Review of $Ti_3C_2T_x$ MXene Nanofluids: Synthesis, Characterization, and Applications

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Received: 15 April 2024 | Revised: 25 April 2024 | Accepted: 30 April 2024

DOI: https://doi.org/10.48084/etasr.7504

ABSTRACT

MXene-based nanofluids are important because of their thermal and rheological properties, influencing scientific and industrial applications. MXenes, made of titanium carbides and nitrides, are investigated for

nanofluid enhancement. This review covers MXene nanofluid creation, characterization, and application. To produce nanoscale MXene particles, two-dimensional materials are dissolved and dispersed in a base fluid. The stability and efficacy of MXene nanofluids depend on production methods, such as chemical exfoliation, electrochemical etching, and mechanical delamination. Improved heat transfer coefficients and thermal conductivity from MXene nanofluids help resolve heat transfer, energy efficiency, and thermal control problems. This extensive review also addresses long-term safety and the necessity for standardized characterization methodologies, helping researchers optimize MXene-based nanofluids in many technological fields.

Keywords-MAX phase; MXene; nanofluid; thermal conductivity

I. INTRODUCTION

Continuous economic growth has resulted in a steady amelioration in the living standards of individuals, accompanied by an extraordinary surge in energy consumption. Consequently, this phenomenon has prompted dynamic advancements in the field of energy. The enhancement of heat transfer efficiency has become a pressing requirement in energy-related applications. This challenge has been partially addressed by the introduction of nanofluids in [1]. Nanofluids consist of solid particles that are incorporated into fluids to provide a stable and homogeneous mixture. As the thermal conductivity of the nanoparticles is frequently higher compared to that of the base fluid, the overall thermal conductivity of the system increases when incorporating solid particles [2]. This, in turn, enhances the overall thermal performance. Nanofluids have been developed as a captivating and promising field of study situated at the convergence of nanotechnology and fluid dynamics, presenting a wide range of potential applications in diverse industries [3]. Research studies on two-dimensional nanomaterials have gained significant attention, leading to the discovery of a new transition metal substance called MXene. MXene is typically created through the selective etching process of the MAX phases, where the A layer of the MAX phases is etched through chemicals. The nomenclature "MAX phases" is derived from its chemical composition, specifically denoted as $M_{n+1}AX_n$ [4]. In this notation, M signifies a transition metal element from the periodic table, A represents a main group element from group III or IV, and X denotes either carbon or nitrogen. The value of n can be 1, 2, or 3. The layered hexagonal symmetric structures of all identified MAX phases consist of $M_{n+1}X_n$ layers that are sequentially intercalated with A [4].

This review not only focuses on synthesis and characterization aspects, but also explores the various applications of MXene nanofluids in multiple industries. This study aims to explore the diverse applications of MXene nanofluids, ranging from enhancing the heat transfer in electrical devices and improving the cooling efficiency in the automotive industry to their potential use in renewable energy systems.

II. SYNTHESIS OF MXENE

More than 20 distinct MXenes have been produced following the process of selectively etching certain atomic layers from precursor materials consisting of layered carbides, nitrides, or carbonitrides [5]. The etchants can be categorized primarily into two groups: acidic solutions that incorporate fluoride ions (such as HF, a combination of NH_4HF_2 or HCl and LiF) and salts that contain fluorine ions (such as NaF, NH_3F, LiF, or KF) [6]. In the initial step, the separation of the MXenes from the MAX phases is achieved through a process that involves the immersion of MAX phases in particular acids, which eventually leads to the disruption of the M-A bonds. In this procedure, it is necessary to have a specific duration for corrosion and complete agitation. $Ti_3C_2T_x$ was the first MXene synthesized at room temperature by the immersion of Ti_3AlC_2 powders in 50% concentrated hydrofluoric acid (HF) for 2 hours [7]. In [8], a solution consisting of lithium fluoride (LiF) and hydrochloric acid (HCl) was successfully employed with enhanced safety properties. This solution was used to immerse Ti_3AlC_2 particles for 24 hours at a temperature of 35°C, which led to the formation of $Ti_3C_2T_x$. A summary of MXene synthetization can be seen in [9]. Typically, the etching parameters necessitate a modification by the M atom and the n value in the chemical composition denoted as $M_{n+1}AX_n$.

