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Review Article

Smart materials finishing and insulation solutions applied to the interior design of a cruise ship cabin

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ABSTRACT

A cruise ship cabin can be outlined using a complex bill of materials, components and sub-assemblies properly interconnected, considering its functional nature as a whole. In this regard, modern scientific achievements have allowed the development of so-called smart materials. The research activity has started with a scoping review of the currently constituent finishing, as well as insulation materials installed on-board. The assessment of smart and high-performance solutions is aimed of optimizing thickness, weight, noise and vibrations parametres. Actual cases under analysis related to finishing materials include performance paints and inks, fabrics with antibacterial and water-repellent properties which, together with a protective action, can generate electricity if exposed to light. Some polymeric fibres can thermally modify their sensitivity to humidity and allow for better adaptability and reversible shrinkage, self-healing surfaces regenerate after the occurrence of a crack. Active safety, failure prevention, and comfort criteria on board passenger ships are the main focus of many of the technological applications under investigation. It is necessary for them to evaluate the compatibility with the marine environment, durability, and compliance with the rules.

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1. INTRODUCTION

The current scoping review activity, connected to the doctoral thesis currently under development, is focused on the interior design of cruise ships, which have the common denominator of implementing high-performance (Wang, Tang, 2022) and smart materials which could increase the overall comfort performance, energy optimization and compliance with safety classification rules.

The suggested taxonomy (Goldade et al., 2015) includes, without any formal disconnection, currently used and potential applicable achievements, with an integration of innovative technologies intrinsically linked to the designed and molecular-controlled substance constitution (Bengisu, Ferrara, 2018) as in the case of smart materials. The simultaneous presence is determined by the design need to integrate the new paradigm with a knowledge that has been diachronically consolidated (Peijnenburg et al., 2021). The regulatory framework currently in use in the field of design will introduce the most common insulation materials. High performance and smart materials solutions principles are described, along with a list of tests used to assess their properties and possible, future applications on board.

2. THE ROLE OF ACOUSTIC AND THERMAL INSULATION IN THE SHIPBUILDING INDUSTRY

Typical noises and vibrational stresses associated with cruise ships are generated by the rushing of water against the hull and related to the operational profile of engines, propellers,

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machinery and air conditioning, as well as sounds generated by onboard activities. These are transferred throughout the structure and spread towards the accommodation areas. Acoustic insulation applications (Adam, 2016) have significant impact in reducing noise levels, minimizing reverberation, eliminating echoes, and improving speech clarity. A proper thermal insulation (Lakatos, 2022), on the other hand, is performed to control and maintain the design temperature within the ship's interior spaces that is, minimizing the transfer of heat between the interior and exterior environments. This would result in an overall increase of the energy efficiency by reducing the reliance on heating or cooling systems.

Thermoacoustic insulation plays a crucial role in ensuring the comfort and safety of passengers and crew on cruise ships accommodation area, especially within cabins.

These latter are regulated by the international SOLAS Convention (Safety of Life at Sea). Is has been issued by the International Maritime Organization (IMO), a specialized agency of the United Nations responsible for regulating shipping on a global scale. The first Convention was adopted in 1914 (after the Titanic disaster) and the current version entered into force in 1974. SOLAS primary goal is to establish minimum requirements for ship construction, equipment, and operation, compatible with their safety. Merchant ships, like cruise ships, are required to comply with these strict safety standards.

It is divided into fourteen chapters and rules that are comprehensively addressed to distinct aspects of safety in the specific environment of ships. Chapter II-2, titled "Construction – Fire protection, fire detection and fire extinction," specifically focuses on fire protection, detection and extinction. The products referenced in this section, including materials and components used in ship construction (bulkheads, decks, fire doors, fire-resistant closures, upholstered furniture, bed components, lining materials, and curtains) have to withstand international requirements for laboratory testing, type-approval and fire test provided by the International Code for Application of Fire Test Procedures, 2010 (2010 FTP Code).

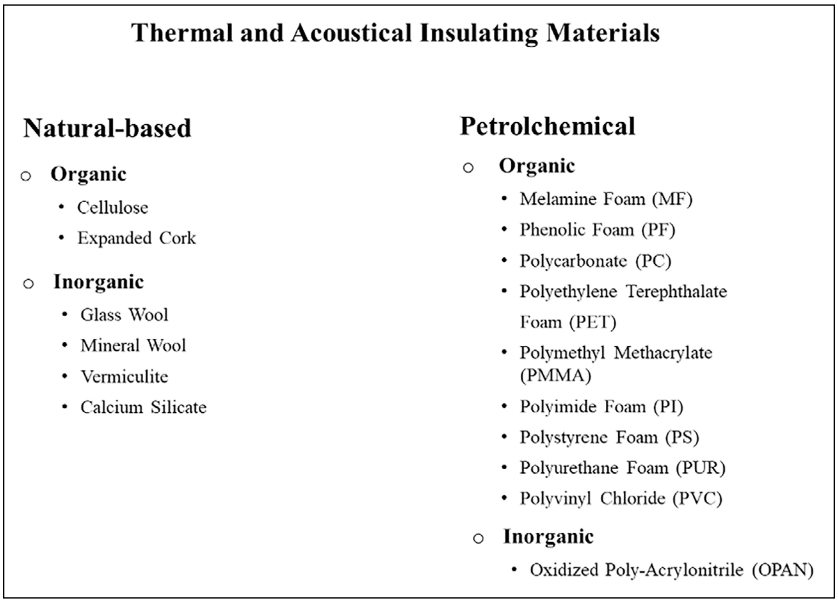
In particular, non-combustibility tests and substance classification are performed according to IMO 2010 FTP Code Part 1, IMO-Resolution MSC.307(88). Surface flammability ones are compliant to Part 5 and fire tests on A and B divisions are achieved in conformity to Part 3. Furthermore, there are threshold values related to the transmission of noise and vibrations established by the ISO 20283-5:2016 (Measurement of vibration on ships — Part 5: Guidelines for measurement, evaluation and reporting of vibration about habitability on passenger and merchant ships).

