Improved Thermal Piping Analysis for Reciprocating Compressor Piping Systems

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Abstract

A thermal analysis, or piping flexibility study, is often required for reciprocating compressor systems, especially where hot piping extends beyond the compressor package to the headers and coolers. Thermal studies involving reciprocating compressor systems require a different approach compared to standard process piping studies because of the dynamic loads involved.

Using a recent project at an Enogex gas plant, this paper will outline current design issues and complications in the piping design. One example is the common practice of modeling pipe clamps as rigid anchors. Consequences include unrealistic stress and loads on piping, pipe supports and nozzles, the potential for an overly conservative (costly) piping layout, and conflicting recommendations to control piping vibration.

This paper is aimed at end users and engineering consultants involved in compressor station design. The recommendations will improve the reliability of piping installations involving reciprocating compressors.

1. Introduction

Piping flexibility studies (thermal studies) are commonly done on piping systems to ensure the static stresses, static forces and static deflections due to loads from pressure, temperature, and weight are within safe limits. In systems that have significant pressure pulsations, like those attached to a reciprocating compressor, there are dynamic forces that must also be considered. These additional dynamic forces cause vibration (dynamic deflection) and vibratory (dynamic) stress, and are typically investigated during a dynamic study.

There is a conflict in mitigating these two types of situations. Controlling vibration, and vibratory stress, typically involves restraining piping with a flat-bar type clamp (Figure 1). The spacing between clamps for vibration control is shorter than required to support the dead weight of the piping, contents and insulation. This is necessary to raise the mechanical natural frequency of the pipe above 2.4 times compressor maximum runspeed, as recommended by API 618, 5th

Edition. API 618 also states that supports must have enough stiffness to stop vibration at the support, and it cautions against the use of hangers and guides.

Mitigating static deflections and stresses typically involves selectively providing flexibility by a mixture of rest supports, guides, line stops, hangers, spring supports, and hold downs. A good design provides enough stiffness to control vibrations and at the same time provide enough flexibility for thermal growth.

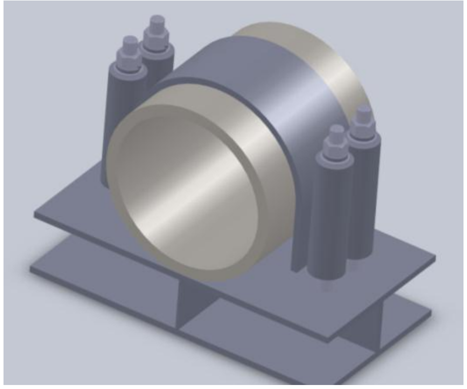

Figure 1. Common pipe clamp design for vibration control

Accurate thermal modeling in reciprocating systems is important. Serious vibration problems can occur when incorrect assumptions are used. For example, an incorrect model may result in the removal of vibration controlling clamps. In a recent project for Enogex, the consequences of two typical modeling techniques are illustrated. The consequences can have impacts on reliability, vibration, stresses, and costs. A recommended procedure is provided to improve the modeling technique used in piping analysis for reciprocating compressors and pumps.

Figure 2. Examples of pipe clamp damaged by incorrect piping analysis

2. Background Issues Affecting Thermal and Dynamic Studies

The static forces generated from thermal expansion are large. They can be 10,000 lbf (44,500 N) and higher. These static forces generate large static deflections and/or large static stresses. The pipe supports need to allow for large movement. Figure 2 shows damage done to a pipe clamp foundation due to these large thermal expansion forces.

Dynamic forces, on the other hand, tend to be 1 or 2 orders of magnitude lower than static forces. For example, pulsation-induced shaking forces are typically limited to 1,000 lbf (4,450 N) or less when a pulsation study is done (as part of a dynamic analysis). Unlike static forces, dynamic forces can cause resonance, which amplifies the vibrations and vibratory stresses. Therefore, although dynamic forces are small, they can have a large damaging effect if the pipe supports are not stiff enough, or not located in the right areas, to control vibrations.

Finite element (FE) analysis is used for both thermal and dynamic studies. However, there are several important differences in the techniques used for each analysis (summarized in Table 1).

