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# Experimental study on the absorption enhancement of $CO_2$ by MDEA-MEA based nanofluids

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**Abstract**

Nanofluids promote the application of nanotechnology in the mass transfer process, which can effectively reduce mass transfer resistance and increase the gas–liquid mass transfer rate. A bubbling absorption system was used to explore the $CO_2$ absorption performance of methyldiethanolamine (MDEA) and monoethanolamine (MEA) blended nanofluids. $TiO_2$ nanoparticles and sodium polyacrylate (ASAP) surfactant were added to MDEA-MEA aqueous solutions to prepare nanofluids. The effects of MDEA concentration, MEA concentration, blended amine ratio, and nanoparticle solid content on $CO_2$ capture performance were investigated, respectively. The study found that, compared with single-component MEA/MDEA solutions, nanofluids have a more significant enhancement in $CO_2$ absorption of blended amines. The increase of MEA concentration in blended amine has a negative effect on the enhanced $CO_2$ absorption of $TiO_2$ nanoparticles. The enhancement factor of MDEA-MEA nanofluids at each solid content is higher than that of two single-component nanofluids. The best solid content of $TiO_2$ nanoparticles in the MDEA-MEA system is 0.6 g/L, while the enhancement factor E in 25% MDEA + 5% MEA nanofluids can reach up to 1.36. Finally, a new empirical formula was proposed to predict the enhancement factor and optimum solid content of $TiO_2$-MEA/MDEA nanofluids.

**KEYWORDS**

carbon dioxide, chemical absorption, mass transfer, MDEA-MEA blended amine, nanofluids

## 1 | INTRODUCTION

The concept of the greenhouse effect was first proposed by Fourier in 1827.[1] As the most important greenhouse gas, $CO_2$ contributes to up to 65% of the greenhouse effect.[2] The IPCC has clearly pointed out that $CO_2$ emitted by human activities is the main cause of global warming, which will continue to pose a threat to the ecosystem and human society.[3] Carbon capture and storage (CCS) is considered to be a feasible method to solve this current dilemma[4]; a great deal of efforts, including absorption, adsorption, catalytic conversion, and membrane separation, have been devoted to provide potential solutions for $CO_2$ separation.[5] Thus, the development of low-cost $CO_2$ separation technology is essential for capture. At present, the chemical absorption method is still the main way to recover $CO_2$ in flue gas, and amine systems are the most mature process.[6] Alkanolamines react with the weakly acidic gas $CO_2$ to form water-soluble salt, so as to achieve the purpose of absorbing $CO_2$.[7]

MEA (ethanolamine) has several advantages in $CO_2$ absorption progress, such as high reactivity, low solvent

  

cost, and high absorbing capacity.[8] However, its disadvantages include high enthalpy of reaction with $CO_2$, leading to higher desorbed energy consumption and more corrosiveness.[9] Compared with MEA, MDEA (methyldiethanolamine) has a high $CO_2$ equilibrium loading capacity, high thermal stability, and low enthalpy of reaction with $CO_2$.[10,11] Chakravarty et al.[12] first proposed a blended amine system by adding small amounts of a primary amine to a tertiary amine, such as blended MDEA-MEA. The blended amine system capitalizes on the performance of tertiary and primary amines, with the low energy requirement for regeneration and high absorption capacity of tertiary amines, and the fast reaction kinetics of primary amines.[13]

Because of the inherent shortcomings of traditional alkanolamines absorbents, the pursuit of green and high-efficiency absorbents has become urgent and essential. As an emerging green and designable solvent, ionic liquids (ILs) have been widely considered in the removal of $CO_2$.[14,15] Moreover, nanofluids have shown potential for developing high performance $CO_2$ capture absorbents. Choi and Eastman[16] first proposed the concept of nanofluids in 1995, and most of the early research focused on the field of enhanced heat transfer.[17] Due to the similarity between mass transfer and heat transfer, nanoparticles also have a wide range of applications in enhancing gas–liquid mass transfer.[18] There are three generally recognized mechanisms: grazing effect, hydrodynamic effect, and inhibition of bubble coalescence. The grazing effect, first proposed by Kars et al. and Alper et al.,[19,20] considers that nanoparticles can penetrate the gas–liquid membrane and achieve the gas absorption-desorption cycle through Brownian motion. The hydrodynamic effect points out that nanoparticles change hydrodynamic properties by creating collisions and disturbances at the gas–liquid interface.[21–23] Inhibition of bubble coalescence theory concludes that nanoparticles easily adhere to the surface of the bubble, which can enhance the stiffness of the bubble, reduce the bubble accumulation speed, and improve the mass transfer coefficient.[24–26]