To highlight the potential localized interventions, it is important to briefly describe the composition of a standard cabin module, which is comprised of steel ceiling and wall panels (in most cases galvanized) or aluminium alloy. The internal face of each of them is finished by applying decorative coatings. Rock wool is the traditional material used to insulate and fire-proof the external facing. Bulkheads between cabins will be comprised of two adjacent panels, with a small hollow space between them. In the same way, if a passenger cabin is adjacent to a public passageway, the tools and methods of partitioning and finishing will be similar since the corridors too are assembled with similar prefabricated panel elements.

2.1. Thermo-acoustic material selection outlines

The research activity has started with a classification of the main insulating materials applied in the shipbuilding sector, considering the constituent type of the fibres (Fig. 1).

A main difference between Natural-based and Petrolchemical materials is taken into account, each of them further divided into organic (Table 1, 2) and inorganic groups (Table 3, 4).



Thermal and Acoustical Insulating Materials

Natural-based

- **Organic**
  - Cellulose
  - Expanded Cork
- **Inorganic**
  - Glass Wool
  - Mineral Wool
  - Vermiculite
  - Calcium Silicate

Petrolchemical

- **Organic**
  - Melamine Foam (MF)
  - Phenolic Foam (PF)
  - Polycarbonate (PC)
  - Polyethylene Terephthalate Foam (PET)
  - Polymethyl Methacrylate (PMMA)
  - Polyimide Foam (PI)
  - Polystyrene Foam (PS)
  - Polyurethane Foam (PUR)
  - Polyvinyl Chloride (PVC)
- **Inorganic**
  - Oxidized Poly-Acrylonitrile (OPAN)

Figure 1. Thermoacoustic material classification.

Table 1. Natural-based organic materials

Type	Technical description	Density [kg/m³]	Thermal conductivity [W/m°C]	Specific heat capacity [J/kg°C]	Acoustic velocity [m/s]	Form	Application
Cellulose [1]	Cellulose-based products made primarily from post-consumer and industrial paper, with recycled newspaper being the main raw material	48–128	0.037	2000	–	Panels	Accommodation and entertainment areas
Expanded cork	Derived from the bark of cork oak trees, specifically quercus suber. It undergoes expansion through heating and pressure treatment	160–240	0.04–0.048	1900–2100	344–525	Sheets, boards	Floors solutions

[1] Referred values for CFAB™ Cellulose-based, thermo-acoustic panels

Table 2. Natural-based inorganic materials

Type	Technical description	Density [kg/m³]	Thermal conductivity [W/m°C]	Specific heat capacity [J/kg°C]	Acoustic velocity [m/s]	Form	Application
Calcium silicate [2]	Inorganic material composed of calcium, silica, and reinforcing fibres. The material is formed through a chemical reaction and heat treatment process, resulting in rigid and fire-resistant boards	280-320	0.07	1100	–	Boards	High-temperature insulation and fireproofing. Acoustic tiles and insulation in ducts a non-combustible autoclaved calcium silicate board
Glass wool	Insulating material made from fine fibres of glass. Glass wool is produced by melting glass and then spinning it into fibres	11–70 [3]	0,033–0.040 [3]	1030 [3]	180 [5]	Boards, rolls	Wall insulation and HVAC (Heating Ventilation and Air Conditioning) system
Mineral wool	Insulating material made from natural or recycled stone The stone is melted and spun into fibres	25–100 [3]	0.033–0.044 [3]	840 [4]	180 [5]	Boards, rolls	Wall insulation and HVAC system
Vermiculite	Composed of hydrated laminar magnesiun-aluminium-ironsilicate which resembles mica. It is most used in its exfoliated (expanded) form	64–160	0.058–0.070	840–1080	630–1360	Hard-core panels, boards	Thermal insulation in structural elements for large public spaces. Acoustic-fireproofing panels

[2] Referred values for Bacchi Spa™ lightweight panel; [3] Hongisto et al. (2022); [4] Rockwool ™ database; [5] Reference value for mineral wools from Isover ™ Database

Table 3. Petrochemical organic materials

Type	Technical description	Density [kg/m^3]	Thermal conductivity [W/m°C]	Specific heat capacity [J/kg°C]	Acoustic velocity [m/s]	Form	Application
Melamine Foam (MF)	Open-cell foam composed of melamine resin, a thermosetting polymer derived from melamine and formaldehyde. It is high porous	9–12	0.032–0.035	1650–1800	95.5–142	Sheets, panels	Cabin ceiling/floors and accomodation areas. HVAC insulation, noise barriers and acoustic absorbers
Phenolic Foam (PF)	Thermosetting plastic foam made from phenol formaldehyde resin. The foam structure consists of a network of cells, providing low thermal conductivity and fire-resistant properties	32–38 (closed cell 0.035)	0.02	1850–1910	334–455	Sheets, boards	Refrigeration and pipes insulation, acoustic panels
Polycarbonate (PC)	Transparent thermoplastic known for its high impact resistance, optical clarity, and UV stability It can be extruded into sheets or molded into panels with varying thicknesses and shapes	1190–1210	0.19–0.22	1150–1250	1390–1430	Sheets, panels	Windows and protective barriers, transparent partitions
Polyethylene Terephthalate Foam (PET)	Closed-cell foam made from polyethylene, a thermoplastic polymer. Lightweight, flexible, and resilient material with closed cells	75–110	0.033–0.035	1140–1260	687–821	Sheets, boards	Core material for sandwich panels, acoustic insulation walls, ceilings, and floors of cabins
Polymethyl Methacrylate (PMMA)	Transparent thermoplastic known for its optical clarity, scratch resistance, and UV stability. It is typically extruded into sheets or molded into panels	1160–1220	0.19–0.21	1400–1480	1410–1800	Sheets, panels	Windows and decorative panels, transparent partitions
Polyimide Foam (PI)	High-temperature resistant foam made from polyimide resin, which is known for its excellent thermal stability and resistance to heat, chemicals, and radiation	15–32	0.032–0.304	1390–1450	119–173	Sheets, rolls	High-temperature insulation and in electronics. Acoustic insulation in machinery spaces
Polystyrene Foam (PS)	Synthetic polymer made from monomers of the aromatic hydrocarbon styrene. Closed-cell structures provides thermal insulation and buoyancy	28–32	0.032–0.036	1200–1220	468–616	Sheets, boards	Insulation boards,walls soundproofing
Polyurethane Foam (PUR)	Foam formed by reacting polyols and isocyanatesopen-cell or closed-cell structure with varying densities	30–34	0.03–0.035	1650–1700	35.1–43.7	Spray foam, boards	Pies and plant insulation
Polyvinyl Chloride (PVC)	Thermoplastic known for its versatility and durability. PVC is produced in various forms through polymerization of vinyl chloride monomer	36–44	0.02–0.03	1120–1140	745–871	Sheets, pipes	Cable insulation Soundproofing and wall coverings

