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Ethane Challenges Compressor Design

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CALGARY–Computer modeling is used to simulate many aspects of reciprocating compressor operation. Typical applications of computer models include simulating compressor performance; torsional and lateral responses; deflection and stress in the skid beams caused by lifting; the dynamic response of the compressor cylinders, bottles and piping; and thermal expansion of the piping.

The focus of this article is modeling performance and pressure pulsations for reciprocating compressor applications. Accurate calculation of compressor performance is important to ensure the compressor will deliver the required flow for the available driver power. Pressure pulsations generated by a reciprocating compressor can have many adverse effects on compressor operation. The most critical impact of pressure pulsations is high vibration, which can lead to failure of piping, vessels and supports. Pressure pulsations also can have adverse effects on compressor cylinder valves, capacity and power losses.

Designers of reciprocating equipment rely on modeling tools to accurately simulate compressor performance and pressure pulsations in piping systems. Accurately simulating these characteristics is difficult for specialty gases such as ethane, and requires special consideration.

Modeling compressor systems requires representing the physical properties of the compressor, vessels, piping and gas. The physical properties of the compressor, vessels and piping are well defined. The physical properties of the gas are determined by testing and thermodynamic theory. Many mathematical models exist for calculating gas properties. Each model has various strengths and weaknesses in terms of the accuracy with which it represents the physical gas properties.

Mathematical models have proven accurate in simulating natural gas in gathering, processing and pipeline applications. However, compressors operating in facilities with specialty gases such as ethane require proper selection of the modeling techniques to ensure that the results from the simulations result in a safe and reliable design, since simulations of physical properties is not well understood. The impact of incorrectly modeling gas properties can be significant and prove costly to the operator of the compression equipment.

Performance Simulation

Simulating or modeling the performance of a reciprocating compressor involves calculating the expected flow, power consumption, discharge temperature, etc., based on the compressor's geometry and operating information. The operating information typically includes inlet pressure, discharge pressure, inlet temperature and gas composition. The gas composition and operating data are used to calculate the thermodynamic properties of the gas.

