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ENERGY-EFFICIENT TECHNOLOGIES IN FLOATING STORAGE AND REGASIFICATION UNITS (FSRUS)

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Abstract. *The increasing demand for flexible and efficient liquefied natural gas (LNG) infrastructure has led to the widespread deployment of Floating Storage and Regasification Units (FSRUs). These facilities play a crucial role in ensuring rapid and scalable access to LNG in regions lacking permanent terminals. However, heat ingress into cryogenic LNG storage tanks remains a persistent challenge, leading to boil-off gas (BOG) generation and associated energy losses. Efficient thermal insulation and advanced BOG management technologies are essential to improving the operational performance and energy efficiency of FSRUs. This paper provides a comprehensive review of modern insulation techniques, mechanisms of heat transfer in cryogenic environments, and current technological solutions for BOG handling. The study also highlights recent advancements in reliquefaction systems, energy recovery technologies, and integrated energy strategies aimed at minimizing losses and enhancing overall system efficiency.*

Key words: *Floating Storage and Regasification Unit (FSRU), liquefied natural gas (LNG), boil-off gas (BOG), thermal insulation, heat loss, energy efficiency, cryogenic storage, LNG technology.*

Introduction.

Liquefied natural gas (LNG) has become a critical component of the global energy mix, offering flexibility in transportation and storage while supporting the transition towards lower-carbon energy systems. Floating Storage and Regasification Units (FSRUs) have gained significant attention as a practical and cost-effective solution for providing rapid access to LNG, particularly in regions lacking developed onshore infrastructure. By combining LNG storage with onboard regasification capabilities, FSRUs enhance energy security and market flexibility.

Despite these advantages, the operation of FSRUs presents complex thermodynamic and engineering challenges, notably the management of heat ingress into cryogenic tanks. The unavoidable heat transfer from the surrounding environment leads to the generation of boil-off gas (BOG) as a result of the evaporation of LNG. This phenomenon not only represents a loss of valuable energy but also requires additional systems for BOG handling, including recompression, reliquefaction, or utilization as fuel.

To address these challenges, modern FSRUs employ a range of technologies aimed at reducing heat ingress, minimizing BOG formation, and improving the overall energy efficiency of regasification processes. This paper reviews the state-of-the-art solutions, focusing on the principles of thermal insulation, heat transfer mechanisms, and technological strategies for effective BOG management within the context of FSRU operations.

Heat Transfer and Insulation in Cryogenic LNG Storage

1. **LNG Storage Tank Designs**

FSRUs typically utilize one of several well-established LNG tank designs, each offering specific thermal and structural characteristics. The most common types include:

❖ **Membrane tanks** (such as those developed by GTT), characterized by a thin metallic membrane supported by insulation layers;

❖ **Moss-type spherical tanks**, which feature self-supporting aluminum alloy spheres within the hull;

❖ **Type-C cylindrical tanks**, commonly used on smaller vessels or in modular applications.

These designs are optimized for the safe containment of cryogenic LNG at temperatures around −162 °C while minimizing heat ingress as much as possible through their structural and insulation configurations.

2. **Mechanisms of Heat Transfer**

The primary modes of heat transfer affecting LNG storage include conduction through the insulation materials, convection within the ullage space, and radiation from the external environment. The net heat flux qqq into the LNG tank can be approximated by Fourier's law of heat conduction:

$$q = k \cdot A \cdot (T_{out} - T_{LNG}) / d$$

where:

- k – thermal conductivity of insulation material [W/m•K],
- A – surface area of the tank [m^2],

- d – thickness of the insulation [m],
- T_{out} – ambient temperature [°C],
- T_{LNG} – LNG temperature (approximately −162 °C).

Dynamic environmental conditions, including solar heating and ambient air fluctuations, contribute to variations in heat ingress, which directly affects BOG generation rates.

3. **Thermal Insulation Technologies**

Modern LNG containment systems rely on highly specialized insulation technologies designed to minimize thermal conductivity and reduce heat transfer. Commonly employed methods include:

✓ **Perlite-based insulation** in combination with nitrogen-purged spaces to limit convection;

✓ **Vacuum insulation systems** for minimizing gas conduction and convection;

✓ **Multilayer insulation (MLI)** incorporating reflective foils and spacer materials to reduce radiation heat transfer.

These insulation solutions are carefully engineered to maintain the thermal integrity of cryogenic storage under operational and environmental conditions typically encountered by FSRUs.

Boil-Off Gas: Formation and Implications

1. Causes and Mechanisms of BOG Generation

Boil-off gas (BOG) is an inevitable byproduct of storing LNG at cryogenic temperatures. Even with advanced insulation technologies, some degree of heat ingress occurs, leading to partial vaporization of LNG within the storage tanks. This vaporized gas accumulates in the ullage space, causing pressure buildup that must be managed to ensure safety and maintain tank integrity.

The rate of BOG formation is influenced by several factors:

- Thermal performance of the insulation system;
- Ambient environmental conditions (temperature, solar exposure);
- Duration of storage and operational cycles;
- Tank geometry and ullage ratio.