Table 1. Summary of differences between thermal and dynamic studies

Analysis Type	Magnitude of Typical Forces	Static Stiffness of Support	Mass of Support	Friction Between Pipe and Support
Static Study	Greater than 10,000 lbf	Included	Not Included	Included
Dynamic Study	Less than 1,000 lbf	Included	Included	Not Included

Both thermal (static) and dynamic studies consider the stiffness of the support (and associated structure). In thermal studies, the stiffness of supports is sometimes modeled as rigid in some or all translational degrees of freedom (X, Y, and Z). Supports are defined as “rigid” if the stiffness used in the support is 2 or more orders of magnitude (i.e., 100 or more times) larger than the stiffness of the piping system. The main reason for using this assumption is lack of information about the actual support design at the time of the static analysis.

Static studies typically do not consider the mass of the support, unlike dynamic studies. The vibration at a support can depend on the mass, especially for supports with low stiffness like elevated supports.

The other difference between dynamic and static studies is the inclusion of friction between the pipe and the support structure. This is important in static studies because the friction can oppose part of the large static forces. This friction comes from not only the dead weight of the pipe, fluid and insulation, but also from the clamping force on the pipe (when a vibration control clamp is used instead of a resting type support). In dynamic systems, the dynamic forces rarely exceed the friction forces, so the effort to model the non-linear effects of friction is not necessary.

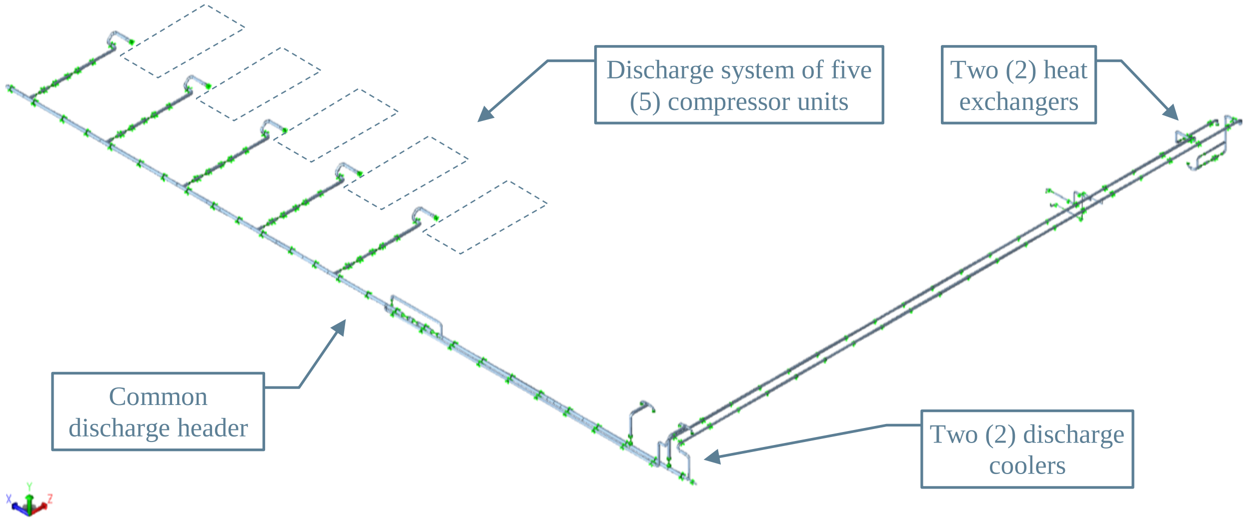

Figure 3. Thermal model of discharge system of Enogex facility

3. Case Study: Enogex Facility

Enogex contracted BETA to analyze the piping system for five (5) reciprocating compressors which discharged onto a common discharge header (Figure 3). The gas goes through two parallel coolers and two heat exchangers (to pre-heat another part of the process). BETA also conducted a dynamic study, including a pulsation study which calculated the dynamic forces in the piping.

There are two typical approaches when doing static analyses:

1. Traditional approach is to assume all supports are rigid initially. This simplifying assumption can lead the designer to identify high stress areas where they do not exist, and miss high stress areas. Misidentified high stress areas may lead the designer to remove clamps which are required for vibration control. Overlooked high stress areas can lead to failure and expensive repairs.
2. Recommended approach is to use a realistic estimate of the support stiffness initially.

