Journal of Molecular Liquids 371 (2023) 121077

Contents lists available at ScienceDirect

Journal of Molecular Liquids

journal homepage: www.elsevier.com/locate/molliq

# Current advancements towards the use of nanofluids in the reduction of $CO_2$ emission to the atmosphere

Ying Chen [a], Azher M. Abed [b,*], Al-Behadili Faisal Raheem [c], Abdulmalik S. Altamimi [d], Yaser Yasin [e], Waheed Abdi Sheekhoo [f], Ghassan Fadhil Smaisim [g,h], Amer Ali Ghabra [i], Nesreen Ahmed Naseer [j]

[a] Chongqing academy of governance, Jiulongpo district, Chongqing 400039, China
[b] Air conditioning and Refrigeration Techniques Engineering Department, Al-Mustaqbal University College, Iraq
[c] University of Ahl Al Bayt, Karbala, Iraq
[d] Department of Pharmaceutical Chemistry, College of Pharmacy, Prince Sattam Bin Abdulaziz University, PO Box 173, Alkharj, 11942, Saudi Arabia
[e] College of Medical Technology, Al-Farahidi University, Iraq
[f] Department of Optical Techniques, AlNoor University College, Bartella, Iraq
[g] Department of Mechanical Engineering, Faculty of Engineering, University of Kufa, Iraq
[h] Nanotechnology and Advanced Materials Research Unit (NAMRU), Faculty of Engineering, University of Kufa, Iraq
[i] Al-Amarah University College, Al-Amarah, Iraq
[j] Mazaya University College, Iraq

ARTICLE INFO

*Article history:*
Received 25 October 2022
Revised 9 December 2022
Accepted 13 December 2022
Available online 16 December 2022

*Keywords:*
Nanofluids
$CO_2$ separation
Greenhouse gases emission
Enhancement mechanisms

ABSTRACT

Development of novel, efficient and cost-effective strategies to diminish the permanent emission of greenhouse gases (GHGs) to the atmosphere has been an indisputable concern for scientists. $CO_2$ is known as the most prominent GHG, which its abnormal amount in the atmosphere accelerates the occurrence of unfavorable environmental events such as acid rain, ocean acidification, global warming, and soil degradation. Nowadays, application of various nanofluids for increasing separation efficiency of $CO_2$ has been an attractive subject due to their certain privileges such as chemical compatibility and great specific area. This paper tries to provide an up-to-date overview of the commonly-employed nanofluids accompanying with their properties and applications to enhance the separation efficiency of $CO_2$. Moreover, important mechanisms toward improving the mass transfer rate and the separation proficiency of $CO_2$ through the nanofluids are comprehensively discussed and summarized. Single material nanofluids (SMNFs) and hybrid nanofluids (HNFs) are considered as major categorizations of commonly-employed nanofluids in the scientific scope of membrane-based gas separation process (MGSP), which are aimed to be discussed in this paper. True recognition of nanofluids application in the $CO_2$ separation process leads to finding its advantages/disadvantages in comparison with other conventional procedures.



**Contents**



* Corresponding author.
*E-mail address:* azhermuhson@mustaqbal-college.edu.iq (A.M. Abed).

https://doi.org/10.1016/j.molliq.2022.121077
0167-7322/

## 1. Introduction

In current decades, the immethodical anthropogenic release of greenhouse gases (GHGs) all has exacerbated the global warming phenomenon, which is a serious barrier towards achieving sustainable development all over the world [1–4]. It is estimated that the emission of GHGs (especially $CO_2$) is predicted to be enhanced by 170 % until the end of 2030 [5]. $CO_2$ can be regarded as the most prominent that allocates nearly 80 % of GHGs. The existence of this detrimental acidic contaminant in industrial-based activities results in the occurrence of serious challenges like corrosion of pipelines and the decrement of the heating value of gaseous fuels. In doing so, finding efficient, reliable, and cost-effective approaches for separating $CO_2$ from disparate industrial gaseous flows is of prime importance [6–8].

The prominent separation techniques of GHGs are mainly on the basis of physical and chemical processes like cryogenic distillation, adsorption and spray tower. Despite prevalence of operation, these separation techniques encounter with different functional/operational/economic difficulties like channeling, flooding, liquid hold up and significant capital costs [9–12]. Thus, numerous scientists are doing their best to replace conventional technologies with state-of-the-art ones to increase efficiency and solve their operational shortcomings. Membrane-based gas separation process (MGSP) is known as a reliable and promising approach for the separation of disparate greenhouse pollutants. Owing to carrying the advantages of both membrane technology and gas absorption (i.e., MGSP has shown brilliant potential of use in the mitigation of major greenhouse gases. The appearance of brilliant advantages such as the non-existence of holdup has made the use of MGSP reliable in separation industries [13–17].

Selection of efficient liquid absorbents is an important milestone in MGSP. In recent years, the use of chemical absorbents in MGSP has been more attractive owing to unacceptable absorption efficiency of water and physical absorbents [18]. Disparate amine-based absorbents like monoethanolamine (MEA), methyldiethanolamine (MDEA), triethanolamine (TEA) ethyl-ethanolamine (EEA), 4-diethylamino-2-butanol (DEAB) and ethylenediamine (EDA) have been vastly applied for the efficient removing of $CO_2$ from industrial gases [19–22]. In a numerical investigation, Shirazian et al. found that DEAB was the most efficient absorbent with the capability of separating approximately 100 % of $CO_2$ absorption from gaseous mixture [23]. Despite great efficiency and rapid reaction rate, the existence of some operational shortcomings such as great corrosion and low capacity have motivated the researchers to make more efforts for finding novel class of chemical absorbents [24,25].

Ionic Liquids (ILs) (i.e., [Bmim][$BF_4$], [Emim][$BF_4$]), amino acid salt solutions, $K_2CO_3$ aqueous solution and alkali solutions (i.e., NaOH) are the other classifications of chemical absorbents, which have shown excellent performance for the separation of various types of GHGs [26–31]. Despite great efficiency of all above mentioned absorbents in GHGs separation, their comprehensive evaluation is being continued with the aim of finding their operational/functional obstacles related to cost, energy consumption as well as their utilization for different industries [32–34].

In recent years, the separation of GHGs (mainly $CO_2$) applying nanofluids has been of paramount attention due to their precious positive points in regulating physical and chemical properties and their high specific area. It is strongly believed that the incorporation of nanofluids to base liquids significantly enhances the solubility of gases and gas–liquid reaction rate, which eventuates in increasing the separation yield of GHGs [35,36]. Nano-based materials like nano-sized zeolites, carbon nanotubes (CNTs), silica and covalent organic frameworks (COPs) have been able to significantly improve the efficiency of $CO_2$ separation [37,38].

