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A pump-free boosting system and its application to liquefied natural gas supply for large ships

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ABSTRACT

This study proposes a new boosting system that is capable of increasing the pressure of a low-temperature liquid such as LNG (liquefied natural gas) and supplying it continuously to a ship engine without using cryogenic pumps. The system consists of two boosters, each of which is equipped with a mini-vaporizer and regulating valves. The two boosters operate alternately to ensure a continuous supply of the low-temperature pressurized liquid. The operating philosophy is that the mini-vaporizer of the first booster increases the internal pressure and supplies the pressurized liquid to the engine while the other booster is filled with the low-pressure fresh liquid, waiting for its turn to supply the liquid to the engine. This boosting system is applied to an LNG fuel gas supply system. Dynamic process simulation is conducted to demonstrate its operational feasibility. Assessment of operation availability and life-cycle cost analysis are also conducted to show that the proposed system offers better reliability and cost-effectiveness than the conventional pump system.

1. Introduction

Global regulations on gaseous emissions of ships are being enforced to limit environmental pollution. Significant amounts of NOx (nitrogen oxides), SOx (sulfur oxides), and PM (particular matter) are discharged from ships that consume HFO (heavy fuel oil). Therefore, naturally clean energy sources are drawing attention as alternative fuels for ships. Among these alternatives, LNG (liquefied natural gas) fuel is considered one of the most promising options to meet strict environmental regulations.

The IMO (International Maritime Organization) established ECAs (emission control areas) to limit the emission of SOx of fuel oils and PM [1]. The limits are subjected to a series of step changes over time. Since January 2015, SOx and PM emissions have been restricted to be less than 0.10% within ECAs. This level is 1/15 of that in 2000. Outside ECAs, SOx and PM levels are restricted to be less than 0.50% until 2020. In addition to establishing ECAs, the IMO introduced mandatory measures to reduce GHG (greenhouse gas) emissions from international ships that entered into service on or after January 2013. The baseline regulatory limits on GHG emissions, which are based on the EEDI (energy efficiency design index) for new ships and the SEEMP (ship energy efficiency management plan) for all ships, is gradually lowered over time [2].

LNG fuel has several advantages over conventional fuels [3]. It is an environmentally friendly clean and economic fuel that can be supplied by stable sources worldwide. Furthermore, it has a higher thermal efficiency and lower specific energy consumption than HFO (heavy fuel oil). For these reasons, it is likely that many ocean-going ships and small coastal ships will be equipped with LNG FGS (LNG fuel gas supply) systems to comply with regulations on gaseous emissions. Several studies on the feasibility of use of LNG as a fuel for land vehicles or power plants have been conducted [4–6], but studies of LNG FGS systems for ships are quite few in number [7–11].

LNG FGS system for ship propulsion is a proven technology. More than 48 LNG-fueled ships have been in service around the world since 2000 [11]. Since the first such ship entered operation in 1964, many LNG carriers have gained extensive experience in utilizing BOG (boil-off gas) as fuel for propulsion machinery, primarily steam turbines [12]. The gas released from the cargo tanks is burned to make steam to drive turbines. Recently, dual-fuel engines that are capable of burning both natural gas and oil fuel have been introduced. These engines require forced pressurization and

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Nomenclature

A	area, m^2
A_{OP}	operational availability
$\overline{A}_{OP}$	operational unavailability
B	breadth, m
BOG	boil-off gas
CAPEX	capital expenditure, US$
c	dryness fraction or quality
D	depth, m
DFDE	dual-fuel diesel–electric
ECA	emission control area
EEDI	energy efficiency design index
FGS	fuel gas supply
f	fugacity, kPa
GHG	greenhouse gas
g	acceleration of gravity, m/s^2
H	head, m
HFO	heavy fuel oil
h	Specific enthalpy, kJ/kg
IGC	international code for the construction and equipment of ships carrying liquefied gases in bulk
IGF	international code for gas-fueled engine installations in ships
IMO	International Maritime Organization
LBP	length between perpendiculars, m
LHV	lower heating value, kJ/kg
LNG	liquefied natural gas
LVF	liquid volume fraction
MARPOL	international convention for the prevention of pollution from ships
MDO	marine diesel oil
MSC	Maritime Safety Committee
$\dot{m}$	mass flow rate, kg/s
NG	natural gas
NOx	nitrogen oxides
OPEX	operational expenditure, US$
P	pressure (absolute), kPa
PBU	pressure build-up unit
PUF	polyurethane foam
Q	heat input rate, kJ/s
q	volume flow rate, m^3/s
PM	particulate matter
SOx	sulfur oxides
t	time, min or day
T	temperature, °C
U	overall heat transfer coefficient, W/m^2K
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 symbols

ρ	density, kg/m^3

Subscripts

A	availability
a	Ambient
b	booster
f	filling
fg	fuel gas
I	inlet
ip	initial pressure
l	liquid phase
max	maximum
mg	margin
min	minimum
O	outlet
P	pipeline
p	pressurizing
pre	preparation
sc	service
stb	stand-by
t	total
tg	target feed condition
tp	target pressure
U	unavailability
v	vapor phase

vaporization processes for fuel conditioning. The new versions of dual-fuel engines can be divided into two categories: high-speed engines for electricity generation and low-speed engines that are directly connected to propeller shafts. The fuel gas pressures required for the two types of dual-fuel engines [13] are substantially different: approximately 600 kPa for the former and approximately 30,000 kPa for the latter.

Typical LNG FGS systems can be divided into three categories, each of which involves a different way to make pressurized fuel gas [14]. In the case of IMO types A and B, which utilize unpressurized tanks, the BOG must be vented out of the tank continuously to maintain an inner pressure below approximately 175 kPa. Although the partially discharged BOG can be used as a fuel gas, continuous emission of excess BOG is unavoidable because of the heat penetration from outside. Furthermore, the composition of the fuel gas can change because the heavy component of the LNG is continuously accumulated in the LNG storage tank. This type of system is only suitable for small ships that require small amounts of fuel gas. Fig. 1-(a) shows an LNG FGS system combined with an unpressurized tank and compressors.

Alternatively, pressurized IMO type C tanks can store LNG for long periods of time without BOG venting. Fig. 1-(b) shows a system with this type of tank where highly pressurized fuel gas is transferred directly to a gas engine from the storage tank. The storage tank must have a PBU (pressure build-up unit) to maintain the high pressure. The PBU is located outside the storage tank and generates the pressurized fuel gas, so it does not require extra pressurizing equipment. However, the energy consumption associated with heating the storage tank is high, and a long time lag occurs in the initial operation mode. This type of LNG FGS system is also suitable for small ships.

In general, the use of a cryogenic pump is the simplest way to pressurize low-temperature liquid. Fig. 1-(c) illustrates the use of a cryogenic pump. This type of equipment is expensive, cannot be repaired on board, and has a high failure rate. When LNG is supplied from a storage tank to a cryogenic pump, part of LNG may be vaporized to NG (natural gas). If the vapor enters the cryogenic pump, the pump can be damaged. Consequently, a suction tank must be installed to separate out entrained vapor bubbles before they enter a cryogenic pump. However, a suction tank is not a