Table 4. Petrochemical inorganic materials

Type	Technical description	Density [kg/m³]	Thermal conductivity [W/m°C]	Specic heat capacity [J/kg°C]	Acoustic velocity [m/s]	Form	Application
Oxidized Poly-Acrylonitrile (OPAN) [6]	Material derived from polyacrylonitrile polymer. It undergoes preoxidation and stabilization processes to enhance its thermal stability and fire resistance	100	0.031	700–750	–	Sheets, rolls	Thermal and fire protection in machinery spaces

[6] Reference values for Zoltex Carbonized PX 35 felt

It could be possible thanks to the application of Granta EduPack Software, currently used in an interdisciplinary matter in the academic field to perform complex analysis which can synoptically consider engineering, design and sustainable development aspects. The user can perform analysis based on three stages. Level 1 database contains an introductory approach of more than 60 records or common engineering materials (metals, plastics, ceramics, glasses, composites and natural materials). A limited set of attributes is linked to records for processes that are used to shape, join or finish them.

Level 2 contains a comprehensive set of mechanical, thermal and electrical properties, as well as Eco Properties and Durability Information, for more than 100 common materials. The materials and the content of the records enable a wide range of selection studies and environmental audits of products. The process records include a simple cost model that allows cost-comparisons between alternative processes.

Belonging to this level is the Building Environment repository, which contains more than 120 materials commonly used in Architectural applications. A set of mechanical, thermal, electrical, hygro-thermal, acoustic is provided, along with durability information.

Level 3 contains a comprehensive set of the previous data, together with mechanical, optical, magnetic and environmental properties for over 4,000 engineering materials. Eco Design database also encompasses environmental properties such as whether a material is restricted, NOx and SOx values, water usage, carbon footprint, embodied energy, and end of life information.

A crossed use of the second and the third level, together with a scoping review activity of the cutting-edge solutions actually present on the market and the support of the scientific literature, helped to create the material classification.

It should be stressed that specific heat and thermal conductivity are related to an ambient temperature set at 23°C. In order to further characterise each substance, the acoustic velocity variable (m/s) has been used, as measure of the speed of longitudinal sound waves in a solid. It is calculated as follows (Equation 1):

$$v = \sqrt{\frac{E}{p}}$$

Equation 1. Acoustic velocity formula

where E is Young Modulus (Pa) and ρ is the material density (Kg/m³).

The speed of sound in a solid material can be used as a further indicator of its insulating properties. It depends on the density and compressibility of the matter through which it propagates. In general, in denser and more rigid materials, such as metals, the speed of sound is higher, while in less dense and more flexible ones, such as thermal insulators like wool, fiberglass and foam, the speed of sound is slower.

The parameters considered are related to the substances used and not to the finishes applied, as they could undergo variations in their weight, depending on the different thicknesses applied and their relative stratigraphy. In many

Table 5. Aerogels test methods

Testing category	Test method	Description	References
Thermal conductivity	Cryogenics test laboratory	Used to determine apparent thermal conductivity (k-value) of thermal insulation systems	Johnson et al. (2010)
Non-destructive method for mechanical properties	Diametral compression test	Application of stress load or force to the point where a material object is split in half (down the diameter of the object)	Haj-Ali et al. (2016)
Mechanical properties of silica aerogels	Micro-indentation technique	The sample material is indented using a sharp, pointed probe, with a controlled force application	Moner-Girona et al. (1999)
	Dynamic compressive test	Tests of cross-linked silica aerogel using a split Hopkinson pressure bar (SHPB) for Poisson's ratio determination	Luo et al. (2006)
Fracture toughness tests	Single-edge-notch bending (SENB)	Specimen is subjected to three-point bending loads	Ehrburger-Dolle et al. (1995)
Density measurement	Torsional oscillator measurements	Body suspended by a thread or wire which twists first in one direction and then in the reverse direction, in the horizontal plane	Crowell et al. (1990)
Hydrophobicity and Hydrophilicity	Contact Angle Measurement	Determine the contact angle of water on the aerogel surface to assess its hydrophobic or hydrophilic properties.	Ślosarczyk (2021)
Aging and Stability Tests	Long-Term Stability	Subject the aerogel to aging tests to simulate real-world conditions and evaluate its stability over time.	Perego (2008)
Environmental Resistance	Optical absorption - UV–Vis tests	Proton irradiation tests Test the aerogel's resistance to ultraviolet (UV) radiation	Wu et al. (2020)

solutions on the market these materials often constitute the core of sandwich and honeycomb compounds to combine the aforementioned properties with structural capacity.

3. SMART AND HIGH-PERFORMANCE MATERIALS FOR ADVANCED INSULATION AND FINISHING SOLUTIONS

They are related but distinct concepts in the field of materials science (Ritter, 2006). Smart materials (SM) are known for their adaptability and responsiveness to external stimuli, allowing them to change their properties or behaviour based on variable conditions, examples of which include Shape Memory Alloys and Self-Healing Polymers. On the other hand, high-performance materials (HPM) stand out in terms of their intrinsic properties, such as strength, durability, or conductivity, and are chosen for applications where outstanding, specified characteristics are crucial. While these categories are different in functionality, it's possible for some materials to belong to both if they combine high-performance attributes with adaptive capabilities (Addington, Schodek, 2005).

3.1. Aerogels (HPM)

Aerogels are highly porous, ultra-lightweight substances with very low thermal conductivity (0.017 W/m°C) (Aegerter et al., 2011), primarily composed of air. They are manufactured through a supercritical drying process that removes the liquid content of a gel. Various materials have been implemented, with silica being the most commonly used (Pierre, Anderson, 2011). Historically, aerogels production has been relatively costly, constraining its usage to advanced aerospace operations (Jin et al., 2023). However, as manufacturing expenses decline, they are finding their way into a wider array of applications, including their incorporation into composite materials such as laminated glazing for thermal insulation or integration into blankets for heat protection and acoustic absorption.