The prominent purpose of this article is to review different nanofluids following with their properties and applications to enhance the separation efficiency of $CO_2$. As the novelty, major mechanisms toward enhancing mass transfer of GHGs in nanofluids and important parameters influencing the separation performance of $CO_2$ inside the nanofluids are comprehensively discussed and summarized. At the end, the employed nanofluids are classified into two prominent classes including single material nanofluids (SMNFs) and hybrid nanofluids (HNFs) and their characteristics are interpreted in detail. Explanation of the nanofluids application in the $CO_2$ separation process results in helping the true recognition of this new technology and finding its advantages/disadvantages in comparison with conventional procedures.

## 2. Definition of nanofluids and their different types

Nanofluids belongs to a novel classification of nanotechnology-based heat/mass transfer fluids, which are fabricated via the dispersion of nano-sized particles (the size range of 1–50 nm) in basic fluids such as water and amine solutions [39–42]. In recent years, various international researchers all over the world have reported the significant enhancement in the thermal and mass transfer properties of basic fluids after the addition of small number of nanoparticles [43–46]. Energy analysis of nanofluids is an important aspect, which has recently increased the motivation of scientists to study it. It is worth mentioning that the incorporation of nanoparticles to base fluids can significantly improve the thermal conductivity/stability and homogeneity compared to base fluids [47,48]. True identification of thermophysical properties of disparate types of nanofluids can be of prime importance for evaluating the feasibility of their application and their efficiency in different heat transfer systems like minichannel and heated pipes [49,50]. In an investigation, Khaleduzzaman et al. studied the effect of incorporating $Al_2O_3$ nanoparticles (with the concentration of 0.1 to 0.25 vol%) to water on the outlet exergy. They concluded the greatest enhancement in the outlet exergy (60.86 %) was achieved for the incorporation of 0.25 vol% $Al_2O_3$ in water at the flow rate of 1 l/min [47].

Nanofluids have attracted numerous attentions in various industrial activities such as reaction engineering, thermal engineering, MGSP, adsorption/extraction and pharmaceutics due to enjoying disparate advantages such as high specific surface area and superior single-phase heat/mass transfer coefficient [49,51–54]. Disparate types of nanofluids have been currently fabricated by the incorporation of single-element nanoparticles (i.e., Cu and Ag), single-element oxide (i.e., CuO and $Al_2O_3$,), alloys (i.e., Cu-Zn and Ag-Cu) and carbon materials (i.e., CNTs) dispersed in basic fluids like water, amines, ethanol and refrigerants [55–57]. Table 1 aims to comprehensively review various nanoparticles applied in MGSP.

Nanofluids can be categorized in two prominent classes including SMNFs and hybrid HNFs. SMNFs are known as the most conventional type of employed nanofluids, which was used by Choi to manufacture the suspension by means of various preparation

**Table 1**
Applied nanoparticles for the separation of greenhouse pollutants.

| Nanoparticle | CAS Number | Appearance | Basic fluid | Morphology | Average particle size (nm) | Separation improvement | Refs. |
|---|---|---|---|---|---|---|---|
| CNT | 308068–56-6 | – | MDEA | Cylindrical | 10–20 | | [51,58,59] |
| | | | $H_2O$ | | | 23 % | |
| | | | | | | 32 % | |
| $SiO_2$ | 7631–86-9 | White/whitish yellow powder | DEA | Spherical | 10–15 | 40 % | [18,60–63] |
| | | | $H_2O$ | | | 24 % | |
| | | | Methanol | | | 9.7 % | |
| $TiO_2$ | 13463–67-7 | White solid | MDEA | Spherical | Less than 50 | 11.5 % | [64–66] |
| $Fe_3O_4$ | 1317–61-9 | Solid black powder | MDEA | Spherical | 40–60 | 92.8 % | [67,68] |
| MWCNT | 308068–56-6 | – | $H_2O$ | Tubular | 10–20 | 38 % | [64,68] |
| $Al_2O_3$ | 1344–28-1 | White solid | DEA | Spherical | Less than 40 | 33 % | [34,69,70] |

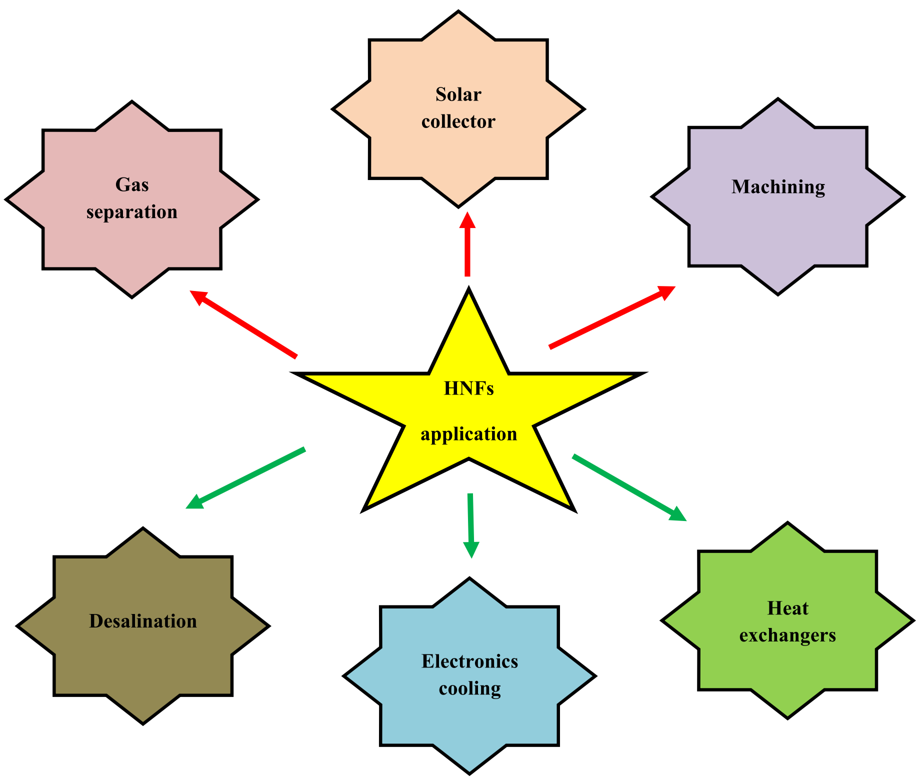


**Fig. 1.** Various applications of HNFs in industrial-based activities. Adapted and re-designed from [78] with permission from Elsevier.

techniques [71,72]. Numerous researchers all over the world have corroborated that SMNFs possess superior efficiency because of having more desirable thermophysical properties than their basic fluid [73–76]. HNFs belong to the modern class nanofluids, which are fabricated via the combination of more than one suspended nanoparticle in a basic fluid. Experimental investigation about the feasibility of HNFs was first conducted by Jana et al. with the aim of improving the fluid properties. They perceived that the stability of the CNT–Cu/$H_2O$ nanofluid was greater than the other types of nanofluids [77]. Fig. 1 demonstrates the application of HNFs.