3.1. Traditional Approach: Assume Rigidly Anchored Supports

Figure 4 shows the results when clamps are modeled as rigid anchors. This common approach would indicate locations of high stress on the laterals from all five compressors. However, it would not indicate significant stresses near the two discharge coolers.

Possible solutions to the high stresses near the compressors might be to remove clamps; this would potentially lower the static stresses, but it would likely increase the vibration and vibratory stresses. A solution to the high stresses at the connection to the header might be adding thermal loops to the laterals. This would need to be done in five locations - a large expense.

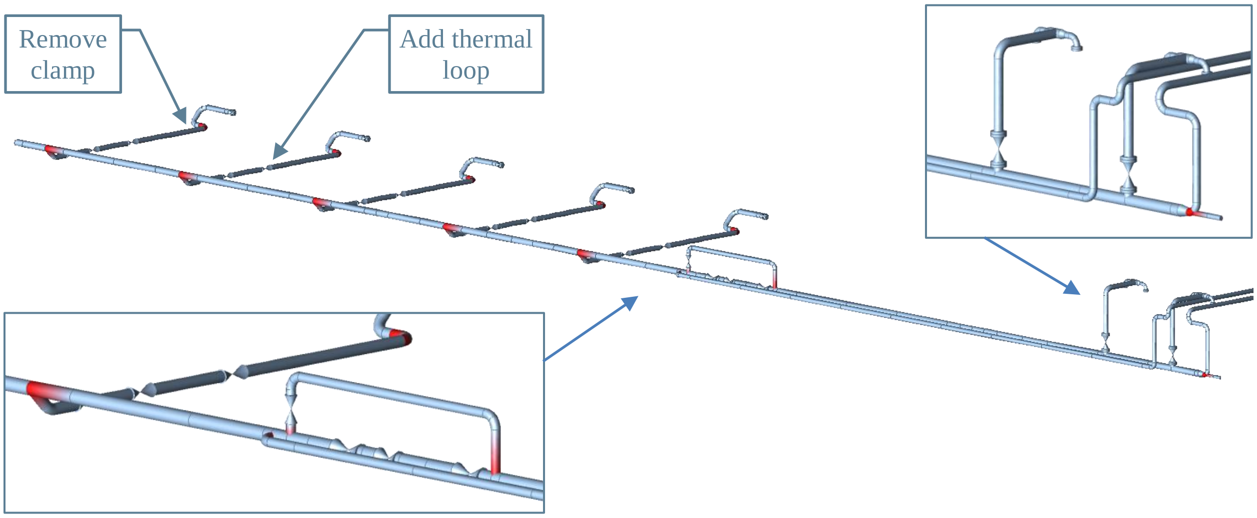

Figure 4. Results from traditional approach

3.2. Recommended Approach: Use Realistic Support Stiffness

The actual thermal study used a more accurate assumption on the stiffness of the supports. Friction due to both the weight and clamping forces was considered. The pipe was allowed to slip through the clamps, in the axial (parallel to pipe centerline) direction.

Figure 5 shows the recommended approach found high stresses in two of the five laterals, but also found significant stresses near the discharge coolers, which were missed in the traditional approach. This illustrates that the traditional approach may not be conservative.

The solution to reduce the high thermal stresses was to use two thermal loops, not five, and use special pipe clamps that reduced the friction force and allowed the pipe to slip through the clamps.

