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Research Article

Floating storage and regasification units face specific LNG rollover challenges: Consideration of saturated vapor pressure provides insight and mitigation options

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Abstract

Floating Storage and Regasification Units (FSRU) form a rapidly expanding sector of LNG business. In many cases, FSRU now provide a more cost-effective and very flexible way to deliver natural gas to end users in comparison with shore-based terminals. Due to enhanced operations FSRU are more complex compared to LNG carriers (LNGC). FSRU are essentially merge of the attributes of shore-based terminals and LNGC. The existing FSRU fleet is formed of new-build vessels and converted LNGC. Together with their advantages FSRU come with the inherent problems of handling and storing LNG. Here we focus on the rollover issues that occur on FSRU and suggest ways to improve handling to minimize the impacts of those events. Rollover is a physical mixing process in a single tank with two or more different parcels of LNG of different compositions, temperatures and densities that can manifest in large boil-off rates, beyond handling-equipment capacities, and large tank pressure increases culminating rapidly. If prevention/mitigation actions are not implemented, uncontrolled venting of boil off gas in vapor form to the atmosphere is a likely consequence involving flammability hazards and tank structure over-pressurization with potential damage.

This study provides in-depth analysis of FSRU rollovers based on observations of more than twenty rollovers on many different FSRU. The analysis focuses on LNG saturated vapor pressure (SVP) rather than the traditional approach of focusing on boil-off rate (BOG). This approach allows efficient rollover management without any in-built rollover prevention means. Strategies are developed for managing a combination of FSRU tanks utilizing rollover prevention and mitigation actions, as well as efficient pre-planning for LNG stock management. Novel rules of thumb for predicting time to rollover onset, based on many observed FSRU rollovers provide operators with real-time insight to what rollover preventive and mitigating actions are effective in specific circumstances.

Keywords: Saturated vapor pressure (SVP); Avoiding FSRU rollover; LNG boil-off rate; Rollover tank pressure impacts; Sequential rollovers; LNG cargo stock management

1. Introduction

The rapidly expanding fleet of Floating storage and regasification units (FSRU) now equip the LNG industry with a technically-enhanced set of vessels that help it to penetrate a wide range of expanding gas markets. FSRU, for small and mid-sized markets typically offer a more cost-effective means to bring natural gas to consumers compared to shore-based terminals. The FSRU fleet includes both new-build vessels and LNG carriers (LNGC) converted for use as FSRU. Each vessel relies on ship-to-ship (STS) transfers of LNG in order to maintain continuous supplies of gas send-out. Due to operating patterns of FSRU, loading new cargo is typically

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performed while there is a large onboard LNG heel (i.e., cargo remaining in the tanks). Such circumstances inherently lead to rollover issue that are regular events on FSRU.

LNG Rollover occurs in a specific tank and involves the physical mixing process, between two or more batches of LNG of different compositions. It is associated with large boil-off gas evaporation rates that lead to significant increases in tank pressure that may become difficult to control. Left uncontrolled rollovers risk hazardous and environmentally damaging consequences, such as structural damage to the tanks and uncontrolled venting of gas to the atmosphere. FSRU rollover events must be managed proactively, with attempts made to predict, prevent and mitigate their consequences. In detail, each observed rollover on an FSRU, or simulated in a laboratory, tends to be unique in its tank pressure trends, but they do show common tendencies which are described here. Understanding the observed trends enables operational strategies to be developed that can effectively deal with rollovers and avoid the need for installing expensive rollover monitoring and prevention equipment.

The FSRU industry is very young. It has existing overview guidance for operating practices [1,2]. However, rigorous standard best-practice operating guidance is not yet established and what is available is inadequate for predicting, preventing and mitigating rollovers with confidence. Boil-off gas rate (BOR) is the guiding indicator typical monitored as a rollover indicator but is not a very effective metric for that purpose. BOR fluctuates during a rollover and is difficult to calibrate with rollover magnitudes and consequences for different FSRU designs. Here we show that tank-pressure variations benchmarked to tank-pressure ratings (Maximum Allowable Relief Valve Setting − MARVS) provide a much better monitoring metric for the safety assessments related to pending rollovers.

