DE GRUYTER Materials Testing 2024; 66(3): 433–446

Testing of Physical and Chemical Properties

Parlindungan Manik, Tuswan Tuswan*, Muhammad Abdullah Azzam, Samuel Samuel
and Aditya Rio Prabowo

Thermal insulation properties of materials for fishing vessel coolboxes

https://doi.org/10.1515/mt-2023-0244

Abstract: Effective insulation is critical for traditional fishing boats because it helps to maintain the quality of the fish catch. Inadequate insulation can lead to significant economic losses for fishermen, as they may have to discard or sell the fish at a lower price. This study aimed to compare the thermal conductivity properties of three different insulation materials: Petung bamboo, polystyrene foam, and polyurethane foam. The experiment involved testing the density of the materials and conducting thermal conductivity tests. The results indicated that polyurethane foam is the best material for insulation because it has the lowest thermal conductivity value compared to laminated bamboo and polystyrene foam. The addition of more isocyanate mass fraction to the polyurethane foam material can increase its density and strength. This is because increasing the isocyanate concentration increases the cross-linking density of the foam, making it more durable and resilient. Moreover, higher density polyurethane foams exhibit lower heat conductivity, indicating better insulation qualities. This study highlights the importance of effective insulation to maintain the quality of the fish catch. The findings suggest that polyurethane foam, particularly with increased isocyanate concentration, is the most suitable material for insulation due to its superior insulation qualities.

Keywords: polyurethane foam; laminated bamboo; polystyrene foam; insulation material; thermal conductivity

1 Introduction

As the world's largest fish-producing country, most fishermen in Indonesia still use traditional fish storage technology. Most traditional fishermen in several regions in Indonesia still use simple fish storage methods such as Styrofoam boxes, ice blocks as cooling media, and ordinary wooden boxes. This traditional technique can be detrimental to fishermen because the process is less isolated, causing the quality of the fish to decrease [1]. On the other hand, fish storage using refrigeration requires high installation and maintenance costs and skills. Therefore, developing and modifying insulation systems on traditional fishing boats are needed to maintain fish quality and prevent temperature changes that can damage fish quality [2].

Wood, as the primary material for making fish storage on traditional fishing boats, is becoming increasingly scarce, so its high price is a constraint for fishermen in renewing their fishing vessel industry. On the other hand, because wood material has conductivity, it is unsuitable for being a suitable insulation material to protect the quality of captured fish. Therefore, it is essential to consider alternative material combinations that can optimize catch products. Some common insulation materials used are Styrofoam [1], sago [1], polyurethane (PU) foam [3], epoxy-based biocomposite [4], and expanded perlite [5]. Styrofoam is lightweight and inexpensive but less effective in maintaining temperature if there are temperature changes in the surrounding environment. Styrofoam boxes tend to break easily and cannot withstand heavy loads, so they are easily damaged. In addition, sago has lower insulation performance than Styrofoam [1]. One alternative material as insulation material for fish storage is PU foam. PU foam is available in foam, which can be flexible with low density. PU foam has high mechanical strength, low heat conductivity, low water absorption, and low density, making it suitable for thermal insulation [6]. PU foam has better insulation ability

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***Corresponding author: Tuswan Tuswan**, Department of Naval Architecture, Universitas Diponegoro, Semarang, 50275, Indonesia, E-mail: tuswan@lecturer.undip.ac.id
Parlindungan Manik, Muhammad Abdullah Azzam and Samuel Samuel, Department of Naval Architecture, Universitas Diponegoro, Semarang, 50275, Indonesia
Aditya Rio Prabowo, Department of Mechanical Engineering, Universitas Sebelas Maret, Surakarta 57126, Indonesia

than Styrofoam, but the material price is relatively high. Therefore, it is essential to develop alternative material combinations for fish storage with a high strength-to-weight ratio and superior technical and economic specifications.

Several studies on developing insulation materials for fish storage need to be studied. Numerical simulation based on computational fluid dynamics (CFD) was conducted by Jia & We [7] on a ship model to analyze temperature distribution. The results show that PU foam is a suitable heat insulation material for refrigerated storage space on fishing boats. In addition, the technical application of insulation materials on fishing boats at Batang fishing vessels, Indonesia, shows that compressing PU foam during the development process can lower insulation quality [8]. Another study developed PU foam with sawdust waste as a mixed insulation for traditional fish storage. The results show that adding 40 % wood powder reduces insulation quality but can increase the added value of the material and economic aspects [9]. The recent experimental study examined how the density of PU foam materials varies with four different PU foam compositions. The outcomes revealed that the varying compositions influence the density of the PU foam. When the isocyanate liquid capacity is raised, it reduces the volume but increases the density. Therefore, it is crucial to comprehend how composition alterations impact the foam material's strength [10].

In addition, bamboo is a lightweight forest product that potentially substitutes high-cost wood. The bamboo material is extensively used in the community owing to its desirable properties, such as its sturdy stems, elasticity, flatness, hardness, straightness, and ease of shaping, which can be achieved with speed and ease [11]. Petung bamboo is a commonly used alternative for fish hatches. It is easily found and thrives in the Southeast Asian region, with the added benefit of cost savings for fishermen [12]. Previous studies have also shown that the utilization of Petung bamboo as a composite raw material with high lignin and cellulose content results in high toughness and tensile strength values [13]. A study further supports this research by recommending bamboo laminates to produce parts on ships such as ivory, galars, skins, boards, and deck beams. The study clarified that Petung and Apus bamboo have nearly identical tensile and flexural strength values [14].

Based on the abovementioned problem, developing a new combination of insulation materials for fish storage is crucial. In this study, the investigation will be conducted to investigate the thermal conductivity performances of different insulation materials. Several insulation materials with different compositions, such as PU foam, polystyrene foam, and Petung bamboo, will be compared. The study employed experimental methods through density tests based on ASTM C134-95 and thermal conductivity tests with ASTM E1225 standards on specimen dimensions of 4 mm and 2 mm. Therefore, the current research outcomes are expected to identify the optimal and efficient insulation material for fishing boats in the future fishing boat industry.

