OUT OF THIS WORLD

NASA has been using multi-layer insulation since the 1960s. Now, **Chris Hebb, Technifab, USA,** looks at vacuum jacketed insulation for small diameter LNG pipes.

With the recent proliferation of its use in construction and automotive fields, and as a general diesel/gas replacement, LNG is now delivered and stored in smaller quantities instead of the pipelines of old. Many of these new uses should cause people to revisit how best to insulate the cryogenic liquid being stored and delivered. Smaller diameter lines and smaller storage containers can mean losses are greater as a percentage of the total available liquid. Many of these uses are not in a tightly controlled environment, and, with extremely low temperatures, safety can be a concern.

Insulating pipe and containers for cryogenic liquids presents particular challenges, not only because of the

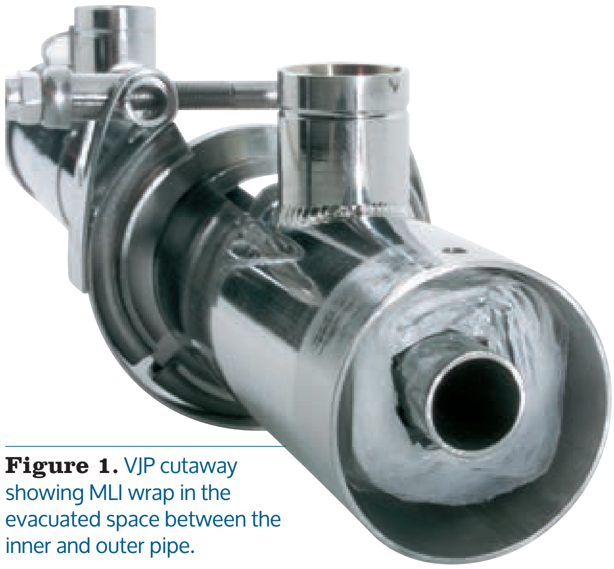

Figure 1. VJP cutaway showing MLI wrap in the evacuated space between the inner and outer pipe.

inherent low temperatures, but because ambient temperature and the liquid's heat of vaporisation often results in a phase change from liquid to gas. This change, with an expansion ratio of 600:1 for LNG, not only reduces the amount of product stored in a vessel, but, if not controlled, will affect system pressure and flow through a pipe.

Cryogenic liquids, including LNG, become gas as the result of the heat 'leaked' into them. Insulation is used to keep the liquid from becoming a gas, reducing the amount of heat transferred into the cryogenic liquid. It can also provide protection against warmer objects becoming colder, including protecting skin from freezing.

A more efficient insulation will reduce the boil-off gas (BOG), and if transferring liquid is the goal, then it will deliver more liquid and initial flow quicker. If the system requires liquid at the use point, better line and storage insulation are even more critical.

This article will review the basics of heat transfer, look at how vacuum jacketing for pipes reduces heat transfer, and finally compare that with other forms of insulation.

Heat transfer basics

Heat transfer occurs through three methods: conduction, convection and radiation.

Conduction occurs through contact with another mass. Heat flow through the material, often measured by the thermal conductivity *k*, is reduced by material selection and decreases the contact area between the materials. Plastic has a lower thermal conductivity than metal. If the insulation layer includes a gas, besides solid conduction, there will be gas conduction. In the construction industry, the opposite of conduction, resistance (i.e. R-value), is used for measuring the ability to transfer heat flow.

Convection occurs when a liquid or gas through movement transfers heat from one surface to another. The rate of movement (e.g. natural vs. forced) influences the amount of heat transferred. The gas between layers of insulation can become the dominant contributor to heat flow since it provides contact between the insulation components.[1]

Radiation is the energy emitted by electromagnetic waves. Much of the energy one feels when sitting in front of a fire, for example, is thermal radiation. While it is less of a factor for cooler bodies, such as cryogenic liquids, when the other two forms are reduced it can become a factor. The relative ability for a surface to emit energy by radiation is usually expressed as emissivity (□).

These methods of heat transfer operate at the same time, although different insulations can affect which method is most dominant. For example, with enough of a vacuum, convection and gas conduction are eliminated.

