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Technical note

Risk-based determination of design pressure of LNG fuel storage tanks based on dynamic process simulation combined with Monte Carlo method

Yeelyong Noh [a], Kwangpil Chang [b], Yutaek Seo [a], Daejun Chang [a,*]

[a] Division of Ocean System Engineering, Korea Advanced Institute of Science and Technology, 291 Daehak-ro, Yuseong-gu, Daejeon 305-701, Republic of Korea
[b] Hyundai Heavy Industries Co. Ltd., 17-10, Mabuk-ro 240beon-gil, Giheung-gu, Yongin-si, Gyeonggi-do 446-912, Republic of Korea

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ABSTRACT

This study proposes a new methodology that combines dynamic process simulation (DPS) and Monte Carlo simulation (MCS) to determine the design pressure of fuel storage tanks on LNG-fueled ships. Because the pressure of such tanks varies with time, DPS is employed to predict the pressure profile. Though equipment failure and subsequent repair affect transient pressure development, it is difficult to implement these features directly in the process simulation due to the randomness of the failure. To predict the pressure behavior realistically, MCS is combined with DPS. In MCS, discrete events are generated to create a lifetime scenario for a system. The combination of MCS with long-term DPS reveals the frequency of the exceedance pressure. The exceedance curve of the pressure provides risk-based information for determining the design pressure based on risk acceptance criteria, which may vary with different points of view.

1. Introduction

With rising fuel costs and a global interest in emission reduction, liquefied natural gas (LNG) is considered a promising alternative fuel for large ships. The use of LNG as fuel is expected to reduce SO_x and NO_x emissions by up to 80% and CO_2 emissions by 15–25%, satisfying the regulations for Emission Control Areas [1].

LNG boils at $-161\ ^{\circ}C$ under atmospheric pressure. Although LNG fuel storage tanks are equipped with an insulating layer, heat ingress inevitably produces boil-off gas (BOG). Because venting this BOG implies both the loss of fuel and the emission of greenhouse gases, it is not acceptable from an environmental or economic perspective. Holding the BOG within tanks, however, leads to an increase in storage tank pressure. Furthermore, the rate at which this pressure increases is accelerated as the cryogenic liquid is consumed because fuel mass and, equivalently, the heat capacity of the inventory decrease with time [2].

LNG fuel must be stored in IMO type 'C' independent tanks, also referred to as pressure vessels [3–5]. There is a commonly used standard in the design of pressure vessels; the American Society of Mechanical Engineers publishes the ASME Boiler and Pressure Vessel Code, which describes how a pressure tank for cryogenic liquid fuel storage should be designed.

During the early stages of pressure vessel design, the design pressure should be determined first. According to the code, the design pressure is defined as the pressure used in the design of a vessel component under the most severe conditions of coincident pressure and temperature expected during normal operation [6].

Operating conditions (i.e., pressure and temperature) have generally been estimated by process simulation. Conventional process simulation has been performed without considering realistic system conditions, such as the incidence of failure and equipment repair events. The failure of equipment has a strong influence on the operating conditions of storage tanks. Thus, practical system operation should be considered. Despite their importance in the design and safe operation of storage systems, realistic operating conditions, particularly realistic pressure profiles and design pressures, are rarely addressed in the literature.

The present study proposes a new methodology in which dynamic process simulation (DPS) is combined with Monte Carlo simulation (MCS), which has been studied extensively and used as a method for evaluating the feasibility of multistate, multioutput offshore installations [7–16].

Using stochastic evolution, MCS provides flexibility in describing the practical aspects of system operation, such as component failure, subsequent corrective maintenance, and preventive maintenance [10]. A Monte Carlo simulation is performed by virtually

* Corresponding author. Tel.: +82 10 4801 0172; fax: +82 42 350 1510.
E-mail address: djchang@kaist.edu (D. Chang).

