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OPEN CELL METAL FOAM IN MODERN ENGINEERING APPLICATIONS: A REVIEW

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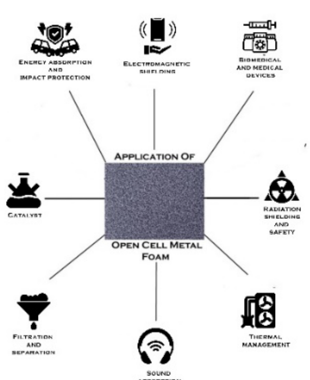
Graphical abstract



Abstract

Cell foam is a versatile material that has been employed in a wide range, of either structural or functional applications. The current review briefly explained an open cell foam (OCF) that can be made up from different materials i.e., ceramics, carbon, polymer and metal, depending on the applications being employed. Open cell metal foam (OCMF) appears to be in high demand and its applications have been extensively discussed in detail through this review. The OCMF possess unique properties like lightweight and porous structure that can be utilized in different fields such as thermal management, sound absorption, filtration and separation, energy absorption and impact protection, electromagnetic shielding, biomedical and medical device and other applications. OCMF seems to conquer most of the applications by considering characteristics of complex interior structure, high strength to weight ratio, large surface area and ability to absorb energy. The significant discovery from the literature is that the OCMF contributes into sustainability and has the potential to address limitations and challenges in emerging technologies and industries.

Keywords: Open cell foam, metal foam, porous metal, engineering applications

Abstrak

Sel berongga (OCF) merupakan bahan serba boleh yang diaplikasikan secara meluas sebagai aplikasi struktur atau fungsi. Artikelini menjelaskan OCFboleh dibuat dari bahan yang berbeza iaitu seramik, karbon, polimer dan logam bergantung pada aplikasi yang digunakan. Logam sel berongga (OCMF) dilihat mendapat permintaan yang tinggi dan aplikasi OCMF telah dibincangkan secara meluas melalui artikel ini. OCMF mempunyai sifat yang unik seperti struktur yang ringan dan struktur yang berrongga boleh diaplikasikan dalam pelbagai bidang seperti pengurusan haba, penyerapan bunyi, penapisan dan pengasingan, penyerapan bunyi dan perlindungan impak, perisai electromagnet, biomedik dan alat medik, serta aplikasi lain. OCMF dilihat lebih banyak diaplikasikan kerana mempunyai struktur yang kompleks, nisbah kekuatan kepada berat yang tinggi, permukaan yang luas dan keupayaan untuk menyerap tenaga.Penemuan yang ketara dalam literatur ini ialah OCMF dapat menyumbang kepada kemampanan dan berpotensi menangani kekurangan dan cabaran dalam teknologi dan industri yang baru.

Kata kunci: Logam rongga terbuka, logam berpori, logam berongga, aplikasi kejuruteraan

1.0 INTRODUCTION

Nature structures and appearances are fascinating and inspiring to many different fields and disciplines including engineers, architects, metallurgists, biologists, designers, and others. Nature is a promised design that is scalable, reliable, and efficient which involves various types of processes [1]. For example, the development of foam materials can be served from the inspiration of coral reefs. The design of foam material can be represented as functional and unique structural properties from the inspiration of the coral reef skeleton. Apart from that, the man-made materials of foam also, is a replication by mimicking the structural nature of bones or woods [2].

The innovation of foam technologies has been advanced where the foam can be divided into open cell foam (OCF) and closed cell foam (CCF). The structure of OCF consists of interconnected pores, which enable fluid to pass through. Comparatively, OCF is well-known for its lightweight, high surface area, and less dense properties [3]. Besides, this type of foam portrays a good characteristic such as mix fluids property, and its soft and sponge-like nature. Nevertheless, in the CCF, the pores are not interconnected, rather cell foam is divided into many isolated sealed cavities. It is characterized as strong, high density, low specific weight, and acoustic damping ability [4].

CCF is applied to flotation devices, insulation, packaging, gaskets, and seals. CCF is commonly used in life jackets, buoyancy aids, and pool noodles because the closed cells contain trapped air, which makes the foam buoyant and resistant to water absorption. Even if the outer layer is punctured, the trapped air in each cell keeps the object afloat. CCF provides effective thermal insulation due to the trapped air within its cells acting as an insulating barrier. It is used for pipe lagging, insulation walls and roofs of buildings, and cooler bags. In terms of gaskets and seals, CCF is ideal for creating tight seals because it forms an airtight seal when compressed. Applications include doors, windows, appliances, and automotive parts. In packaging, CCF serves as a protective packaging material because it cushions fragile items during shipping and resists water damage. This makes it suitable for electronic packaging and temperature-controlled shipping containers. The closed cell is chosen for these applications due to its water resistance, durability, and buoyancy [4].

The OCF can be employed in cosmetics, air filters, acoustic dampening, packaging, aerospace, automotive and biomedical engineering [3]. In cosmetics, OCF acts as applicators, for applying makeup, creams, and lotions due to its compatibility of interconnected pore structure. This structure allows the product to be absorbed by the applicator and then distributed evenly onto the skin [5]. In air filtration, OCF plays a crucial role in keeping the environment clean and hygienic. The vacant space in OCF allows air to pass through while effectively capturing dust, pollen, and other airborne particles. These filters find application in air purifiers, vacuum cleaners, and ventilation systems. OCF structure also makes it ideal for acoustic dampening. By absorbing sound waves, it contributes significantly to noise reduction applications including acoustic panels, soundproofing materials, and microphone windscreens. The cushioning and support properties of OCF make it a valuable material for various applications like furniture padding, mattress toppers, and sports equipment padding. The benefits of OCF like open structure, lightweight, low density, breathability, and flexibility make high demand of the OCF in many applications [6]. Hence, OCF holds promise for both structural and functional applications which lead to offering opportunities to explore mechanical, thermal, and acoustic properties.