Kim et al.[27] prepared $SiO_2$-$H_2O$ nanofluids with particle sizes of 30, 70, and 120 nm, and used nanofluids to absorb $CO_2$ for the first time. Since then, a variety of alkanolamines have also been used as base fluids to prepare $CO_2$ absorbents.[28–30] In the research of Jiang et al.,[31] nanofluids based on MEA and MDEA solutions were prepared to study the influence of nanoparticles on $CO_2$ absorption. Although the reaction rates of MEA-$CO_2$ and MDEA-$CO_2$ are different, the effects of key parameters in MEA and MDEA nanofluids are similar. MEA/MDEA nanofluids have been widely used in $CO_2$ absorption systems, but the $CO_2$ absorption characteristics of blended amine nanofluids need further research.

In this study, a bubbling reaction system was used to evaluate the $CO_2$ absorption performance of MDEA-MEA blended amine nanofluids. $TiO_2$ nanoparticles and surfactant sodium polyacrylate (ASAP) were used to prepare nanofluids before ultrasonic vibration treatment. The characteristics of outlet $CO_2$ concentration, cumulative $CO_2$ absorption volume, and enhancement factor were determined by important parameters such as amine component concentration, blended amine ratio, and nanoparticle solid content. In addition, an empirical equation for predicting the enhancement factor of amine nanofluids was proposed.

## 2 | MATERIAL AND METHODS

### 2.1 | Experimental materials

In this experiment, the amine absorbent was MEA and MDEA (Tianjin Kemiou, China) with a purity of 99%. The nanoparticles were $TiO_2$ (Hebei Yigui, China) with a purity of 99.5% and particle size of 40 nm. The surfactant was ASAP (Tianjin Kemiou, China) with a purity of 99.5%. Gas cylinders (Meisaier High-Tech, China), with a purity of 99.9% $CO_2$ and $N_2$, respectively, were applied to generate simulated gas.

$TiO_2$ is usually required as a photocatalyst to reduce $CO_2$ to low-valence carbon-containing fuels. However, in this study, according to the special physical properties of $TiO_2$, stable nanofluids were prepared to enhance the absorption of $CO_2$. Due to the high density of $TiO_2$, the movement inertia of each particle is large, which easily moves relative to the base fluid and causes disturbance to the boundary layer. With the same solid content, the number of nanoparticles is small, and the interference and agglomeration effects between particles are reduced. In addition, $TiO_2$ nanoparticles have a certain adsorption of $CO_2$, so the enhancement factor of $TiO_2$ nanofluids is relatively large. To sum up, $TiO_2$ nanoparticles were selected to prepare nanofluids to study $CO_2$ absorption enhancement.

### 2.2 | Nanofluids preparation

The preparation method of nanofluids is mainly divided into the one-step method and two-step method, with the two-step method having wide versatility and stability.[32] Dispersion techniques such as adding surfactants, ultrasonic vibration, and changing the pH value of the base fluid are usually adopted to obtain better dispersion performance[33,34]; the surfactant ASAP and ultrasonic cell disruption are needed in this experiment.

