Cryogenic System Design

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Understanding the basic properties of liquid nitrogen and the fundamentals of cryogenic pipe design can help plant engineers specify distribution systems that comply with safety protocols, meet user expectations and maximize efficiency.

Liquid nitrogen is used in myriad diverse applications, including flash freezing seafood, creating "fogging effects" for the Las Vegas entertainment circuit, cold shock testing parts destined for the space shuttle and preserving biological samples. For most high-use facilities with cryogenic cooling operations, a bulk tank of liquid nitrogen provides a readily available source. But what is the best way to distribute the liquid nitrogen throughout the system?

In some ways, liquid nitrogen is perplexing. It looks like water, and one might mistakenly assume that its fluid transfer properties mimic those of water. But too many missteps in the early system design phase of a project can result in the liquid nitrogen literally going "up in smoke" later, leaving users frustrated and wreaking havoc with operating costs. Fortunately, the basic parameters of liquid nitrogen transfer and the corresponding fundamentals of cryogenic pipe system design are easy to demystify. Armed with this solid understanding, plant engineers can work effectively with cryogenic pipe vendors to make sound design decisions that satisfy both users and management.

Consider the Physical

Liquid nitrogen is cold — -320°F (-196°C). Once liquid nitrogen starts to pick up heat, one part of the liquid warms and expands into 700 parts of gaseous nitrogen.

Rigid vacuum-insulated pipe often is used for the outside portion of distribution systems.

Cryogenic distribution systems typically experience two types of heat leaks: initial losses and steady-state losses. Initial cool-down losses occur when the cryogenic fluid is introduced into an ambient pipe system. The cooling capacity of liquid nitrogen (heat of vaporization) will be needed to cool the pipe to cryogenic temperatures. Steady-state losses refer to the amount of liquid nitrogen that is consumed to keep the pipe at cryogenic temperatures once the system has reached cryogenic levels.

Most distribution systems are composed of the industry-standard vacuum-jacketed piping. This all-stainless-steel, coaxial process pipe is designed to allow for thermal expansion and contraction as well as to minimize heat transfer due to radiation, convection and conduction. The inner pipe is wrapped with a special insulating material, and spacers support the inner pipe to keep it separated from the outer pipe. A chemical getter material (a material intended to absorb impurities) is used to ensure longevity.

The entire spool section is thoroughly evacuated (pumped down) and sealed at the factory. Spool sections are joined together with vacuum-insulated bayonet connections, which remain frost-free during operation. Steady-state losses are minimized in a vacuum-jacketed system. Vacuum-insulated pipe is available in rigid or bendable pipe configurations, with many systems using rigid pipe outside the building and bendable pipe (which is more forgiving of existing ductwork and other components) inside the building.

To ensure proper sizing and design, it is important to know the users' needs and expectations of the distribution system. At a minimum, each user should report the pressure requirements (both maximum and minimum), maximum flow requirements and any application-specific requirements.

System Characteristics

Bendable vacuum-insulated pipe is more forgiving of existing ductwork and other components.

Several basic features are common to all cryogenic systems. At a minimum, the safety-relief valve, the need for a venting device and the end terminations all should be taken into consideration during the early design phase.

The safety-relief valve protects the system against overpressurization. Whenever liquid nitrogen has the potential to be trapped between two shutoff valves (e.g., a bulk-tank shutoff valve and a use-point shutoff valve), the potential exists to create a large volume of gas, which could overpressurize and burst or damage the pipe system. The safety-relief valve provides a pathway for the excess gas to vent out of the system safely. (Note that safety-relief valves are designed into the system as a safety precaution. Under normal operating conditions in a well-designed system, the safety-relief valves should not need to open to relieve excess line pressure.)

Most systems also will have an integral gas trap at a use point. The gas trap positively impacts liquid nitrogen conservation during periods of nonuse by providing a barrier between the liquid nitrogen and a nonvacuum-insulated shutoff valve. In a riser, a gas trap occurs naturally — some liquid nitrogen warms and turns into gas, which rises to the use point. In a drop, a gas trap is created with an internal loop in the pipe system. The gas pocket prevents percolation of liquid nitrogen during nonuse.

During extended periods of nonuse, the liquid nitrogen inside a pipeline eventually will warm up and turn into gas, and this gas will "push back" to the bulk tank. When there is demand for liquid nitrogen, a user often will experience a "wait time," during which the system once again is being cooled down to cryogenic temperatures.

To minimize the wait time, many systems incorporate an inline venting device to keep the line wetted with liquid nitrogen. The trade-off in this scenario is that some nitrogen will be consumed in the process of keeping the line wet (cold) even if no downstream demand for liquid nitrogen exists. To work properly, a venting device must be installed at a high point in the system. It is critical that the pipe to and from the venting device be sloped properly.

Specialty Designs

Certain applications require more refined delivery systems. These systems are supported with high-volume phase separators, triaxial pipe and other specialty equipment.

For example, closed-loop systems for molecular beam expitaxy (MBE) applications use a low-pressure, closed-loop liquid nitrogen delivery system to feed cryopanels. The cryopanels support vacuum conditions, which, in turn, maximize product yield.

Another specialty design is a liquid-on-demand system. These systems can support peak flow rates with essentially no wait time — even if the system has been idle for some time. Such systems require an intricate balance of venting capacity and liquid nitrogen holding tanks.

With an understanding of cryogenic principals and user requirements, plant engineers can develop specifications for a fundamentally safe and efficient cryogenic distribution system. Likewise, by understanding some of the nuances of specialty applications, engineers can facilitate communication between users and system designers to achieve a successful project implementation. Such skills are easily transferable and highly valued in any liquid nitrogen application.

What About Foam-Insulated Copper Pipe?

In the opinion of this author, foam-insulated copper pipe is an outdated approach to liquid nitrogen delivery systems. Readily available with a deceptively low initial price tag, foam-insulated copper systems can turn into maintenance headaches quickly.

Foam-insulated copper pipe often has steady-state losses ten to twenty times those of a vacuum-jacketed system. This high heat leak translates into wet, frosty pipes; poor-quality liquid (i.e., much gas mixed in with the liquid) at the use points; and high liquid nitrogen consumption.

These issues, as well as high installation costs and the need for routine maintenance, are all factors that need to be considered when evaluating the true system cost.

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