FIGURE 1

Typical Phase Diagram

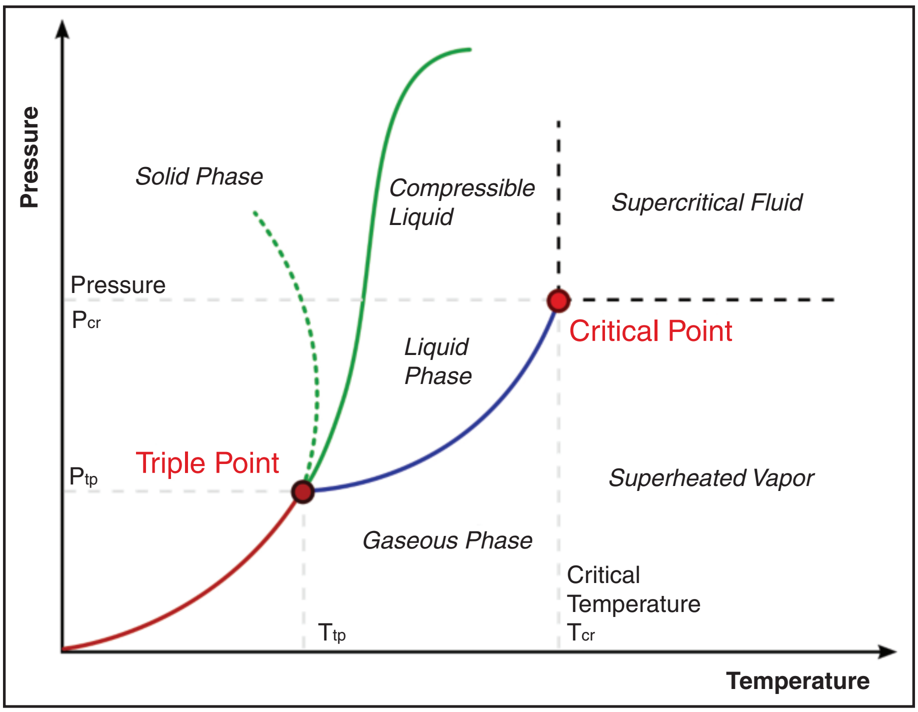
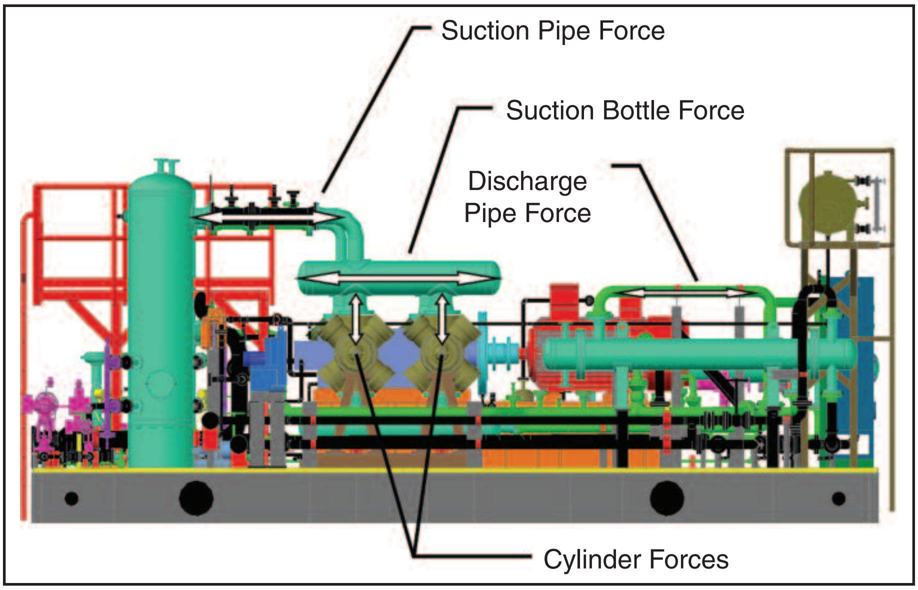


FIGURE 2

Shaking Forces in Reciprocating Compressor Package



These properties are used in the performance calculations.

The ratio of specific heats is a physical, or thermodynamic, characteristic of the gas. There is no theoretical means to calculate characteristics such as the ratio of specific heats for gases. Typically, experimentation is done to determine these properties at a few temperatures and pressures, and then models or equations of state (EoS) are derived. The equations of state can be used to calculate the thermodynamic properties of gases for a range of pressures and temperatures. Many EoS have been developed, and all of them have pressure and temperature ranges and gas mixtures that make them more or less accurate than others at given conditions, so care must be taken to properly select the appropriate equation for the particular application.

Another factor that is important in calculating gas properties is determining where the particular operating point is relative to the "critical point," or critical state, which specifies the temperature and pressure conditions at which a phase boundary ceases to exist. It is extremely difficult to obtain the fluid properties at or around the critical point experimentally, or from EoS models. The other region where an EoS is inaccurate is at very high pressures, both above and below the critical temperature, unless careful modifications are made to the EoS.

Figure 1 shows a representative pressure/temperature phase diagram for water. Calculating the gas properties is relatively simple for a gas when the process remains within the gaseous phase and below the critical temperature/pressure. In some cases, the gas process transitions from one area of the phase diagram to another, requiring a more robust model of the gas properties.

As noted, discharge temperature is one output from the compressor performance simulation depends on accurately calculating gas properties. Other compressor performance results–including volumetric efficiency, flow and power–depends on gas properties such as compressibility, ratio of specific heats, polytropic exponent, viscosity and specific gravity. Accurately calculating these gas properties is critical to accurate compressor performance calculations.

Pressure Pulsations

Simulating pressure pulsations generated by reciprocating compressors involves many of the same aspects of simulating gas properties. One key parameter in understanding pressure pulsations in a reciprocating compressor system is the acoustic velocity, or speed of sound, in the gas. Acoustic velocity is one of the most fundamental and critical characteristics calculated for a pulsation analysis. Other acoustical characteristics also depend on the gas properties. Accurately calculating gas properties is key for an accurate pulsation analysis.