Foam exhibits remarkable characteristics, including a high strength-to-weight ratio and exceptional energy absorption capabilities. However, despite significant advancements and technological developments, persistent challenges still hinder the full realization of foam's potential. This review paper provides a comprehensive overview of modern engineering applications, with a particular focus on OCF due to its versatility and unique benefits across various technologies and industries.

2.0 MATERIAL OF OPEN CELL FOAM (OCF)

Open cell foam being a synthetic cellular material consists of an interconnected network of ligaments or struts that form on the edge of a casually packed cell which evolve during the foaming process, the cells are regularly polyhedron from 9 to 17 faces when the foam is almost monodisperse [7]. The attractive properties of the foam are made possible by ligaments by creating an open and interconnected pore structure. Figure 1 shows a 3D model of OCF from X-Ray Computed Tomography (CT) scan consisting an interconnected ligaments and pores that resulting as a highly porous material. Previous study by Chukwuemeka *et al.* (2024) found that different pore density of OCF play a role in determining the surface area which correlate with the volume of ligaments [8]. Gibson and Ashby (1997) explained the ligaments in OCF could have different geometries that build up from thin-walled tubes and beams. The combination is crucial because it can affect the mechanical properties of foam in aspects of stiffness, energy absorption capability and compressibility [7].

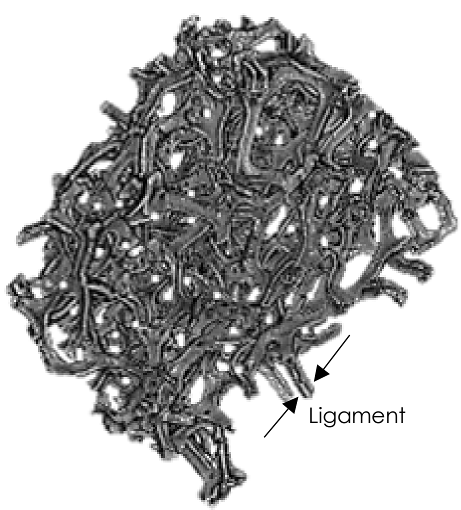


Figure 1 3D model of open cell metal foam (OCMF)

Apart from that, the selection of foam materials was made based on the suitability and functionality to be employed in certain applications. OCF can be made from metal [9,10], ceramics [11], carbon [12,13], and polymer [14, 15], depending on its applications [3]. Each material offers advantages and unique characteristics to be applied for specific applications.

Table 1 shows different materials of OCF with their applications across various industries. Their key advantage lies in their lightweight nature combined with functionalities like energy and sound absorption, and heat dissipation.

Table 1 Applications of open cell foam (OCF) using different materials

Materials	Applications	Advantages
Ceramics [11]	• Insulation • Structural components • Filters	• High-temperature resistance • Chemical stability
Carbon [12-13]	• Thermal insulation • Aerospace • Automotive • Electronics	• Low density • High strength • Thermal stability
Polymer [14-15]	• Cushioning • Packaging • Soundproofing • Filters	• Versatility • Cost-effectiveness
Metal [9-10]	• Aerospace • Automotive industry • Petrochemical industry • Building materials.	• Lightweight • Energy & Sound absorption • Heat dissipation • Electromagnetic shielding

These properties make them attractive to be used in various fields from cosmetics to engineering. like aerospace and automotive industries (for lightweight components and structures), petrochemical industry (components requiring energy absorption and heat dissipation), building materials (sound and thermal insulation) and electromagnetic shielding (due to good in electrical conductivity).

In cosmetics, Zouch Converters (2018) explained how the open cell structure has been used in makeup applicators like sponges, puffs, and eyelash protection foam to blend and distribute products evenly on the skin. These applicators are effective for applying creams and lotions, allowing controlled dispensing and ensuring the right amount is used. They can also be included as inserts in product packaging to help maintain the products' integrity and freshness. The absorbent and lightweight properties of foam offer numerous benefits, making it well-suited for the cosmetic industry. Additionally, industrial cosmetics leverage the remarkable skin-enhancing effects of foam, along with its easy maintenance and cleaning properties due to its unique structure [5].

Baillis *et al.* (2000) demonstrated the potential of open-cell carbon foam for applications involving radiative heat transfer. Their study presents a novel approach to determine the key spectral radiative properties (absorption coefficient, scattering coefficient, and phase function) of this material. These properties are crucial for understanding and predicting how open-cell carbon foam interacts with thermal radiation across a broad spectrum, ranging from visible to infrared wavelengths (0.1-15 am). The proposed method utilizes a combination of experimental measurements, and a theoretical model based on geometric optics and diffraction theory. Two types of measurements were employed i.e., directional-hemispherical (0.1-2.1 μm) and directional-directional (2-15 μm) transmittance and reflectance. This comprehensive approach ensures accurate determination of radiative properties throughout the desired wavelength range [12].

Ceramic sponges are open cell solid structures with advantageous properties, including low pressure drop, high specific surface area, relatively high heat transfer rates, and effective cross-mixing in fluid flow. When designing technical equipment, a homogeneous model can be employed to calculate heat transport within these sponges. The key parameter for this model is the two-phase thermal conductivity. Dietrich (2015) experimental results for two-phase thermal conductivity, both with and without flow, were obtained for various aluminium oxide (Al2O3) sponge types. The temperature range investigated extended up to 1000°C, where thermal radiation plays a significant role in heat transfer. These results enable the estimation of heat transfer performance in any ceramic sponges [16].

Many applications leverage the unique properties of OCF depending on either functionality or structural. Apart from that, the type of OCF material is important to ensure the purpose of OCF usage is achieved. Each of the materials in Table 1 have their own characteristics which make their suitability to be used in the respective fields.

In engineering applications, open cell metal foam (OCMF) has become a high demand because the porous structure has made it a lightweight material, which suitable in many fields like construction and aerospace industries. Weight being a very important and considerable factor in these industries, makes OCMF advantageous in lightweight packaging, padding, insulation, and grating [3]. Automotive industries use OCMF for thermal insulation due to the ability of OCF structure in creating thermal barriers. Soloveva *et al.* (2022) pointed out that porous materials like OCF are used in areas like construction, transport, gas absorption, power engineering and many more because of how stable and cheap the materials are [17].