Thermal conductivity is a measure of a material to conduct heat and is often reported when comparing different kinds of insulation. But like many specifications, the term can mean different things to different people and has been loosely used in literature and manufacturer's specifications. ASTM C168-13, which defines terminology for thermal insulation, covers two forms: thermal conductivity (□) and apparent thermal conductivity ($\square_a$). □ is for homogeneous material, a single mode of heat transfer, and is independent of material thickness. $\square_a$ should be used for materials that have several modes and will vary with material variations such as thickness. Both are often measured with a small change in temperature (i.e. 20°C).

Effective thermal conductivity (k_e) is now defined in ASTM-C1774-13. k_e is the thermal conductivity through the total insulation thickness between boundary temperatures in a specified environment. This is perhaps the most useful form of thermal conductivity because it can be used to compare different insulations, can be measured experimentally, and often is reported with a larger temperature difference. Perhaps the recent definition (2014) in ASTM C-1774-13 will encourage more usage.

Thus it is important to understand the terms and conditions under which thermal conductivity is reported, especially when comparing small differences in the numbers.

How vacuum jacketing works

To create the highest level of thermal isolation, engineers and scientists enclose the vessel or pipe with a separating space that is vacuum evacuated. Vacuum jacketed insulation was developed by James Dewar when liquefying oxygen and hydrogen in the 1890s. It was the space programme development of multi layer insulation (MLI) around 1960 that brought about an even higher performance solution in reducing heat transfer by radiation. NASA used it for insulating not only containers but in piping used to deliver cryogenic liquids for spacecraft.

To explain how vacuum jacketing works best, describing a particular example may help. Vacuum jacketed pipe (VJP), or vacuum insulated pipe as it is sometimes called, consists of an inner pipe that carries the cryogenic liquid enclosed by an outer pipe with a vacuum between the inner and outer piping. The pipe design controls the heat transfer by:

- Creating a very small heat path from the outer to the inner vessel, which typically controls conductive heat transfer. Using a material with very low thermal conductivity properties, such as G-10 NEMA Grade

Fiberglass and/or low-density ceramics also reduces conduction.

- With an ambient vacuum 24-hour settle pressure in the 10^{-4} torr range, convective heat transfer across this space is virtually eliminated.
- Radiated heat transfer is controlled by placing a barrier between the inner and outer vessel to prevent heat from radiating into the inner vessel. MLI provides the best barrier for radiated heat transfer.

Vacuum insulation, especially when done at higher vacuum levels, has the advantage because it can virtually eliminate two of the three methods of heat transfer. But vacuum insulation can be challenging to achieve and maintain unless built in a factory controlled environment or if a vacuum pump is continuously removing molecules from the jacket. Most vacuum jacketed piping systems today use a static design that is evacuated and sealed when built. Dynamic systems require a vacuum pump to maintain the vacuum insulation.

The reduction in radiation occurs through the addition of MLI. Like leaves on a tree on a hot sunny day, the alternating reflective shielding/conductive insulating layers are wrapped around VJP to allow the pipe to reach the very low levels that are seen today. MLI is considered an effective protection and especially stands out when space is limited.

Building and creating the vacuum in a factory can significantly reduce the cost and produces a higher level of quality than can be achieved in the field. It only takes a small amount of contaminant, such as oil or even a fingerprint, to cause outgassing and reduce the vacuum over time. Ultra small cracks or porosity can also ruin a vacuum over time, but using a leak detector, helium gas, and measuring the vacuum after a 'sit time', the manufacturer can ensure that a long-lasting product will be achieved. Today, static VJP can have up to a 10 year warranty on the vacuum insulation.

Other forms of cryogenic pipe insulation

An un-insulated pipe can be an option, and often represents the lowest initial cost. However, due to safety and heat loss concerns, it is usually ruled out except where absolutely necessary. The ice that forms on the non-insulated portion becomes a form of insulation, although the condensate dripping and unsightliness usually generates complaints. Ice is one of the things that insulation attempts to reduce or eliminate.