III. MXENE NANOFLUID PREPARATION

The two primary approaches in the field of nanofluid development are the one-step and two-step methods [10]. Through the one-step method, nanoparticles are simultaneously created and dispersed across a fluid medium without going through any steps, such as drying, storing, or dispersing multiple nanoparticles. However, the elevated production cost can be connected to the intricate classification of the preparation procedure [9]. The latter process, which is straightforward and low-cost and is frequently adopted to create nanofluids, includes precisely and proportionately introducing the nanoparticles created into the base fluid [11]. The one-step technique offers significant benefits in terms of producing a high purity and an appropriate dispersion of nanoparticles. However, it also presents drawbacks, such as increased complexity and potential scalability issues. On the contrary, the two-step strategy is favored when the focus is placed on the opportunity to choose materials, cost efficiency, and scalability, even if further processing is required to prevent clumping and contamination. In [12], the one-step and two-step methods were compared, finding that it does not matter which technique is used, but stability plays a crucial role in improving performance. As far as it is known, most MXene nanofluids have been synthesized deploying the two-step approach [9]. Table I provides a comprehensive overview of the existing $Ti_3C_2/Ti_3C_2T_x$ MXene variants, base fluids, concentration levels, and preparation methods. The details shown in this table indicate that most MXene nanomaterials are derived from $Ti_3C_2/Ti_3C_2T_x$, obtained through the etching process of Ti_3AlC_2. Thus, it can be inferred that the prevalent MXene nanomaterials are mostly derived from $Ti_3C_2/Ti_3C_2T_x$, achieved by etching Ti_3AlC_2.

There is a potential for significant improvement in the effectiveness of heat transmission if using MXene nanofluids. MXenes can significantly improve the thermal conductivity of the base fluid due to their unique characteristics, playing a key role in making heat transfer more efficient [13]. In addition, MXenes might be able to work well as stabilizers, preventing nanoparticles from sticking together and ensuring that the nanofluid stays stable over time [14]. These characteristics render MXene nanofluids a highly desirable option for applications that prioritize effective heat transfer, such as those found in electronics and power production systems.

TABLE I. MXENE NANOFLUID PREPARATION METHOD

Nano-material	**Base fluid**	**Concentration**	**Preparation Method**	**Ref.**
Ti_3C_2	Olein palm oil	0.01-0.2 wt.%	A hot plate was utilized to agitate and synthesize nanofluid for 30 minutes. The nanofluid underwent ultrasonication for one hour.	[15]
Ti_3C_2	Silicon oil	0-0.1 wt.%	A hot plate was utilized to agitate and synthesize nanofluid for 30 minutes. The nanofluid underwent ultrasonication for 30 minutes.	[16]
$Ti_3C_2T_x$	Water	5-60 ppm	Surfactant Sodium Citrate was introduced and subjected to ultrasonication for 20 minutes.	[17]
$Ti_3C_2T_x$	Water	10-200 ppm	TritonX-100 was added and ultrasonication for 1 hour	[18]
$Ti_3C_2T_x$	Ethylene glycol	0.5-5.5 vol%	Ultrasonication for 3 hours	[19]
Ti_3C_2	water	0.0005-0.05 wt.%	A hot plate was utilized to agitate and synthesize nanofluid for 30 minutes. The nanofluid underwent ultrasonication for one hour.	[20]