The following table show the test methods aimed at characterizing aerogels main properties (Table 5).

In cruise ship design, suitable features and applications can include:

- Internal cabin insulation: it can be used aerogels low thermal conductivity helps maintain comfortable inside temperatures, reducing the reliance on heating and cooling systems. This can lead to energy savings and lower operational costs;
- Energy-Efficient Windows: aerogels can be integrated into windows frames to enhance their thermal insulation properties. This helps reduce heat gain during sunny days and heat loss during cold weather, contributing to energy savings in the ship's overall HVAC system;
- Soundproofing: in addition to thermal insulation, aerogels can provide soundproofing benefits. Installing aerogel-based insulation in cabin walls and ceilings can help minimize noise transfer between cabins and common areas;

Table 6. Vacuum Insulation Panels (VIPs) test methods

Testing category	Test method	Description	References
Standard specification for Vacuum Insulation Panels	ASTM C1484-10(2018)	Specification covers the general requirements for vacuum insulation panels	Nikafkar and Berardi (2020)
Thermal testing	DIN EN 12667:2001	Determination of thermal resistance	Davraz and Bayrakçı (2013)
Fire test method	ISO 834-11:2014	One side of the specimen is exposed to the furnace and measured according to its appearance and ignition	Y. U. Kim et al. (2021)
Insulation performance test	ASTM C 1363	Temperatures of the constant temperature chamber and the low are measured	
Airtightness test	ASTM E 783	Pressure of the test specimen is increased in steps and the airtightness is measured until the flow rate becomes stable	
Aging and Durability Testing	International Energy Agency (IEA) - Annex 39	Thermal cycling and humidity exposure to assess their durability over time	J. Kim et al. (2017)
	Cold Climate Housing Research Center, Mobile Test Lab (CHRC's MTL)	Used to evaluate different wall configurations for durability under high interior moisture loads.	Garber-Slaght and Craven (2012)

- Fire Safety: aerogels are non-combustible materials, which is crucial for safety in cruise ship design;
- Space Constraints: the thin profile is helpful in cruise ship design, where space is often limited. It allows for effective insulation without compromising cabin space or vessel design.

3.2. Vacuum Insulation Panels (VIPs) – (HPM)

VIPs consist of a core material (typically a rigid, porous material like fiberglass or silica aerogel), enclosed in a vacuum-sealed panel, which minimizes heat transfer by eliminating air molecules. They provide high insulation efficiency in a thin profile, making them suitable for space-constrained applications (Baetens, 2010). Here's how VIPs work and why they can be effective also in the maritime field:

- Vacuum Core: core material is placed in a vacuum or near-vacuum environment, which reduces the conduction and convection of heat;
- Airtight Encapsulation: core material is sealed within a gas-tight envelope made of high-quality barrier materials, often metallic or laminated films. This envelope prevents air from entering and disrupting the vacuum, ensuring long-term insulation performance;
- Longevity: if properly maintained and protected from physical damage or perforations, VIPs can maintain their insulation properties for an extended period, making them a durable and cost-effective insulation solution over the long term.

The following table show the test methods aimed at characterizing VIPs main properties (Table 6).

3.3. Phase Change Materials (PCMs) - (SM)

This category includes all smart materials capable of undergoing reversible changes in response to external stimuli, in particular they exhibit phase changes dependent on temperature (Delgado et al., 2018). In the construction and architecture sectors, the term "PCM" has gained relevance concerning materials and products utilized for temperature regulation purposes. PCMs store and release heat energy during phase transitions, such as from solid to liquid or vice versa. They can absorb excess heat during the day and release it at night, helping to maintain a stable indoor temperature. PCMs can be embedded in insulation materials or used as standalone panels.

The following table show the test methods aimed at characterizing PCMs main properties (Table 7).

Potential applications aboard cruise ships may include:

- Temperature Control: PCMs are effective at stabilizing indoor temperatures by absorbing and releasing heat during phase transitions. In cruise ship cabins, PCMs can absorb excess heat during the day when the sun is intense and release it at night when temperatures drop, ensuring a consistent and comfortable environment for passengers;
- Space Efficiency: they are typically applied as thin layers within walls or ceilings, making them ideal for cruise ship cabins with limited space. Their slim profile allows for efficient insulation without sacrificing valuable cabin space;
- Condensation Prevention: PCMs can help prevent condensation on cabin surfaces, which is essential for maintaining a healthy and comfortable indoor environment. Condensation can lead to moisture-related issues like mold growth and corrosion;
- Retrofitting Capabilities: in some cases, existing cruise ships may undergo renovations or upgrades to improve energy efficiency and passenger comfort. PCMs can be integrated into cabin insulation during retrofitting projects to enhance insulation properties;
- Emergency Energy Backup: in the event of a power outage or HVAC system failure, PCMs can temporarily maintain indoor temperatures, ensuring passenger safety and comfort until normal operations are restored.

Table 7. Phase Change Materials (PCMs) test methods

Testing category	Test method	Description	References
Latent Heat of Fusion	Calorimetry	Measure the heat absorbed or released during the phase transition	Kotzé et al. (2014)
Thermal Cycling Stability	Repeated Heating and Cooling Cycles	Assess the stability of the material over multiple cycles, checking for performance degradation	Putra et al. (2019)
Thermal Conductivity	Standardized Methods	Measure the material's ability to conduct heat during solid and liquid phases	C. Xu et al. (2022)
Encapsulation Efficiency	Encapsulation Assessment	Evaluate the efficiency of the encapsulation process, ensuring containment and leak prevention	Y. Huang et al. (2023)
Durability and Long-Term Performance	Extended Testing Periods	Conduct long-term tests to assess durability and performance over extended periods	Egea et al. (2022)
Material Compatibility	Compatibility Tests with Other Materials	Investigate how well the PCM interacts with materials commonly used in specific applications	Ostrý et al. (2019)
Environmental Impact	Environmental Assessment	Evaluate the environmental impact, considering factors like recyclability and potential hazards	Di Bari et al. (2020)

3.4. Shape Memory Materials (SMMs) – (SM)

These materials have the remarkable ability to "remember" a specific shape and return to it when exposed to a certain stimulus, typically heat (Sun et al., 2012) (Vili, 2007). Shape-memory alloys (SMA's) exhibit two distinct crystal structures linked to a phase transformation between a low-temperature, martensitic phase and a high-temperature, austenitic phase. In the first configuration, the metal can easily be deformed into any shape; when the alloy is heated the memory metal is able to recall the shape it had before the deformation. This property enables the creation of dynamic, shape-changing structures and components like self-opening/closing windows and furniture mechanisms that can change their shape or configuration based on temperature changes (Jani et al, 2014).