Apart from that, OCMF provides a high surface area, which is especially advantageous in thermal management applications related to heat transfer [17]. Additionally, the pore size and distribution in open-cell foam are customized to meet the precise needs of each application, whether for efficient heat transfer or optimal product interaction. In addition, OCMF offers unique advantages in wide industries and its versatility lies in its ability to be customized for specific functionalities through material selection, pore structure, and overall design. Therefore, the OCMF was further discussed.

2.1 Open Cell Metal Foam (OCMF)

In 1925, metal foams were first made by Meller in the year 1951, John Elliott started improving the preparation method introduced or described by Meller. However, metal foams gained its highest popularity in research around the 1990s, which proves that metal foams have been around for decades and have widely applied in many industries due to its well-developed class of engineering materials, which can be produced by many techniques and various desired shapes [18].

The fascinating properties of OCMF include thermal conductivity, energy and sound absorption and high strength to weight ratio, had attracted many industry players to apply it in their processes. Besides, the lightweight, high surface area, and less dense properties also contributed to the wide applications in various industries. In comparison, its capacity to mix fluids, along with its soft, sponge-like nature, reveals that this material is highly suitable for many applications. The high strength-to-weight ratios give advantages to be applied in the construction, aerospace, and biomedical implants. Metal foams are highly recommended because of their extraordinary properties both physically and mechanically, like their high strength and toughness, high thermal and electrical conductivity, very low density, specific surface area with great ability to absorb energy, and low cost [6].

The metal becomes a hotspot material in OCF especially for absorption experiments due to its ability to absorb a higher amount of energy. OCMF has become a lighter material due to its foam structure and low-density properties [19]. Apart from this, the OCMFs were also considered among the best materials for high-temperature applications because owns a better thermal insulation and corrosion resistance properties [20].

OCMF can be fabricated using the method of solid-state processing (metallurgy), liquid state processing (melt), melt vapor processing and metal ion processing. The common method is metallurgy, where a space holder is used by mixing with powder of the metal and as well mixed with a binder and the purpose of mixing is to make sure of equal distribution of the space holder particles [2]. Powder metallurgies were developed at Fraunhofer Institute in Bremen Germany, and the process involves the mixing of metal powder with a blowing agent. This led to the mixture being compacted densely to form into desired shape. The foam structure was achieved after the compacted powder was sintered to bond the metal particles and decompose the blowing agent. The powder metallurgy method is not limited to only aluminum and its alloys, as the method can be used for zinc (Zn), brass, lead (Pb), tin (Sn), gold (Au) and many more metals.

Apart from that, metal foam can be produced by using a gas injection method which makes use of a blowing agent. Through this approach, the blowing agent is injected into a molten metal, and it creates gas bubbles which form the foam structure [21]. To produce the desired shape of the metal foam, sintering loose powder was employed and sintered by creating metal bonding in its structure with open cells. Furthermore, the electro-deposition technique, with the aid of electric current was used to deposit metal ions from selected electrolytes onto a mold, leading to the formation of the foam structure [11]. The fabrication of metal foams involves thoughtful design, material selection, and optimization of morphological features. These versatile materials continue to inspire innovations across industries, from aerospace to energy-efficient construction.

3.0 APPLICATIONS OF OPEN CELL METAL FOAM

OCMF has been employed in broad applications such as heat exchangers, catalysis, filtration, medical devices, energy, and sound absorption as shown in Figure 2 [22]. In terms of thermal management, Ozmat *et al.* (2008) show how OCMF's high porosity and large surface area promote heat dissipation and absorption and applications like heat exchangers, which help in enhancing efficiency in various industries (automotive, electronics). Heat sinks, draw away heat from electronic components and thermal insulation, maintaining desired temperatures in specific environments [22]. Commonly, the purpose of employing OCMF in various applications is to utilize its unique structure to become functional in absorbing, shielding, heat transfer, filtration, and implants as shown in Figure 1.

The large surface area of the OCMF could enhance heat transfer in heat exchangers [23]. Besides, the complex design of OCMF has improved catalyst effectiveness in catalyst application. The ability of this OCMF absorbing energy allows it to be applied in vehicles, car crumple zones, motorcycle helmets and bicycle frames. The foam absorbs collision energy, which significantly reduces the forces transmitted to the vehicle occupants. In building construction materials, the OCMF was incorporated with building structures to aid in absorbing the energy from earthquakes or explosions. Meanwhile, in electronics applications, deploying OCMF proves its effectiveness in safer packaging of delicate electronic components. It provides protection during transportation or accidental drops. In terms of soundproofing, OCMF is the most effective and excellent material for sounding walls, ceilings and engine compartments, the open cells successfully trap sound waves within the foam structure and through friction, which converts the sound energy into heat. Furthermore, the ability of foam to absorb vibrations makes it very valuable for isolating sensitive equipment, it improves and enhances overall system performance in many ways like preventing noise and potential damage [24].

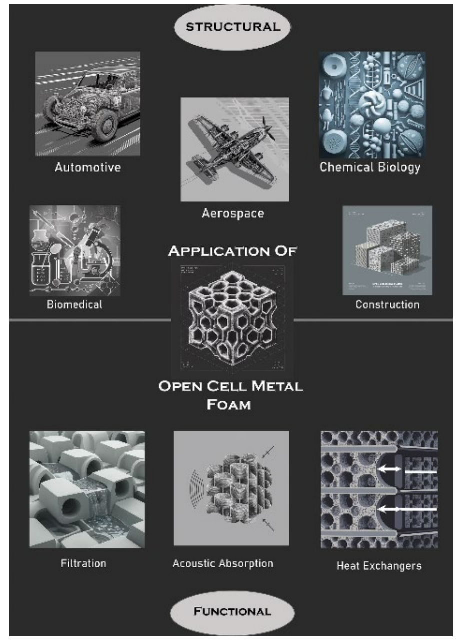


Figure 2 Application of open cell metal foam (OCMF)

The majority usage of OCMF is in engineering applications such as heat exchangers, energy absorption fuel cells, tubular reactors, heat sinks, filtration, recuperators, and condensers [2]. Foams with high porous metallic and ceramic are known for their properties like highly energy and sound absorption, Hence, the aim of current research is to provide a comprehensive overview of modern engineering applications using OCMF.

