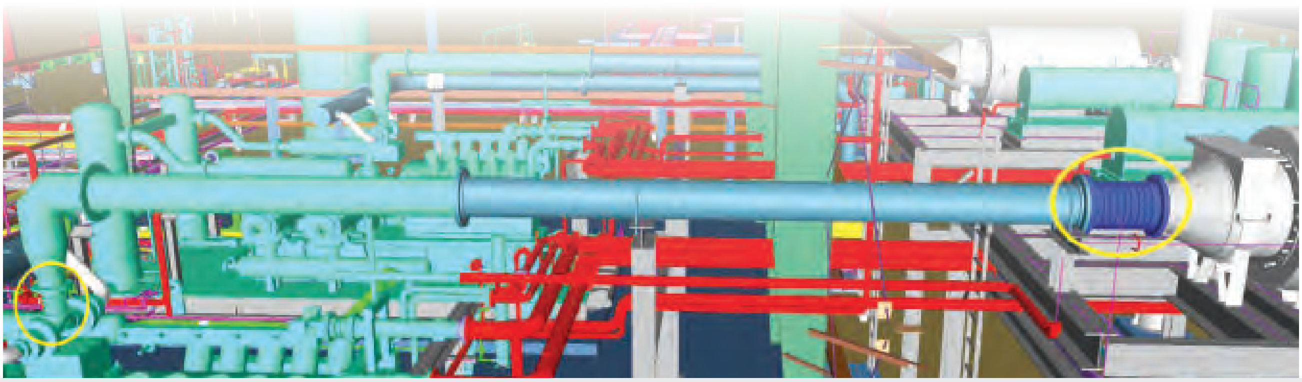
Proper Design And Analysis Of High-Speed Engine Exhaust Systems Improve Safety And Reliability > GCC provides insight into best design practices

BY NORM SHADE



As originally designed, the exhaust systems on the engines depicted in this CAD model experienced failures of the vertical expansion joint connected to the engine turbocharger exhaust and to the horizontal expansion joint connected to the exhaust catalyst outside the building wall.

High-speed natural gas engine application specifications limit the forces and moments at all the connection points to the engine. This ensures that engine alignment is maintained and excessive piping-induced stresses on engine components are avoided during operation. Typical connection points include oil and coolant lines, starting air or gas lines, and, especially, the large flanges connecting intake air to the turbocharger blower inlet and connecting the exhaust system to the turbocharger turbine outlet.

Packaged engine compressor systems have evolved to address these connection issues reliably on field-skidded units. The engine exhaust line, one of the larger and more difficult engine connections, is usually supported by mounting the muffler and catalytic converter on top of the package cooler. This typically results in a short run of piping with a natural bend that can accommodate the attendant thermal expansion without overloading flexible connections or transferring excessive forces and moments to the turbocharger exhaust flange.

However, when compressor packages are housed inside buildings, which is the case with many of the larger midstream and central gas gathering and boosting facilities, the exhaust lines can be long, heavy and difficult to support properly. In addition, they must be arranged in a manner that enables crane access to the engine and compressor for removal and reinstallation of cylinder heads and other large components for periodic maintenance.

Thermal stresses caused by the engine's hot exhaust gas, along with the weight of the exhaust pipe and the need to pass through a building wall, make the proper design and construction of the exhaust system a complex undertaking.

Expansion joints or flexible bellows are commonly used to absorb the deflection of exhaust piping and other system components, so as to limit the forces and moments transferred back to the turbocharger exhaust flange. Too often, the exhaust system is designed without proper analysis, fails in service and has to be modified or replaced after a short period of operation.

When an exhaust piping system is not designed properly, safety, environmental or even building or structural hazards can result. An all too common problem in exhaust systems is the failure of the expansion joints. Expansion joint failures can result in hot exhaust leakage that poses a risk of fire, heat damage to wiring insulation and accessory devices, noise, high carbon dioxide (CO_2) and carbon monoxide (CO) concentrations inside the building, and untreated exhaust emissions bypassing the catalyst.