It should be noted that fluctuating pressures and temperatures in reciprocating compressors means the gas properties will be time dependent. Typically, these gas property dependencies on temperature are small, but they can be significant in some cases.

The mathematical model of flow dynamics is as important as calculating gas properties. There are different computer programs available for simulating pressure pulsations in reciprocating compressor installations. The programs fall into two basic groups. The first is frequency domain (FD) programs: the first generation of tools based on acoustic plane wave theory. These programs include many simplifying assumptions that allow acoustic equations to be solved in the frequency domain.

The second is time domain (TD) pro-

FIGURE 3A

Compressor Plan View

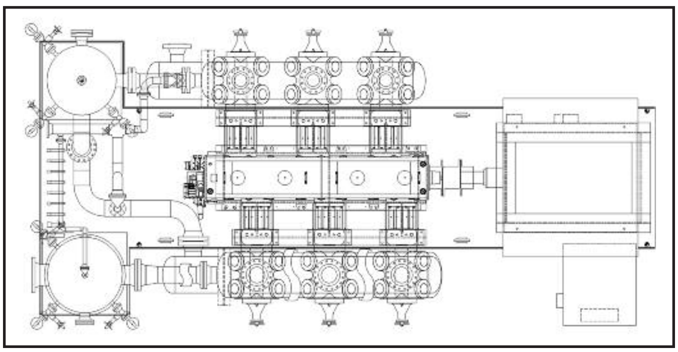


FIGURE 3B

Compressor Elevation View

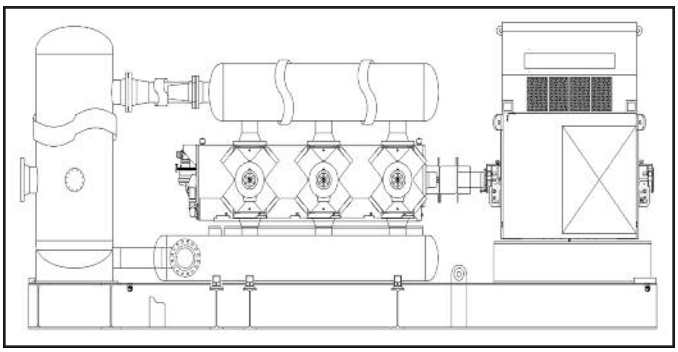
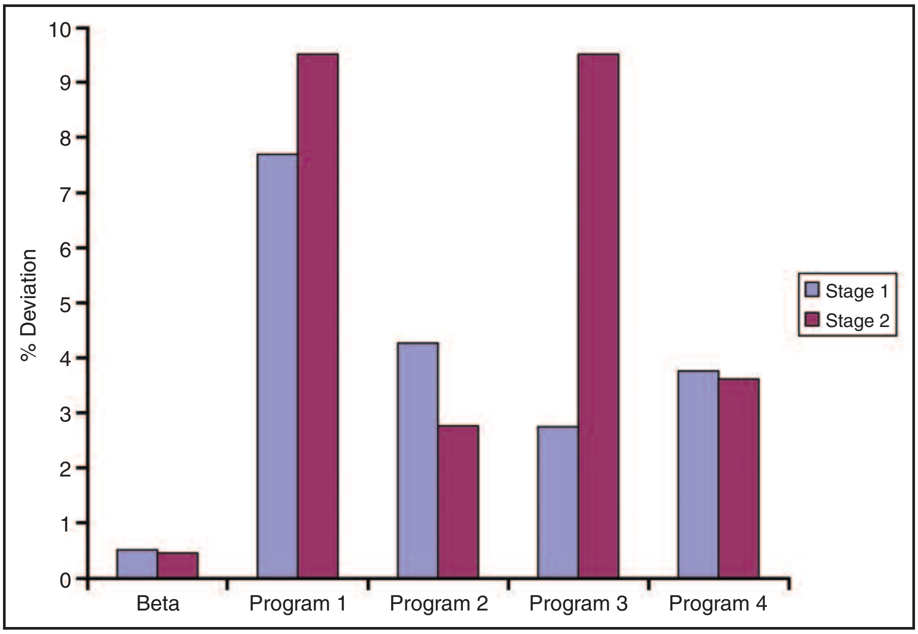