2 Literature review

2.1 Characteristics of PU foam

PU foam is widely regarded as one of the most superior and efficient insulation materials. This polymer material comprises urethane functional groups (NHCOO–) within its main chain, formed through a reaction between isocyanate and hydroxyl groups. PU A or Polyol A is a stable and finely dispersed liquid polyester containing solid polymers like vinyl, copolymers, polyureas, and polyurethanes. Currently, polyol polymer serves as an essential intermediate group for elastic polyurethanes, obtained through a hydroxylation reaction that involves two stages, including the formation of an epoxy ring (oxirane) and the opening of the oxirane ring [15]. Moreover, PU B or isocyanate, a functional group with the chemical formula R–N=C=O, is produced in tandem with a polyol to create PU foam [16]. So, PU foam comprises a blend of polyol and isocyanate as its core, and new properties can be attained by altering the composition of this blend [17].

One of the notable advantages of PU foam is its ability to be sourced from natural sources such as vegetable oil. Polyols can be derived from various sources such as soybean, castor, palm oil, sunflower, and rapeseed oil. These have been synthesized and investigated as alternative petrochemical polyols for producing PU foam [18]. Previous studies have favoured PU foam for its optimal performance in regulating room temperature and promoting energy savings [19]. It exhibits low thermal conductivity with more than 50 % energy usage, and solid PU foam simplifies installation production. Using PU foam as a core material results in improved rigidity and stiffness of the panel, a more evenly integrated structure, and higher core material strength. Additionally, the economic value of PU foam is higher compared to other foam cores, making it easier to produce on a large scale with a density range of 48–800 kg m^{-3}. Its thermoplastic foam nature makes it ideal for applications up to 408.15 K.

2.2 Characteristics of laminated Petung bamboo

The substitution of wood in shipbuilding with Petung bamboo as an alternative structural material is a widespread practice. Petung bamboo is abundant in Indonesia and has a wide distribution from lowlands to highlands (±1300 m above sea level), lining riverbanks and hillsides with greenish–yellow skin. Its stem can reach a length of 10–14 m, with a node length ranging from 40 to 60 cm, and diameter of 6–15 cm, and a wall thickness of 10–15 mm. Petung bamboo is renowned for being more robust and more water-resistant than other varieties of bamboo.

Bamboo composite possesses distinctive characteristics compared to other materials, particularly low conductivity at high densities compared to similar wood products. Bamboo has a tensile strength of approximately twice that of wood and a compressive strength of about 1.5 times stronger than wood. The study findings revealed that NaOH treatment affects mechanical properties like tensile, flexural, and impact strength. The study established that laminated bamboo, a bamboo-based composite created by bonding bamboo strips or laminas under controlled temperature or pressure, could enhance the mechanical properties of developed materials compared to single lamination [20].

Moreover, Tuswan et al. [21] also pointed out that developing a new generation of bamboo-based composites is cost-effective and generates significant demand, particularly in ship structure manufacturing. Their study investigated the correlation between lamina direction and the mechanical characteristics of laminated bamboo composites for ship structures, revealing that adding Waru fibers enhances mechanical properties, such as bending strength by around 3.17–14.18 % and tensile strength in the range of 4.88–20.28 %. These findings provide crucial information for the fishing industry that uses bamboo composite laminates for their ship hulls. Moreover, Manik et al. [22] identified strategies for improving the strength of laminated bamboo, which could significantly benefit the shipbuilding industry. The study showed that laminated bamboo strength could be enhanced by using thinner laminates with more layers of bamboo. It was discovered that bamboo composites with seven layers and a higher epoxy mass matrix have superior mechanical properties compared to those with three and five layers with the same thickness. The study results concluded that only specimens with seven layers meet the Indonesian Classification Bureau's (BKI) bending and tensile strength threshold.

Table 1 provides an overview of the mechanical properties of Petung bamboo, including its bending strength, compressive strength perpendicular to the grain, compressive strength parallel to the grain, shear strength, tensile strength, and modulus of elasticity (MOE) [23]. Furthermore, bamboo has the potential to be an environmentally friendly and energy-efficient material in addition to its unique characteristics and mechanical properties. Bamboo is becoming popular among many due to its energy efficiency, high productivity, and reduced environmental impact [24].

Table 1: Mechanical properties of Petung bamboo [23].

Material properties	Value (MPa)
Flexural strength	95.08
Compressive strength perpendicular to the grain	47.44
Compressive strength parallel to the grain	37.33
Shear strength	7.88
Tensile strength	226.39
Modulus of elasticity (MOE)	12248.58

2.3 Characteristics of polystyrene foam

Expanded polystyrene foam (EPS) is a lightweight and versatile material widely used in packaging, construction, and other applications [25]. Several characteristics of polystyrene foam have been extensively studied in several works of literature. Tang et al. [26] reported that EPS is an industrial material widely used in road construction, automotive, architecture, etc. Compared to non-foam polystyrene plastic, EPS has a lower density, lower thermal conductivity, and higher weight-bearing cushioning strength per unit weight. More importantly, the properties of polymer foam can be easily regulated by controlling pore size, relative density, cell structure, and additives. EPS is widely used in the industry due to its lightweight, easy moldability, and moisture resistance.

EPS is also an eco-friendly lightweight material often used in construction. Due to its lightweight and good thermal properties, EPS concrete has been widely used in non-structural and structural elements, such as walls and slabs [27]. EPS also has good thermal insulation properties, so it is often used as insulation material in buildings and other applications that require temperature control [28]. EPS is also used as thermal insulation to protect against temperature or heat disruptions. Adding EPS can significantly improve the thermal insulation properties of a material. EPS is also often used in the food and beverage industry to create cold storage, as it can help maintain a cool and stable room temperature. Therefore, EPS is also common in the fishing vessel industry.

EPS is also a very lightweight material. Due to its lightweight, EPS is often used as packing material in shipping, as it can protect the goods without adding excess weight. EPS is also a good shock absorber, so it is often used in packaging and shipping to protect products from damage during transportation, including in the fishing vessel industry. EPS is not resistant to moisture or water as it can absorb water. However, EPS is designed to be moisture-resistant and used in wet environments. EPS is known as closed-cell polystyrene foam, which has tight cells and cannot absorb water easily. This type of closed-cell EPS is often used as a coating or filler material on walls, roofs, and floors in areas that tend to be damp, such as bathrooms, basements, and fishing vessels. It is caused by the use of EPS waste, which can increase compressive strength and reduce the density of a material.