GCC Inc. investigated multiple failures of exhaust expansion joints directly connected to the exhaust manifold of several Waukesha 7044GSI gas engines driving Ariel JGK/4 2-stage booster compressor units at a Weld County, Colorado, compression facility in the Niobrara Shale. "GCC was tasked with investigating the failures and coming up with a solution for the end user," said James J. Aldridge, associate engineer.

Formerly known as Gas Compressor Consultants, Denver, Colorado-based GCC Inc. is an engineering company that provides comprehensive project management, facility development, gas processing, system optimization and service solutions to the oil and natural gas industry. “With vast, hands-on experience from the pad to the point of sale, we understand that various factors influence the economic success of a project,” said Wayne Sartori, president. “Our team approach allows us to provide fast, technically sound and cost-effective solutions to virtually any gas operation situation.”

“In the subject case investigated by GCC, failures were occurring at the expansion joint directly connected to the turbocharger exhaust outlet flange on the engine,” Aldridge said. “The failures resulted in equipment damage and exhaust venting into the building.”

The original system had two expansion joints. One was a vertically mounted original equipment manufacturer (OEM)-provided expansion joint at the engine designed to handle vertical thermal growth in the exhaust system piping and to isolate the exhaust system piping from engine vibration. The other was a horizontally mounted custom expansion joint at the other end of the exhaust line just before the catalytic converter, designed to handle horizontal thermal growth in the exhaust system piping.

During two site visits, pictures and measurements of the exhaust system and surrounding support structures were obtained and compared to end user-provided drawings and computer-aided designed (CAD) models. Using CAESAR II software, GCC analyzed stresses throughout the exhaust system with and without external insulation. Waukesha EngCalc and AFT Arrow software was used to predict the amount of heat and temperature in the exhaust system based on fuel compositions provided by the end user. These engineering tools were used to compute the piping and exhaust connection stresses caused by thermal expansion, coupled with the weight of the exhaust system itself.

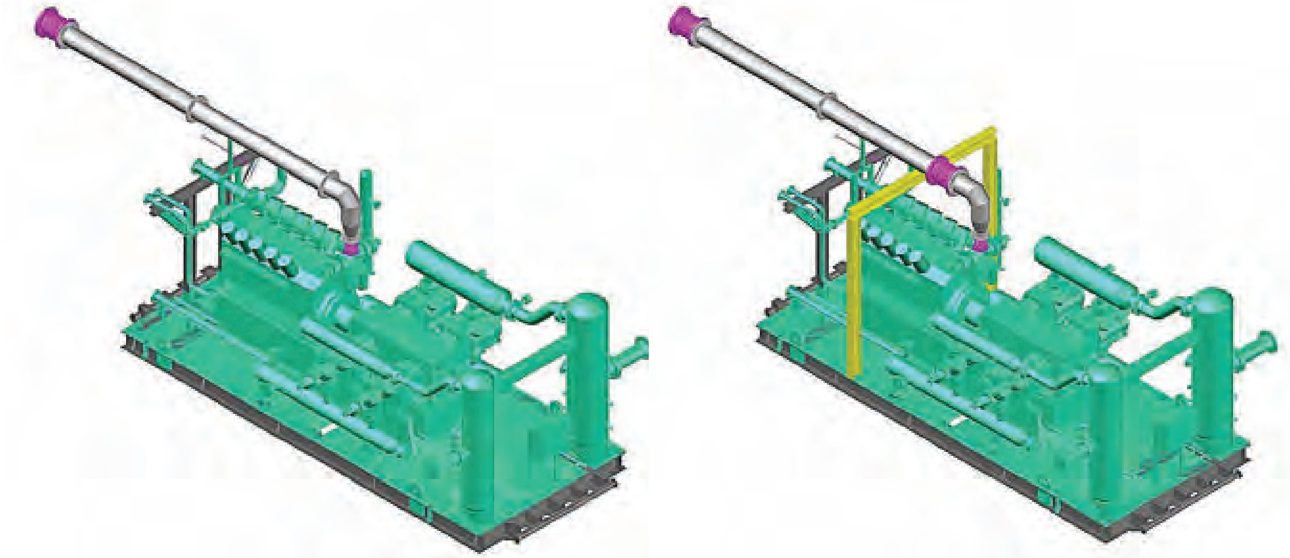
The analysis revealed that the expansion joint failures resulted from thermal expansion forces in the horizontal plane of the vertically mounted