Stimulus-responsive configurations refer to the ways in which shape memory materials (SMMs) can be triggered or activated to exhibit their shape-changing properties. Different types of shape memory materials respond to various stimuli, allowing for a range of applications in diverse fields. Here are some common stimulus-responsive configurations:

- Thermal Activation: the most common stimulus for shape memory materials is temperature change. For shape memory alloys (SMAs), heating above a certain transition temperature (often called the austenitic finish temperature) causes a reversible phase transformation, allowing the material to recover its original shape;
- Light Activation: some shape memory materials, particularly polymers, can be activated by exposure to light. Photothermal heating induces the required temperature change for triggering the shape memory effect. This feature is often exploited in biomedical applications where light can be precisely controlled;
- Electrical Activation: Applying an electric current to shape memory alloys can generate Joule heating, causing the material to undergo the phase transformation and recover its original shape. This electrical activation is useful in micro actuators and other electronic applications;
- Magnetic Activation: certain shape memory alloys, such as nickel-titanium, are responsive to magnetic fields. This latter induces mechanical deformation, making it possible to control the shape memory effect remotely;
- Chemical Activation: reversible chemical reaction, leading to a change in the polymer's structure and, consequently, in its shape;
- pH Activation: they can to respond to changes in pH. The pH-induced changes can alter the polymer's structure, leading to a reversible shape change;
- Moisture Activation: particularly in hydrogels They can react to changes in moisture levels. Absorption or loss of water can induce a change in the material's conformation and trigger the shape memory effect;
- Mechanical Activation: in some cases, shape memory materials can be activated by applying mechanical stress. This might involve stretching, compression, or other mechanical deformation to initiate the shape memory response;
- Dual/Multi-Stimulus Activation: some advanced configurations involve materials that respond to multiple stimuli simultaneously or sequentially.

The following tables show the test methods aimed at characterizing SMM main properties (Table 8, 9).

Between the possible application we can list the following cases:

- Adaptive Insulation: since SMM can change shape or thickness in response to temperature fluctuations, during colder periods they can expand to provide additional insulation and during summer, they could contract to allow better ventilation. This adaptability can

Table 8. Shape memory polymers (SMPs) test methods

Testing category	Testing method	Description	References
Shape Memory Effect (SME)	Shape Fixity and Recovery Test	Subject the material to a deformation at a certain temperature, then allow it to recover its original shape upon heating	Tcharkhtchi et al. (2014) Zhou and Huang (2015) Abdullah et al. (2012)
	Programming and Recovery Cycles	Assess the material's ability to go through multiple shape memory cycles without significant degradation	Li & Wang, (2016) Zhao et al. (2015) Lendlein (2010)
Thermal Characterization	Differential Scanning Calorimetry (DSC)	Measure the heat flow associated with the phase transitions in the SMP, such as the glass transition and melting temperatures	Martins (2019) McKinley (2004) Staszczak et al. (2022)
Mechanical Testing	Tensile Testing	Assess the tensile properties of SMPs, such as modulus, strength, and elongation, both below and above their transition temperatures	Fisher et al. (2020) Kim et al. (2021) Ohki et al. (2004) Tobushi et al. (2015
	Compression Testing	Investigate SMP response to compressive forces and shape recovery	
Thermo-Mechanical Analysis (TMA)	Coefficient of Thermal Expansion (CTE)	Evaluate dimensional changes in response to temperature variations	Fulcher et al. (2010) Ibarra et al. (2022)
Rheological Testing	Shear Testing	Study flow and deformation behavior under shear stress	Mohamed et al. (2022)
Dynamic Mechanical Analysis (DMA)	Frequency Sweep	Measure viscoelastic properties under dynamic loading conditions	Azra et al. (2013) Wang et al. (2023)
Chemical Resistance Testing	Exposure Tests	Expose SMP to different chemical environments for stability assessment	Jacobson and Iroh (2021) B. Wang et al. (2023)
Microscopic Analysis	Scanning Electron Microscopy (SEM)	Examine microstructure effects of deformation and recovery	Gall et al. (2002) Goda et al. (2020)
Electrical and Thermal Conductivity Testing	Electrical Resistance Measurement Thermal Conductivity Testing	Assess electrical conductivity in deformed and recovered states Evaluate thermal conductivity and heat transfer characteristics	X. Huang et al. (2021) Rybak et al. (2021) Pradhan et al. (2022)

help maintain optimal cabin temperatures without relying entirely on HVAC systems;

- Sealing and gasketing: SMMs can be employed in sealing and gasketing applications to ensure airtight seals around doors, windows, and other openings. They can change their shape or compress when necessary to maintain a tight seal, preventing drafts and heat loss.

It is important to note that SMMs are not commonly used for large-scale applications like cruise ship design at present. While they offer peculiar advantages, their adoption has to be assessed by factors such as cost, complexity, and the need for reliable control mechanisms.

3.5. Thermochromic materials (TMs)–(SM)

Thermochromic materials can be integrated into cruise ship cabin design to enhance insulation and improve the overall passenger experience (Boscolo et al., 2007). They change colour or optical properties in response to temperature variations, which can be used to create adaptive insulation systems and achieve energy efficiency in cruise ship cabins:

- Smart Window Systems: thermochromic coatings or films can be applied to cabin windows to control solar heat gain and glare. When exposed to sunlight or high temperatures, these materials darken, reducing the amount of heat and light entering the cabin. In cooler conditions or at night, they become transparent, allowing natural light to enter and potentially aiding in passive solar heating.

- Temperature-Responsive Surfaces: they can be used on cabin walls, ceilings, or other surfaces to visually indicate temperature changes. When the temperature inside the cabin rises or falls, these surfaces change colour or appearance, providing passengers with a visual cue about the thermal conditions. This can help passengers make informed decisions about adjusting the cabin temperature and HVAC settings.

