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Polymeric foams for cryogenic temperature application: Temperature range for non-recovery and brittle-fracture of microstructure

Seong-Bo Park [a], Chi-Seung Lee [a], Sung-Woong Choi [b], Jeong-Hyeon Kim [a], Chang-Seon Bang [c], Jae-Myung Lee [a,*]

[a] Department of Naval Architecture and Ocean Engineering, Pusan National University, Busan 609-735, Republic of Korea
[b] LNG and Cryogenic Technology Center, Department of Extreme Energy System, Korea Institute of Machinery & Materials, Gimhae 621-842, Republic of Korea
[c] System Research & Development, Cryogenic Research Development Center, Samsung Heavy Industries Co., Ltd, Seongnam 463-400, Republic of Korea

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ABSTRACT

In the present study, low-temperature material characteristics of polyurethane foam, glass fiber-reinforced polyurethane foam, and polyisocyanurate foam were investigated. These foams are key candidate materials for use in membrane-type liquefied natural gas insulation systems. Liquefied natural gas insulation systems should be able to withstand severe environmental conditions, such as fluid induced impact loading under cryogenic temperatures. For the robust design of insulation system, both failure characteristics and deformation recovery capacity of the materials must be evaluated. Therefore, the failure characteristics and the deformation recovery ratio of the foams were investigated at various temperatures and strain rate levels. The present study revealed that the fracture behavior and the recovery ratio were significantly affected by decreases in temperature. As a newly obtained insight, it has been found that the recovery ratio for all tested materials significantly decreased at −163 °C. This finding is the opposite of the behavior that typically occurs at low temperatures. In particular, polyurethane foam specimen after experiment at the temperature of −163 °C was easily broken into pieces even under the application of small loads. In addition, it has been revealed that polyisocyanurate foam showed superior mechanical characteristics at cryogenic temperatures owing to the ring structure of isocyanurate.

1. Introduction

Polymeric foams such as polyurethane foam (PUF), glass fiber-reinforced polyurethane foam (RPUF) and polyisocyanurate foam (PIF) are widely used in industry as insulation. Polymeric foams possess many advantageous properties, such as low thermal conductivity, light weight, low water absorption/permeability, and dimensional stability. In particular, polymeric foams do not change in volume along temperature gradients, in other words, they exhibit significant size stability [1,2].

The aforementioned three types of polymeric foams are fabricated using two different types of manufacturing methods. First, PIF and PUF are fabricated by the foam expansion of isocyanates and polyols, respectively. The chemical composition of PIF is similar to that of PUF; however, PIF contains larger amount of methylene diphenyl diisocyanate than PUF. In addition, PIF is mostly composed of polyester-derived polyol while PUF is principally made of polyether polyol. By virtue of the structure of isocyanurate, PIF has low thermal conductivity, and good flame retardancy [3].

Second, RPUF is fabricated by combining high-density polyurethane foam and glass fiber. Chopped glass fibers are scattered on the bottom plane, and then liquid polyurethane is foamed perpendicularly to the bottom plane in order to increase the elasticity as well as the size stability of RPUF. Owing to the presence of the glass fiber, the elastic and bulk moduli and the yield strength of RPUF are greater than those of the pure polyurethane foam. For this reason, RPUF is more frequently adopted as insulation material for MARK-III-type liquefied natural gas (LNG) cargo containment system (CCS) than two other foams in industrial fields [4,5].

However, there is a limitation associated with using glass fibers: the thermal insulation capacity of RPUF is worse than that of the pure polymeric foams, i.e., PIF and PUF. This reduced capacity occurs because the thermal conductivity of glass fiber is approximately 15–17 times greater than that of PUF; the thermal conductivities of glass fiber and PUF are 1.30 W/mK and 0.076–0.083 W/mK, respectively. In addition, the manufacturing

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* Corresponding author. Tel.: +82 51 510 2342; fax: +82 51 512 8836.
E-mail address: jaemlee@pusan.ac.kr (J.-M. Lee).

