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Thermal Stress Analysis of the LNG Corrugated Cryogenic Hose During Gas Pre-Cooling Process

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In this study, thermal-fluid-solid coupled simulations on the gas-phase pre-cooling operation of corrugated cryogenic hoses are performed. Attention is focused on the temporal evolution and spatial distribution of transient thermal stress in the hose structure caused by convective heat transfer of the cooling medium, liquefied natural gas boil-off gas (BOG). The effects of different corrugated hose parameters, i.e., boundary conditions, hose lengths, BOG inlet flow rates, and corrugation shapes (C-type and U-type), on the transient thermal stress behavior are assessed. The thermal stress developed at different locations of the corrugated hoses with these parameters is found to be governed by two major factors: Boundary constraint and local temperature gradient. The objective of this study is to offer practical insights for the structural strength design of corrugated cryogenic hoses and effective pre-cooling strategies, aiming to mitigate structural safety risks caused by excessive thermal stress.

INTRODUCTION

The exploration and development of natural gas resources in deep-sea regions present both significant opportunities and challenges. These resources, predominantly composed of methane, offer a substantial and relatively untapped energy potential. For deep-sea natural gas development, the collected gas is first transported to a nearby floating, liquefied natural gas (LNG) production storage and offloading unit (FLNG) before received by an LNG carrier for transportation back to land (Won et al., 2014). Traditionally, LNG transport between the FLNG and the LNG carrier is achieved by rigid discharge arms, which requires side-by-side alignment of the two vessels with minimal relative motion (Eide et al., 2011). However, under harsh environmental conditions, this requirement is quite difficult to satisfy with the current mooring technology. As an alternative to the rigid discharge arms, corrugated cryogenic hoses (as shown in Fig. 5) have been developed to tackle this problem (Chen et al., 2024). With insulation to prevent pipeline leakage and vaporization and the ability to float in the water, they can be deployed at a distance of up to 100 meters between the FLNG and LNG carriers, thus enhancing operational safety in harsh offshore conditions. In recent years, corrugated cryogenic hoses have been increasingly used in offshore LNG production and transportation. Most of the relevant studies focused on the overall design (Yang et al., 2017), structural strength analysis (Yan et al., 2022), and flow and heat transfer characteristics of the internal flow (Yang et al., 2022; Zhu et al., 2023). However, safety issues that may be encountered in the practical field application of the cryogenic hose are not fully understood.

The inner corrugated pipe of the LNG hose is usually made of austenitic stainless steel (e.g., 316 L), which has a high coefficient of thermal expansion and is therefore susceptible to excessive thermal stresses under severe temperature changes (Nilsson et al., 2016; Li et al., 2020). Therefore, the hose needs to be slowly cooled to near its operating temperature (i.e., −162°C) before transporting LNG to avoid plastic deformation of the structure due to thermal stress or thermal fatigue under repeated operations. However, there has been no widely accepted practice for pre-cooling the corrugated cryogenic hose. In contrast, pre-cooling techniques for LNG transfer lines (smooth cryogenic pipelines) at LNG receiving terminals are more mature. The pipeline is usually pre-cooled to around −120°C (gas-phase pre-cooling) by low-temperature nitrogen or LNG boil-off gas (BOG), and then further cooled to its boiling point with LNG (liquid-phase pre-

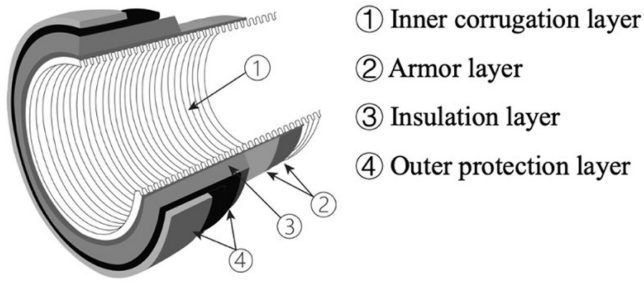

Fig. 1 Typical corrugated cryogenic hose

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KEY WORDS: Pre-cooling, LNG, cryogenic hose, thermal stress, thermal-fluid-solid coupling.