3.1 Thermal Management

Thermal management involves the practice of controlling and regulating temperature within a system to ensure optimal performance and reliability, as well as prevent further damage. Thermal management is essential in various fields, like automobiles for cooling down engines, transmissions, and brakes to prevent overheating. Apart from that, it is important to manage heat generated from electronics such as processors, graphics cards, and other components in devices like computers, laptops, and smartphones. Aerospace is inescapable of high-speed flight, and re-entry into the atmosphere including rockets, missiles, and spacecraft which are crucial to control the heat. Besides buildings and facilities have been rely on thermal management systems for regulating and cooling the indoor environment for occupants' well-being.

OCMF are revolutionizing thermal management across various engineering disciplines. Their unique combination of high surface area, low density, and efficient heat transfer properties makes them ideal for a diverse range of applications. Like enhancing heat exchanger performance, they excel as heat exchanger material due to their intricate network of pores. This structure promotes turbulence in the working fluid, leading to enhanced convective heat transfer. Additionally, the high surface area maximizes contact between the fluid and the foam, facilitating efficient heat exchange [22, 23]. Also, in terms of optimizing air-cooled condenser towers, OCMFs are finding increasing use in both regenerative and dissipative air-cooled condenser towers. Their highly porous structure allows for efficient heat dissipation to the surrounding air, reducing the need for additional cooling systems and lowering overall energy consumption. The lightweight nature and high thermal conductivity of OCMF make them ideal for compact heat sinks in power electronics applications. These foams efficiently dissipate heat generated by electronic components, improving device performance and reliability [24].

In the aerospace industry, the jet engine operating temperatures are only limited by the operating temperature of the turbine material. However, complex cooling schemes can be adopted to overcome overheated turbine components if the temperature exceeds. Azzi *et al.* (2004) suggested the use of an ultra-high temperature OCMF ring to be placed in front of the combustion area and the turbine section too, which may improve and mitigate the temperature from overheating. The mixing function of the metallic foam mitigates thermal cycling fatigue on turbine vanes and blades and subsequently contributes to an extended operational lifetime for the engine. Infrared imaging of aluminum foam samples with nominals of 5 and 10 pores per inch (PPI) effectively demonstrated the mixing role of the metal foam. Besides, by averaging hot and cool gases, the foam improved the temperature profile, and the pressure drop testing indicated that meticulous design consideration related to its pore size, ligament thickness, and foam thickness which could yield an ultra-high temperature OCF ring with minimal pressure drop and as well enhanced heat transfer capabilities [25].

Xiao *et al.* (2023) found a valuable understanding of, OCMF potential benefits and how making use of metal foam improves the heat transfer capabilities of the corrugated sandwich structure. Based on the results, the Nusselt number of metal foam and corrugated sandwich structure foam composite at a Reynolds number of 240 was enhanced by 51.3% and 102.3%, correspondingly and the study concludes that OCMF improved the thermal performance of the corrugated sandwich structure [26].

Wei *et al.* (2016) conducted an experiment on OCMF that could enhance heat sink for electronics cooling, as it helps to improve heat dissipation from electronic components. The result concludes that using metal foam increased the surface area of the heat sink wall, which helped in increasing the Nusselt number from 0.00676%. This study investigated everything about aluminum foam in heat transfer, by using a solid aluminum core to increase the surface area of the heat sink wall [27].

Arshad *et al.* (2022) conducted an experiment on the weak heat transfer performance of phase change materials (PCM) and how using OCMF proves an effective method of enhancing PCMs. The characteristics of metal foams improve the thermal performance of PCMs by rendering a higher conductive and sturdy structure. Their experiment proved how PCM metal foam composite thermally performs better (both heat transfer and heat storage capabilities) than PCMs [28].

Thomas *et al.* (2023) conducted a heat-transfer experiment to investigate how metal foam could enhance heat transmission between separated water streams at various temperatures. They found that the shell tube foam recuperator achieved a maximum heat transfer efficiency of 48.1%, compared to only 12.2% efficiency with a copper tube. Another finding was that the pressure drops across the external foam increased with the flow rate, ranging from 1.19 kPa at 1.0L/min to 7.36 kPa at 3.0L/min. The experiment conducted between hot and cold mass streams, with three different data groups, shell tubes with A356 foam, ZA27 foam, and exposed copper tubes. The results indicated that A356 foam heat exchangers demonstrated a significant enhancement in heat transfer compared to conventional copper tubes. In conclusion metal foam (A356 foam) proved to enhance heat transfer and is the best for the development of compact heat exchangers [29].

Metal foams have been found to be useful in thermal management applications due to their low density, high surface area to volume ratio, and high thermal conductivity, which significantly justified the reasons they are used in various applications, such as compact heat exchangers, solar thermal facilities, and thermal energy storage.