## 3. Enhancement mechanisms

There are disparate mechanisms for improving the separation efficiency of $CO_2$ from various mixtures by affecting mass transfer rate and diffusion of $CO_2$ in the liquid absorbents. This section aims to present prominent mechanisms of $CO_2$ separation enhancement in various types of nanofluids.

### 3.1. Grazing effect

This phenomenon was initially offered by Kars et al. [79]. Theoretically, grazing effect is defined as the absorption process of gaseous molecules via nanoparticle surfaces at the bubble interface following to the removal of adsorbed gas from the surface of particles to the fluid phase [80,81]. On the basis of the grazing effect, the separation rate of GHGs through the nanofluid increases substantially by the presence of solid particles in a gas–liquid-solid system. Vigorous adsorption of the diffusing gas phase component through the dispersed particles results in reducing the concentration amount of gas phase reactant in the liquid near the interface and consequently an improvement in the absorption rate. By passing a determined contact time, the withdrawal of solid nanoparticles to the liquid bulk causes the regeneration of particles. This occurrence dramatically enhances the mass transfer coefficient [82–84].

### 3.2. Bubble breaking effect and inhibition of bubble coalescence

Krishnamurthy et al. have perceived by the conduction of their experiment that the velocity field (due to the movement of solid particles in nanosize) is the prominent cause of mass transfer enhancement in nanofluid systems [85]. The nanoparticles collision following with nanoparticles-bubbles collision takes place in the bubble absorption process. By the motion of solid nanoparticles toward the interface, nanoparticles strike the gas–liquid interface and causes the breaking of bubbles, which considerably enhances the diffusion area, mass transfer and consequently $CO_2$ separation efficiency [86,87]. By colliding two bubbles in the liquid phase, the liquid film between gases drains to submicron size by passing the time [87]. The inhibition of coalescence among the bubbles through the gas–liquid dispersions is done via a mixed liquid phase. This technique focuses on this reality that very small solid particles possess great potential to modify the interfacial area and influence the overall mass transfer coefficient [88].

### 3.3. Brownian motion and hydrodynamic effect in the gas–liquid boundary layer

Brownian motion of nano-sized particles inside a base fluid is regarded as a noteworthy mechanism for increasing the thermal conductivity and mass transfer performance of nanofluids. Brownian motion can be defined as the random movements of nanoparticles, which may result in the enhancement of velocity and the induction of micro-convection around the nanoparticles [58,89,90]. Combination of the gas–liquid boundary layer is defined as hydrodynamic effect mechanism. According to this mechanism, those nano-based materials encompassing the bubbles break the diffusion boundary layer, which eventuates in the creation of a thin effective layer. Preparation of thinner effective layer significantly improves the diffusion of gas into the liquid film due to the existence of the nanoparticles in the vicinity of the bubble–liquid interface, which increases the mass transfer rate and turbulence of the flow and as the result, separation efficiency of acidic gas [91]. Fig. 2 presents a schematic illustration of three major mechanisms for the enhancement of $CO_2$ separation efficiency inside the nanofluids.

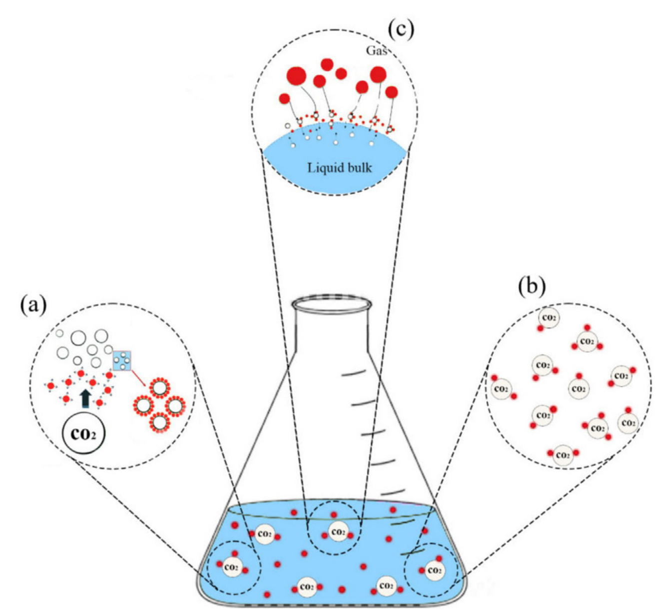


**Fig. 2.** Major mechanisms for the enhancement of $CO_2$ separation efficiency inside the nanofluids. A) Bubble breaking mechanism, (b) Brownian motion mechanism, and (c) Grazing effect mechanism [62].

## 4. Modeling and simulation approaches

In recent years, various mathematical models and computational simulation have been conducted to predict the separation performance of $CO_2$ pollutant applying different types of nanofluids inside various gas–liquid contactors such as hollow fiber membrane contactors (HFMCs) and wetted wall columns (WWCs) [59,92–98]. Schematic depiction of a HFMC following with its geometrical domains and Happel's free surface model is presented in Fig. 3. As can be seen, by moving the gaseous flow in the shell section and nanofluid in the tube compartment, the occurrence of concentration gradient results in the diffusion of $CO_2$ molecules from the shell to the hollow fibers' micropores and then its separation via the flowing nanofluid in the tube compartment. Indeed, concentration gradient is main cause of the $CO_2$ molecular separation in the gas–liquid HFMC [99]. In a theoretical investigation, Ghasem developed a mathematical-based simulation to evaluate the separation performance of $CO_2$ from $CO_2/N_2$ gaseous mixture using water-based CNT nanofluids in gas–liquid HFMC. He concluded from his study that at a constant value of inlet gas flow rate, increment of the concentration of CNT nanofluid from 0.1 to 0.25 wt% almost doubled the $CO_2$ separation percentage from about 20 to 45 % [92].