Foam insulation

Cryogenic foam insulation and the variants have been used for years. It has been commonly used on small and large diameter pipes along with some tanks and containers. Spray-on foam can be particularly attractive for tanks and irregularly shaped containers, but it has also been used on pipes. Some applications add a vapour barrier to reduce moisture ingress; others by design rely on the foam material to prevent moisture ingress. If the foam is preformed and sections applied in the field, the joints must be sealed or moisture/condensate will get through at the joint sections.

Initial cost of foam, product familiarity, and simple shipment/manufacturing still makes this a popular choice. Foams generally provide a barrier to heat conduction due to a cellular structure that greatly reduces conduction. Typical foam insulation includes polyurethane foam, polyamide foam, and foam glass. Choice of materials used influences thermal conductivity of the foam, which helps with low temperature performance and also influences convection within the cells.

However, deterioration over time will cause a significant drop in the insulation (*k*-factor) value. Some closed cell foams use specialised blowing agents to fill the foam cells so the gas conduction and convection heat transfer is reduced. This helps foam performance, but, over time, gas in the cells will diffuse out. This is partly why insulation *k*-factor standards are measured after 180 days in many tests.

Foam insulation deterioration can be significant; a detailed NASA study of spray-on foam insulation (Fesmire) measured approximately a 25% increase in thermal conductivity in the first six months and it continued out to 24 months.

The different expansion ratio between foam and the inner carrier (4 - 10 times for steel) means foam cannot be directly bonded to the inner pipe unless cracks or gaps in the insulation occur. VJP handles this cryogenic temperature expansion difference through internal or external bellows, but with foam covered pipe it must instead slide on the pipe, which presents another heat leakage point. Since it cannot be vapour sealed, this contributes to the foam insulation degradation, which becomes significant over time.

Other insulation materials

Recently, there has been extensive research using a combination of foam and MLI insulation and then a vacuum to provide additional insulation qualities. The foam/MLI combination can be formed and cut into shapes where the MLI would be difficult to attach or wrap, making it useful for some vessels or containers where only MLI will not work. But MLI with a hard vacuum (meaning less than 1 torr) still provides excellent insulation and may have a slight cost advantage.

Cellular glass insulation is another possibility that has been used for large diameter LNG piping in particular. It can be made pre-fabricated but is similar to foam in that it needs a vapour barrier. In addition, the conductivity is significantly higher than products using a vacuum.

Powdered insulations, such as perlite and some aerogels, are commonly used as insulation in containers and vessels. However, it is not possible to use them with pipes or hoses. Perlite is like blown insulation and settling can often occur. It can provide apparent thermal conductivities lower than foam when used with a vacuum. When used in tanks, the expansion/contraction cycle from the colder materials can cause additional settling. Aerogel blankets can have better performance than perlite at atmospheric pressure, but perlite can have an advantage with a higher vacuum level.

Figure 2. LNG liquefaction/storage facility connections used to fill an LNG trailer. Flanges are not attached to the concrete wall due to the non-bellows rigid pipe contraction when filled with LNG.

Figure 3. Modern LNG filling station. Many of these still use non-vacuum jacketed hoses to fill the vehicle tanks.

Table 1. Effective thermal conductivity values for different insulations with liquid nitrogen

Material	Thermal conductivity
Perlite powder, atmospheric pressure	35 mW/m-K
Spray on foam, atmospheric pressure	21 mW/m-K
Aerogel blanket, atmospheric pressure	11 mW/m-K
Aerogel blanket with vacuum (10^{-4} torr)	1.5 mW/m-K
Perlite power with vacuum (10^{-4} torr)	1 mW/m-K
MLI with vacuum (10^{-4} torr)	0.03 - 0.1 mW/m-K

Other advantages

The reduced heat transfer for industrial gases is usually the most obvious advantage that VJP has over other insulations. Comparisons between insulations for pipes become challenging because of the different methods and conditions discussed earlier. Most of the data is also at liquid nitrogen (or helium) temperatures and may also omit the insulation thickness at which the comparison is done. Perhaps the best comparison source to date is the newly released ASTM C1774-13, which does not include all forms of insulation, but at least compares them under similar conditions. However, there is a real opportunity to use the newly established ASTM standard definition for thermal conductivity (k_e) to compare the different types of insulation.

