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Cryogenic sandwich-type insulation board composed of E-glass/epoxy composite and polymeric foams

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ABSTRACT

Liquefied natural gas (LNG) is a clean energy source whose consumption has recently increased greatly due to the failure of a nuclear power plant. LNG is transported with LNG carriers that store LNG at the cryogenic temperature of −163 °C. Because the cargo containment system (CCS) of LNG carriers should be operated for more than 40 years at the cryogenic temperature, its reliability against thermal and mechanical loads should be guaranteed without compromising its thermal insulation performance. For reasons of both mechanical and thermal performance, the faces and cores of conventional insulation boards are made of plywood and high-density (110 kg/m^3) polymeric.

In this study, an advanced sandwich-type insulation board composed of E-glass/epoxy composite faces and a low-density polymeric foam core with a composite box configuration was developed to seal a foam blowing gas of low thermal conductivity. The mechanical performance of the advanced sandwich-type insulation board was simulated using the finite element analysis (FEA) software ABAQUS (SIMULIA, USA). The sealing performance of the composite box was also investigated experimentally.

Finally, the thermal performance of the advanced sandwich-type insulation board was numerically investigated using thermal conductivity equations.

1. Introduction

Recently, the consumption of liquefied natural gas (LNG) has increased dramatically after the failure of a nuclear power plant. LNG is clean and energy-efficient. Because LNG source sites are spread worldwide like other energy sources, reliable transportation of LNG is very important. LNG carrier ships are typically used for mass transportation of LNG from source sites to gas manufacturers [1–4].

LNG is typically transported at the cryogenic temperature of −163 °C under a pressure of 1.1 bars, which is slightly higher than the atmospheric pressure of 1.0 bar. Therefore, LNG carriers should be designed for high thermal insulating performance as well as high mechanical performance under the thermal stress and pressure caused by LNG containment at the cryogenic temperature [5–9]. Also, the containments of the LNG ships have the metal and composite adhesive joints, then the research to improve the performance of the adhesive joints have been investigated [10–12]. Thermal efficiency requirements for LNG carriers have become more stringent because the BOR (boil-off rate) should be less than 0.12%/day. Good and efficient design of the insulation board for the cryogenic containment system (CCS) for LNG carriers is important because the thick insulation board has good insulation characteristics, but decreases LNG cargo capacity and increases the material cost.

Conventional insulation board has a sandwich construction with a core of high-density polymeric foam reinforced with glass fibers and faces of plywood. This construction satisfies the functional requirements of high thermal insulation and high fracture toughness under thermal and mechanical stress, as shown in Fig. 1a [13,14]. Although the thermal insulation performance of polymeric foam is optimal at a density of 30–50 kg/m^3 [15], high-density polymeric foam of 135 kg/m^3 reinforced with a chopped strand mat of glass fibers is currently used to provide reliability against mechanical and thermal failure.

The blowing gas which is used to fill the insulation board with polymeric foam during the foaming process is an important factor in the thermal performance of the insulation board. The thermal conductivity of low-density polymeric foam is largely dependent on the blowing gas, which usually has a lower thermal conductivity than that of air [16]. However, air could be exchanged with the blowing gas by diffusion if the polymeric foam is exposed to the ambient environment without any sealing. Therefore, prohibiting exchange between the air and the blowing gas is important to

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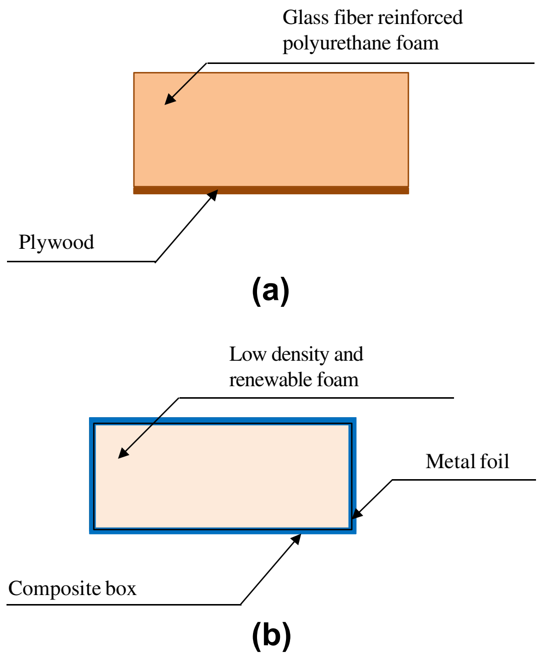