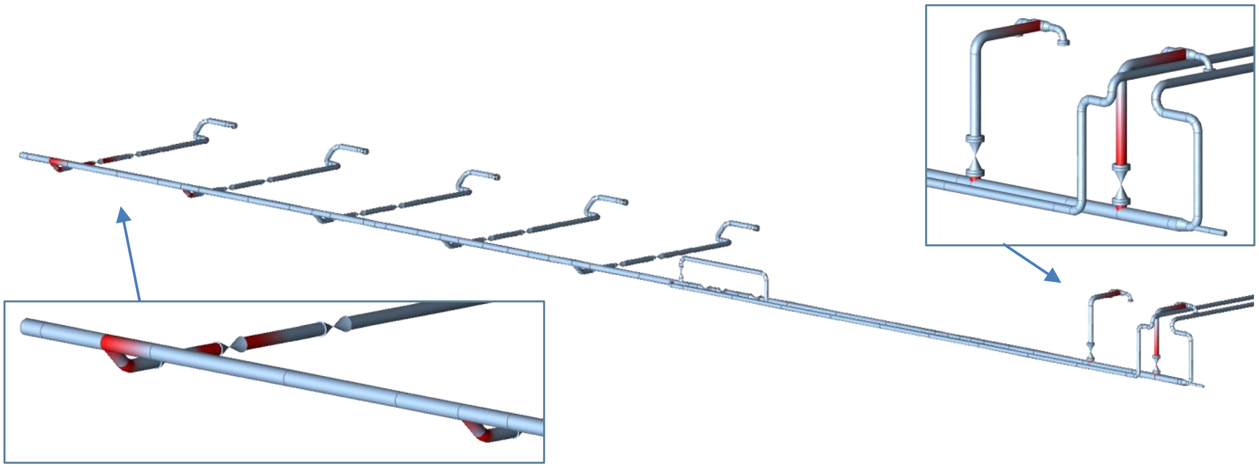

Figure 5. Results from recommended approach

This case study illustrates some key points:

- The traditional approach is widely used in industry to design piping system. However, this method produces unrealistic results which may mislead the designer to remove vibration controlling clamps, or change them to resting supports or guides, causing vibration problems.
- The pipe support stiffness assumptions can have a big impact on the predicted stress, and resulting recommendations. As shown above, there can be higher costs and vibration risks when supports are assumed to be rigid.
- Using more accurate assumptions in the model can reduce the risk of vibration problems and potentially un-needed thermal loops and other modifications. In this case a large number of thermal loops can be avoided (only 2 loops were needed on the final design).
- Standard vibration control clamps are typically more flexible and allow more displacement than designers realize, and can be safely used in systems with thermal forces and displacements.

4. Recommendations for Improved Thermal Study Modeling

The first step to achieving a more accurate thermal study is to use a realistic stiffness for the static stiffness of the support. The stiffness of a support is a combination of the stiffness of all parts of the support, including the clamp itself, structural steel, concrete pier, and even soil stiffness. BETA has evaluated the actual support stiffness of various support designs (Figure 6), and found that a well-designed support generally has a stiffness between 1E5 to 1E7 lbf/in (1.8E7 to 1.8E9 N/m). A commonly used thermal stress analysis software

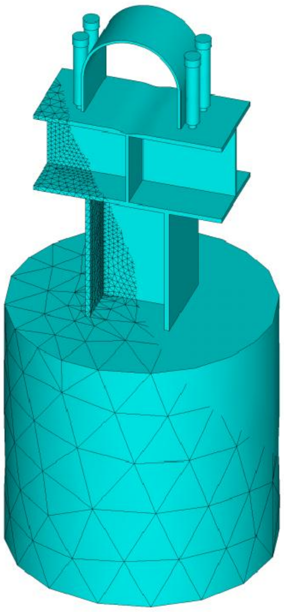

Figure 6. Example clamp and support structure

assumes a rigid support has a stiffness of 1E12 lbf/in (1.8E14 N/m).

Tall supports, especially supports on elevated pipe racks, have significantly less stiffness than shorter supports. In fact, the stiffness of a post-type support varies inversely with the height of the post raised to the 3rd power. A post that is twice as tall is 1/8th as stiff.

The second step to a more accurate thermal study is to accurately model friction between the pipe and the support. The friction force between two surfaces acts in a direction parallel to the surfaces but varies with the normal force perpendicular to the surfaces. The ratio between the normal force and the friction force (called the coefficient of friction) depends on the materials of the pipe, the clamp, and any shimming material placed between them.

This normal force includes not only the weight of the pipe but also the clamping force created by the vibration control clamp. This clamping force is equal to the sum of the preload on all the clamp bolts. Even with this clamping force, field experience has shown than pipe will slip through a clamp along its axis under thermal loads, even when the clamp is tightened and shimmed. If less friction force is required for a better thermal clamp design, special clamps can be used which minimize the clamping force or coefficient of friction and allow more slipping of the pipe.