IV. THERMAL CONDUCTIVITY OF MXENE NANOFLUIDS

The applicability of nanofluids in industrial applications is greatly influenced by their thermal conductivity [21]. Most of the time, nanoparticles are introduced to fluids to improve thermal conductivity and maximize heat transmission. Compared to spherical nanoparticles, those with a large specific surface area and aspect ratio demonstrate improved thermal network formation capabilities, allowing effective heat transmission in preset directions and ultimately ameliorating heat transfer efficiency [22]. The hydrophilic qualities of MXenes also play a certain part in the interaction between base fluids and nanoparticles, resulting in the formation of a liquid layer at the molecular level [9]. The enhanced structural organization of the liquid layer around the nanoparticles leads to an increase in the average distance traveled by the particles in the fluid, facilitating the efficient propagation of phonons [9]. This phenomenon contributes to an augmentation in thermal conductivity. The rise in temperature causes an increased Brownian motion of the nanoparticles in suspension, which in turn leads to a greater possibility of particle collisions [23]. Thus, this random thermal motion improves thermal conductivity. In [15], a comparison was carried out between the impact of temperature and nanoparticle concentration on the enhancement of the thermal conductivity of nanofluid, using palm oil as a base fluid to disperse MXene nanoparticles. The findings revealed that the increase in MXene concentration had a more pronounced effect on thermal conductivity. In [16], a similar finding was attained, as the impact of nanoparticle concentration on MXene-integrated silicone oil-based nanofluids had a more pronounced influence on the increase of thermal conductivity than on temperature increase. Figure 1 portrays the MXene nanofluid process and the rise in thermal conductivity as the temperature increases [24]. Hence, the predominant mechanism of bulk fluid transport exhibited by MXene nanoparticles was found to be more pronounced compared to the influence of Brownian motion, which aligns with the findings from other studies [25]. Furthermore, the increase in thermal conductivity observed at normal room temperature was comparatively lower than the increase at elevated temperatures. The lack of a substantial impact of the Brownian motion at ambient temperature was the underlying cause of this result. As the fluids contain chain mechanisms, the thermal performance of the whole system is significantly improved [26]. Both the thermophoresis effect and the Benard-Marangoni effect can be affected by the interactions of these chain processes [27]. In addition, the nanofluids themselves exhibit an inherent enhancement in their thermal conductivity. In general, the introduction of MXene nanoparticles and an increase in temperature will both contribute to an increase in the thermal conductivity of nanofluids. MXenes are a two-dimensional family of materials that have been observed to exhibit extraordinary thermal conductivity [28], concluding that this phenomenon occurred as a direct result of the MXene thermal conductivity property.

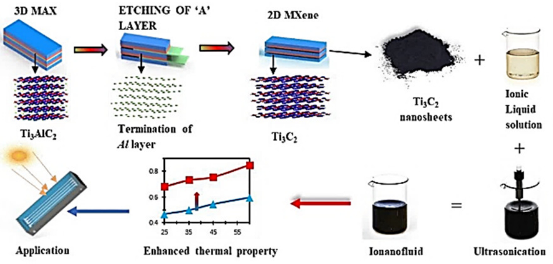

Fig. 1. Preparation of MXene-based nanofluids and their application [24]. Reproduced under open access CC BY 4.0 license.

V. VISCOSITY OF MXENE NANOFLUID

Viscosity is an intrinsic characteristic of fluids that emerges as the internal resistance to flow and significantly influences heat transfer processes. Multiple studies have disclosed that the viscosity of the MXene nanofluids remains remarkably stable despite the shear rate applied to the fluid [29]. Additionally, there is a correlation between the shear rate and the shear stress, which is essentially linear. This indicates that MXene nanofluids display Newtonian fluid behavior [19]. In addition, the viscosity of the MXene nanofluid is primarily influenced by changes in temperature. In [15], it was found that the viscosity of MXene-integrated palm oil-based nanofluids, with mass fractions ranging from 0 to 0.20 wt.%, did not manifest significant changes at certain temperatures. In [16], a similar finding was presented, where the addition of MXene to silicone oil at low concentrations resulted in a consistent viscosity in all nanofluid samples. In [19, 30] the effect of MXene concentrations, ranging from 0-1 vol% and 0-0.2 vol%, on the viscosity of nanofluids based on ethylene glycol and propylene glycol was investigated. The findings revealed a decrease in viscosity as particle concentration increased. The formation of hydrogen bonds between the molecules of ethylene glycol and propylene glycol is the primary factor that determines the viscosity of the two substances. The introduction of MXenes at low concentrations results in the perturbation of hydrogen bonding interactions amongst the constituent molecules of the underlying liquid.