The accumulation of BOG directly correlates with the energy balance of the system. The energy required for LNG vaporization is governed by the latent heat of vaporization, approximately 510 kJ/kg for methane-based LNG. Therefore, any reduction in heat ingress proportionally decreases the volume of BOG generated.

2. **Operational and Environmental Implications**

Uncontrolled BOG formation poses significant operational challenges:

✓ **Pressure Management:** Excessive BOG leads to increased pressure within the storage tanks, necessitating regular venting, reliquefaction, or combustion.

✓ **Energy Efficiency:** Energy is required to manage BOG, either through recompression or reliquefaction, contributing to the vessel's operational load.

✓ **Environmental Impact:** Venting or flaring BOG releases methane, a potent greenhouse gas, and carbon dioxide into the atmosphere, conflicting with regulatory efforts to minimize emissions (e.g., IMO MARPOL Annex VI).

As a result, optimizing BOG management is critical not only for operational efficiency but also for environmental compliance and the economic performance of FSRUs.

Technologies for BOG Management on FSRU

1. Compression Systems

One of the most established methods for handling BOG is recompression. BOG compressors are used to pressurize the vaporized gas for reintegration into the fuel gas system or for direct combustion in onboard generators or boilers. This approach ensures continuous utilization of BOG without the need for venting, aligning with energy efficiency and emissions reduction goals.

Modern FSRUs often integrate multi-stage compressors with intercooling systems to manage the compression process efficiently while minimizing energy consumption.

2. Reliquefaction Units

Reliquefaction systems condense BOG back into liquid form, returning it to the LNG cargo tanks. Several thermodynamic cycles are utilized in these systems:

- **Single Mixed Refrigerant (SMR) Cycle**
- **Nitrogen Refrigerant (NR) Cycle**

- **Cascade Refrigeration Systems**

These systems differ in complexity and energy demand, with SMR and NR cycles being prevalent in marine applications due to their relative simplicity and reliability. Recent advancements focus on improving thermodynamic efficiency and reducing the power requirements of these systems.

3. Utilization as Fuel

BOG can also serve as a valuable energy source. Many FSRUs are equipped to utilize BOG directly in their onboard gas engines or gas turbines, reducing reliance on liquid fuels and contributing to lower greenhouse gas emissions. This approach integrates BOG management into the vessel's overall energy strategy, enhancing fuel flexibility and sustainability.

In some configurations, BOG is routed through waste heat recovery units or Organic Rankine Cycle (ORC) systems to maximize energy utilization.

4. Hybrid Approaches and Energy Integration

Advanced FSRUs employ hybrid solutions combining multiple BOG management strategies. For example, reliquefaction systems may operate alongside compression units, with dynamic control systems optimizing energy use based on real-time operational data.

Integration with onboard energy management systems (EMS) allows for load balancing and synergy between BOG handling, HVAC systems, and other auxiliary loads. Such integrated approaches contribute to improved overall energy efficiency and reduced operational costs.

Future Trends and Research Directions

1. Advanced Insulation Materials

Ongoing research in cryogenic insulation materials focuses on achieving even lower thermal conductivity while maintaining durability and compliance with maritime regulations. Emerging materials include:

- **Aerogels** with ultra-low thermal conductivity;
- **Vacuum Insulation Panels (VIPs)** with multi-layered barriers;
- **Hybrid composites** combining reflective and absorptive properties.

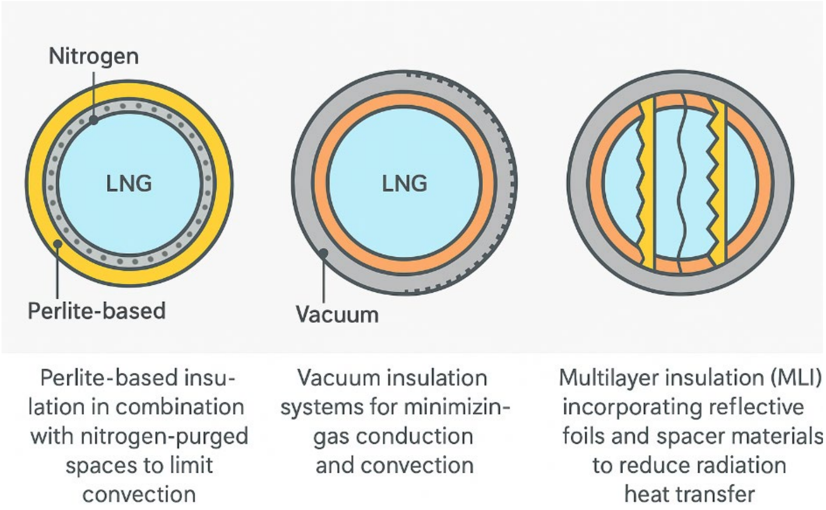

Figure 1 - Schematic representation of insulation types (author's illustration based on [1–5]

These materials aim to further reduce heat ingress, thus minimizing BOG formation and enhancing storage efficiency on FSRUs.