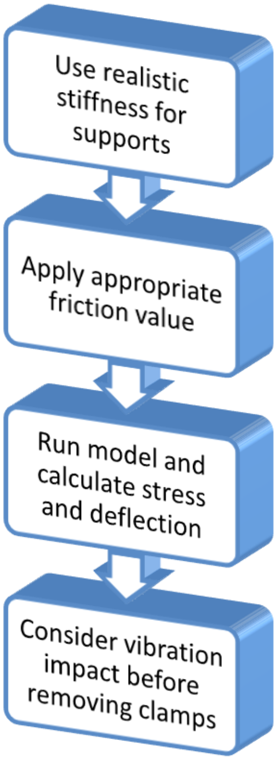

Figure 7. Recommend thermal modeling approach

The recommended modeling approach is summarized in Figure 7.

- Use an estimated stiffness for clamps based on field experience, finite element analysis, or even simple one-dimensional beam theory calculation.
- Apply friction forces to the model in the direction opposite of pipe movement.
- While the above two steps may take a bit more time at the front of the project, it will save time later on by avoiding rework.

API 618, 5th Edition, recommends that the piping vibration analysis and flexibility analysis be conducted by the same party. This helps balance modifications to reduce static stress with the potential for increasing vibrations and vibratory stress.

5. Other Solutions

As mentioned in Section 3.2, one part of the solution for the Enogex facility was to use a special clamp to allow more thermal growth of the pipe through the clamps. BETA and others have developed thermal pipe clamps for this type of application (Figure 8). The clamp is useful because it is stiff enough to control vibrations caused by dynamic forces, but allows flexibility for large thermal growth.

In the Enogex case study, the clamps had to allow 5.5 inches (140 mm) of displacement on the discharge header. Traditionally clamps cannot support this displacement. The clamps and supports would experience failure (similar to Figure 2). BETA thermal clamps feature disk springs which control the amount of clamping force applied to the pipe. This, in turn, reduces the amount of friction force which resists the thermal growth of the pipe. Another option to control the friction force is to reduce the coefficient of friction between the pipe and the clamp by using slide plates or liners made of PTFE or other low friction materials.

Using these clamps and two thermal loops, the static stresses were controlled and the vibration risks were minimized.

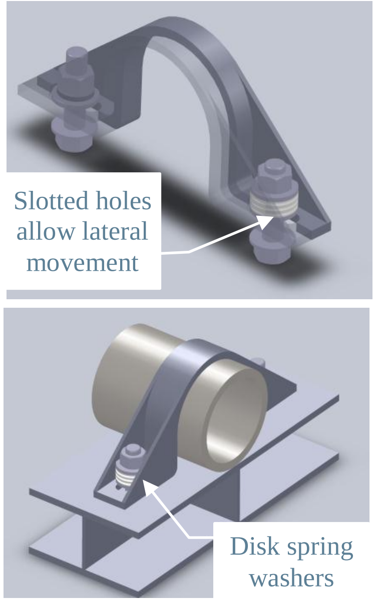

Figure 8. Example thermal clamps which allow thermal expansion and vibration control

6. Conclusion and Summary

Applying an appropriate thermal stress modeling technique is more critical in applications which include reciprocating compressors. The traditional approach is to assume pipe supports are rigidly anchored. This assumption often causes errors, which can then lead to vibration problems and/or additional costs for complex designs. In the worst case, stresses in critical areas are missed which can lead to failures. The case study shows that using rigid supports is not a conservative assumption.

The recommended approach is to use a realistic stiffness for the support, apply the appropriate friction force, and consider the effect that any modifications would have to vibrations. Consider using a clamp which balances the thermal stress and vibration control requirements, if necessary. It is more efficient to have one party conduct both the thermal and dynamic analysis. These techniques are practical and field-proven through years of successful piping and vibration studies.

7. References

- ASME Code for Pressure Piping; ASME B31.3-2010
- K.E. Eberle, “A Recommended Approach to Piping Flexibility Studies to Avoid Compressor System Integrity Risk,” Gas Machinery Conference 2011
- Det Norske Veritas Recommended Practice, “Structural Analysis of Piping Systems,” DNV-RP-D101, October 2008
- API Standard 618 5th Edition, “Reciprocating Compressors for Petroleum, Chemical, and Gas Industry Services,” December 2007