3.2 Sound Absorption

While metal foams weren't a major player, a combination of passive control techniques, early forms of active control, and regulatory efforts formed the foundation for noise pollution control before the 1990s. But since the 1990s, metal foam has made a great impact in sound absorption, as acoustic panels and baffles due to their ability to dissipate sound energy. The intricate network of pores allows for internal friction and air movement within the foam, effectively reducing noise levels [24, 30]. This makes them ideal for applications like concert halls, theaters, and recording studios, where minimizing reverberation and improving sound clarity is crucial [31]. This is also applicable in automotive noise reduction as it finds use in car interiors, lining vehicle panels, wheel wells, and engine compartments. This helps to mitigate road noise, engine noise, and wind noise, enhancing passenger comfort. Also, metal foams effectively absorb noise generated by industrial equipment like compressors, generators, and pumps. Their lightweight nature facilitates easy integration into noise enclosures [30]. In terms of aerospace applications, it contributes to noise reduction in aircraft and spacecraft by lining cabin walls, cargo compartments, and engine nacelles, leading to a more acoustically comfortable environment for passengers and crew, as well as dampen vibrations and reduce noise in electronic devices. They are used in speaker cabinets, computer chassis, and home appliances, applied to underwater structures like submarines and offshore platforms can absorb sound waves, thereby minimizing noise pollution within the aquatic environment [31]. The attractive structure and properties of metal foam enables it to be effective in reducing noise level [24]. The acoustic property of metal foam is basically related to micro-scale pore morphology.

OCMF has got its popularity in various acoustic applications, as it serves as an excellent material for sound absorption. The nature of OCMF materials like lightweight, resistant to high temperature and corrosion, and mechanically strongness is why Ni-based Inconel 625 superalloy foam works efficiently as sound absorbers in high temperature, and harsh environments for industry like aerospace. OCMF is best for sound absorption because of the open cell structure. An experiment conducted on IN625 foam proves that the sound absorption mechanism is governed by the viscous thermal losses due to the rigid foam skeleton structure [32].

OCMF proved to be effective in automotive noise control as it serves as a noise absorber. Teruna *et al.* (2020) experiment result proves that OCMF is an effective multifunctional noise reduction. They conducted a study on the noise reduction mechanisms of an OCMF trailing edge. The study examined the aeroacoustics of a porous trailing edge to study its noise reduction mechanisms. Numerical investigations were carried out for a NACA 0018 aero foil with three different types of trailing edge: a baseline solid trailing edge, a fully porous trailing edge, and a blocked-porous variant in which a solid core is added at the symmetry plane. Studies found that the regular porous trailing edge reduces noise substantially, particularly at low frequency, whereas the blocked variant retains similar noise characteristics as the solid one. The permeability of the porous trailing edge allows for acoustic scattering along the porous medium surface that promotes destructive interference, and in turn, attenuates far-field noise intensity [33].

In architectural acoustics, OCMF is used in controlling reverberation and sound quality. The foam can be found in walls, ceiling panels and suspended baffles, which helps in reducing echoes and reflections. Langlois *et al.* (2020) conducted a study of the acoustical properties of monodisperse open cell solid foam. The study includes the production of solid foam samples with good control of both pore size (0.2 to 1.0 mm) and solid volume fraction (6% to 35%). Acoustical measurements are performed by the three-microphone impedance tube method. The visco-thermal parameters, including viscous permeability, tortuosity, viscous characteristic length, thermal permeability, and thermal characteristic length, were determined for a certain number of foam samples. The visco-thermal parameters of body centered cubic (bcc) foam numerical samples are also calculated on the whole range of solid volume fraction (0.5% to 32%) using Surface Evolver and finite-element method calculations. Numerical results are then used to find approximate formulas of visco-thermal parameters. A systematic comparison between measurements and predictions of the Johnson-Champoux-Allard-Lafarge (JCAL) model using measured visco-thermal parameters as input parameters, reveals a consistent agreement between them [34].

In industrial noise control, OCMF is used in controlling the noise from machinery and other equipment. OCMF proved effective in controlling aerodynamic noise of an axial-flow fan, an elaborate experiment result confirmed the use of metal foam in reducing the tonal broadband noise (Xu *et al*., 2017). The study employed a configuration of semi-OCMF combined with a backing cavity to attenuate the tonal component, while an OCMF was used to absorb the broadband component. The visco-thermal parameters, including viscous permeability, tortuosity, viscous characteristic length, thermal permeability, and thermal characteristic length, were determined for an extensive number of foam samples. The study found that the tonal noise is greatly reduced by the semi-OCMF and the OCMF shows potential of absorbing the broadband noise [35].

OCMF was used in reducing noise in aircraft engines. Azzi *et al.* (2004) studied examines the potential of using OCMF as a refractory material in jet engines. The study found that OCMF has a high potential for use in jet engines due to its high porosity, high surface area, and high thermal conductivity. The study also found that OCMF can be used to reduce noise in aircraft engines by absorbing sound waves and reducing the amount of noise that is transmitted through the engine [25].

3.3 Filtration and Separation

The porous nature of OCMF makes it ideal for filtration [36]. In general, OCMF is ideal for filtration due to its highly interconnected network of pores, resulting in high porosity. This allows for efficient filtration by enabling the passage of fluid or gas through the foam while trapping and capturing contaminants or particles. The open-cell structure of metal foam provides a large surface area per unit volume, enhancing filtration efficiency by maximizing the contact area between the fluid or gas to be filtered and the foam material, promoting effective filtration and particle capture. OCMF can be designed with different pore sizes and thicknesses to create multistage filtration systems. This will allow for the trapping of particles of different sizes across multiple layers of the foam, which results in improved filtration performance and higher particle removal efficiency. Metal foams, particularly those made from corrosion-resistant metals such as stainless steel or nickel alloys, exhibit excellent resistance to high temperatures and various chemicals, making them suitable for filtration applications including harsh operating conditions. OCMF possess good mechanical strength and structural stability, maintaining their shape and filtration efficiency even under high flow rates, preventing collapse or particle breakthrough.