Pahnavar et al. computationally analyzed the separation enhancement of $CO_2$ from $CO_2$/air gaseous flow by the incorporation of 0.5 wt% CNT and silica to base fluid. They perceived that the addition of 0.5 wt% CNT and silica to base fluid significantly enhanced the absorption rate by 47.6 and 39.6 %, respectively [100]. In another mathematical study, Rashidi and Mamivand evaluated the addition of $Al_2O_3$ nanoparticle to water base fluid to improve the mass transfer and separation efficiency of $CO_2$ in a WWC. They corroborated that the incorporation of 0.0125 and 0.025 %v/v $Al_2O_3$ substantially increased mass transfer rate by 40.3 % and 67.16 %, respectively [97]. Rasaie et al. studied the role of functionalized $Fe_3O_4$ nanoparticles on increasing the physical/-chemical separation of $CO_2$ through a polypropylene HFMC. They achieved this result that the application of $Fe_3O_4$, $Fe_3O_4$-proline, $Fe_3O_4$-lysine, $Fe_3O_4$@$SiO_2$-proline and $Fe_3O_4$@$SiO_2$-lysine resulted in a considerable increment in the $CO_2$ separation performance by about 27.5, 57.14, 64.28, 72.8, and 96.42 %, respectively [95]. Taheri et al. evaluated addition of silica and alumina nanoparticles to DEA absorbent on the separation enhancement of $CO_2$ from natural gas. Based on their result, incorporation of 0.05 wt% of $Al_2O_3$ and $SiO_2$ increased carbon dioxide separation performance by 33 and 40 %, respectively [69].

In recent years, Artificial Intelligence (AI) have been taken into consideration as a trustworthy alternative procedure for computational fluid dynamics (CFD) approaches [101–103]. This technique has great potential to overcome the prevalent disadvantages of CFD approaches like the restrictions of CPU time and great computational requirements for solving complex stiff/non-stiff problems in various scientific scopes like nanofluids, thermal engineering, drug delivery, membrane-based GHGs removal and reaction engineering. and are becoming more and more popular at present [104,105]. For instance, Babanezhad et al. developed a CFD-AI based hybrid technique to simulate an air–water bubble column reactor. They found that the best accuracy of model prediction when the input numbers and cross-over are 4 and 0.2, respectively [76].

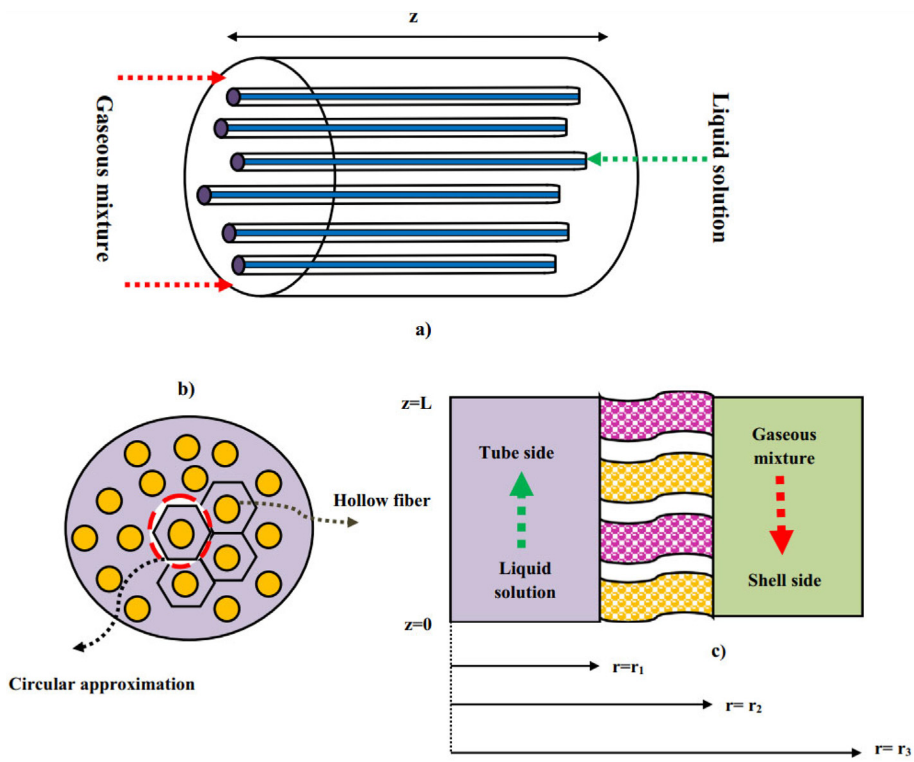


**Fig. 3.** Schematic demonstration of a) a HFMC, b) Happel's free surface model and c) the geographical domains of HFMC. Reprinted from [37] with permission from Elsevier.

## 5. Conclusion and future perspectives

In recent decades, numerous efforts have been made by various scientists to employ high-tech, promising, cost-effective and efficient strategies to mitigate the anthropogenic emission of deleterious GHGs, especially $CO_2$, with the aim of hindering their negative effects on environment such as ocean acidification, global warming, soil degradation, acid rain and water pollution. Application of nanofluids for enhancing the separation efficiency of $CO_2$ has been recently of great interest owing to their valuable advantages compared with conventional liquid absorbents like higher surface area, superior heat conductivity and greater mass transfer rate. This paper aims to present a comprehensive review on the application of different types of nanofluids to improve the separation performance of $CO_2$ from disparate gaseous flows. Evaluating the role of three prominent mechanisms (bubble breaking, Brownian motion and grazing effect) on increasing the mass transfer rate and consequently separation efficiency of $CO_2$ inside the nanofluids is another important aspect of this review paper. Based on the results, $Fe_3O_4$, $SiO_2$ and CNT are introduced as the most efficacious nanofluids for GHGs separation. As future perspectives, more theoretical/experimental studies must be conducted to evaluate the effect of base fluids and operational parameters such as gas/liquid flow rate, nanoparticles concentration on the separation efficiency of $CO_2$ and other GHGs. Moreover, investigating on the use of novel nanoparticles needs to be done to introduce more promising nanoparticles for enhancing the separation performance of GHGs. Ultimately, more analysis needs to be done for studying the feasibility of using nanofluids for the separation of other types of GHGs such as $NO_2$ and $SO_2$.

## CRediT authorship contribution statement

**Ying Chen:** Conceptualization, Formal analysis, Writing – review & editing. **Azher M. Abed:** Supervision, Resources, Writing – original draft. **Al-Behadili Faisal Raheem:** Writing – review & editing, Resources, Formal analysis. **Abdulmalik S. Altamimi:** Writing – original draft, Formal analysis. **Yaser Yasin:** Writing – original draft, Formal analysis, Resources, Methodology. **Waheed Abdi Sheekhoo:** Writing – original draft, Formal analysis, Resources, Methodology. **Ghassan Fadhil Smaisim:** Writing – review & editing, Methodology, Funding acquisition. **Amer Ali Ghabra:** Writing – review & editing, Formal analysis. **Nesreen Ahmed Naseer:** Writing – original draft, Methodology, Supervision.