FIGURE 4

Percent Deviation in Calculated Absolute Discharge Temperature From Measured



grams. As the name implies, these programs simulate the fluid dynamics in the time domain. This second generation of pressure pulsation simulation programs uses a more sophisticated fluid dynamics model, and considers nonlinearities and time-varying boundary conditions at the compressor cylinder valves.

TD pulsation analysis programs are much more sophisticated than the FD-based programs, yielding more accurate results. TD programs also are able to calculate characteristics such as dynamic pressure drop, which cannot be accurately determined by FD programs. The main drawback to TD programs is longer solution times. Faster computer hardware and more advanced solvers are required.

The methodology used by the pulsation analysis program to analyze the reciprocating compressor system is also important to a successful design. Shaking forces are generated by pressure pulsations, coupled with piping geometry. These forces must be minimized to ensure vibrations are acceptable. API 618 (fifth edition) includes guidelines for shaking forces from pressure pulsations on piping and pulsation bottles. However, there are other pulsation shaking forces that must be evaluated that are not yet included in API 618.

One example is the shaking force acting between the pulsation bottle and the compressor cylinder, referred to as the cylinder shaking force. Figure 2 shows this force for a typical horizontal reciprocating compressor package. This shaking force is the result of the different pressure pulsation amplitudes and phases in the gas passage and pulsation bottle, and has been shown to cause excessive vertical vibration on horizontal compressors. In some extreme cases, it has caused the failure of head-end cylinder supports. This shaking force also can result in high vibration in vertical compressors.

Ethane Compressor Case Study

The following case study illustrates the effect of gas properties on simulating compressor performance and pulsation analysis. It involves a six-throw, two-stage horizontal compressor in specialty gas service, in this case ethane. Figures 3A and 3B show plan and elevation views of the compressor package.

The compressor is driven by a 5,200-horsepower induction motor with a fixed full-load speed of 885 rpm. Nominal suction and discharge pressures are 413 to 1,215 psi. The compressor package is relatively simple with scrubbers on the first- and second-stage suction, and no interstage cooler. The discharge temperatures are well within the allowable range of safe operation.

The gas in this service is 96 percent ethane, with the remainder of the gas being methane, propane, and iso-butane, resulting in a specific gravity of 1.04. Once the unit was in operation, the owner had noted that the compressor was not performing as expected. There was a noticeable difference in the flow and power requirement.

A review of the performance calculations showed a significant difference between the calculated and measured temperature of the first-stage discharge. A cursory review of the original performance calculations showed the expected first- and second-stage discharge temperatures were 79 and 129 degrees Fahrenheit, respectively, compared with the observed temperatures of 124 and 191 degrees–a 10 percent difference in the absolute temperature. The temperatures are measured at the cylinder nozzles and include the valve heating effects.

A 10 percent difference between a compressor performance model and observation is generally acceptable, but in this case, the error continued to be compounded since temperature was used in other calculations of compressor performance and gas properties, as well as by the fact that there was no cooler between the first and second stages. Further investigation showed that other performance factors (such as flow and power) were significantly different–and much higher than 10 percent–when the original performance calculations were compared with the observations.

Before the pulsation model could be investigated, the inaccuracies in the compressor performance model needed to be resolved. Additional performance calculations were done using a variety of original equipment manufacturer programs, commercial programs, and a proprietary compressor performance program.