3 Materials and methods

3.1 Material preparation and manufacture

The properties of PU foam are strongly influenced by the type and amount of polyol and isocyanate used in the manufacturing process. PU foam comprised polyol and isocyanate collected from Justus Kimiaraya, Semarang, Indonesia. The comparison of the volume and mass fractions of PU foam content is presented in Table 2. In this case, PU foam composition was varied by changing the polyol and isocyanate mass fractions, as presented in Table 3. A total of six specimen variations were developed. Isocyanate determines the foam's reaction time, cross-linking density, and thermal insulation properties. In this case, the resulting specimens were molded into standardized sizes of 40 mm in diameter and 4 mm and 2 mm in height for thermal conductivity testing, as depicted in Figure 1. Notably, the mixture of polyol and isocyanate can expand by up to 14 times its initial composition, making it an attractive choice for insulation applications [29].

Petung bamboo lamina was used as the primary reinforcement material for the ship structure. Bamboo was collected and harvested from natural forests in the Getasan area, Salatiga, Central Java, Indonesia. The bamboo used was three years old with an average diameter of 150 mm. The selected part of the bamboo stem, 1 m from the base to 4 m, was used to make the lamina. The initial step was conducted to produce laminated bamboo panels by cutting the bamboo into strips of the same widths and thicknesses. The bamboo stalks were cut at a height of 1 m above the ground, and only the portion of the stem above 1–4.5 m was used for the process. The bamboo was cross-cut into 40 cm sections and split into slats, from which 400 × 20 mm blades were generated using a splitting method. These blades were then planned to achieve the desired thicknesses. To preserve the bamboo laminas, bamboo lamina was soaked in a solution containing 2.5 % sodium tetraborate and then dried in an oven until the moisture content was less than 13 %. After that, the bamboo slats were grouped by thickness and sanded with a sandpaper machine to smooth the surface. Finally, the dried bamboo laminas were used to manufacture the laminated bamboo panel. In manufacturing laminated bamboo panels, a polymer epoxy resin was utilized in conjunction with hand lay-up methods to act as a binding agent. The first step involved applying epoxy glue uniformly across the entire surface of the bamboo as the base layer. Next, a cold press machine was used to compress the bamboo at a pressure of 2 MPa or 30 bar, and once the desired level of pressure was reached, the bolts on the iron clamp mold were tightened. The crushed laminated bamboo planks were placed in the clamp for 24 h to enhance layer adhesion before removal.

Producing EPS involves a series of complex processes that require careful control of temperature, pressure, and timing to produce high-quality foam products (Figure 2). EPS is a versatile material that can be processed into various forms, and its unique properties make it a popular choice for a wide range of applications. EPS collected from Justus Kimiaraya was investigated as a third insulation material. A total of two densities of EPS variations were analyzed by varying styrene, which formed the cellular structure, and pentane, which was used as a blowing agent. EPS was manufactured in three stages: pre-expansion, maturing/stabilization, and molding. The polymerization of styrene is a chemical process that involves the addition of monomer molecules to each other, forming long chains of repeating units called polymers. This reaction was initiated by heat. EPS was produced through a process known as bead molding, where the polystyrene beads were expanded using steam and then molded into a circular shape. The beads were heated to a temperature of around 363–373 K, which caused them to expand and fuse. The resulting foam block was then aged for several days to allow the blowing agent to diffuse out of the foam, reducing the potential for shrinkage and distortion during the molding process. Figure 3 depicts the two variations of EPS test specimens with different densities.

Table 2: Comparison of volume and mass fractions of PU foam.

Material content	Volume	Net mass	Density
Polyol	1 ml	1.08 g	
Isocyanate	1 ml	1.24 g	
Polyurethane foam	14 cm^3	15.60 g	230 $\mathrm{kg\ m}^{-3}$

Table 3: Comparison of specimen composition of PU foam

Specimen code	Compositions (polyol: isocyanate)		Bold volume of 4 mm specimen (ml)	Mass of 4 mm specimen ($\times 10^{-3}$) (kg)	Bold volume of 2 mm specimen (ml)	Mass of 2 mm specimen ($\times 10^{-3}$) (kg)
PU foam A	Polyol	1	2.51	2.73	1.26	1.37
	Isocyanate	1	2.51	3.13	1.26	1.56
PU foam B	Polyol	1	2.01	2.18	1.01	1.09
	Isocyanate	1.5	3.02	3.75	1.51	1.88
PU foam C	Polyol	1	1.68	1.82	0.84	0.91
	Isocyanate	2	3.35	4.17	1.68	2.09
PU foam D	Polyol	1	1.44	1.56	0.72	0.78
	Isocyanate	2.5	3.59	4.47	1.80	2.23
PU foam E	Polyol	1	1.26	1.37	0.63	0.68
	Isocyanate	3	3.77	4.69	1.89	2.35
PU foam F	Polyol	1	1.12	1.21	0.56	0.61
	Isocyanate	3.5	3.91	4.87	1.96	2.43

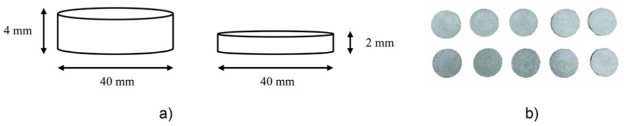

Figure 1: Specimen testing a) specimen geometry and b) specimen visualization.

Figure 2: Laminated Petung bamboo specimens.

Figure 3: EPS test specimens.

3.2 Material testing procedures

Density tests play a vital role in material science, particularly in developing new materials and enhancing existing ones, as they provide valuable information about the material's physical properties, which can impact its performance and behaviour. ASTM C 134–95 was utilized to ascertain the density of a material. Density specimens were shaped into cylindrical shaped forms to facilitate the test. It is important to note that specimens must be allowed to rest for at least 72 h after manufacture before being cut for testing purposes. The test was conducted in the Laboratory of Ship Construction, Diponegoro University, using the FUJITSU FSRB1200. Additionally, specimens should be stored for no less than 16 h at standard atmospheric conditions or in dry conditions, and their mass or volume should be recorded. The density can then be determined using Equation (1).

$$\rho = \frac{M_{\mathrm{k}}}{v}\ (\mathrm{kg\ m^{-3}}) \tag{1}$$

with ρ: density (kg $\mathrm{m^{-3}}$), M_{k}: sample mass (kg) and v: sample volume ($\mathrm{m^3}$).