2. Energy Recovery Integration

The recovery of cold energy from LNG processes is a growing area of interest, particularly through integration with Organic Rankine Cycles (ORC) or reverse Brayton cycles. These systems can convert residual cold energy into electrical power or cooling for auxiliary systems, thereby improving the overall energy footprint of FSRUs.

Potential developments include:

❖ Integration of **multi-stage ORC systems** utilizing different working fluids for enhanced efficiency;

❖ Application of **CO_2-based cycles** for low-temperature heat recovery.

3. Digitalization and Predictive Maintenance

The digital transformation of maritime operations extends to BOG management and insulation performance monitoring. Predictive maintenance algorithms, coupled with real-time data from sensors embedded in insulation systems and BOG handling equipment, allow for:

- Early detection of insulation degradation;

- Optimization of compressor and reliquefaction cycles;
- Enhanced energy management through machine learning models.

Digital twins of FSRU thermal systems can enable operators to simulate various scenarios and optimize operational strategies dynamically.

4. Environmental and Regulatory Drivers

Stricter environmental regulations, such as IMO's EEXI and CII measures, drive innovation in energy efficiency. FSRU operators must align with future standards by:

✓ Reducing methane slip and CO_2 emissions;

✓ Enhancing energy recovery from LNG processes;

✓ Improving BOG management to minimize environmental impact.

These regulations will likely shape future investments and technological developments in FSRU energy systems.

Summary and conclusions.

Efficient thermal insulation and boil-off gas (BOG) management remain central to the operational and environmental performance of Floating Storage and Regasification Units (FSRUs). Advances in insulation materials, BOG handling technologies, and integrated energy recovery systems have significantly improved the energy efficiency and sustainability of LNG storage and regasification processes.

Modern FSRUs employ a combination of compression, reliquefaction, and fuel utilization strategies to manage BOG effectively, minimizing both operational losses and greenhouse gas emissions. Future developments will likely focus on further enhancing insulation performance, leveraging cold energy recovery, and incorporating digital solutions to optimize system efficiency.

Continued research and technological innovation, driven by environmental regulations and economic considerations, will play a pivotal role in shaping the next generation of FSRU designs and LNG infrastructure.

References:

1. International Energy Agency (IEA). Gas Market Report, Q4-2023.
2. Lee, J., & Kim, H. (2021). Thermodynamic optimization of LNG

regasification processes on FSRUs. *Energy, 235*, 121314.

3. Zhang, Y., et al. (2022). Utilization of cold energy in LNG systems using organic Rankine cycles. *Journal of Natural Gas Science and Engineering, 95*, 104208.

4. Wang, X., et al. (2020). Boil-off gas management in LNG carriers: System modeling and operational optimization. *Journal of Marine Science and Engineering, 8(11)*, 852.

5. ISOPE Conference Proceedings. (2022). Design of BOG handling systems for offshore LNG terminals.

6. Song, K., et al. (2023). Advances in LNG insulation technologies: A review. *Cryogenics, 135*, 103035.

7. Park, S., et al. (2019). Performance evaluation of vacuum insulation panels for LNG tanks. *International Journal of Refrigeration, 102*, 57–65.

8. Liu, X., et al. (2021). Multilayer insulation performance under marine conditions. *Applied Thermal Engineering, 190*, 116833.

9. Chen, H., et al. (2020). Experimental study on perlite insulation for cryogenic storage. *Cryogenics, 109*, 103100.

10. DNV (2023). Energy management systems for LNG carriers and FSRUs: Guidelines and best practices.

11. IMO MARPOL Annex VI, 2023 revisions.

12. Hirose, Y. (2021). Heat ingress control in LNG storage. *Journal of Cryogenic Engineering, 66*(1), 57–62.

13. Zhang, Y., & Li, P. (2020). Simulation study of BOG management strategies in LNG carriers. *Energy Conversion and Management, 224*, 113353.

14. Gao, Z., et al. (2019). Comparative analysis of nitrogen and mixed refrigerant cycles in LNG plants. *International Journal of Energy Research, 43*, 8214–8229.

15. Khalilpour, R., et al. (2015). Waste heat recovery in LNG carriers using ORC. *Applied Energy, 158*, 263–276.

16. Choi, B., et al. (2018). Energy optimization of LNG FSRU regasification. *Energy, 148*, 383–394.

17. Shin, J., et al. (2022). Cold energy utilization from LNG: A comprehensive

review. *Renewable and Sustainable Energy Reviews, 165*, 112553.

18. Bae, J., et al. (2017). Comparative study of insulation systems for cryogenic applications. *Cryogenics, 84*, 15–21.

19. Verma, P., et al. (2021). Modeling and optimization of cryogenic insulation systems. *Energy Reports, 7*, 1755–1763.

20. ISO 21013-3:2016. Cryogenic vessels — Insulation performance.

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