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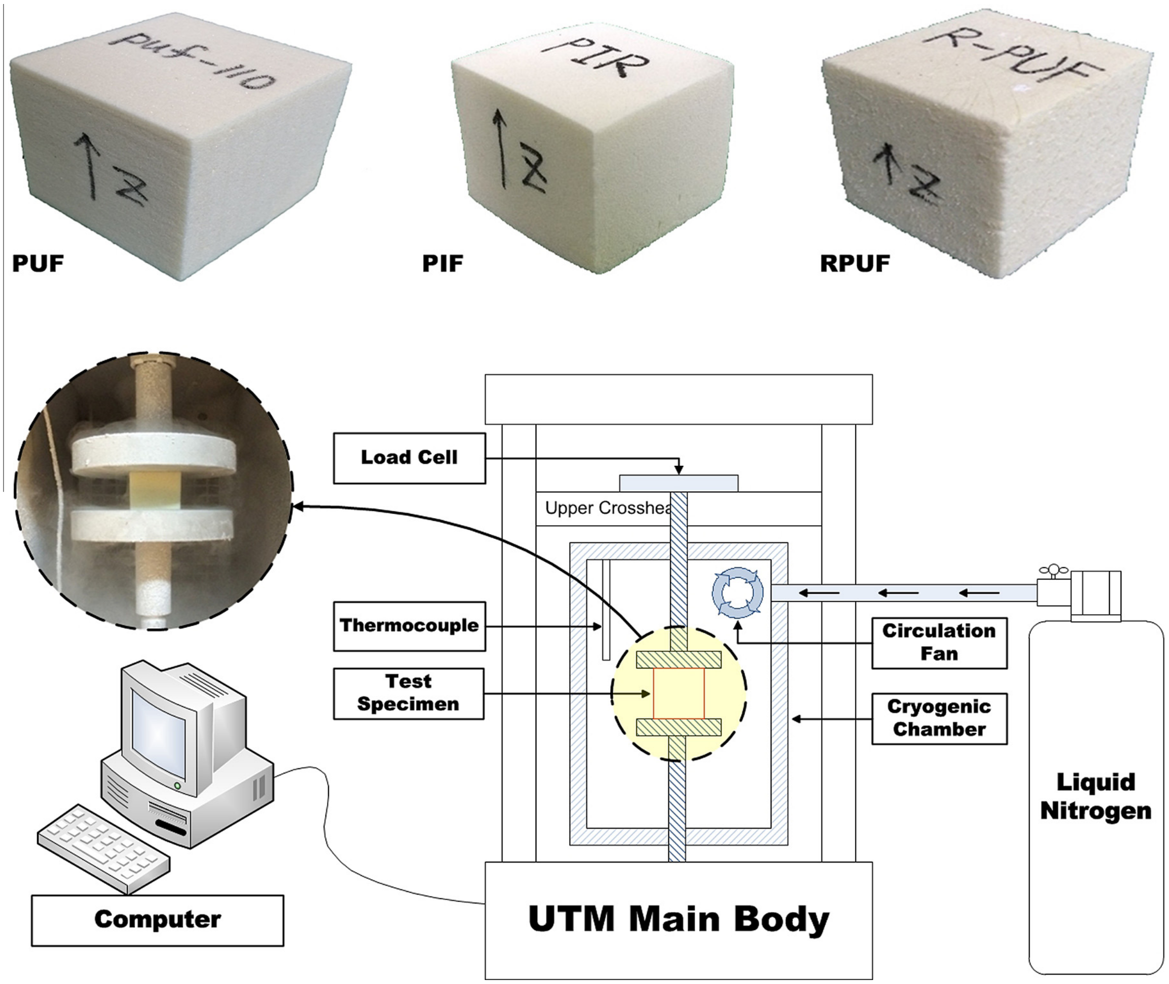

Fig. 1. PUF, PIF and RPUF test specimens for the compression test and a schematic diagram of the experimental apparatus for the cryogenic compression test.

Table 1
Test scenario for cryogenic compression test.

Case no.	Temperature (°C)	Strain rate (/s)
1	20	0.001
2	20	0.0001
3	−50	0.001
4	−50	0.0001
5	−110	0.001
6	−110	0.0001
7	−163	0.001
8	−163	0.0001

costs for RPUF are relatively greater than for PIF and PUF. Hence, the thermal insulation capacity as well as the mechanical properties should be improved simultaneously in order to design/fabricate robust and efficient LNG insulation structures.

Several research groups have experimentally investigated the mechanical properties of PUF, PIF and RPUF under various material states, environmental conditions, namely, temperatures, strain rates, etc. For example, changes in the material properties for RPUF were investigated with regard to the effects of the following: fiber reinforcement [6,7], fiber and matrix volume fraction [8], impact energy [9], surrounding temperature [10], and strain rate [11]. The mechanical features of PUF were investigated at various material densities [12] and quasi-static and high strain rates [13,14]. Moreover, the microscopic characteristics [15], cushioning properties [16], energy absorption [17], thermal conductivity [18], and static compressive loading [19] of PUF were also investigated for identifying the material characteristics of PUF. In addition, Panowicz and Miedzinska [20] carried out the uniaxial compression tests of PIF at nominal densities of 60 and 100 kg/m^3 and evaluated the stress–strain nonlinear behavior using a unit cell-type microstructural finite element model developed by the authors.

However, in those previous studies, neither the failure nor the fracture characteristics of the polymeric foams were identified. Furthermore, these earlier studies investigated neither the significant micro-structural changes that occurred in the polymeric foams at low and cryogenic temperatures nor their mechanism. In order to evaluate the precise compressive material behavior and failure of these materials under various temperature conditions, it is necessary to accurately identify material characteristics such as compressive failure mode, nonlinear stress–strain relationships, and maximum and permanent deformation (i.e., recovery ratio) by performing a series of compression tests. Based on the results of the aforementioned investigations, it is certainly possible to design/fabricate robust LNG CCS and/or insulation structures that are constantly exposed to cryogenic temperatures, in particular, −163 °C.

In the present study, the extensive material behavior and failure characteristics of PIF, PUF and RPUF at low and cryogenic temperatures and under static compressive loads were identified