Thermal conductivity measurement is an important process for determining the ability of a material to transfer heat. Accurate measurement of thermal conductivity helps in the design of efficient heat transfer materials. ASTM E1225 standard was used for thermal conductivity measurement, ensuring that the measurement was taken under stable conditions. Utilizing a standardized test specimen ensures the measurement results are comparable across different laboratories and experiments. The test was conducted at Heat and Mass Transfer Laboratory at the Faculty of Mechanical Engineering at Gadjah Mada University, which

Figure 4: Thermocouple test equipment.

utilized test specimens of 40 mm in diameter and 4 mm and 2 mm in height, respectively. The thermal conductivity measuring apparatus type OSK 4565, manufactured by Tokyo Meter Co., model HVS-4000SE, was used. The thermal conductivity measurement was carried out by a thermal conductivity tester, which used a thermocouple with 12 heat-conducting wire positions, with a 4 mm test material between thermocouples 4 and 5, and a 2 mm test material between thermocouples 6 and 7, as illustrated in Figure 4. The thermocouple with 12 heat-conducting wire positions ensured that measurements were taken at different points along the material's surface, which provided a comprehensive understanding of thermal conductivity. The location of the test material between thermocouples four and five and then between thermocouples six and seven ensured that the material was tested at different thicknesses, providing insights into the material's thermal conductivity at different depths.

At the outset of the test, the test equipment was adjusted to an initial temperature of 301 K in accordance with the ambient room temperature. After that, the temperature of the equipment was modified based on the thermal value data corresponding to the temperature being examined, and the resultant temperature change was determined by measuring the output temperature. The data acquired from this process was meticulously recorded, and a temperature chart was generated to represent the results visually. Utilizing this graphical data, the coefficients *a* and *b* were calculated to ascertain the thermal conductivity of each specimen with the temperature increase. For the calculation of the thermal conductivity of a given material, Equations (2) and (3) are employed [30].

$$\lambda = \frac{L_b - L_a}{\left\{\frac{L_b}{\lambda_{b'}} - \frac{L_a}{\lambda_{a'}}\right\}}\ (\mathrm{W\ m^{-1}\ K^{-1}}) \qquad (2)$$

with λ: thermal conductivity of the material (W m^{-1} K^{-1}), L_a: length of material where the temperature is measured (m), L_b: length of material after the temperature measurement point (m), $\lambda_{a'}$: Thermal conductivity of material at the point where the temperature is measured (W m^{-1} K^{-1}), and $\lambda_{b'}$: thermal conductivity of material after the point where the temperature is measured (W m^{-1} K^{-1}).

Equation (2) is based on Fourier's law of heat conduction, which states that the heat flow (or heat transfer rate per unit area) through a material is proportional to the temperature gradient (or temperature change over a certain distance) within the material. By using the lengths L_a and L_b, the temperature gradient within the material can be calculated, and then the thermal conductivity at two points to calculate the overall thermal conductivity of the material can be assumed by using Equation (3) [30].

$$\lambda_{a'} = \frac{\Delta t_\mathrm{R}\, L_a}{\Delta t_\mathrm{a}\, L_\mathrm{R}}\, \lambda_\mathrm{R} \ \text{ and } \ \lambda_{b'} = \frac{\Delta t_\mathrm{R} L_\mathrm{a}}{\Delta t_\mathrm{b} L_\mathrm{R}}\, \lambda_\mathrm{R}\ (\mathrm{W\ m^{-1}\ K^{-1}}) \qquad (3)$$

with $\lambda_{a'}$: thermal conductivity of the material at the point a where the temperature is measured (W m^{-1} K^{-1}), $\lambda_{b'}$: thermal conductivity of the material at the point *b* where the temperature is measured (W m^{-1} K^{-1}), Δt_R: temperature difference between two points (K), L_a: Length of the material at the point *a* where the temperature is measured (m), L_b: Length of the material at the point *b* where the temperature is measured (m), Δt_R: temperature difference between two points (K), L_R: length of the material between two points and the distance between them. Δt_R: thermal conductivity of the material at the point where the temperature difference (W m^{-1} K^{-1}). In this case, $L_a = 0.02$ m, $L_b = 0.04$ m, $L_R = 0.30$ m, $\lambda_R = 320$ W m^{-1} K^{-1}.

Equation (3) is based on the fundamental principle of heat conduction, where heat flow through a material is proportional to the temperature gradient within the material. By using Equation (3), the thermal conductivity of the material at a specific point ($\lambda_{a'}$) using the thermal conductivity of the material at another point with a known distance (λ_R), as well as the temperature difference and the length of material between the two points (Δt_R and L_R) can be calculated. To calculate Δt_a, Equation (3) with a different point at a distance of L_a, allowing us to determine the temperature difference between the two points was used.

4 Result and discussion

4.1 Result of density test

The density assessment involves a comprehensive procedure that entails the determination of the mass and volume of the sample specimen, followed by the measurement of the density value using Equation (1). In this study, cylindrical-shaped specimens with a diameter of 40 mm and height of 4 mm were employed. The comparison of specimen density is presented in Table 4. Notably, the findings revealed that the utilization of varying compositions of polyol and isocyanate in PU foam F hindered the complete expansion and development of the specimen, consequently rendering it unfit for measurement. The result showed that the addition of isocyanate caused an increase in density value. The higher the addition of isocyanate, the higher the density increase. Isocyanate is denser than polyol and fills the space between the cells, making the foam more compact. Increasing the amount of isocyanate can also shorten the foam's reaction time, which can be useful in certain manufacturing processes. The results demonstrated that PU foam E had the highest density value of 76 kg m^{-3} and the lowest density value of 34 kg m^{-3} in PU foam A.

Figure 5 reveals that increasing the isocyanate mass fraction significantly increased the PU foam density. The addition of isocyanate also affects the ability of PU foam to expand. Specifically, higher quantities of isocyanate result in reduced expansion capacity. Hence, it is apparent that increasing the isocyanate in the mixed PU foam reduced its shape volume while increasing its density. In addition, laminated Petung bamboo has the highest density value compared to PU foam and polystyrene foam, with a value of 751 kg m^{-3}. In addition, polystyrene foams A and B have a lower density than PU foam.

Table 4: Comparison of specimen density of different insulation materials.