## Data availability

No data was used for the research described in the article.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgments

The authors would like to express their gratitude to the Al-Mustaqbal University college for support of project.

## References

[1] M. Asadollahzadeh, N. Raoufi, M. Rezakazemi, S. Shirazian, Simulation of nonporous polymeric membranes using CFD for bioethanol purification, Macromol. Theory Simul. 27 (2018) 1700084.
[2] A.T. Nakhjiri, A. Heydarinasab, O. Bakhtiari, T. Mohammadi, Influence of non-wetting, partial wetting and complete wetting modes of operation on hydrogen sulfide removal utilizing monoethanolamine absorbent in hollow fiber membrane contactor, Sustainable Environ. Res. 28 (2018) 186–196.
[3] M.K. Mondal, H.K. Balsora, P. Varshney, Progress and trends in CO2 capture/separation technologies: A review, Energy 46 (2012) 431–441.

[4] M. Pishnamazi, A.T. Nakhjiri, M. Ghadiri, A. Marjani, A. Heydarinasab, S. Shirazian, Computational fluid dynamics simulation of NO2 molecular sequestration from a gaseous stream using NaOH liquid absorbent through porous membrane contactors, J. Mol. Liq. 313 (2020).
[5] N. Hajilary, M. Rezakazemi, CFD modeling of CO2 capture by water-based nanofluids using hollow fiber membrane contactor, Int. J. Greenhouse Gas Control 77 (2018) 88–95.
[6] A. Marjani, A.T. Nakhjiri, M. Pishnamazi, S. Shirazian, Evaluation of potassium glycinate, potassium lysinate, potassium sarcosinate and potassium threonate solutions in CO2 capture using membranes, Arab. J. Chem. 14 (2021).
[7] Y. Han, W.W. Ho, Polymeric membranes for CO2 separation and capture, J. Membr. Sci. 628 (2021).
[8] F. Russo, F. Galiano, A. Iulianelli, A. Basile, A. Figoli, Biopolymers for sustainable membranes in CO2 separation: A review, Fuel Process. Technol. 213 (2021).
[9] D.Y. Leung, G. Caramanna, M.M. Maroto-Valer, An overview of current status of carbon dioxide capture and storage technologies, Renew. Sustain. Energy Rev. 39 (2014) 426–443.
[10] Y. Cao, A. Khan, A.T. Nakhjiri, A.B. Albadarin, T.A. Kurniawan, M. Rezakazemi, Recent advancements in molecular separation of gases using microporous membrane systems: A comprehensive review on the applied liquid absorbents, J. Mol. Liq. 337 (2021).
[11] A.T. Nakhjiri, A. Heydarinasab, O. Bakhtiari, T. Mohammadi, Experimental investigation and mathematical modeling of CO2 sequestration from CO2/CH4 gaseous mixture using MEA and TEA aqueous absorbents through polypropylene hollow fiber membrane contactor, J. Membr. Sci. 565 (2018) 1–13.
[12] W. Gao, S. Liang, R. Wang, Q. Jiang, Y. Zhang, Q. Zheng, B. Xie, C.Y. Toe, X. Zhu, J. Wang, Industrial carbon dioxide capture and utilization: state of the art and future challenges, Chem. Soc. Rev. 49 (2020) 8584–8686.
[13] Y. Zhou, Membrane-Based Gas Separation For Carbon Capture, The Ohio State University, 2020.
[14] R.S.K. Valappil, N. Ghasem, M. Al-Marzouqi, Current and future trends in polymer membrane-based gas separation technology: A comprehensive review, J. Ind. Eng. Chem. 98 (2021) 103–129.
[15] A.T. Nakhjiri, M.H. Roudsari, Modeling and simulation of natural convection heat transfer process in porous and non-porous media, Appl. Res. J 2 (2016) 199–204.
[16] N. Norahim, P. Yaisanga, K. Faungnawakij, T. Charinpanitkul, C. Klaysom, Recent membrane developments for CO2 separation and capture, Chem. Eng. Technol. 41 (2018) 211–223.
[17] M. Babanezhad, A. Masoumian, A.T. Nakhjiri, A. Marjani, S. Shirazian, Influence of number of membership functions on prediction of membrane systems using adaptive network based fuzzy inference system, ANFIS, Sci. Rep. 10 (2020) 1–20.
[18] A. Golkhar, P. Keshavarz, D. Mowla, Investigation of CO2 removal by silica and CNT nanofluids in microporous hollow fiber membrane contactors, J. Membr. Sci. 433 (2013) 17–24.
[19] R. Faiz, M. Al-Marzouqi, Mathematical modeling for the simultaneous absorption of CO2 and H2S using MEA in hollow fiber membrane contactors, J. Membr. Sci. 342 (2009) 269–278.
[20] J. Lu, L. Wang, X. Sun, J. Li, X. Liu, Absorption of CO2 into aqueous solutions of methyldiethanolamine and activated methyldiethanolamine from a gas mixture in a hollow fiber contactor, Ind. Eng. Chem. Res. 44 (2005) 9230–9238.
[21] A.T. Nakhjiri, A. Heydarinasab, Efficiency evaluation of novel liquid potassium lysinate chemical solution for CO2 molecular removal inside the hollow fiber membrane contactor: Comprehensive modeling and CFD simulation, J. Mol. Liq. 297 (2020).
[22] L. Zhang, R. Qu, Y. Sha, X. Wang, L. Yang, Membrane gas absorption for CO2 capture from flue gas containing fine particles and gaseous contaminants, Int. J. Greenhouse Gas Control 33 (2015) 10–17.
[23] S. Shirazian, A. Taghvaie Nakhjiri, A. Heydarinasab, M. Ghadiri, Theoretical investigations on the effect of absorbent type on carbon dioxide capture in hollow-fiber membrane contactors, PLoS One 15 (2020) e0236367.
[24] K. Maneeintr, K. Photien, T. Charinpanitkul, Mixture of MEA/2-MAE for Effective CO 2 Capture from Flue Gas Stream, Chemical, Eng. Trans. 63 (2018) 229–234.
[25] A.T. Nakhjiri, A. Heydarinasab, O. Bakhtiari, T. Mohammadi, Modeling and simulation of CO2 separation from CO2/CH4 gaseous mixture using potassium glycinate, potassium argininate and sodium hydroxide liquid absorbents in the hollow fiber membrane contactor, Journal of Environmental, Chem. Eng. 6 (2018) 1500–1511.
[26] H.M. Polat, S. Kavak, H. Kulak, A. Uzun, S. Keskin, CO2 separation from flue gas mixture using [BMIM][BF4]/MOF composites: Linking high-throughput computational screening with experiments, Chem. Eng. J. 394 (2020).
[27] A. Taghvaie Nakhjiri, H. Sanaeepur, A. Ebadi Amooghin, M.M.A. Shirazi, Recovery of precious metals from industrial wastewater towards resource recovery and environmental sustainability: A critical review, Desalination 527 (2022).