First, organic amine solutions with different mass fractions were prepared as the base liquid, and then the required mass of nanoparticles (0.4–1.4 g/L) and surfactants (0.1 wt.%) were weighed into the solutions. Finally, the absorbent was dispersed by ultrasonic cell disruption to prepare stable nanofluids. Ultrasonic cell disruption (900 W, 20–25 kHz) transmits vibration waves through the amplitude transformer (6 mm) immersed in the sample solution, thereby achieving the purpose of dispersing particles. Because vibration could cause local high temperature and high pressure, an intermittent vibration mode of working time 3 s and rest time 5 s was adopted. The total time of ultrasonic vibration was 107 min, of which the effective time was 40 min.

## 2.3 | Nanofluids characterization

The particle size distribution diagram of $TiO_2$ nanoparticles was obtained by a nanoparticle size analyzer (Figure 1). A $TiO_2$ sample with particle size of 40 nm was selected for measurement. The figure shows that the number of nanoparticles is the largest at 40 nm, indicating that there is no mutual interference or agglomeration between the nanoparticles.

For further comparison, the blended amine nanofluids (0.1 wt.% ASAP, 0.6 g/L $TiO_2$) were diluted five times and put into a turbidity meter, and the stability of the nanofluids was characterized by the turbidity analysis method. The turbidity of the obtained solutions is shown in Table 1.

It can be found that the turbidity of the prepared nanofluids does not decrease much after standing, which indicates that the dispersion and stability of the nanofluids meet the experimental requirements.

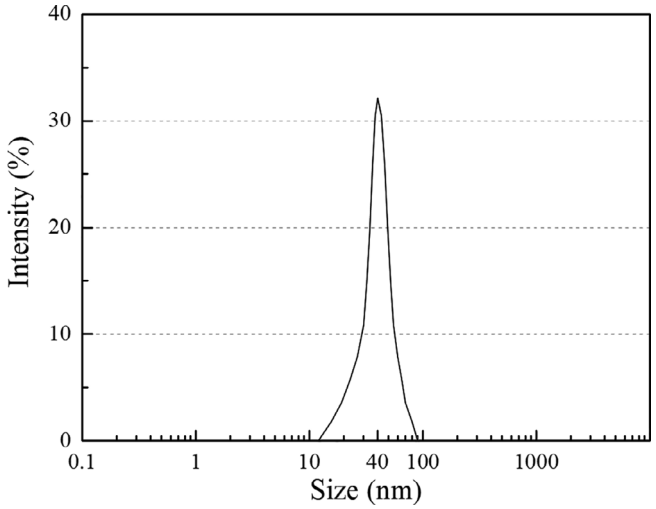


FIGURE 1 $TiO_2$ nanoparticle size distribution

## 2.4 | Experimental process

The experimental system mainly includes three parts: the simulated flue gas system, $CO_2$ absorption system, and $CO_2$ concentration measurement system. The simulated flue gas system uses a mass flow controller (MFC) to achieve the mixture ratio, and the gas mixture selects $N_2$ (60 ml/min) and $CO_2$ (7 ml/min) to simulate flue gas. The $CO_2$ absorption system consists of three parts: a thermostatic water bath, a gas–liquid reactor, and a drying tube. The bubble absorption bottle is selected as the gas–liquid reactor for the absorption experiment. The concentration of $CO_2$ in the exhaust gas is measured by an infrared gas analyzer. The volume fraction of $CO_2$ in the exhaust gas is recorded through the experimental measurement system, so as to calculate the absorption amount and absorption rate of $CO_2$ and characterize the nanofluids' absorption capacity of $CO_2$.

Temperature is an important factor affecting the gas–liquid mass transfer of $CO_2$ and nanofluids. Lee and Yong[35] investigated the particle agglomeration and $CO_2$ absorption enhancement of $Al_2O_3$ nanofluids at 10, 20, and 30°C. The results show that the cluster size of $Al_2O_3$ at 10°C is significantly higher than that at 20 and 30°C, and the absorption enhancement factor is also the lowest at 10°C. Fang et al.[36] also reached a similar conclusion. At different temperatures (15, 20, and 25°C), the mass diffusion coefficient of Cu nanoparticles increases with the increase of temperature. Higher temperature is conducive to the Brownian motion of nanoparticles, which in turn promotes gas transfer during the absorption process. Thus, the temperature of the water bath was set at 25°C in this experiment.

