SPRAYING FOR SUCCESS

Andreas Norberg, LNT Marine, Norway, provides an introduction to the design, research and development of spray foam insulation systems for a variety of LNG fuel and cargo storage applications.

Thermal insulation systems play a vital role within LNG storage systems. For seaborn applications, the system protects the hull from temperatures below acceptable limits, and ensures that the heat rate from surroundings and the corresponding boil-off gas (BOG) are dimensioned in accordance with the chosen means for boil-off handling. Since the difference in temperature between the LNG and the atmosphere is so significant, high thermal insulation is beneficial not only for hull protection, but also for the power consumption associated with gas handling. Improved thermal performance reduces the need for energy consuming boil-off handling, such as a reliquefaction system or other alternatives, and thus reduces OPEX. Over the last decade, spray foam insulation systems have proven their reliability and gained a strong foothold in both the LNG carrier and fuel tank markets. This article provides an introduction to the research and

Figure 1. Spray foam installation.

Figure 2. Spray foam insulation system with polymeric coating.

development of spray foam insulation systems, and gives an overview of design configurations for cargo and fuel tank applications.

Spray foam insulation system

A spray foam insulation system is a fully bonded insulation system, sprayed and fixed directly onto the tank of a self-supporting independent tank. The thermal insulation system is thus separated from the inner hull and avoids direct exposure to the cargo. Spray foam insulation systems are designed to mechanically resist structural movement of the tank when exposed to thermal and mechanical loads. This is enabled by a combination of design elements, consisting primarily of polyurethane foam (PUF) and foam reinforcements dimensioned and fine-tuned for project specific tank behaviours and boundary conditions.

Structural buildup

The structural buildup of spray foam insulation systems consists of PUF with embedded reinforcements, normally called crack barriers, for foam stabilisation and mechanical strengthening. To restrict the intrusion of humidity and exposure to solar radiation, as well as to improve fire resistance and mechanical protection, various types of surface materials are offered depending on project requirements. The PUF is sprayed onto the tank in several layers with a spray gun. To achieve strong bonding between the tank shell and the first foam layers, cryogenic polyurethane primer is applied. During spraying of the PUF, a two-component iso-cyanate and a polyol resin mixture are blended together at the tip of a foam spray gun. The composition of the blended components, as well as the mixture ratio during application, are predetermined and carefully controlled during application. When the foam mixture is sprayed onto the tank, it instantly starts to expand, and a self-adhering homogeneous layer of foam is created. The first layers of PUF typically have higher mechanical strength than the outer layers, and are designed with suitable ductility and thermal contraction coefficients. The purpose for doing so is to increase the strength/stress ratio and to align structural movements of the insulation material with the tank shell, where movements from thermal loads are most significant. The outer layers are typically designed with lower densities to reduce material consumption. In between spray foam layers, glass fibre meshes are applied to structurally strengthen the system and to restrict any crack generation and propagation. The crack barrier is typically applied in two layers depending on project specific insulation thickness requirements. During application and installation, thickness, temperature, humidity and curing time are carefully controlled. To verify suitable foam properties, test samples are regularly analysed and tested in laboratories. After application of the foam, the insulation surface becomes homogenous and seamless without joints or voids within the system. The risk of cold bridges in joints (which is absent) and the accumulation of moisture inside the system is reduced to a minimum. By spraying the foam onto the tank, the insulation system is constructed in an additive manner, resulting in low waste and limited production infrastructure.

History and development

The first spray foam insulation system design for seaborne LNG storage tank applications was developed by Marine Gas Insulation (now LNT Marine), and had its commercial breakthrough on the *Norgas Innovation* (now *Coral Frasier*). The vessel was delivered by Wuzhou Shipbuilding in 2010. The system has so far affirmed its reliability throughout approximately nine years of operation. Indeed, spray foam insulation systems have since gained a strong market position and become the preferred choice for IMO Type C tanks for both small scale LNG carriers and mid scale LNG fuel tanks.

The research and development of the first spray foam insulation systems was a complex engineering challenge. The insulation system had to have sufficient cryogenic reliability when exposed to extreme contraction and expansion movements, whilst simultaneously offering a high thermal insulation performance in order to offer a competitive specific heat rate. Additionally, the system had to be in accordance with classification rules and IGC Code requirements.

To guarantee adequate structural strength for intended services, structural behaviour and strength were assessed in combination during experimental laboratory tests and mock-up tests. Initial tank movements were identified with finite element (FE) analysis when exposed to representative mechanical and thermal loads. Furthermore, an analysis of the stress levels in the insulation system was performed in a multibody FE analysis, which included the tank structure, supports and insulation system. To assess the thermal performance of the insulation system, thermal FE analysis was performed with extreme IGC Code boundary conditions, both for boil-off rate estimations and for thermal distribution analysis. The material properties used as input in the FE models were obtained from actual laboratory tests performed in accordance with recognised standards. Thermal and mechanical properties were tested at various temperatures (from ambient down to cargo temperatures), in order to obtain representative input data for numerical analysis. Experimental tests to verify thermal stability, the coefficient of thermal expansion, thermal conductivity and strength properties were performed. For cryogenic tests, a cryogenic chamber was employed. Extreme cooldown tests using liquid nitrogen, including several representative mock-up tests for various configurations, were also performed to visually verify integrity with destructive testing, and to evaluate and compare numerical analyses with empirical test data.

Configurations

Today, several spray foam insulation system configurations are available with various technical and functional characteristics. The structural buildup is typically similar for each, but different configurations are optimised for different surface materials, and for project specific needs. For cargo and fuel tanks in voids with a controlled, dry atmosphere, a special vapour retardant coating has proven to offer satisfactory mechanical protection to prevent ingress of humidity and to prevent damage during construction and inspections. For some projects, such as passenger and cruise vessels, additional rockwool fire insulation has also been used to improve fire safety. Such tanks may include additional A60 grade fire insulation, including an integrated aluminium foil vapour barrier, in addition to stainless or galvanised cladding. For fuel tanks in general, systems with integrated aluminium foil vapour barriers with stainless or galvanised cladding are an excellent solution. For deck tanks, additional layers of glass-reinforced plastic (GRP) or fibre-reinforced plastic (FRP) can be offered to improve resistance for water permeation and solar irradiation.

Recent developments

The practice of using hydrofluorocarbons (HFCs) as blowing agents in PUFs is currently being phased-out. As of 1 January 2023, it will be prohibited under the EU F-Gas regulation. Unlike chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), HFCs do not harm the ozone layer, but they do contribute to global warming, possessing a significantly higher warming potential than carbon dioxide. A lot of work has been done to research alternative blowing agents to compensate for inferior performance. Hydrofluorolefins (HFOs) seem to be one of the most suitable candidates to replace HFCs in spray foams. From recent tests performed by LNT Marine, the effective thermal conductivity and material properties of HFO-based PUFs are confirmed to be satisfactory and in accordance with proven PUFs.

Conclusion

Spray PUF systems for independent tank Type C LNG containment systems have proven to be a reliable and efficient insulation system. With approximately 10 years of operational track record, spray foam insulation systems have gained a strong foothold in the small scale LNG market, as well as the LNG fuel tank markets. Different configurations are developed to satisfy project specific requirements, for example, with regards to fire safety, heat ingress, solar irradiation and weather protection. Recent experimental tests show that PUF spray foam systems will not be affected by new regulations that prohibit HFC-based blowing agents. **LNG**