Table 1 shows the effective thermal conductivity (k_e) values for different insulations using liquid nitrogen (-196°C) and ambient (20°C) with 25 mm (1 in.) thickness (see ASTM C1774-13 for more details).

Differences in manufacturing and pipe assembly methods will create differences in the heat leakage into cryogenic liquid delivery systems. The level of vacuum achieved, method of manufacturing the pipe, and the joints used between sections will all make a difference in the heat transferred into the liquid. Still, there is no substitute for vacuum to get the best performance in cryogenic insulation.

Installation issues

A benefit of VJP, besides the lower heat leak/conductivity, can be field installation. Static VJP comes pre-evacuated and for smaller diameter lines is assembled with bayonets. 'Spools' of VJP are inserted together and clamped at the bayonet connection. No additional insulation needs to be applied.

Another factor to consider is expansion and contraction of the pipe. Metallic pipes, when chilled, will contract about 6 cm per 30 m of length (2.4 in. per 100 ft) at LNG temperatures. There are many methods of compensating for the expansion; a common method for VJP is to include expansion bellows on the inner pipe so that the external pipe dimensions do not change. A VJP system that uses internal bellows can be mounted using normal hanger clamps.

VJP can also be made into flexible lines, allowing the lines to be moved and preventing the insulation from falling off or being damaged. Vacuum jacketed transfer lines have been used in the industrial gas industry for decades, making situations where a line needs to be connected to another fitting a much safer process. Expansion bellows are not needed for flexible lines.

Conclusion

Since NASA and the space programme started using liquid cryogenic fuel in the 1960s, vacuum insulation with a MLI wrap has been a benchmark for delivering the highest quality cryogenic liquid fuels. Choosing an insulation type, like many engineering choices, is full of trade-offs between desired functionality, design, ease of installation and cost. VJP can offer distinct advantages, especially in smaller diameter pipes, and, as such, the LNG industry should consider this technology for application more often. **LNG**

Note

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Reference

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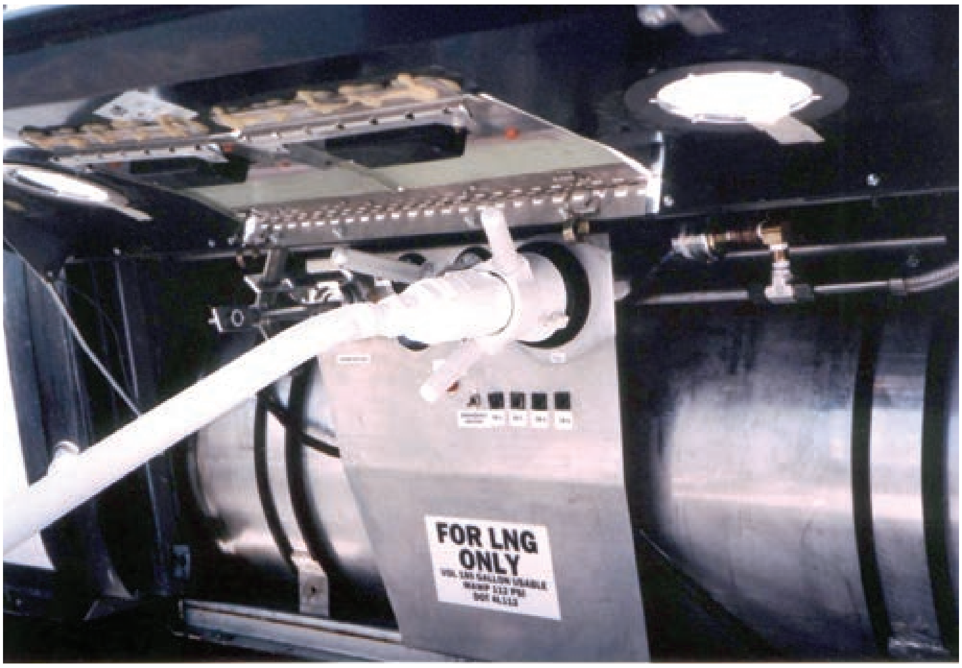

Figure 4. Fuelling hose filling a on-highway truck's on-board LNG fuel tank. Note the frost on the non-vacuum jacketed line from the -160°C (-260°F) LNG flowing through the line.