In terms of gas and liquid filtration, OCMF is used because the porous structure is effective in trapping impurities while the needed fluid passes through [37]. Kim *et al.* (2016) OCMF are widely used in applications where particulate and/or droplet capture is important [38]. This makes them valuable in water treatment, chemical processing, and oil filtration applications. Research by Płaczek *et al.* (2015) and Das *et al.* (2006) sheds light on the hydrodynamics of fluid flow through open OCMFs channels. Płaczek *et al.* (2015) focused on predicting gas void fraction, a crucial parameter in gas-liquid flow through OCMF channels. Their work adapted methods previously developed for porous media. Das *et al.* (2006) presented fundamental governing equations for fluid flow through OCMF. Their study validated various pressure drop prediction models against experimental data, offering valuable insights for diverse foam geometries. Also, while both studies contribute significantly to understanding OCMF behavior in filtration, their focus areas differ as Płaczek *et al.* (2015) provides in-depth analysis of gas void fraction prediction in OCMF and Das *et al.* (2006) emphasizes the fundamental equations governing fluid flow and pressure drop within OCMF. But together, these studies provide a comprehensive picture of OCMF behavior in gas and liquid filtration applications. [39, 40]

OCMF has been a subject of interest in air and water purification. In terms of air purification, air pollutants have caused so many environmental disasters like acid rain and haze for the past decades [41]. In the long term it has resulted in lung cancer and respiratory disease in human beings [42]. To resolve this, advanced air purification material was needed. Metal foam properties make it ideal choice, the three-dimensionally interconnected structure helps by enabling many active sites and as well small transfer path within a lower pressure drop [43]. In water purification, the properties of OCMF like high surface area and porosity enhanced the removal of contaminants during filtration. Apart from that, OCFs also can act as air and water filters in air and water purification. According to de Carvalho *et al.* (2023), OCMF's high surface area per unit volume and low density makes them very attractive as filters [44].

Advancement in the fuel cell technology for a cleaner power source has been ranking consistently high in research, and this is because fuel cells are ideal for replacing internal combustion engines and for power plants. Many researchers have investigated various ways to improve and solve proton exchange membrane fuel cells (PEMFC). The investigation was initiated on the pinhole in the membrane electrode assembly for the durability of PEMFC [45]. Then, to the cold-start phenomenon in PEMFC [46] and to the low pressure drop which decreases the reaction and efficiency of PEMFC [47]. This leads researchers to investigate the use of metal foam as a flow field and the experiments show that using a metal foam flow field produces better performance than the old graphite plate with a serpentine channel, better operating temperature at the membrane at (55–87 °C) and as well best polarization [48].

Open cell metal having high porosity 3D structure makes it a strong material for oil-water separation. Hu *et al.* (2018) designed and fabricated a metal foam based for oil-water separation, which is used to improve the conventional separator with metal foam possessing superhydrophobic and super oleophilic properties. The innovation addresses the challenges associated with both industrial wastewater and offshore oil spills [49]. Yu *et al.* (2019) conducted an experiment with magnetic polystyrene foam for the selective absorption of oils from oily wastewater; however, residual oils in its pores decreased the absorption rate. Zhou *et al.* (2019) enhanced this approach by using copper foam instead of magnetic polystyrene foam. They developed a novel copper foam with ordered hole arrays as catalyst support for a methanol steam reforming microreactor. This innovation significantly improved the hydrodynamics of gas and liquid flow in channels filled with ordered copper metal foams, showcasing the superior performance and practical benefits of metal foams in such applications [51].

Udayakumar *et al.* (2021) conducted an experiment on the absorption efficiency of polydopamine (PDA) coated copper foam towards various oils and reported that the PDA coated copper foam exhibited excellent separation performance for various oil/water mixtures and emulsions. The water and oil separation flux can reach 21,035 L/m².h and 14,500 L/m².h, respectively. The highest separation efficiency reached 99.6% for petroleum ether/water [52]. Wang *et al.* (2019) focused on fabricating superwetting copper foam for oil-water separation. They employed laser-heat surface treatment to alter surface wettability, achieving high separation efficiency and repeatability by exploiting opposite extreme wetting behaviors for water and oil [53]. Zhao *et al.* (2021) constructed a superoleophilic/superhydrophobic surface on copper (Cu) foam, demonstrating its strong capability for oil-water separation. Their approach offers a simple and effective method for separating oil-water mixtures [47].

3.4 Energy Absorption and Impact Protection

OCMF, with its exceptional energy-absorbing properties, serves as a critical protective material in various scenarios. During aircraft impacts or bird strikes, it acts as a buffer, safeguarding critical components. Additionally, it provides protective enclosures for explosive bolts and other pyrotechnic devices, preventing collateral damage. OCMF ensures safe containment of latch release mechanisms, minimizing the risk of unintended releases. In space applications, OCMF shields protect against micrometeoroid impacts, preserving spacecraft integrity. Furthermore, it enhances energy absorption in military vehicle seating, improving safety during impacts or explosions. Lastly, in explosive ordnance disposal (EOD), OCF effectively absorbs energy which reduces the impact force during controlled detonations.

Apart from the remarkable mechanical properties and lightweight nature of aluminum foam, Zhang *et al.,* (2021) have proven that the open cell nature of aluminum foam makes it an appealing choice for spacecraft landing buffering and energy absorption during deep space exploration. They established a cell-based model using Voronoi tessellation to study open cell aluminum foam. Also, the energy-absorbing properties of crash members in automotive collisions significantly impact the safety of passenger compartments and the fascinating properties of open cell aluminum foams like high strength-to-weight ratio and deformability, offer excellent crashworthiness while potentially reducing overall weight [19]. Kim *et al*. (2016) employed a multiscale framework to evaluate the crashworthiness of aluminum foam-filled components. By constructing a micromechanical model using x-ray microtomography, they characterize foam behaviour without physical tests. The validated model demonstrates that the foam structure effectively absorbs energy, outperforming hollow tube designs of equal weight [38].

Furthermore Davari *et al*. (2020) supported the motion as their study introduced an open cell aluminum foam as an energy absorber to ensure passenger safety in automobile and airplane accidents. Analytical equations of absorbed energy were extracted, and the analytical results had acceptable agreement with numerical and empirical ones. The graded nature of natural impact absorbers was used as a basis for the graded design of the helicopter seat impact absorber. Optimization methods, including a genetic algorithm and sequential quadratic programming algorithm, were used to create an optimum graded impact absorber that satisfied the standard requirements of the JAR-27 air standard. The designed impact absorber was then modeled in ABAQUS software to calculate the absorbed energy, acceleration, and force applied to the passenger and the Head Injury Criterion (HIC) for the protected passenger. According to the results, the graded foam satisfies all requirements for helicopters during emergency landing. The derived analytical equations can be used to study the energy absorption of other foams [54].

