Thermal insulation and pipe stress

An often-overlooked function of insulation in piping designs is to mitigate weather effects

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Thermal insulation is mainly used to reduce heat loss and noise level. It is also used to prevent burn injuries. However, a lesser-known yet important function of thermal insulation is to reduce pipe stress.

In a petrochemical/refinery complex, piping systems are constantly subjected to the abuses of weather and environmental changes. Occasional rain showers, for instance, can generate very high pipe stresses. Repeated occurrences can eventually lead to pipe failure. Some typical situations when a seemingly innocent rain shower may damage a pipe are discussed. Some field problems can actually be solved with a simple application of insulation. Unfortunately, the engineer who relies only on a computer to design and analyze piping will miss out on this kind of common sense.

A case history. Fig. 1 shows a piping system used to transfer a hot gas mixture from the primary reformer to the secondary reformer in an ammonia fertilizer plant. The gas mixture was operating at approximately 1,500°F and 500 psi. The main portion of the piping was constructed with thick, internal refractory-insulation to reduce the pipe metal temperature to approximately 200°F. This section of the piping is called the cold-wall portion, in contrast to the externally insulated hot-wall portion, whose metal temperature is close to the fluid temperature of 1,500°F. Carbon steel is used for cold-wall piping, and alloy steel is used for hot-wall piping.

This plant was built in the early 1970s. Most of the piping was designed using a cold-wall approach due to economic benefits of using common carbon steel material and the desire to reduce thermal expansion. Hot-wall construction was used only at the piping segments connecting to the reformers. Four transition joints connected cold-wall pipe to the hot-wall pipe.

After operating without problems for the first 10 years, maintenance was performed on the piping to repair the refractory and to replace the hot-wall special-alloy pipe. Strangely, after this revamp, the miter elbows at points A and B near the cold-wall/hot-wall junctions developed leaking cracks about every four months. The revamp contractor was called in to investigate the problem.

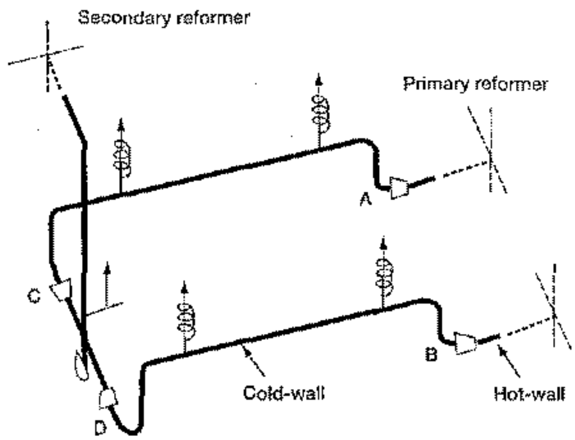

Fig. 1. Ammonia plant reformer piping.

As expected, their first step was to input the system into a computer for a stress analysis. However, all the computer indicated was that everything was in good shape. So the contractor modified some springs based on the computer analysis. Ironically, the original design was probably done without the help of a sophisticated computer program. After spending thousands of dollars replacing the spring hangers, the system still faithfully failed about every four months. You can bet it was very frustrating for the plant engineers.

After this exercise, the plant engineers decided to get help from a large contractor. For unknown reasons, the original contractor was not called. A large contractor naturally has a greater depth of engineers. The contractor first performed a series of heat-transfer calculations to check the cold-wall section's metal wall temperature. They understood that a good analysis needs good data. With the newly calculated metal wall temperature, they made a refined stress analysis of the system. Again, the computer said everything was in good order. Nothing could be done, or needed to be done.

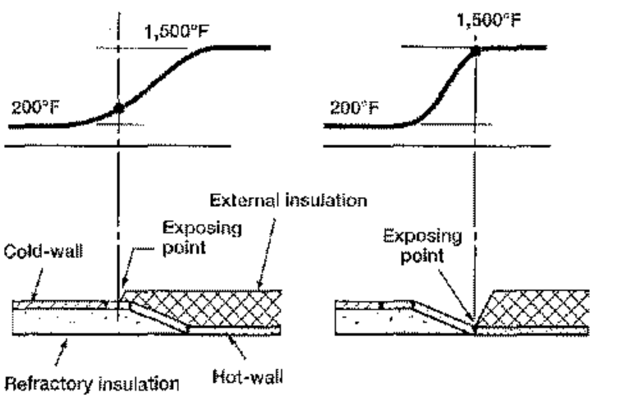

Fig. 2. Cold-wall to hot-wall junctions in the a) correct arrangement and b) wrong arrangement.

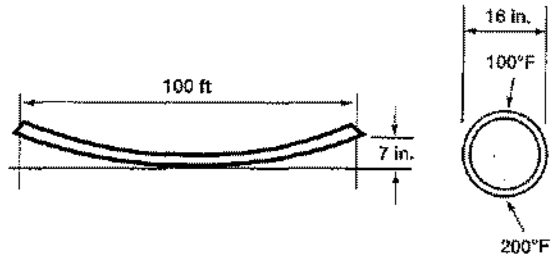

Fig. 3. Thermal bowing effect.