[28] A. Taghvaie Nakhjiri, A. Heydarinasab, O. Bakhtiari, T. Mohammadi, Numerical simulation of CO2 / H2S simultaneous removal from natural gas using potassium carbonate aqueous solution in hollow fiber membrane contactor, Journal of Environmental, Chem. Eng. 8 (2020).
[29] S.Y.W. Chai, L.H. Ngu, B.S. How, Review of carbon capture absorbents for CO2 utilization, Science and Technology, Greenhouse Gases, 2022.
[30] H. Zhang, K. Xue, C. Cheng, D. Gao, H. Chen, Study on the performance of CO2 capture from flue gas with ceramic membrane contactor, Sep. Purif. Technol. 265 (2021).
[31] A.T. Nakhjiri, A. Heydarinasab, O. Bakhtiari, T. Mohammadi, The effect of membrane pores wettability on CO2 removal from CO2/CH4 gaseous mixture using NaOH, MEA and TEA liquid absorbents in hollow fiber membrane contactor, Chin. J. Chem. Eng. 26 (2018) 1845–1861.
[32] R. Kumar, R. Mangalapuri, M.H. Ahmadi, D.-V.-N. Vo, R. Solanki, P. Kumar, The role of nanotechnology on post-combustion CO2 absorption in process industries, International Journal of Low-Carbon Technologies 15 (2020) 361–367.
[33] S. Yang, S.A. Jasim, D. Bokov, S. Chupradit, A.T. Nakhjiri, A. El-Shafay, Membrane distillation technology for molecular separation: a review on the fouling, wetting and transport phenomena, J. Mol. Liq. 118115 (2021).
[34] B. Devakki, S. Thomas, Experimental investigation on absorption performance of nanofluids for CO2 capture, International Journal of Air-Conditioning and Refrigeration 28 (2020) 2050017.
[35] M. Meshksar, M.A. Makarem, Z.-S. Hosseini, M.R. Rahimpour, Chapter 5 - Effect of nanofluids in solubility enhancement, in: M.R. Rahimpour, M.A. Makarem, M.R. Kiani, M.A. Sedghamiz (Eds.), Nanofluids and Mass Transfer, Elsevier, 2022, pp. 115–132.
[36] A. Marjani, A. Taghvaie Nakhjiri, M. Adimi, H. Fathinejad Jirandehi, S. Shirazian, Modification of polyethersulfone membrane using MWCNT-NH2 nanoparticles and its application in the separation of azeotropic solutions by means of pervaporation, PLoS One 15 (2020) e0236529.
[37] A. Marjani, A.T. Nakhjiri, A.S. Taleghani, S. Shirazian, Mass transfer modeling absorption using nanofluids in porous polymeric membranes, J. Mol. Liq. 318 (2020).
[38] W. Yu, T. Wang, A.-H.-A. Park, M. Fang, Review of liquid nano-absorbents for enhanced CO 2 capture, Nanoscale 11 (2019) 17137–17156.
[39] S.U. Choi, Nanofluids: from vision to reality through research, J. Heat Transfer 131 (2009).
[40] Y. Cao, Z.U. Rehman, N. Ghasem, M. Al-Marzouqi, N. Abdullatif, A.T. Nakhjiri, M. Ghadiri, M. Rezakazemi, A. Marjani, M. Pishnamazi, Intensification of CO2 absorption using MDEA-based nanofluid in a hollow fibre membrane contactor, Sci. Rep. 11 (2021) 1–12.
[41] Y. Cao, S.M. Seyed Alizadeh, M.T. Fouladvand, A. Khan, A. Taghvaie Nakhjiri, Z. Heidari, R. Pelalak, T.A. Kurniawan, A.B. Albadarin, Mathematical modeling and numerical simulation of CO2 capture using MDEA-based nanofluids in nanostructure membranes, Process Saf. Environ. Prot. 148 (2021) 1377–1385.
[42] M. Elveny, A. Khan, A.T. Nakhjiri, A.B. Albadarin, A state-of-the-art review on the application of various pharmaceutical nanoparticles as a promising technology in cancer treatment, Arab. J. Chem. 14 (2021).
[43] V. Kugarajah, A.K. Ojha, H. Hadem, N. Dasgupta, B.N. Mishra, S. Ranjan, S. Dharmalingam, Chapter 2 - Nanoparticles and nanofluids: Characteristics and behavior aspects, in: K. Pal, A. Sarkar, P. Sarkar, N. Bandara, V. Jegatheesan (Eds.), Food, Medical, and Environmental Applications of Nanomaterials, Elsevier, 2022, pp. 41–71.
[44] A. Minakov, E. Mikhienkova, V. Zhigarev, A. Neverov, V.Y. Rudyak, A study of the influence of nanoparticles on the properties of drilling fluids, Colloid J. 80 (2018) 418–426.
[45] V.Y. Rudyak, A. Belkin, On the effect of nanoparticles on fluid structure, Colloid J. 81 (2019) 487–490.
[46] W. Zhuang, K. Hachem, D. Bokov, M. Javed Ansari, A. Taghvaie Nakhjiri, Ionic liquids in pharmaceutical industry: A systematic review on applications and future perspectives, J. Mol. Liq. 349 (2022).
[47] S. Khaleduzzaman, M. Sohel, R. Saidur, I. Mahbubul, I. Shahrul, B. Akash, J. Selvaraj, Energy and exergy analysis of alumina–water nanofluid for an electronic liquid cooling system, Int. Commun. Heat Mass Transfer 57 (2014) 118–127.
[48] M. Babanezhad, I. Behroyan, A.T. Nakhjiri, M. Rezakazemi, A. Marjani, S. Shirazian, Thermal prediction of turbulent forced convection of nanofluid using computational fluid dynamics coupled genetic algorithm with fuzzy interface system, Sci. Rep. 11 (2021) 1–12.
[49] Q. Nguyen, A. Taghvaie Nakhjiri, M. Rezakazemi, S. Shirazian, Thermal and flow visualization of a square heat source in a nanofluid material with a cubic-interpolated pseudo-particle, ACS Omega 5 (2020) 17658–17663.
[50] M. Babanezhad, A. Taghvaie Nakhjiri, M. Rezakazemi, S. Shirazian, Developing intelligent algorithm as a machine learning overview over the big data generated by Euler-Euler method to simulate bubble column reactor hydrodynamics, ACS Omega 5 (2020) 20558–20566.
[51] B. Rahmatmand, P. Keshavarz, S. Ayatollahi, Study of Absorption Enhancement of CO2 by SiO2, Al2O3, CNT, and Fe3O4 Nanoparticles in Water and Amine Solutions, J. Chem. Eng. Data 61 (2016) 1378–1387.
[52] Y. Cao, A.T. Nakhjiri, M. Ghadiri, Numerical investigation of ibuprofen removal from pharmaceutical wastewater using adsorption process, Sci. Rep. 11 (2021) 1–11.
[53] J. Lee, I. Mudawar, Assessment of the effectiveness of nanofluids for single-phase and two-phase heat transfer in micro-channels, Int. J. Heat Mass Transf. 50 (2007) 452–463.
[54] M. Babanezhad, I. Behroyan, A.T. Nakhjiri, A. Marjani, S. Shirazian, Computational modeling of transport in porous media using an adaptive network-based fuzzy inference system, ACS Omega 5 (2020) 30826–30835.