Material types	Mass (kg)	Volume (m^3)	Apparent density (kg m^{-3})
PU foam A	1.7×10^{-4}	5.03×10^{-6}	34
PU foam B	2.5×10^{-4}	5.03×10^{-6}	50
PU foam C	3.0×10^{-4}	5.03×10^{-6}	60
PU foam D	3.4×10^{-4}	5.03×10^{-6}	68
PU foam E	3.8×10^{-4}	5.03×10^{-6}	76
PU foam F	–	–	–
Petung bamboo	3.78×10^{-3}	5.03×10^{-6}	751
Polystyrene foam A	1.6×10^{-4}	5.03×10^{-6}	32
Polystyrene foam B	1.0×10^{-4}	5.03×10^{-6}	20

Figure 6 shows the relationship between density and reaction time of PU foam materials. In this case, as the density of PU foam increases, the reaction time tends to decrease. This is because higher density foams typically require more chemical reactants and have a higher cross-linking density. The increased crosslinking density results in a faster reaction rate, leading to a shorter reaction time. However, it is important to note that other factors can also influence the reaction time of PU foam, and the relationship with density may not always be straightforward. Some of these factors include the specific formulation of the foam, the type and concentration of catalysts used, the ambient temperature, and the presence of any additives or fillers.

4.2 Result of thermal conductivity test

The thermal conductivity measurement is an essential experimental test used to evaluate the ability of materials to conduct heat. In this study, thermal conductivity measurements were performed on specimen diameters of 4 mm and 2 mm with the same diameter, using a thermal conductivity tester at three different temperatures of 313 K, 323 K, and 333 K. The comparison of thermal conductivity results between the three developed materials is presented in Table 5. The test results five revealed the varying thermal conductivity of developed PU foam A–E, laminated Petung bamboo, and polystyrene foam A & B. It can be found that the increasing temperature caused an increase in thermal conductivity. Notably, all specimens had the lowest thermal conductivity values at 333 K, except for PU foam A, which recorded the lowest value at 323 K. The differences can be attributed to the influence of temperature on the physical properties of developed insulation materials, as reviewed in previous studies [31]. These outcomes suggest that the heat conduction performance of the materials investigated in this study is significantly affected by temperature, emphasizing the importance of considering the temperature in industrial applications that require high thermal conductivity materials.

To further explore the obtained results, a more detailed examination of Figure 7 reveals that adding higher isocyanate can increase the thermal properties. It can be found that PU foam C with polyol: isocyanate 1:2 has optimum thermal conductivity performance with the lowest thermal conductivity value. This means that the PU foam C has a low ability to conduct heat. Materials with a low thermal

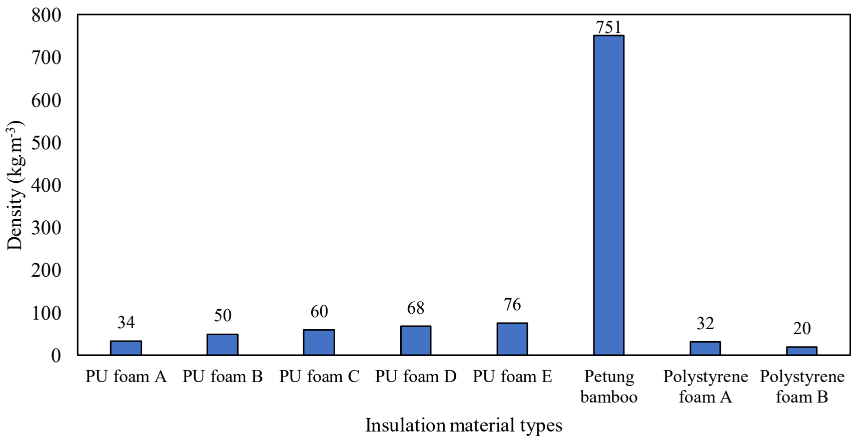

Figure 5: Comparison of density value under different insulation materials.

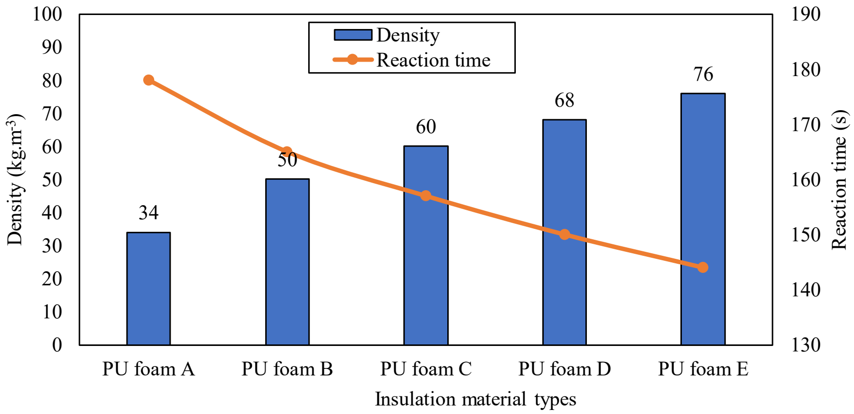

Figure 6: Comparison between density and reaction time of PU foam materials.

conductivity value will resist heat flow and will not allow heat to pass through easily. In contrast, PU foam A has the lowest thermal conductivity performance. PU foam A has the highest thermal conductivity value of 0.140 W m^{-1} K^{-1}, indicating that its composition has a higher proportion of materials that are poor conductors of heat.

These findings provide useful insights into the thermal conductivity properties of the investigated materials and their potential for use in various thermal management applications. The thermal conductivity test results in this study highlight the critical influence of temperature on the thermal conductivity properties of materials. The findings underscore the importance of considering temperature in selecting materials for high thermal conductivity applications. Furthermore, the results provide valuable information on the thermal conductivity properties of various materials, which can inform the design and optimization of industrial applications that require effective heat transfer.

Table 5: Comparison of thermal conductivity value under different insulation materials.

Material types	Thermal conductivity (W m^{-1} K^{-1})			
	313 K	323 K	333 K	Mean
PU foam A	0.140	0.062	0.049	0.082
PU foam B	0.067	0.040	0.032	0.046
PU foam C	0.062	0.031	0.021	0.038
PU foam D	0.068	0.032	0.023	0.041
PU foam E	0.069	0.033	0.023	0.042
Petung bamboo	0.076	0.073	0.040	0.068
Polystyrene foam A	0.071	0.058	0.037	0.056
Polystyrene foam B	0.063	0.057	0.039	0.053

Figure 8 demonstrates the average thermal conductivity values from three measurement temperatures of the PU foam specimens. PU foam A, which has the highest thermal conductivity value of 0.082 W m^{-1} K^{-1}, contained the lowest proportion of isocyanate, which is a good heat conductor. In contrast, PU foam C exhibits the lowest average thermal conductivity value of 0.038 W m^{-1} K^{-1}, indicating that its composition has poor conductors of heat. In addition, PU foam D and E seem to have similar thermal conductivity values of 0.041 W m^{-1} K^{-1} and 0.042 W m^{-1} K^{-1}, respectively. In contrast, PU foam B has a higher thermal conductivity value than PU foams C, D, and E. The difference in thermal conductivity values among the PU foams can be attributed to their compositions that influence thermal conductivity.