- Customized Cabin Experience: cruise ship cabins often host passengers with varying preferences for temperature and lighting. Thermochromic materials can be incorporated into cabin controls, allowing passengers to adjust the cabin environment to their liking. For example, passengers can control the tint level on windows or the colour of cabin surfaces.

The test methods aimed at characterizing TH main properties are included in the following section table, since both smart materials acts in a similar way (Table 10).

Table 9. Shape memory alloys (SMAs) test methods

Testing category	Testing method	Description	References
Shape Memory Effect (SME)	One-way Shape Memory Effect	Deform material at a certain temperature and observe recovery	Naresh et al. (2016) Lexcellent et al. (2000) Meddour and Brek (2018) Gan et al. (2012)
	Two-way Shape Memory Effect	Assess ability to recover different shapes upon cooling and heating	
Thermal Characterization	Martensitic Transformation Temperature (Ms)	Determine critical temperatures using DSC or Differential Thermal Analysis	Hartl and Lagoudas (2008) Baradari et al. (2021)
	Austenitic Finish Temperature (Af)	Measure temperature associated with complete phase transformation	
Heat Treatment Analysis	Differential Scanning Calorimetry (DSC)	Study phase transformations and thermal behavior during heat treatment	Liu and Huang (2006)
	Metallography after Heat Treatment	Examine changes in microstructure due to heat treatment processes	Kožuh et al. (2018)
Mechanical Testing	Tensile Testing	Measure strength, yield strength, elongation, and modulus of elasticity	Lavernhe-Taillard et al. (2009)
	Compression Testing	Evaluate compressive strength and deformation behavior	Hashemi et al. (2023)
	Hardness Testing	Assess material hardness using Brinell, Vickers, or Rockwell tests	Arciniegas et al. (2008)
	Impact Testing	Evaluate toughness and resistance to impact loading	Sofocleous et al. (2013)
Chemical Composition Analysis	X-ray Fluorescence (XRF)	Determine elemental composition of the alloy	Alım et al. (2018)
	Atomic Emission Spectroscopy (ICP-AES)	Analyze element composition, especially traces	G. Fisher (2003) Fink et al. (2023)
Non-Destructive Testing (NDT)	Ultrasonic Testing (UT)	Detect internal defects or flaws in the alloy	Lee et al. (2023) Meir et al. (2011)
	Radiographic Testing (RT)	Use X-rays or gamma rays to inspect the internal structure	
	Eddy Current Testing	Detect surface and near-surface flaws in conductive materials	Testing high performance small diameter Nitinol wire - the largest portal of nondestructive testing (NDT). https://www.ndt.net/search/docs.php3?id=22368
Corrosion Testing	Salt Spray Test	Evaluate corrosion resistance in a saline environment	Charfi et al. (2009) Sampath et al. (2023) Rondelli (1996) Soltan et al. (2023)
	Electrochemical Corrosion Testing	Measure corrosion rate under controlled electrochemical conditions	
Fatigue Testing	Rotating Beam Fatigue Test or Axial Fatigue Test	Assess fatigue strength and behaviour under cyclic loading	Dornelas et al. (2021) Kang and Song (2015)

Table 10. Thermochromic (TMs) and electrochromic (ECMs) materials test methods

Testing category	Testing method	Description	References
Optical Properties	Transmittance Spectroscopy	Measure transparency in visible and near-infrared regions	Rai et al. (2020) Jelle and Hägen (1993)
	Coloration Efficiency	Quantify color change per unit of applied charge	Fabretto et al. (2007)
Electrochemical Properties	Cyclic Voltammetry (CV)	Examine redox behavior through potential sweeps	Elgrishi et al. (2017)
	Chronoamperometry	Study electrochemical response over time	K. Zhou (2020)
	Impedance Spectroscopy	Analyze electrical impedance as a function of frequency	Pehlivan et al. (2021)
Mechanical Properties	Durability Testing	Evaluate stability under repeated cycling	Tracy et al. (1999)
	Adhesion Strength	Assess adhesion between electrochromic layer and substrate	Ko et al. (2022)
Environmental Stability	Chemical Resistance	Test resistance to moisture, chemicals, temperature	Fan et al. (2020) Jensen et al. (2013) Borui et al. (2022)
	Long-Term Stability	Assess performance over an extended period	Ye et al. (2018) Chang et al. (2018) (TM) Y. Liu et al. (2023) (TM)
	Colour retention test	Examines how well the material retains its original color after multiple thermal cycles	Wałęsa-Chorab and Skene (2020)
Color transition temperature (TM)	Differential Scanning Calorimetry (DSC)	Measure the heat flow associated with the material's phase transitions, providing information on the color transition temperature	Fu and Hu (2017) Strbac (2022) (TM) Viková and Vik (2023)
Thermal Conductivity (TM)	Thermal Conductivity Measurements	Evaluate the material's ability to conduct heat, which can impact its response time to temperature changes	Ning et al. (2023)
Morphological Changes (TM)	Scanning Electron Microscopy (SEM)	Examine the material's surface morphology to understand any structural changes induced by temperature variations	Jia et al. (2021)
Electrochromic Device	Switching Speed	Measure transition time between colored and bleached states	Bessinger et al. (2021) Xu et al. (2016)
Performance	Cycling Stability	Evaluate performance over numerous coloration/bleaching cycles	Padilla et al. (2023) Fiksman (1997) (TM) Wu et al. (2023)
	Response to external stimuli	Assess material's response to factors like light intensity or temperature changes	R. Li et al. (2021) Hassab et al. (2018)
Energy Efficiency	Energy consumption	Evaluate energy efficiency during coloration and bleaching	Park et al. (2021)

3.6. Electrochromic materials (ECMs) – (SM)

Electrochromic materials change their optical properties in response to an applied electrical voltage quicker than the previous class. To manage solar heat gain and reduce heating or cooling, windows can be controlled by controlling their transparency or reflectivity (Somani, Radhakrishnan, 2003). However, they can contribute to energy efficiency and passenger comfort in cruise ship cabins through the control of natural light and glare (Granqvist et al., 2018). Here's how electrochromic materials can be applied in cruise ship design:

- Smart Windows: cruise ship cabins can incorporate electrochromic windows to control the amount of incoming natural light and reduce glare. They provide passengers with control over their cabin's lighting conditions, allowing them to adjust the opacity of the windows to control visibility from outside the cabin, thus enhancing privacy.
- Energy Efficiency: while not a direct insulation material, electrochromic windows can contribute to energy efficiency by reducing the need for artificial lighting and shading in cabins. By optimizing natural light levels, cruise ships can lower their energy consumption for lighting and cooling, resulting in cost savings and reduced environmental impact.