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Nomenclature

NO_x	nitrogen oxides
SO_x	sulfur oxides
f	fugacity, bar
h	specific enthalpy, J/kg
i	components
P	pressure, bar
q	volume flow rate, m^3/s
Q	heat flow rate, J/s
t	time, s or day
T	temperature, °C
U	overall heat coefficient, W/m^2 °C
V	volume, m^3
x	liquid mass fraction
$X(i)$	X value of component i
$X(t)$	X value at time t
$X(i,t)$	X value of component i at time t
y	vapor mass fraction

Greek letters

ρ	density, kg/m^3
λ	failure rate, per 10^6 h
μ	transition of repair

Subscripts

L	liquid phase
V	vapor phase
I	inlet
O	outlet

observing many identical stochastic systems, each one behaving differently because of its distinct stochastic character, and monitoring their failure [11,12]. A feasible lifetime scenario of a system is created by certain random and discrete events generated in the simulation [13]. This simulation provides information about when the next transition (i.e., component failure or repair event) occurs and how the system configuration changes as a consequence of the transition.

In the proposed method, the realistic lifetime scenario obtained by MCS is used to run a DPS. In DPS, the operation of an LNG FGS system depends on the realistic lifetime scenario; after obtaining the lifetime scenario, a practical pressure profile is estimated. Finally, the results of the long-term simulation provide risk-based information for determining the design pressure.

2. System description

2.1. LNG fuel storage and related systems

The LNG fuel gas supply system was designed to provide engines with natural gas from LNG fuel storage tanks. This system consists of four main components: LNG storage tanks, a suction drum, a pump, and a vaporizer, as shown in Fig. 1. LNG fuel is stored in cylindrical pressure vessels and pressurized by the cryogenic pump. Before the LNG passes by the pump, the suction drum removes BOG to prevent the gas from entering the pump. The pressurized LNG evaporates in the vaporizer and is then supplied to a dual fuel engine.

The LNG composition used in this study refers to that described by the IGF guideline [3], as shown in Table 1.

The target ship considered in this study is an Aframax tanker, which is one of the most popular crude carriers. The specifications

Table 1
LNG composition.

Component	Mole fraction
Methane (C1)	0.940
Ethane (C2)	0.047
Propane (C3)	0.008
Butane (C4)	0.002
Nitrogen (N_2)	0.003

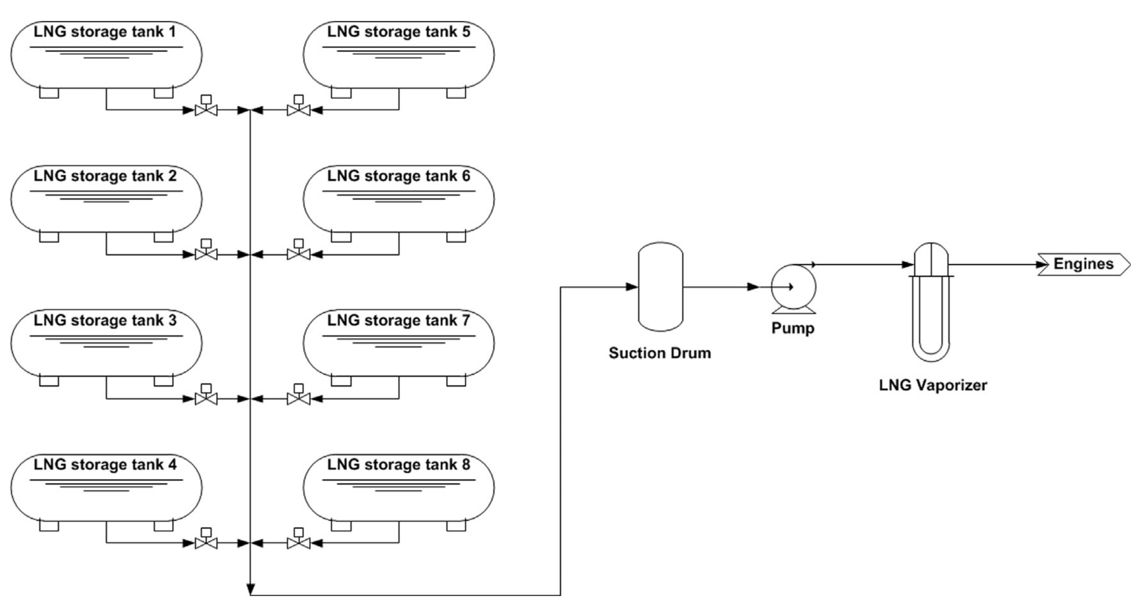

Fig. 1. Proposed LNG fuel gas supply system.