[55] M. Gupta, V. Singh, R. Kumar, Z. Said, A review on thermophysical properties of nanofluids and heat transfer applications, Renew. Sustain. Energy Rev. 74 (2017) 638–670.

[56] N.K. Gupta, A.K. Tiwari, S.K. Ghosh, Heat transfer mechanisms in heat pipes using nanofluids–A review, Exp. Therm Fluid Sci. 90 (2018) 84–100.

[57] L.S. Sundar, K. Sharma, M.K. Singh, A. Sousa, Hybrid nanofluids preparation, thermal properties, heat transfer and friction factor–a review, Renew. Sustain. Energy Rev. 68 (2017) 185–198.

[58] L. Sumin, X. Min, S. Yan, D. Xiangjun, Experimental and theoretical studies of CO2 absorption enhancement by nano-Al2O3 and carbon nanotube particles, Chin. J. Chem. Eng. 21 (2013) 983–990.

[59] M. Darabi, M. Rahimi, A.M. Dehkordi, Gas absorption enhancement in hollow fiber membrane contactors using nanofluids: Modeling and simulation, Chem. Eng. Process. 119 (2017) 7–15.

[60] W.-G. Kim, H.U. Kang, K.-M. Jung, S.H. Kim, Synthesis of silica nanofluid and application to CO2 absorption, Sep. Sci. Technol. 43 (2008) 3036–3055.

[61] I.T. Pineda, J.W. Lee, I. Jung, Y.T. Kang, CO2 absorption enhancement by methanol-based Al2O3 and SiO2 nanofluids in a tray column absorber, Int. J. Refrig 35 (2012) 1402–1409.

[62] B. Aghel, S. Janati, F. Alobaid, A. Almoslh, B. Epple, Application of Nanofluids in CO2 Absorption: A Review, Appl. Sci. 12 (2022) 3200.

[63] M.-L. Nguyen, A.T. Nakhjiri, M. Kamal, A. Mohamed, M. Algarni, S.T. Yu, F.-M. Wang, C.-H. Su, State-of-the-Art Review on the Application of Membrane Bioreactors for Molecular Micro-Contaminant Removal from Aquatic Environment, Membranes 12 (2022) 429.

[64] P. Zare, P. Keshavarz, D. Mowla, Membrane absorption coupling process for CO2 capture: application of water-based ZnO, TiO2, and multi-walled carbon nanotube nanofluids, Energy Fuel 33 (2019) 1392–1403.

[65] A. Hajatzadeh Pordanjani, S. Aghakhani, M. Afrand, B. Mahmoudi, O. Mahian, S. Wongwises, An updated review on application of nanofluids in heat exchangers for saving energy, Energ. Conver. Manage. 198 (2019).

[66] S.H. Li, Y. Ding, X.S. Zhang, Enhancement on CO2 bubble absorption in MDEA solution by TiO2 nanoparticles, in, Advanced Materials Research, Trans Tech Publ (2013) 127–134.

[67] S. Komati, A.K. Suresh, CO2 absorption into amine solutions: a novel strategy for intensification based on the addition of ferrofluids, Journal of Chemical Technology & Biotechnology: International Research in Process, Environmental & Clean Technology 83 (2008) 1094–1100.

[68] A. Peyravi, P. Keshavarz, D. Mowla, Experimental investigation on the absorption enhancement of CO2 by various nanofluids in hollow fiber membrane contactors, Energy Fuel 29 (2015) 8135–8142.

[69] M. Taheri, A. Mohebbi, H. Hashemipour, A.M. Rashidi, Simultaneous absorption of carbon dioxide (CO2) and hydrogen sulfide (H2S) from CO2–H2S–CH4 gas mixture using amine-based nanofluids in a wetted wall column, J. Nat. Gas Sci. Eng. 28 (2016) 410–417.

[70] Y. Cao, A.T. Nakhjiri, S.M. Sarkar, M. Ghadiri, Time-dependent numerical investigation of 3-hydroxypropionic acid extraction using a microporous membrane contactor, The European Physical Journal Plus 137 (2022) 1–9.

[71] S.U. Choi, J.A. Eastman, Enhancing thermal conductivity of fluids with nanoparticles, in, Argonne National Lab.(ANL), Argonne, IL (United States), 1995.

[72] N. Ali, J.A. Teixeira, A. Addali, A review on nanofluids: fabrication, stability, and thermophysical properties, J. Nanomater. 2018 (2018).

[73] M.M. Tawfik, Experimental studies of nanofluid thermal conductivity enhancement and applications: A review, Renew. Sustain. Energy Rev. 75 (2017) 1239–1253.

[74] M. Modak, S.S. Chougule, S.K. Sahu, An experimental investigation on heat transfer characteristics of hot surface by using CuO–water nanofluids in circular jet impingement cooling, J. Heat Transfer 140 (2018).

[75] L. Yang, K. Du, A comprehensive review on heat transfer characteristics of TiO2 nanofluids, Int. J. Heat Mass Transf. 108 (2017) 11–31.

[76] M. Babanezhad, I. Behroyan, A.T. Nakhjiri, A. Marjani, M. Rezakazemi, S. Shirazian, High-performance hybrid modeling chemical reactors using differential evolution based fuzzy inference system, Sci. Rep. 10 (2020) 1–11.

[77] S. Jana, A. Salehi-Khojin, W.-H. Zhong, Enhancement of fluid thermal conductivity by the addition of single and hybrid nano-additives, Thermochim Acta 462 (2007) 45–55.