The failure of this expansion joint (left) located at the engine turbocharger exhaust flange resulted from inadequate support and excessive thermal growth of the long exhaust line (right) running from the engine to the catalyst outside the building wall.

expansion joint. With the engine running at full temperature, with the original support system, the analysis predicted a lateral force of 2298 lb. (1042 kg) acting on the first expansion joint. The engine manufacturer’s specifications indicated that the expansion joint was designed for axial load with a deflection limit of 0.23 in. (5.84 mm), but not designed to tolerate any lateral load, having a lateral deflection limit of only 0.07 in. (1.8 mm).

The analysis pointed to additional concerns involving the horizontal joint mounted directly before the catalytic converter, being significant enough to require attention. Upon further investigation, it was discovered that this expansion joint had also failed in the past. The GCC analysis showed an axial force of 1667 lb. (756 kg) on the horizontal expansion joint. This resulted from the spring force of the expansion joint as it was compressed by the thermal expansion of the piping and other elements of the system. This force exceeded the design force limits of 500 lb. (227 kg) lateral and 1000 lb. (454 kg) axial on the cone that supports the catalyst.

From the analysis results, it was concluded that both expansion joint failures were occurring because the horizontal expansion joint at the catalytic converter was improperly sized. The thermal expansion was fully compressing the custom expansion joint



After looking at many options to improve the reliability of the original exhaust system (left), GCC's solution (right) was to replace the expansion joint at the catalytic converter, add an additional expansion joint in the horizontal axis of the exhaust system right after the 90° bend from the vertical section of pipe, and add a support to fix the vertical section of pipe horizontally, eliminating horizontal forces on the vertically mounted expansion joint.

and the remaining thermal expansion was propagating back to the vertical expansion joint at the engine, which was not designed to handle horizontal forces or movement.

GCC explored multiple options to eliminate the expansion joint failures. The first solution involved modifying the exhaust system piping and supports to minimize forces and bending moments so that the existing expansion joint at the turbocharger exhaust flange could be used without being overloaded. The changes involved adding a 4.5 ft. (1.4 m) loop in the exhaust system to provide more flexibility, adding additional vertical supports and replacing the expansion joint at the catalyst with one having a softer spring constant (i.e., permitting more deflection for the same force).

Analysis of the first proposed solution at maximum operating temperature showed that the lateral force would be limited to 22 lb. (10 kg) at the expansion joint connected to the turbo exhaust outlet. The calculated axial force of 473 lb. (214 kg) was also well within the acceptable level. At the catalyst end of the exhaust pipe, the proposed new expansion joint was predicted to have an axial force of 441 lb. (200 kg), or only 40% of the maximum allowable force that the cone nozzle at the catalyst can withstand.

Unfortunately, in addition to adding the loop of piping and requiring a different expansion joint at the catalyst end, it was determined that the current beam holding up the exhaust pipe would have to be removed and replaced with a different beam structure, placed in such a way that it did not interfere with the intake air piping. But placement of the new beam would interfere with the maintenance platform on that side of the engine, requiring even more site modifications. Although this would have provided a robust design solution, it was agreed with the end user that GCC would investigate alternate solutions that would be easier to implement without compromising access to the engine for maintenance.

After multiple design iterations intended at eliminating the horizontal forces and subsequent movement in the vertical expansion joint at the engine, GCC's proposed solution was to replace the expansion joint at the catalytic converter, add an additional expansion joint in the horizontal axis of the exhaust system right after the 90° bend from the vertical section of pipe, and add a support that fixed the vertical section of pipe horizontally, so that no horizontal forces could act upon the vertically mounted expansion joint. This proposed arrangement eliminated all the excess forces in the system that were causing the failures, and it is similar to most engine manufacturers' current exhaust system installation guidelines.