Fig. 1. Insulation board system: (a) conventional board system; (b) advanced sandwich-type insulation board system.

achieving the expected thermal insulation performance of the insulation board.

In this study, an advanced sandwich-type insulation board was developed to achieve lower thermal conductivity at the cryogenic temperature than that of a conventional insulation board, without compromising mechanical performance. The advanced sandwich-type insulation board was composed of box-type faces of E-glass/epoxy composite and a core of low-density polymeric renewable (or thermoplastic) foam rather than polyurethane foam, as shown in Fig. 1b. The box-type composite face resists thermal and mechanical loads, while the low-density polymeric foam largely resists shear loads. To prevent leakage of the foaming gas and reduce radiation heat transfer, a metal liner was adhesively bonded or co-cure bonded to the inside of the composite face.

The composite face was made of plain weave E-glass/epoxy composite and the core consisted of low-density polystyrene (PS) foam or polyvinylchloride (PVC) foam. The mechanical performance of the advanced sandwich-type insulation board was simulated with ABAQUS 6.10 (SIMULIA, USA). The sealing performance of the foaming gas was measured with a composite box specimen with a metal liner. Finally, the thermal performance was evaluated using thermal conductivity equations and compared to the simulation results.

2. Composition of the advanced sandwich-type insulation board

The advanced sandwich-type insulation boards used in this study were composed of composite box-type faces fabricated with prepregs of plain weave E-glass/epoxy composite (GEP118, SK chemicals, Korea) and cores of PS foam (Gold foam, Green-pia, Korea) or PVC foams (H35 and H45, DIAB, Sweden). The densities of the foams ranged from 30 to 50 kg/m^3. This range was selected for good insulation performance [15]. The Gold foam (the commercial brand name of the PS foam), H35 foam and H45 foam had densities of 30 kg/m^3, 38 kg/m^3 and 48 kg/m^3, respectively. The material properties of the E-glass/epoxy composite, Gold foam, H35 foam and H45 foam are listed in Table 1.

3. FEM analysis of mechanical performance

A two-dimensional (2-D) analysis model was established to simulate the mechanical performance of the advanced

Table 1
Material properties of E-glass/epoxy composite, foam raw materials and foams.

Plain weave E-glass/epoxy composite					
Tensile modulus (GPa)					
E1	21.7	E2	21.7	E3	4.6
Shear modulus (GPa)					
G12	3.52	G23	1.84	G13	1.84
Poisson's ratio					
ν12	0.15	ν23	0.30	ν13	0.30
Other properties					
Density (kg/m^3)		Thermal conductivity (W/m K)		Coefficient of thermal expansion	
2100		1		14	
Raw material of the foam core					
		Density (kg/m^3)		Thermal conductivity (W/m K)	
Polyurethane (PU)		1200		0.320	
Polystyrene (PS)		1050		0.157	
Polyvinylchloride (PVC)		1380		0.150	
Foam core					
		PS foam	PVC foam		
Product name		Gold foam	H35		H45
Density (kg/m^3)		30	38		48
Compressive modulus (MPa)		12	40		50
Compressive strength (MPa)		0.23	0.45		0.60
Shear strength (MPa)		0.20	0.40		0.56
Thermal conductivity (W/m K)		0.029	0.028		0.030
Coefficient of thermal expansion		80	40		40