3.5 Electromagnetic Shielding

OCMF characterised by its intricate three-dimensional structure, offers unique properties for effective electromagnetic shielding. These materials seamlessly blend metallic strength with lightweight and energy-absorbing characteristics. Exploring the multifaceted applications of OCMF in electromagnetic shielding in this review and emphasizing its role in safeguarding sensitive devices and signals [55]. Ni *et al*. (2013) investigated the shielding effectiveness of nickel foam at different frequencies. They found that open-cell nickel foam exhibits good shielding performance across a wide range (1-18 GHz) due to multiple attenuation mechanisms (reflection, absorption, multiple scattering) [56]. In terms of material optimization. Lee *et al*. (2008) explored the impact of cell size and pore wall thickness on the shielding effectiveness of copper foam. Their results suggest that smaller cell sizes and thicker pore walls enhance shielding performance [57]. Zhao *et al*. (2017) studied the use of metal foams coated with carbon nanotubes (CNTs) for enhanced shielding. They observed a synergistic effect, where CNTs improve both absorption and reflection properties [58]. Giusto *et al*. (2017) proposed the use of open-cell metal foams for electromagnetic shielding in electronic devices. Their study highlights the potential for lightweight and efficient electromagnetic interference shielding solutions [59].

Electromagnetic interference (EMI) shielding is essential for preserving electronic circuit performance. It mitigates disruptions caused by external electromagnetic waves. EMI can occur through various modes like, Conducted EMI (via conductive paths). Radiated EMI (through open space). Capacitive EMI (between closely spaced conductors) and Magnetic EMI (like capacitive coupling).

Kumar *et al*. (2019) presented a simple and cost-effective method for preparing lightweight open cell aluminum foam by impregnating aluminum powder into a substrate polyurethane foam template. The aluminum powder impregnated polyurethane foam was converted into open cell aluminum foam by several heat treatments under an inert atmosphere and reduced atmospheric pressure. The open cell aluminum foam prepared by this sacrificial template technique was found to possess a compressive strength of 6.2 MPa. The electromagnetic interference shielding of aluminum foam with a relative density of 0.22 was found to be −44.6 dB. Their work proves how OCF is most acceptable in this term [60].

3.6 Biomedical and Medical Device

OCMF inspired by the optimized structures by nature, provides substantial benefits for biomedical implant applications. Their cellular structure closely resembles cancerous bone, making them potential candidates for future implants. Biocompatible materials, such as titanium and Ti-6A1-4V, allow better interaction with bone due to bone growth into porous surfaces, and efficient fluid transport. Additionally, tailoring the elastic modulus of foam metals to match natural bone minimizes elastic mismatch, improving overall implant performance [61].

Like in orthopedic implants, the lightweight and biocompatibility offers promise for bone repair. Titanium OCFs are particularly interesting for orthopedic implants due to their biocompatibility, as they promote osseointegration and osteoconduction. While for the bone-like stiffness, their mechanical properties resemble natural bone [62,63]. Also, their porous structure allows for cell growth and interaction, making them suitable for implants and their low density makes them effective for insulation.

Recent studies have shown significant advancements in the preparation methods of biodegradable metallic foams for biomedical applications. Oriňaková *et al*. (2021) discussed the recent trends and progress in synthesizing porous magnesium (Mg), iron (Fe), Zn, and their alloys, specifically aimed at orthopedic applications. These materials, known for their biocompatibility, facilitate better interaction with bone, promoting bone growth into porous surfaces and efficient fluid transport. Tailoring the elastic modulus of these foam metals to match natural bone helps to minimize elastic mismatch, thereby enhancing overall implant performance [64].

Agbedor *et al*. (2021) highlighted the effects of processing parameters on the structure and mechanical properties of porous Mg-based foams. These foams, utilized for bioresorbable implants, carbon dioxide (CO_2) trapping systems, filters, heat exchangers, and absorbent panels, require careful control of processing parameters such as sintering temperature, pressure, and cooling rate. By tailoring these parameters, researchers can achieve the desired pore morphology and mechanical strength, making these materials suitable for various biomedical applications, including orthopedic implants where their lightweight and biocompatibility offer significant advantages [65].

Apart from that, surface modifications play a vital role in enhancing the biocompatibility and degradation properties of biodegradable metallic foams. Oriňaková *et al*. (2021) discussed the progress in designing advanced degradable metallic biomaterials with various coatings, including polymer, inorganic ceramic, and metallic. These surface modifications promote osseointegration and osteoconduction, making them particularly interesting for orthopedic implants. The porous structure of these foams allows for cell growth and interaction, further enhancing their suitability for biomedical applications. Despite challenges in achieving uniform coatings, these modifications improve the performance of metallic foams, ensuring they meet the stringent requirements of medical implants.

3.7 Other Applications

3.7.1 Catalyst

The automotive industry requires high temperature resistant materials with high permeability and greater strength for catalytic converting. OCMF made of corrosion-resistant steels such as iron-chromium-aluminum (FeCrAl) alloys are interesting for catalysis due to their high inner surface and strength, as well as they save material and increased durability compared to conventional bulk catalysts [66,67].

Summa *et al*. (2024) optimized an OCF based nickel-magnesium-aluminum (Ni-Mg-Al) catalyst for enhanced carbon dioxide (CO2) hydrogenation to methane, showcasing the potential of OCMFs in catalytic processes [68]. Additionally, Liu *et al*. (2019) also underscores the potential of OCMFs in catalysis. The researchers developed a novel copper foam with ordered hole arrays, tailored for use as a catalyst support in methanol steam reforming microreactors. This innovation significantly enhanced the hydrodynamics of gas and liquid flows in channels filled with OCMFs, demonstrating improved performance and efficiency in catalytic processes [69].

Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM (2023) listed some of the applications for OCMFs, which include corrosion-resistant catalyst carriers for automotive engineering, cleaning of industrial exhaust gases, vanadium-chromium (VCR) catalysts, selective oxidation, reactors for hydrogen production, and filters for soot particles. They are used in various lightweight structures like aerospace components, thermal and sound insulation, and energy storage.

3.7.2 Radiation Shielding and Safety

North Carolina State University (2015) reported lightweight composite metal foams are effective at blocking X-ray, gamma rays and neutron radiation [70]. The other applications that can be employed include nuclear safety, medical technology applications and space exploration. Rabiei *et al*. (2015) demonstrated that lightweight composite metal foams could efficiently block X-rays, gamma rays, and neutron radiation, in addition to absorbing the energy of high-impact collisions. The research highlighted the potential of these foams for developing safer systems for transporting nuclear waste, creating more efficient spacecraft designs, and offering new shielding options for CT scanners [71]. Further research conducted by McBlief (2016) showed that composite metal foams could provide structural support, protect against high impacts, and offer effective radiation shielding. The high-Z steel-steel foam was particularly effective at blocking low-energy gamma rays and neutron radiation [72].

3.7.3 Water Treatment

Furthermore, for environmental applications OCMFs are used for water treatment. Hassein-Bey *et al*. (2023) investigated the fluid flow through zinc OCFs produced by the Excess Salt Replication (ESR) process. These porous materials, with porosities ranging from 46% to 66%, were proposed as structured catalysts for wastewater treatment. The study identified that airflow in ESR foams was dominated by the "strong inertia regime," and calculated permeability and inertia coefficients for various samples [73]. Yang *et al*. (2022) conducted an experimental study on capillary microflows in high porosity OCMFs. The research specifically focused on the wicking characteristics and their potential applications in thermal management systems. The findings underscore the critical role of surface properties and capillary performance in these materials, suggesting significant implications for their use in water treatment applications [74].

4.0 CHALLENGES AND FUTURE DIRECTIONS

Practically, OCMF's attractive properties make it a versatile material with a wide range of applications. However, there are still some challenges and limitations yet unsolved, like the manufacturing process, the production of OCMFs is energy intensive and requires high temperatures and pressures, also the process is expensive and requires exotic metals. The availability of low-cost manufacturing processes for mass production is still limited [75], and OCMFs are prone to fail easily under tensile mechanical load [76].

Despite the challenges and limitations of OCMF, there are still many potential areas for future research and development. These include improving manufacturing processes to make them more cost-effective and less energy-intensive, improving the mechanical properties of OCMF to make them more durable and resistant to failure under tensile mechanical load, and exploring new applications for OCMF in fields such as biomedical devices, sound absorbers, and vibration-damping materials.

Research has shown that methods like controlled crystallization and particle reinforcement can enhance the mechanical properties of materials, making them more durable and resistant to failure under tensile mechanical load [77]. For instance, the study on Cobalt-Chromium-Iron-Nickel-Titanium (CoCrFeNiTi) high-entropy alloy demonstrated that the synergistic effect of two types of η phase significantly improved its mechanical properties [78]

OCMF represents a promising frontier in sustainable materials, with their unique properties poised to revolutionize various sectors. By addressing economic, social, and environmental challenges, OCMF contributes significantly to the Sustainable Development Goals (SDGs). In terms of economic efficiency, it significantly reduces the weight of components in transportation (e.g., cars, airplanes) and construction (buildings, bridges), with the benefits of improved fuel efficiency, lower operating costs, reduced greenhouse gas emissions and streamlined manufacturing processes [79]. OCMF exhibits exceptional strength and durability compared to traditional materials, with implications for extended product lifespans. reduced maintenance needs and fewer replacements, leading to cost savings. For social impact, OCMF contributes to cleaner air and water through their use in air and water filtration systems and in the medical and biomedical field, OCMF finds its application in bone implants, because of its lightweight structure and compatibility with human tissue [80]. Additionally, the lightweight nature of OCMF components enhances safety in various industries, as lighter tools and equipment reduce physical strain and minimize work-related injuries. While for environmental benefits, OCMF's lightweight properties improve fuel efficiency, resulting in lower energy consumption and reduced carbon footprint. Notably, it excels in thermal management, enhancing energy efficiency in buildings and industrial processes. The high strength-to-weight ratio of OCMF allows for less material compared to traditional methods, with the implications of reduced resource consumption and minimized waste generation. Also, many OCMFs are readily recyclable, minimizing their environmental impact at the end of their service life. OCMF possesses a very homogenous structure, which guarantees constant characteristics in wide-ranging areas [81].

5.0 CONCLUSION

In conclusion, OCMF represents an evolving material with significant potential in a broad range of applications. OCMF's unique combination has many uses, including thermal management applications, sound absorption, filtration and separation, energy absorption and impact protection, and biomedical and medical device applications. In the field of thermal management, OCMF's high surface area-to-volume ratio and excellent heat dissipation capabilities make it ideal for use in heat exchangers and cooling systems. Its sound absorption properties are beneficial for reducing noise pollution in urban environments and enhancing acoustic comfort in buildings and transportation systems. Additionally, OCMF's ability to filter and separate gases and liquids is invaluable for industrial processes and environmental protection. The energy absorption and impact protection characteristics of OCMF make it a preferred material for automotive and aerospace industries, where safety and efficiency are paramount. In the biomedical sector, OCMF's biocompatibility and ability to mimic the structure of natural bone have led to its use in orthopedic implants and other medical devices, improving patient outcomes and quality of life. Future research and development should focus on optimizing manufacturing processes to enhance the cost-effectiveness and sustainability of OCMF. Additionally, exploring new applications and further improving the mechanical properties of OCMF will continue to drive innovation and expand its use across various industries.

Overall, the versatility and potential of OCMF position it as a key material for addressing current and future engineering challenges, contributing significantly to the achievement of Sustainable Development Goals (SDGs) and promoting a more sustainable and efficient future.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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