The following tables show the test methods aimed at characterizing TM and EM main properties (Table 10).

3.8. Dynamic insulation systems

They can be designed to mitigate the effects of vibrations and motions experienced by passengers in their cabins. These systems use sensors, actuators, and control algorithms to counteract ship motions caused by waves, engine vibrations, and other factors, thereby enhancing passenger comfort (Fawaier, Bokor, 2022). Here's how active vibration control works in cruise ship cabins:

- Sensors: vibration sensors are strategically placed in the cabin to detect any vibrations and motions. These sensors continuously monitor the cabin's movement in multiple axes, capturing data about the ship's vibrations and oscillations;
- Control Algorithms: advanced control algorithms process the sensor data in real-time. They calculate the optimal corrective actions needed to counteract the vibrations and motions and maintain a stable and comfortable environment inside the cabin;
- Actuators: devices able to generate forces to counteract the detected vibrations and motions. They are typically located beneath the cabin's floor or within the cabin's structure. These actuators can include hydraulic pistons, electromechanical devices, or other mechanisms capable of applying forces in various directions;
- Feedback Control: it uses feedback from the sensors to adjust the actuators' output. By applying forces in the opposite direction to the detected vibrations and motions, the system effectively cancels out or dampens the cabin's motions;
- Adaptive Control: some advanced systems use adaptive control techniques that continuously adapt to changing ship conditions and passenger preferences. They can optimize their performance based on real-time data and adjust to different sea conditions, cruise speeds, and passenger activities;
- User Interface: passengers may have control over the system through a user-friendly interface in the cabin. They can adjust the level of vibration control or turn it off if they prefer a more natural experience.

Potential benefits of applicating active vibration control in cruise ship cabins can include:

- Improved Comfort: Guests experience less discomfort and motion sickness, especially during rough sea conditions or when the ship is manoeuvring.
- Safety and Structural Benefits: These systems can also help protect the structural integrity of the ship by reducing the wear and tear caused by vibrations over time.

4. SMART MATERIALS FINISHING SOLUTIONS TO REDUCE HUMIDITY IN WET UNITS OF A CRUISE SHIP CABIN

Reducing humidity in these area is crucial to guarantee passenger comfort and preventing issues like mold growth and moisture damage. Several smart materials and technologies can be employed to achieve this target:

- Hygroscopic Coatings: they are designed to absorb moisture from the air. Applying these coatings to cabin surfaces, such as walls and ceilings, can help reduce humidity levels. These coatings could be designed to release the absorbed moisture back into the air when conditions are drier (Hickey et al., 1990);
- Moisture-Absorbing Fabrics: textiles treated with moisture-absorbing compounds can help absorb excess humidity from the air. These fabrics could be used for shower curtains, towels, and other cabin textiles (Wang, 2017);
- Membrane Dehumidification: these systems use selectively permeable membranes to allow moisture vapor to pass through while preventing liquid water from entering (Zhao, 2015);
- Control Systems: a centralized control system that monitors cabin humidity levels and coordinates the operation of various humidity-reducing technologies can ensure efficient and effective humidity management;
- Data Analysis and Feedback: collecting and analysing data on cabin humidity cevels and the performance of humidity-reducing technologies can provide valuable insights for continuous improvement and adjustment.

4.1. Self-cleaning surfaces

Often referred to as "hydrophobic" surfaces, are designed to repel dirt, water, and other contaminants, making them resistant to staining and facilitating easier cleaning. These can be achieved through the use of various technologies and materials (Liu, Jiang, 2012) like:

- Hydrophobic Coatings: designed to repel water, preventing water droplets from adhering to the surface. This not only prevents water spots but also helps to carry away dirt and contaminants as water rolls off (Schmidt et al., 1994);
- Photocatalytic Coatings Surfaces: when exposed to light, they can break down organic compounds and pollutants on the surface. This process helps to keep the surface clean by decomposing dirt and organic matter (Yoshida et al., 2016). Furter characterization will be provide in the next paragraph, with a specific focus on their application in HVAC components;
- Superhydrophobic Coatings: they go beyond hydrophobic coatings by creating a surface with extreme water-repellent properties. These coatings can cause water droplets to form near-perfect spheres and easily roll off the surface, taking dirt and contaminants with them (Wang et al., 2020);
- Self-Cleaning Glass: it is coated with a photocatalytic and hydrophobic layer that breaks down organic matter and allows rainwater to wash away dirt and debris (Chabas et al., 2008);
- Electrodynamic Surface Cleaning: some surfaces can be designed to generate an electrostatic charge that repels dust and particles, helping to keep the surface cleaner over time (Deputatova et al., 2018);
- Anti-Static Coatings: they can help preventing the arise of static charges able to attract dust and dirt, keeping the surface cleaner for longer (Al-Dahoudi et al., 2001).
- Oleophobic Coatings: Oleophobic coatings repel oils and grease, making them particularly effective for surfaces that come into contact with oily substances (Cao, Gao, 2010).

Applications of Self-Cleaning Surfaces in Interior Design can include:

- Wet unit surfaces: self-cleaning surfaces in bathrooms can prevent soap scum, mineral deposits, and water spots on fixtures and tiles;
- Windows and Glass: self-cleaning glass can help maintain clear visibility by repelling water and dirt, reducing the need for frequent cleaning;
- Furniture and Upholstery: self-cleaning upholstery can resist spills and stains, making furniture more durable and easy to maintain.