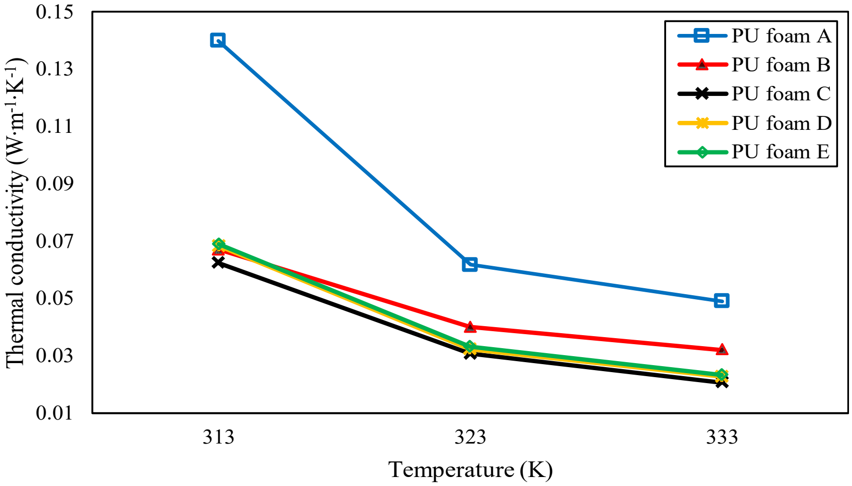

Figure 7: Comparison of thermal conductivity value of PU foam material.

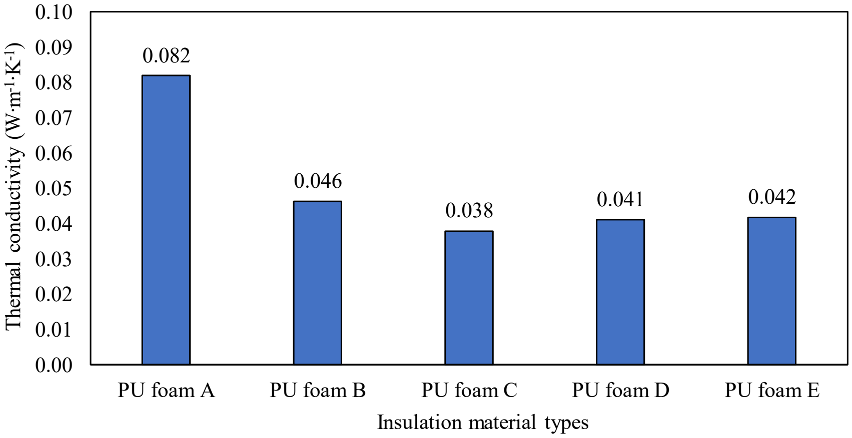

Figure 8: Comparison of average thermal conductivity value of PU foam material.

This study compared thermal conductivity values among three different materials, namely PU foam, Petung bamboo, and polystyrene foam A & B, as presented in Figure 9. A similar trend was found in which the thermal conductivity value decreased as the temperature increased. The thermal conductivity value at 333 K exhibited the lowest thermal conductivity values. At the temperature of 333 K, Petung bamboo demonstrated a thermal conductivity value of 0.040 W m^{-1} K^{-1}, while polystyrene foam A and polystyrene foam B exhibited values of 0.037 W m^{-1} K^{-1} and 0.039 W m^{-1} K^{-1}, respectively. These three samples showed higher values than PU foam C, demonstrating a thermal conductivity value of 0.021 W m^{-1} K^{-1}.

Figure 10 shows that Petung bamboo exhibits the highest average thermal conductivity value of 0.068 W m^{-1} K^{-1}. Polystyrene foam B presents a thermal conductivity value higher than PU foam C by 0.053 W m^{-1} K^{-1} and falls short of the thermal conductivity value of polystyrene foam A, which stands at 0.056 W m^{-1} K^{-1}. The results suggest that PU foam C is the most effective insulator among the materials listed, followed closely by PU foam B. PU foam A, D, and E have higher thermal conductivity values, indicating that they are less effective insulators. Petung bamboo has a thermal conductivity value of 0.068 W m^{-1} K^{-1}, higher than all of the PU foams listed. It suggests that it is a poorer insulator than the PU foams. In addition, the two types of polystyrene foam listed have intermediate thermal conductivity values, with polystyrene foam B having a slightly lower value than polystyrene foam A. The obtained results indicate that Petung bamboo and polystyrene foam A and B possess inferior thermal conductivity values compared to PU foam C. Overall, the results suggest that PU foam C is the most effective insulator among the materials listed, followed closely by PU foam B. In contrast, Petung bamboo has the highest thermal conductivity value, indicating that it is the poorest insulator. Consequently, the ideal materials for the fish hold application can effectively impede the transmission of external heat sources across the hatch surface, thereby maintaining the desired temperature inside the fish hold.

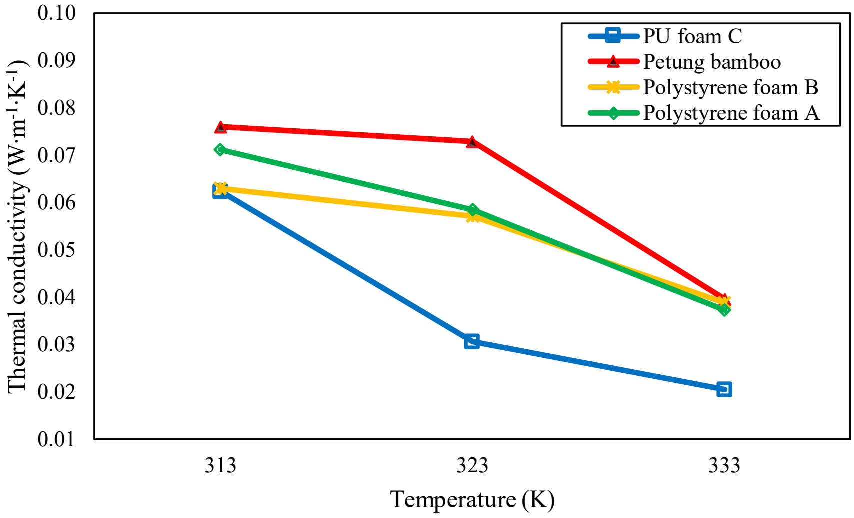

Figure 9: Comparison of thermal conductivity value between PU foam, Petung bamboo, and polystyrene foam.

