standard valve configuration, with modifications to couple it to an electromagnetic voice coil.

The foundation of the semi-active electromagnetic plate valve is similar to existing plate valves in service today. Only slight modifications are needed to facilitate the addition of the voice coils. Initial



The SwRI-developed semi-active electromagnetic plate valve design allows for a soft landing of the valve, thereby extending its life by 3 to 11 times that of standard valves. Valve replacement is a significant cost for the gas industry.



A standard plate valve in motion experiences high impact velocity and multiple bounces (blue line), while the SwRI-developed semi-active electromagnetic plate valve demonstrates a single soft landing (red).

testing showed that the valve profile becomes rounded, thus reducing the impact velocity. Reduced impact velocities result in a significant increase in valve life, since high cycle fatigue is the primary cause of valve failures. The financial benefit of this valve technology is based on the increased life and the associated reduced maintenance cost for valve change-out. However, the new valve technology will require some additional cost per change-out. The valve life improvement is a factor of 10 and the increased cost is a factor of two. If, for example, the current life is a half year and change-out cost is $30,000, the overall maintenance cost benefit is calculated to be $240,000 over a five-year period, or a normalized annual savings of $48,000.

The SwRI valve design has proven to be worth further evaluation. The next step is to reduce the size and complexity of the unit, investigate a self-powering feature and eventually field test the unit in actual pipeline compressors.

Other ARCT Developments

During the course of Phase 1 of this project, other successes included 18 additional technology solutions. These technologies have been developed to a proof-of-concept stage. The industry has recommended advancing half of these technologies to the next stage. A conservative estimate for the value of this suite of technologies is $50,000 per installation per year.

For the future, solutions are needed for both slow-speed and high-speed compression. For slow-speed compression, optimum flow rate turndown will be accomplished with a combination of speed and clearance. Advances in pulsation control will recover capacity lost due to pressure drop. Advances in valves will extend valve life with low-pressure loss penalty. The combination of these technology improvements will provide the potential of 95 percent thermal efficiency with three-year valve life and expanded flow rate turndown.

For high-speed compression, optimum flow rate turndown will be accomplished with unit speed. Tapered cylinder nozzles will resolve the nozzle pulsation problem with half the pressure loss and also eliminate cylinder vibration. An additional new technology developed during this program is a tunable side-branch-absorber that addresses the fundamental frequency vibration in the lateral piping over the entire speed range with minimal pressure loss penalty. The semi-active electromagnetic plate valve will extend valve life with half the pressure loss penalty. The combination of these technology improvements will provide the potential of 90 percent thermal efficiency with two-year valve life, 50 percent flow rate turndown and vibrations of less than 0.75 inches per second.

SwRI engineers believe that the program will develop sufficient technology solutions to address the current limitations of modern high-speed compression, thus enabling this equipment to meet its full potential. If so, this program will meet its stated objective of creating the next generation of reciprocating compressor technology that provides added pipeline flexibility at reduced costs.

Engineers tested the semi-active electromagnetic plate valve at the SwRI Metering Research Facility.

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