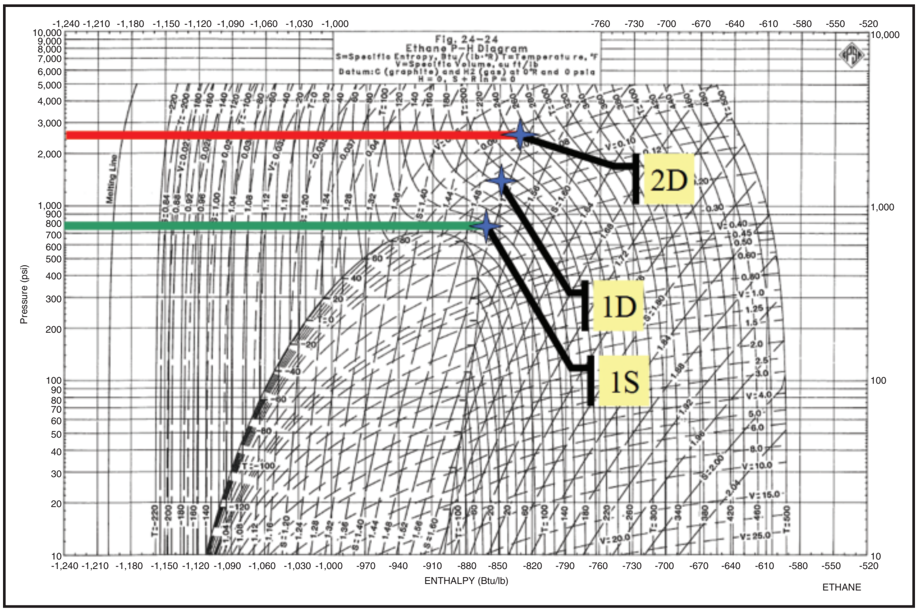
Resolving Inaccuracies

The results of the different performance programs showed wide variations. None of the OEM or commercial programs tested were able to accurately calculate the compressor performance. Several of the programs were not able to calculate the compressor performance for the two-stage operation because the proper gas properties could not be calculated and the programs were not able to achieve a mass balance for the first- and second-stages (the programs crashed or aborted because of errors). However, the proprietary compressor performance program calculated the first- and second-stage discharge temperatures to be 121 and 188 degrees, less than 1 percent difference between the calculated and measured absolute temperatures.

Figure 4 shows the difference between

FIGURE 5

Mollier Chart Showing Two-Stage Compression



the discharge temperatures that were calculated by the various performance programs compared with the observed discharge temperatures. The discharge temperature is one of the fundamental characteristics of compressor performance that must be calculated accurately. Errors in discharge temperature calculations will be compounded in later calculations, resulting in greater errors.

The main reason for the variation in the discharge temperature calculated in this case is that the first-stage discharge conditions were significantly above the critical pressure and temperature of the ethane phase diagram. Figure 5 is a Mollier diagram for ethane, with the first- and second-stage operating points shown. Additional corrections are required for ethane in this region to accurately calculate the gas properties used in the compressor performance.

Compressor valve loss calculations would also be inaccurate because of errors in thermodynamic property variations. This error would lead to inaccurate overall performance predictions for the compressor system. Careful consideration of the EoS and how it predicts pressure, volume and temperature relationships needs to be considered. As noted, inaccurate prediction of these relations would be carried over to all thermodynamic properties.

A pulsation analysis of the compressor package was done with the initial, incorrect compressor performance. The original study resulted in pulsation bottles with baffles and choke tubes to create filters that controlled pulsations to very low levels. This design resulted in bottles being overly conservative.

Pulsation analysis was conducted with the more accurate compressor performance model. Results indicated the pulsation control was very conservative. A solution with lower pressure drop and horsepower losses could have been developed if the original pulsation study had been done with a more accurate compressor performance model.

The case study shows that a thorough understanding of specialty gas properties is key to accurately simulating the performance of reciprocating compressors. Many performance programs have difficulty accurately simulating compressor performance in some applications. Pulsation analysis software that considers specialty gas properties and a nonlinear time domain model of fluid dynamics is necessary to accurately perform API 618 pressure pulsation studies.

Frequency domain pulsation software has severe limitations and produces less accurate modeling results, which may compromise the safety of a reciprocating compressor installation. The proper computer modeling software, along with field-proven modeling techniques, is required to ensure reciprocating compressor designs suit their intended purpose and are a safe, reliable design. ❒

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