A different example of problems involving an improperly designed exhaust system had even more severe implications. In this case, a long, improperly supported exhaust line was originally supported by part of the building wall structure. The thermal growth of the long exhaust pipe span caused the building wall to deflect outward. In addition, vibration in the pipe excited the wall so that it also vibrated, creating noise and a risk of structural failure of the building itself. Left uncorrected, the vibration could have damaged electrical conduit, lights and other items, caused false shutdowns, and even destroyed the entire building wall in the worst case. The problem was resolved by adding a goal post structure to properly support the heavy exhaust line before it went through the building wall. Welding the goal post frame to the wall also stiffened the wall and eliminated the noise and vibration.

Both examples show the challenges of dealing with failures of an improperly designed or installed exhaust system in the field. Ongoing failures pose unacceptable risks, remediation is costly and usually cumbersome, and access

Where it exits the building at upper left, this large engine exhaust pipe was originally supported directly on the building wall (left). This arrangement caused vibration of the wall that raised the noise level and likely would have led to structural failure of the building. Bracing and structural support were added in the form of a large goal post, partially visible near the wall (right), which is welded to the building structure, making the wall much stiffer while also supporting the weight of the exhaust line.

to the engine and other parts of the system for routine maintenance and top-end overhaul is often compromised.

A best practice, therefore, is to properly design and analyze exhaust systems during the engine compressor package and building design processes. At a minimum, this requires interaction between the compressor packager, the building engineering contractor, and the end user. In addition, one of these entities needs to be accountable for ensuring the system is installed as required by the design.

Based on the extensive experience of the GCC engineering team, Aldridge pointed out a number of important considerations that must be considered when designing an exhaust system for high-speed natural gas engines.

"Fundamentally, in addition to providing for support of the weight of the system, it is extremely important to account for thermal expansion of piping in every direction and ensure that the forces caused by expansion are accounted for by properly sized expansion joints and properly located support systems," he said.

When designing an exhaust system for high-speed natural gas engines, there are a number of safety and reliability concerns that must be addressed. Exhaust system temperatures can range between 700° and 1000°F (371° and 538°C) depending on the engine configuration, i.e., naturally aspirated, low emissions, ultralean burn, etc. At such high temperatures, worker safety becomes a concern. Exhaust systems therefore must incorporate internal or external thermal insulation to protect both workers and equipment that might come into contact with the hot surfaces.

Thermal expansion of the exhaust system piping or ducting is also a concern, as evidenced by the examples discussed earlier. Expansion joints, also known as exhaust bellows, should be integrated into an exhaust system to absorb the thermal expansion in all directions. When deciding where to place exhaust bellows, it is important to note that they are designed to only handle axial compression forces due to thermal expansion. Typical exhaust bellows are not designed to handle large axial offsets or lateral forces. Lateral forces, i.e., any forces in a direction that are not acting along the central axis of the expansion joint, create a risk of overstressing the bellows in the expansion joint, leading to a failure.

Supports for the exhaust piping must be placed to bear the system's weight as well as forces caused by thermal expansion. In all cases, the system must be analyzed with appropriate engineering methods and computational tools to ensure that the forces and moments applied to the engine turbocharger exhaust connection, the catalyst, and all expansion joints are within limits specified by the corresponding manufacturers. This must be analyzed with the system in cold, hot (typically at rated engine output) and transient (e.g., warmup, cool down or temporary overload) operating conditions. In addition, it must be ensured that the total thermal expansion to be accommodated by each expansion joint is acceptably within the expansion joint manufacturer's specifications.

Implications on the building support structure, penetration through the building wall, and proximity of electrical wiring, controls and other temperature-sensitive devices or systems also must be considered in the overall design of the exhaust system and its surroundings. This requires close coordination with the building engineering and construction contractors, as well as the end user, during the design and construction processes.

"With experience, manufacturers' specifications and analysis tools available today, the design of a safe and reliable exhaust system is a reasonable task," Aldridge said. "Especially for units that are placed inside buildings, every reciprocating engine-driven compressor procurement specification should require a proper mechanical and thermal engineering analysis of the exhaust system."