Rollover is a routine occurrence on FSRU with their prevailing modes of operation. Most FSRU do not have any inbuilt equipment specifically focused on handling rollovers. Moreover, there is no standard rigorous management practice in the FSRU sector for monitoring and responding to rollovers. Indeed, there are some significant misconceptions among FSRU operators regarding rollovers and effective ways to control them. For rollovers to occur, the different batches of LNG being mixed in a tank must have distinct compositions, temperatures and densities that result in stratification (distinct layers of LNG) developing in the tank.

LNG rollovers were first described for many decades ago [3]. Several distinct numerical models based upon experiments and observations of rollovers were proposed from the 1970s to the 1990s [4−15]. These attempted to explain the sequence of events that make up a rollover and identify the factors that influence rollover onset. The concept being that some influencing factors could be used to predict rollover consequences. The early models paid particular attention to the interface layer [16], i.e., the thin layer separating stratified layers of LNG of distinct composition existing in different states in a tank. They tried to understand how stratification evolved as rollover proceeded. Trying to explain the significant rollover accidents that occurred during that period, e.g., at La Spezia (Italy) in 1971 [17]; at Foss-sur-Mer (France), 1978 [18]; and, Partington (U.K.), 1993 [19] was the focus of those models. An overview of these serious rollover incidents is provided by GIIGNL [1]. These incidents were, of course, all related to onshore LNG receiving terminals.

The laboratory studies mentioned confirmed the unique nature of rollover events, each involving stages mixing that depended on a range of tank conditions. Rollover and its handling on FSRU is not a trivial issue and requires careful and effective handling. However, the existing industry guidance for handling FSRU rollovers remains limited because: 1) there are a range of distinct vessel designs with different tank pressure (MARVS) ratings; 2) in some cases the vessels and tanks were originally built for LNGC service; 3) tanks are typically not equipped with specific “anti-rollover “equipment; 4) most FSRUs are not equipped with “densitometers” throughout their tanks; and, 5) FSRU industry procedures are often ill-suited to the operational patterns imposed on the vessels; those patterns are quite distinct from LNG tanks in other types of facility and vessel.

Experimental and modeling studies conducted in the past fifteen years [20−23] demonstrate that significant disagreement exists regarding the detailed processes involved in LNG rollover. Rollover prediction models that simulate observed rollover data, in a range of tank conditions, are unable to match in detail the tank pressure, LNG temperature and density and BOR over time scales during which real rollovers unfolded [24−26]. Stratification and pressure variations of cryogenic liquids in tanks has been extensively investigated [27−30]. Advanced LNG storage tank and rollover management techniques have been proposed [31], but most focus on the operating patterns that prevail in onshore LNG receiving terminals. It is typical to rely on BOR as the primary rollover monitoring metric [32]. Optimization analysis of rollovers in offshore LNG storage tanks [33,34] continue to focus on BOR without sufficient consideration given to tank pressures and their MARVS ratings. This makes accurate and realistic rollover predictions extremely difficult. Indeed, some existing rollover models, and rollover prediction software based upon them, make the simplistic but incorrect assumption that the stratified LNG layers in tanks invert or overturn during rollover onset. This simplifies some of the calculations, but does not reflect the gradual, variable, and exponentially accelerating mixing processes between the stratified LNG layers that experiments, laboratory simulations and real rollover observations observe.

There are two approaches to improving the handling of rollovers on FSRU: 1) the installation of specialist monitoring and loading equipment in the LNG tanks that is costly and requires retro-fitting in existing FSRU; and 2) establishing reliable operating measures that allow rollovers to be handled effectively. Our focus here is on the second approach and describes a novel concept for assessing rollover consequences by considering the LNG's saturated vapor pressure (SVP) in relation to the tank-pressure rating. In this approach the boil-off rate (BOR) is considered but as a secondary factor to