## 2.5 | Data processing

In the whole absorption experiment, the volume of $N_2$ is constant before and after the reaction. The infrared gas analyzer can directly record the volume fraction of $CO_2$ in the exhaust gas, so the absorption volume can be calculated to characterize the absorption effect of $CO_2$ by the absorption liquid.

Suppose the total volume flow of the blended gas before absorption is $Q_0$, the volume fraction of $CO_2$ is $C_0$, the total volume flow of the blended gas after absorption

TABLE 1 Turbidity of nanofluids

| Sample solutions | Turbidity (NTU) |
|---|---|
| After ultrasonic dispersion | 764.9 |
| Standing for 5 h | 756.3 |
| Standing for 12 h | 747.7 |
| Standing for 24 h | 724.8 |

is $Q_1$, and the volume fraction of $CO_2$ is $C_1$. The volume of $N_2$ remains unchanged before and after the absorption, as shown in Equation (1):

$$Q_0(1-C_0) = Q_1(1-C_1) \tag{1}$$

Therefore, the absorption volume of $CO_2$ per unit time can be expressed as Equation (2):

$$\Delta V_{CO_2} = \Delta Q = Q_0 - Q_1 = Q_0 \times \frac{C_0 - C_1}{(1-C_1)} \tag{2}$$

In this experiment, the infrared gas analyzer is set to record a datapoint every 5 s, so the $CO_2$ volume flow difference obtained by Equation (2) is the flow difference within 5 s. For the entire absorption process, the cumulative volume of $CO_2$ absorption is estimated using Equation (3):

$$V_{CO_2} = \sum \Delta V_{CO_2} \tag{3}$$

Instantaneous absorption of $CO_2$ N (mol) refers to the amount of $CO_2$ absorbed per unit time. Since the simulated gas can be treated as an ideal gas, the instantaneous absorption is defined in Equation (4):

$$N = \frac{P(V_{in} - V_{out})}{RT} \tag{4}$$

In order to directly express the enhancement effect of nanoparticles on the absorption of $CO_2$ by blended amine solution, the absorption enhancement factor E is introduced. It is defined as the ratio of average absorption rate $\overline{N'}$ (mol/s) of nanofluids and the absorbent without adding nanoparticles ($\overline{N}$, mol/s), as shown in Equations (5) and (6):

$$E = \frac{\overline{N'}}{\overline{N}} \tag{5}$$

$$\overline{N} = \frac{\int_0^t N}{t} = \frac{\int_0^t \frac{P(V_{in} - V_{out})}{RT}}{t} \tag{6}$$

where the average absorption rate $\overline{N'}$ (mol/s) is the ratio of the integration of absorption rate with absorption time t (s).

## 3 | RESULTS AND DISCUSSION

### 3.1 | Comparison of blended amines and single amines

MDEA is a tertiary amine and has a higher absorption capacity for $CO_2$, while MEA is a primary amine and has a faster absorption reaction rate with $CO_2$.[37] The concentration of an amine solution is usually not higher than 30 wt.% in organic amine absorption in industry. Therefore, $TiO_2$ (0.6 g/L, 40 nm) blended amine (10% MEA + 20% MDEA) nanofluids were prepared to compare with the nanofluids of the single-component of MEA/MDEA, and the blank control groups without nanoparticles were added. The experimental results of outlet $CO_2$ concentration and $CO_2$ instantaneous absorption volume are shown in Figures 2 and 3.