In summary, as the temperature increases, the viscosity decreases due to the increased movement of the nanoparticles and the weakening of the intermolecular interactions [31]. In general, an increase in the nanoparticle concentration was seen to result in a rise in viscosity.

VI. APPLICATION OF MXENE NANOFLUID

The optical characteristics of MXenes, in conjunction with their notable physical attributes, make them particularly attractive for application in photovoltaic (PV) thermal systems and solar thermal collectors [32]. The main function of the PV module in a PV/Thermal (PV/T) system is the effective conversion of incident light energy into electrical energy [33]. The heat collector component is responsible for concurrently collecting residual light energy and heat produced by PV cells [34]. In [16], a numerical analysis was carried out to evaluate the performance of MXene/silicone oil nanofluids in a Concentrated PV/T (CPV/T) system. The results displayed that an increase in the sun concentration levels was associated with a decrease in both electrical and thermal efficiencies. This can be attributed to the disparity between the increase in the input energy and the generation of thermal and electrical energy. It was discovered that increasing the amount of MXene nanoparticles added to the silicone fluid increased both the thermal efficiency and the electrical efficiency of the system. An increased density of nanoparticles and higher solar irradiation were shown to be associated with a more substantial reduction in the average temperature of the PV module, thus promoting enhanced cooling and overall performance improvement.

In [20], the use of low-concentration MXene/water nanofluids in a hybrid PV/T system led to greater overall performance compared to a conventional PV/T system. Higher nanoparticle concentrations resulted in lower electrical energy production and higher thermal energy production, due to the increased absorption of nanofluids. Therefore, it was determined that MXene nanofluids possess a superior capability to harness solar energy compared to conventional fluids, rendering them ideal for application in scenarios involving high and medium temperatures. Furthermore, the optimization of both nanoparticle size and shape, along with the careful selection of suitable surfactants, are essential factors that must be considered to attain consistent performance. In [35], a thorough evaluation of solar collectors equipped with three different cavity receivers (hemispherical, cubic, and cylindrical) was conducted. This evaluation investigated MXene/soybean oil nanofluids employing both numerical models and experimental studies. The results revealed that the hemispherical solar collectors demonstrated the highest degree of thermal efficiency. The nanofluids exhibited the most significant enhancement effect when subjected to high levels of solar irradiation and low volume flow rates.

In conclusion, the utilization of a heat transfer fluid facilitates the cooling of the posterior portion of the cellular structure. PV/T systems are deemed appropriate for scenarios where there is a need for the concurrent production of both thermal energy and electrical power [36]. The system's efficiency can be broken down into two categories: electrical and solar thermal. The efficiency of the entire system is significantly affected by the choice of the working fluid. Nanofluids have the potential to increase the effectiveness of photovoltaic/thermal systems since they outperform traditional fluids, such as water and oil, in terms of thermal performance.

VII. CONCLUSION

In summary, $Ti_3C_2T_x$-MXene shows great promise in improving the efficiency and capacity of solar energy storage systems. Its two-dimensional structure and customizable surface functions improve electrical conductivity and electrochemical characteristics. The increased charge storage and transfer properties of $Ti_3C_2T_x$-MXene make it a desirable option for more efficient and durable solar energy storage systems. This breakthrough could increase the adoption and optimization of renewable energy, which are essential for sustainable energy solutions. As researchers continue to refine synthesis procedures and improve characterization methods, such as specific heat and photothermal properties, the MXene nanofluids are foreseen to have a promising future, with their expected potential extending to environmentally sustainable and economically advantageous technologies.

ACKNOWLEDGMENT

The authors would like to thank the University Malaysia Pahang Al-Sultan Abdullah for providing a research grant under no. UIC230821 and RDU232409.

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