[78] M. Sheikholeslami, E. Abohamzeh, Z. Ebrahimpour, Z. Said, 8 - Brief overview of the applications of hybrid nanofluids, in: Z. Said (Ed.), Hybrid Nanofluids, Elsevier, 2022, pp. 171–202.

[79] R. Kars, R. Best, A. Drinkenburg, The sorption of propane in slurries of active carbon in water, The Chemical Engineering Journal 17 (1979) 201–210.

[80] S. Karamian, D. Mowla, F. Esmaeilzadeh, The effect of various nanofluids on absorption intensification of CO2/SO2 in a single-bubble column, Processes 7 (2019) 393.

[81] M. Zhou, W.F. Cai, C.J. Xu, A new way of enhancing transport process–The hybrid process accompanied by ultrafine particles, Korean J. Chem. Eng. 20 (2003) 347–353.

[82] D.W.F. Brilman, W.P.M. van Swaaij, G. Versteeg, A one-dimensional instationary heterogeneous mass transfer model for gas absorption in multiphase systems, Chem. Eng. Process. 37 (1998) 471–488.

[83] J. Kluytmans, B. Van Wachem, B. Kuster, J. Schouten, Mass transfer in sparged and stirred reactors: influence of carbon particles and electrolyte, Chem. Eng. Sci. 58 (2003) 4719–4728.

[84] A. Marjani, A.T. Nakhjiri, M. Adimi, H.F. Jirandehi, S. Shirazian, Effect of graphene oxide on modifying polyethersulfone membrane performance and its application in wastewater treatment, Sci. Rep. 10 (2020) 1–11.

[85] S. Krishnamurthy, P. Bhattacharya, P. Phelan, R. Prasher, Enhanced mass transport in nanofluids, Nano Lett. 6 (2006) 419–423.

[86] J.H. Kim, C.W. Jung, Y.T. Kang, Mass transfer enhancement during CO2 absorption process in methanol/Al2O3 nanofluids, Int. J. Heat Mass Transf. 76 (2014) 484–491.

[87] V.S. Craig, Bubble coalescence and specific-ion effects, Curr. Opin. Colloid Interface Sci. 9 (2004) 178–184.

[88] J. Jiang, B. Zhao, Y. Zhuo, S. Wang, Experimental study of CO2 absorption in aqueous MEA and MDEA solutions enhanced by nanoparticles, Int. J. Greenhouse Gas Control 29 (2014) 135–141.

[89] K. Rafique, M.I. Anwar, M. Misiran, I. Khan, A.H. Seikh, E.-S.-M. Sherif, K.S. Nisar, Brownian motion and thermophoretic diffusion effects on micropolar type nanofluid flow with Soret and Dufour impacts over an inclined sheet: Keller-box simulations, Energies 12 (2019) 4191.

[90] S.P. Jang, S.U. Choi, Role of Brownian motion in the enhanced thermal conductivity of nanofluids, Appl. Phys. Lett. 84 (2004) 4316–4318.

[91] Z. Zhang, J. Cai, F. Chen, H. Li, W. Zhang, W. Qi, Progress in enhancement of CO2 absorption by nanofluids: A mini review of mechanisms and current status, Renew. Energy 118 (2018) 527–535.

[92] N. Ghasem, Modeling and simulation of CO2 absorption enhancement in hollow-fiber membrane contactors using CNT–water-based nanofluids, Journal of Membrane Science and Research 5 (2019) 295–302.

[93] H. Mohammaddoost, A. Azari, M. Ansarpour, S. Osfouri, Experimental investigation of CO2 removal from N2 by metal oxide nanofluids in a hollow fiber membrane contactor, Int. J. Greenhouse Gas Control 69 (2018) 60–71.

[94] M. Pishnamazi, A.T. Nakhjiri, A.S. Taleghani, A. Marjani, M. Rezakazemi, S. Shirazian, Molecular investigation into the effect of carbon nanotubes interaction with CO2 in molecular separation using microporous polymeric membranes, Sci. Rep. 10 (2020) 1–12.

[95] M. Rasaie, A. Elhambakhsh, M. Eskandari, P. Keshavarz, D. Mowla, Highly Selective Physical/Chemical CO2 Separation by Functionalized Fe3O4 Nanoparticles in Hollow Fiber Membrane Contactors: Experimental and Modeling Approaches, Energy Fuel 36 (2022) 4456–4469.

[96] L. Li, G. Ma, Z. Pan, N. Zhang, Z. Zhang, Research progress in gas separation using hollow fiber membrane contactors, Membranes 10 (2020) 380.

[97] H. Rashidi, S. Mamivand, Experimental and numerical mass transfer study of carbon dioxide absorption using Al2O3/water nanofluid in wetted wall column, Energy 238 (2022).

[98] P. Valeh-e-Sheyda, A. Afshari, A detailed screening on the mass transfer modeling of the CO2 absorption utilizing silica nanofluid in a wetted wall column, Process Saf. Environ. Prot. 127 (2019) 125–132.

[99] Y. Cao, A. Taghvaie Nakhjiri, M. Ghadiri, CFD investigation of CO2 separation from anesthesia gaseous stream applying novel cholinium lysinate amino acid-based ionic liquid inside the gas–liquid membrane contactor, The European Physical Journal Plus 137 (2022) 1–12.

[100] N. Pahnavar, F. Keramat, A. Azari, S. Osfouri, Computational fluid dynamics analysis of CO2 absorption intensification in an hollow fiber membrane contactor using SiO2 and carbon nanotubes nanofluids, Environ. Prog. Sustain. Energy 41 (2022) e13777.

[101] H. Malik, S. Srivastava, Y.R. Sood, A. Ahmad, Applications of artificial intelligence techniques in engineering, Sigma 1 (2018).

[102] R. Abduljabbar, H. Dia, S. Liyanage, S.A. Bagloee, Applications of artificial intelligence in transport: An overview, Sustainability 11 (2019) 189.

[103] M. Babanezhad, A. Taghvaie Nakhjiri, M. Rezakazemi, A. Marjani, S. Shirazian, Functional input and membership characteristics in the accuracy of machine learning approach for estimation of multiphase flow, Sci. Rep. 10 (2020) 1–15.

[104] M. Bahiraei, S. Heshmatian, H. Moayedi, Artificial intelligence in the field of nanofluids: A review on applications and potential future directions, Powder Technol. 353 (2019) 276–301.

[105] M. Babanezhad, A.T. Nakhjiri, A. Marjani, S. Shirazian, Pattern recognition of the fluid flow in a 3D domain by combination of Lattice Boltzmann and ANFIS methods, Sci. Rep. 10 (2020) 1–13.