5. SMART MATERIALS FOR CABIN AIR IMPROVEMENT

Smart materials can play a significant role in improving room air quality by actively monitoring and addressing pollutants, allergens, and other contaminants (Grinshpun et al, 2006). Here are some types of smart materials, strictly related to the previous ones, that can be used for cabin air improvement:

- Photocatalytic coating in HVAC system: a photocatalyst, usually Titanium Dioxide, is applied as a thin coating on a surface within the air purification system, which is often part of a filter or a material that can be exposed to UV light. UV-C LEDs lamps emit ultraviolet light with a wavelength in the range of 254 to 365 nanometres, coinciding with the peak UV absorption of virus RNA (Nunayon et al., 2019). When this latter interacts with the photocatalyst, it triggers a photocatalytic reaction, generating highly reactive oxygen radicals, which break down and oxidize a wide range of indoor air pollutants, including volatile organic compounds (VOCs), bacteria, viruses, and odorous compounds (Zaleska et al., 2010);
- Air-Purifying Paints: these paints contain photocatalytic materials that react as described in the previous topic. Among paints currently available on the market them we can find also Activated Carbon Paints, which can adsorb and trap volatile organic compounds (VOCs) and odours from the air and Mineral-Based paints, which incorporate natural minerals like zeolites, which can neutralize certain pollutants, including ammonia and formaldehyde;
- Active Ventilation Systems: smart materials can be integrated into ventilation systems to actively filter and purify incoming air, removing contaminants before they enter the room.
- Intelligent Air Quality Sensors: smart sensors that detect pollutants, allergens, and other air quality parameters can trigger ventilation or purification systems for real-time air improvement.

6. SELF-HEALING FINISHING SOLUTIONS

Self-healing materials (SHM) can repair damage automatically without external intervention, potentially reducing the need for maintenance (Blaiszik et al., 2010).

They could be used in interior spaces to maintain aesthetics. For example, in cabins or public areas, self-healing coatings on furniture or wall surfaces could help minimize visible damage (White et al., 2001). Here are some examples of self-healing insulation materials and their characteristics:

- Microcapsule-based systems: they contain tiny capsules filled with a healing agent or polymer. When the insulation material is damaged, such as by a crack or hole, the capsules break, releasing the healing agent, which then fills the gap and solidifies, restoring the insulation's integrity;
- Shape Memory Polymers: as seen in the dedicated paragraph, they are materials that can "remember" their original shape and return to it when triggered by a specific stimulus, such as heat;
- Self-Healing Gels: they can autonomously repair themselves when damaged. These gels typically consist of a polymer matrix and a healing agent. When the material is damaged, the healing agent is released and reacts with the polymer to fill the damaged area and restore original properties (Zhao et al., 2014);
- Chemically Responsive Materials: certain materials are designed to be chemically responsive to environmental factors. For instance, they can sense changes in pH,

Table 11. Self-healing materials (SHMs) test methods

Testing category	Test method	Description	References
Microcapsule Healing Test	Microcapsule Preparation	Embedding of microcapsules containing healing agents within the material Evaluated parametres are: size, distribution, and content	J. Lee et al. (2021) White et al. (n.d.) B. Liu et al. (2023) Pan et al. (2022) Bekas et al. (2016) Ma et al. (2023)
	Damage Introduction	Damage is induced, and the release of the healing agent is monitored Techniques like indentation or scratching can be employed	
	Healing Assessment	Recovery of mechanical, thermal, or chemical properties is assessed using techniques such as tensile testing, thermal analysis, or spectroscopy	
Vascular Healing Test	Vascular Network Design	Design and fabrication of vascular networks within the material, ensuring proper distribution and connectivity	Selvarajoo et al. (2020) Shields et al. (2021) Hamilton et al. (2011) M. W. Lee et al. (2018)
	Damage and Healing	Controlled damage is introduced, and the response of the vascular system, including the release and distribution of healing agents, is observed	
	Characterization	Techniques like microscopy, imaging, or chemical analysis are used to characterize the healing process and the effectiveness of the vascular system	
Autonomous Healing Test	Inherent Healing Mechanisms	Identification and understanding of the inherent mechanisms responsible for autonomous healing	Arroyave et al. (2023) Mao et al. (2020) Gojević et al. (2023) Rahman et al. (2012)
	Damage Scenarios	Testing the material under various damage scenarios to observe how it autonomously repairs without external triggers	
	Performance Metrics	Quantifying the recovery in terms of mechanical, thermal, or other relevant properties without external intervention	
Durability	Ageing Tests	Evaluate the long-term stability and performance of the self-healing insulation material under various environmental conditions	Mirzamojeni et al. (2023) Haimei et al. (2023) Zhang et al. (2022)
Failure	Failure Analysis	failure analysis to understand the limitations and potential failure modes of the self-healing material	Mphahlele et al. (2017)

moisture, or temperature and initiate self-healing processes accordingly, often through chemical reactions that bond or seal damaged areas;

- Nanotechnology-Enhanced Materials: they are self-healing materials with nanoscale components. For instance, nano capsules filled with healing agents can be dispersed throughout the material to facilitate autonomous repairs (Amendola, Meneghetti, 2009);
- Carbon Nanotube Networks: they can be used to reinforce materials and provide self-healing capabilities (Joo et al., 2018). When damage occurs, the carbon nanotube network can redistribute stress and prevent further degradation;
- Microfluidic Systems: materials with embedded microfluidic channels can transport healing agents to damaged areas through a network of channels, facilitating autonomous repair (DeMello, 2016).
- Electrochemical Materials: they rely upon an electrochemical process to repair damage by redistributing ions and rebuilding material structures.

The following tables show the test method aimed at characterizing SHM main properties (Table 11).

7. CONCLUSION

In the cruise ship design field there are many constraints that limit the choice of materials and the application of cutting-edge technologies. However, through an analysis of the current state of thermo-acoustic insulation, to the optical and mechanical performance of surfaces, linked to sanitation and wear activities, it is possible to consider the introduction of adaptive solutions which can intrinsically react to external stimuli. The analysis of smart materials has highlighted how they can contribute to increasing safety and comfort on board, even if there could be problems related to the scalability of the solutions and the economic and their practical application feasibility. The taxonomy of smart materials and solutions presents, in a brainstorm-like attempt, a wide range of possible implications which, permeating from and into other areas of scientific research, could provide practical application in the more or less distant future.

DATA AVAILABILITY STATEMENT

The published publication includes all graphics and data collected or developed during the study.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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