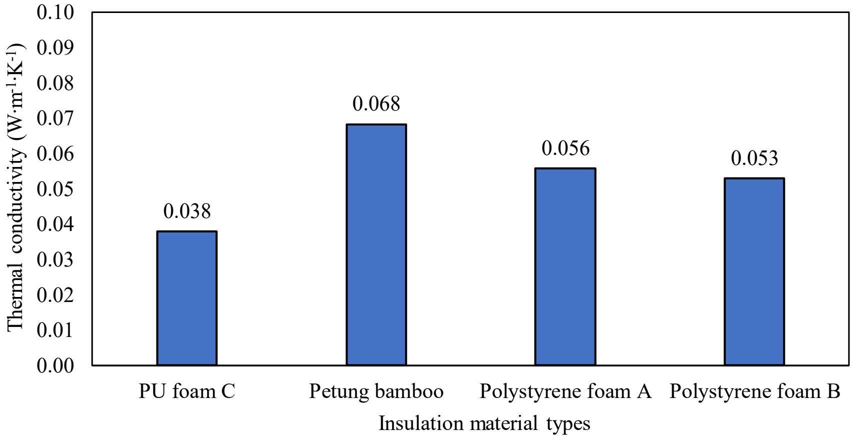

Figure 10: Comparison of average thermal conductivity value between PU foam, Petung bamboo, and polystyrene foam.

4.3 Relationship between thermal conductivity and density and tensile strength of PU foam

Further, to investigate the relationship between the thermal conductivity values of PU foam variations and density, the current study compared the result to the previous test result by Utomo et al. [10]. Utomo et al. [10] developed PU foam as a core material for ship structure by varying similar polyol and isocyanate mass fraction composition. Several tests have been conducted, including density, hardness, tensile, and bending tests. Figure 11 compares the thermal conductivity and density of different PU foam compositions. The relationship between thermal conductivity and density in PU foam is complex. It can vary depending on various factors, such as the chemical composition of the foam, the manufacturing process, and the environmental conditions in which the foam is used. Thermal conductivity and density of the specimens have a direct relationship. When the composition qualities alter, both physical attributes change [32]. From the result, it can be found that the increase in density caused a decrease in thermal conductivity value. Increasing isocyanate can increase the density and decrease the thermal conductivity value. Higher density of PU foams tends to have lower thermal conductivity values, indicating that they are better insulators. The denser the foam, the more closely packed the cells are, and the less room for air to circulate. Air is a poor conductor of heat, so when there is less of it in the foam, there is less heat transfer through the material.

The relationship between the density and tensile strength of PU foam is complex. It depends on several factors, such as the chemical composition of the foam, the manufacturing process, and the environmental conditions in which the foam is used. Figure 12 shows different PU foam specimens' density and tensile strength relationships. Based on the results, the higher the density value of the specimen, the higher the tensile strength. The higher mass fraction of isocyanate can increase both density and tensile strength. This condition is influenced by the morphological characteristics of the PU foam, where the density of the foam is

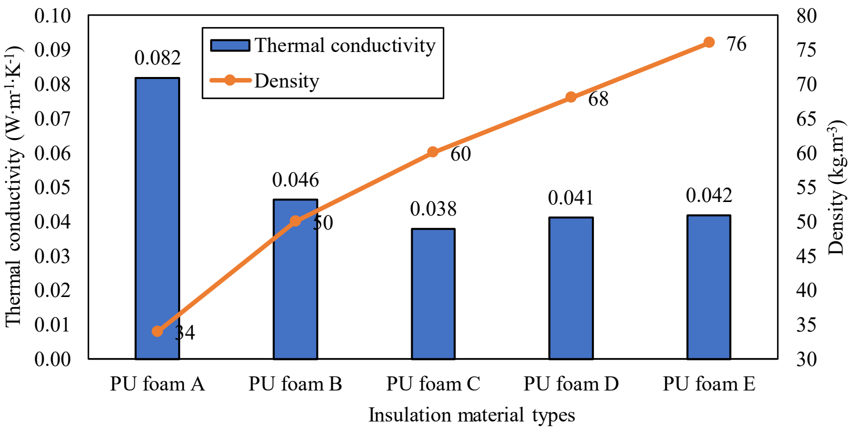

Figure 11: Relationship between density and thermal conductivity obtained from Utomo et al. [10] of different PU foam compositions.

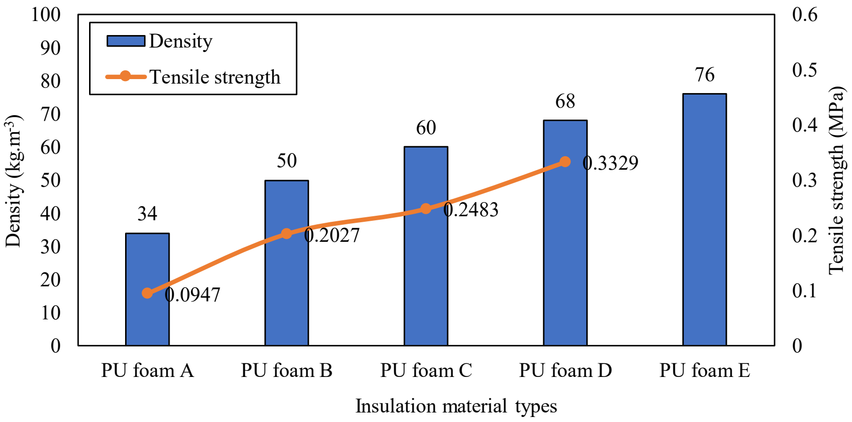

Figure 12: Relationship between density and tensile strength of different PU foam compositions.

controlled by the amount of gas released during the reaction with the isocyanate liquid [33]. The denser foams have a higher concentration of the material, which leads to a stronger and more rigid structure. Increasing the amount of isocyanate can also increase the cross-linking density of the foam, resulting in foam with higher strength and durability. Additionally, the density of the foam can impact the cell size and shape, affecting its tensile strength. Foams with smaller, more uniform cell sizes tend to have higher tensile strength than those with larger, irregular cell sizes.