However, out of professional conscience, or maybe to justify the fee for their service, they recommended that all the spring hangers be replaced with constant-effort springs. Result: the same frequent failure except the system changed into a pile of twisted spaghetti piping. The constant-effort spring hangers had a difficult time holding the system together.

The problem was later solved by a small modification in the insulation arrangement. It all started with a casual look at photos and some casual discussions with the plant engineers. Subsequently, all the original spring hangers were reinstalled. The fancy constant-effort spring hangers were removed and destined to fill the warehouse.

Cold-wall/hot-wall junctions. Joints connecting the cold-wall pipe and hot-wall pipe require special arrangements in both pipe material and insulation. Just like a roof contractor who knows how to treat a shingle-to-wall junction, an experienced piping contractor knows exactly how the cold-wall to hot-wall junction must be constructed. A small mistake in the detail by the roofer normally results in constant roof leakage.

Fig. 2 shows two arrangements of cold-to-hot junctions. The two do not really appear different to the inexperienced eye; however, the consequence is the difference between failure and safety. Fig. 2a shows the correct arrangement, and Fig. 2b shows the often-used wrong arrangement. The original system in Fig. 1 was constructed with the arrangement shown in Fig. 2a, yet the drawing somehow had indicated Fig. 2b. Due to the revamp contractor's inexperience, the junctions were constructed as Fig. 2b, causing constant cracks of the pipe.

The pictures are not obvious, but once the temperature profiles are constructed using some common sense, they become very clear. In case 2a, the pipe wall temperature decreases gradually from 1,500°F to the design cold-wall temperature of 200°F. Ensure that the wall temperature at the dissimilar weld location is below 500°F to avoid high thermal stress due to different expansion rates between carbon steel and high-alloy steel.

Conversely, the temperature in case 2b drops much faster than in 2a. The focal point is at the location called the exposing point. This is the highest temperature point exposed to open air that can be quenched by a rain shower. In 2a, the temperature at the exposing point is about 400°F, whereas in 2b, the temperature at the exposing point is close to 1,500°F. It is clear that a much higher thermal stress will be generated in case 2b.

Thermal stress. The thermal stress caused by a temperature gradient or discontinuity normally does not produce any gross distortion. Therefore, it is often overlooked. However, if we appreciate how high a stress can be generated, we would pay more attention to it. The magnitude of the thermal stress can be roughly estimated by:

$$S = E\,a\,T \tag{1}$$

where S = thermal stress, psi
a = expansion rate, in./in./°F
E = modulus of elasticity, psi
T = temperature difference, °F

For carbon steel pipe, a 500°F discontinuity will mean a 105,000-psi thermal stress. The stress will be even greater for a stainless steel pipe due to its higher expansion rate. This kind of stress greatly exceeds the safe reference value of twice the yield strength and should not be ignored. It is difficult to estimate exactly how much of a temperature gradient can be generated by a rain shower, but any local area with a metal temperature of 500°F or higher should be protected.

Showers. In a petrochemical/refinery complex, some locations are especially susceptible to rain shower damage:

High-temperature flange connections. The ASME B31.3 piping code contains a clause that stipulates that the design temperature of uninsulated flanges, including those on fittings and valves, can use 90% of the fluid temperature (par.301.3.2). Thus, some high-temperature flanges are purposely designed without insulation covering. Although the situation has changed since the 1970s energy crisis, many uninsulated high-temperature flanges are still in the field. These can easily develop leaks and cracks after repeated rain showers. It should be cautioned, however, that insulating these flanges now might make them unacceptable to the code due to a design temperature increase.

Expansion joints. It could be for ease of inspection or just due to logistical problems in construction, but many expansion joints are not insulated. Once it is built that way, the plant engineers will not change it, even if it develops cracks. They are very often incensed at knowing that the simple application of insulation will solve the problem. They thought that it was something they had to suffer through due to technological impossibilities that prevent these joints from being properly constructed.

High-temperature valves on the cold-wall section. Due to practicality, valves used in the cold-wall portion of hot-fluid applications often use hot-wall design (meaning without internal refractory insulation). These valves are often left uninsulated for the same reasons as high-temperature flange connections. If insulation is not desirable, then at least some type of rain shield should be provided.

Thermal bowing. For thermal stresses, we are concerned mainly with the high-temperature areas. These are the areas that can create high enough thermal stresses to cause cracks. However, in some systems, even though the temperature is not high, another thermal effect may create a different kind of problem. This is the lesser-known bowing effect.

For example, assume we have a 16-in. gas line that is not insulated and operates at 200°F. During a summer shower, the pipe's top may suddenly quench to 100°F while the bottom maintains 200°F. This 100°F quench on the top produces a shrinkage of 0.00065 in./in. of pipe surface. This shrinkage will bend the pipe into an arc with a radius of curvature equal to R = 16/0.00065 = 24,615 in. This bowing effect (Fig. 3) can potentially lift the ends of a 100-ft long pipe up 7 in. Although the actual lift will be greatly reduced by the pipe's weight, its significance cannot be ignored.

Damage caused by thermal bowing is often very ghostly. It normally happens without anybody actually seeing it. In the above example, when the shower starts, the ends move up and possibly tear off some supports or small connections. However, when the rain stops or when the temperatures even out, the pipe returns innocently to its initial position. It leaves the damage without giving any clue of the cause. ■

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