Moreover, the relationship between tensile strength and thermal conductivity value of different PU foam mass fractions is depicted in Figure 13. In general, there is no direct relationship between tensile strength and thermal conductivity in PU foam. Tensile strength refers to the ability of the foam to resist stretching or tearing, while thermal conductivity refers to its ability to conduct heat. However, the chemical composition of the foam can impact both its tensile strength and thermal conductivity. Based on the current result, increasing the amount of isocyanate in PU foam can

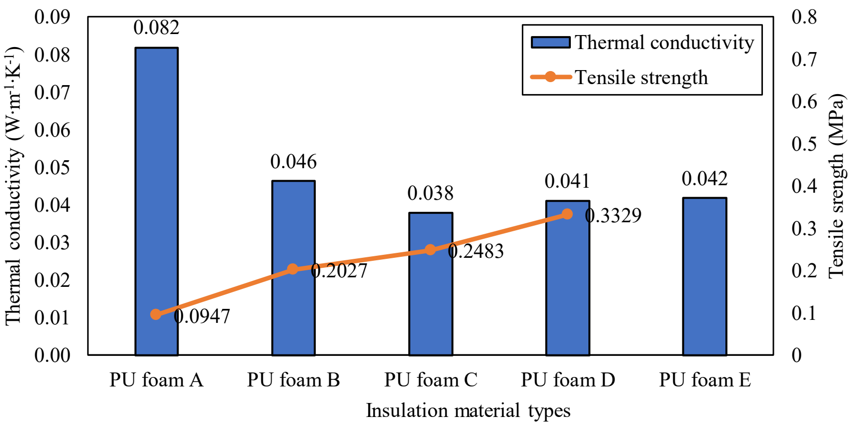

Figure 13: Relationship between thermal conductivity and tensile strength obtained from Utomo et al. [10].

increase its tensile strength. Isocyanate is a key component in the production of PU foam. Increasing its concentration can produce a stronger chemical bond between the polymer chains, resulting in higher tensile strength. However, it is important to note that the relationship between isocyanate concentration, tensile strength, and thermal conductivity is not always straightforward and can vary depending on other factors, such as the specific formulation of the foam and the environmental conditions in which it is used.

5 Conclusions

The comparison of thermal conductivity performances of several insulation materials such as PU foam, polystyrene foam, and Petung bamboo was investigated. Experimental methods through density tests and thermal conductivity tests were conducted to compare three insulation materials with different compositions. The results indicate that PU foam, with the lowest thermal conductivity value, has better insulation performance than polystyrene foam and laminated bamboo. It should be noted that the optimum mass fraction composition of PU foam is polyol: isocyanate 1:2 with a thermal conductivity value of $0.038\ \mathrm{W\,m^{-1}\,K^{-1}}$. In contrast, Petung bamboo has the highest thermal conductivity value with $0.068\ \mathrm{W\,m^{-1}\,K^{-1}}$, indicating the poorest insulator.

A greater amount of isocyanate can lead to an increase in both density and tensile strength. Additionally, elevating the quantity of isocyanate can augment the foam's cross-linking density, thereby producing a more durable and robust foam. Moreover, raising the amount of isocyanate can result in a rise in density and a reduction in thermal conductivity. PU foams with greater density typically exhibit lower thermal conductivity, suggesting better insulation properties.

Acknowledgment: The authors would like to express gratitude to the Laboratory of Ship Construction at Diponegoro University, Indonesia and Heat and Mass Transfer Laboratory at the Faculty of Mechanical Engineering at Gadjah Mada University for providing research facilities and assistance with experimental testing.

Research ethics: Not applicable.

Author contributions: All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Competing interests: The authors state no conflict of interest.

Research funding: The research has received financial support from the International Publication Research (RPI) 2023 research scheme from Universitas Diponegoro with contract number 225-33/UN7.D2/PP/IV/2023. The authors gratefully acknowledge the support.

Data availability: The authors declare that the data supporting the findings of this study are available within the article.

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The authors of this contribution

Parlindungan Manik

Parlindungan Manik is an Associate Professor at Diponegoro University (UNDIP) Semarang, Indonesia. His undergraduate education was pursued at the Department of Naval Architecture, Sepuluh Nopember Institute of Technology (ITS) in 1997. His Master’s degree in Engineering (M. Eng) was obtained from the Faculty of Marine Technology, Sepuluh Nopember IT’S Surabaya in 2002. He pursued a doctoral degree (Dr.) in material technology at the Department of Mechanical Engineering, UNDIP, with the research topic of the study of composite materials from bamboo fiber material for ship skin materials.

Tuswan Tuswan

Tuswan Tuswan received his B. Eng. degree in the Department of Naval Architecture at Diponegoro University, Semarang, Indonesia, in 2016. He received his Doctoral degree (Dr.) in Marine Engineering Science at Institut Teknologi Sepuluh Nopember, Indonesia, in 2021. He currently works in the Department of Naval Architecture at Diponegoro University, Semarang, Indonesia. His research interests include ship structure and material.

Muhammad Abdullah Azzam

Muhammad Abdullah Azzam received a bachelor’s degree in engineering from Diponegoro University in 2023. He completed his Naval Architecture study program at the Faculty of Engineering, Diponegoro University. He was currently working in the maritime domain, especially on ships for offshore industrial purposes.

Samuel Samuel

Samuel Samuel received his B. Eng. degree in the Department of Naval Architecture, Diponegoro University, Semarang, Indonesia in 2008. He received his M. Eng. degree in Marine design and Offshore Engineering at Institut Teknologi Sepuluh Nopember, Indonesia, in 2010. He received his PhD degree in the Department of Naval Architecture And Marine Systems Engineering at Pukyong National University, Busan, South Korea, in 2019. He is currently an Associate Professor in the Department of Naval Architecture at Diponegoro University, Semarang, Indonesia. His research interests include fluid mechanics, small craft ships, and computational fluid dynamics analysis.

Aditya Rio Prabowo

Aditya Rio Prabowo pursued his Dr. Eng. degree at the Interdisciplinary Program of Marine Convergence Design at Pukyong National University, South Korea. He is interested in accident-related phenomena in marine environments, including collision, grounding, and explosion. His work also concerns extreme regions for engineering operations, such as Arctic Engineering and Polar Sciences. His research is dedicated to investigating the structural crashworthiness of marine structures, including ships and containers. He is currently an Associate Professor in the Department of Mechanical Engineering at Universitas Sebelas Maret, Surabaya, Indonesia.