It can be seen from Figure 2 that the initial absorption rate of MEA is the fastest but then drops rapidly, while the enhancement effect of nanoparticles is correspondingly weakened. MDEA hydrolyzes itself first and then absorbs $CO_2$ to form an unstable bicarbonate, so the overall process can be regarded as physical absorption.[38] Although the absorption rate is relatively slow, the enhancement effect of MDEA nanofluids is more obvious than that of MEA. Compared with two single amine systems, nanoparticles have a better absorption enhancement effect on MEA-MDEA blended amines. According to the mechanism of nanofluids enhancing mass transfer, nanoparticles mainly affect the process of diffusion control. Initially, the reaction rate of MEA/MDEA and $CO_2$ is very fast, absorption is a diffusion control process, and the addition of nanoparticles is highly effective. As the active components are gradually consumed, the absorption process is transformed from diffusion control to reaction control. The increase of the solution load and the agglomeration of nanoparticles lead to a sharp rise in the viscosity of the absorbent, while nanofluids lose the enhancement effect on mass transfer.

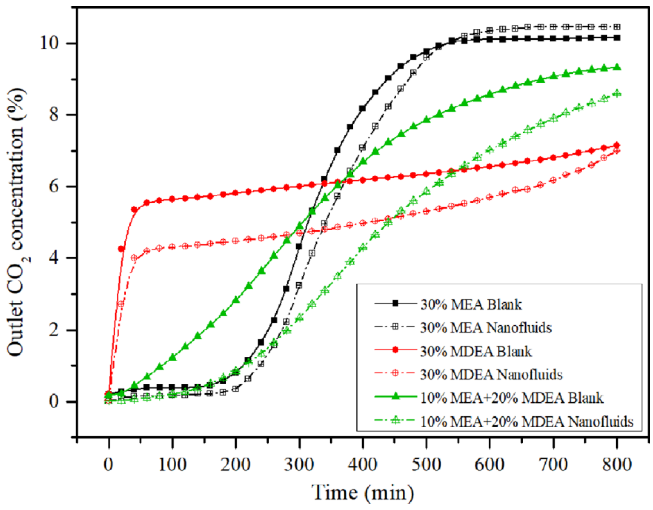


**FIGURE 2** Comparison of outlet $CO_2$ concentration between blended amines and single-component amines (absorbent of 50 g, absorption time of 800 min)

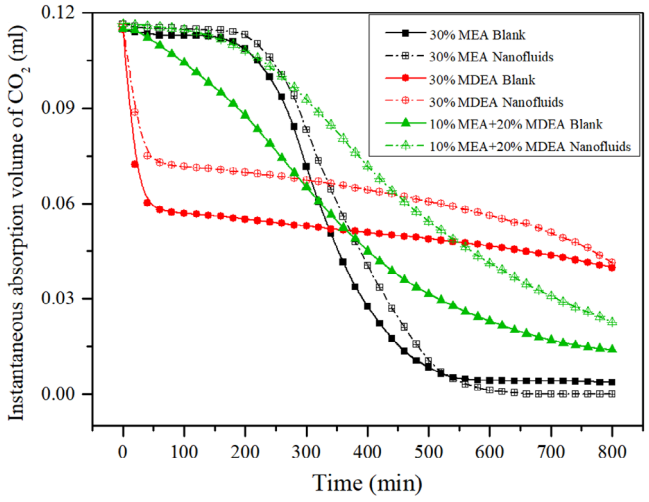


**FIGURE 3** Comparison of $CO_2$ instantaneous absorption volume between blended amines and single-component amines (absorbent of 50 g, absorption time of 800 min)

Based on the constant volume of $N_2$ before and after the absorption, the $CO_2$ absorption volume per unit time is obtained, which is called the $CO_2$ instantaneous absorption volume. Figure 3 shows that the instantaneous absorption volume of MEA/MDEA nanofluids is clearly higher than that of the blank solutions within 400 min, whereas the gap has narrowed after 450 min, and the absorption volume of MEA nanofluids is even lower than that of the blank. Since the enhancement of nanoparticles in MEA-MDEA blended amines is greater, the enhancement of $TiO_2$ particles in blended solutions does not decrease evidently until 700 min. The cumulative absorption volume change of the nanofluids and blank solutions is presented in Figure 4. The gap between MEA/MDEA nanofluids and blank absorbents stabilized after 500 min, at which time $TiO_2$ has almost lost the absorption enhancement effect. The action time of nanoparticles in the MEA-MDEA blended amine is

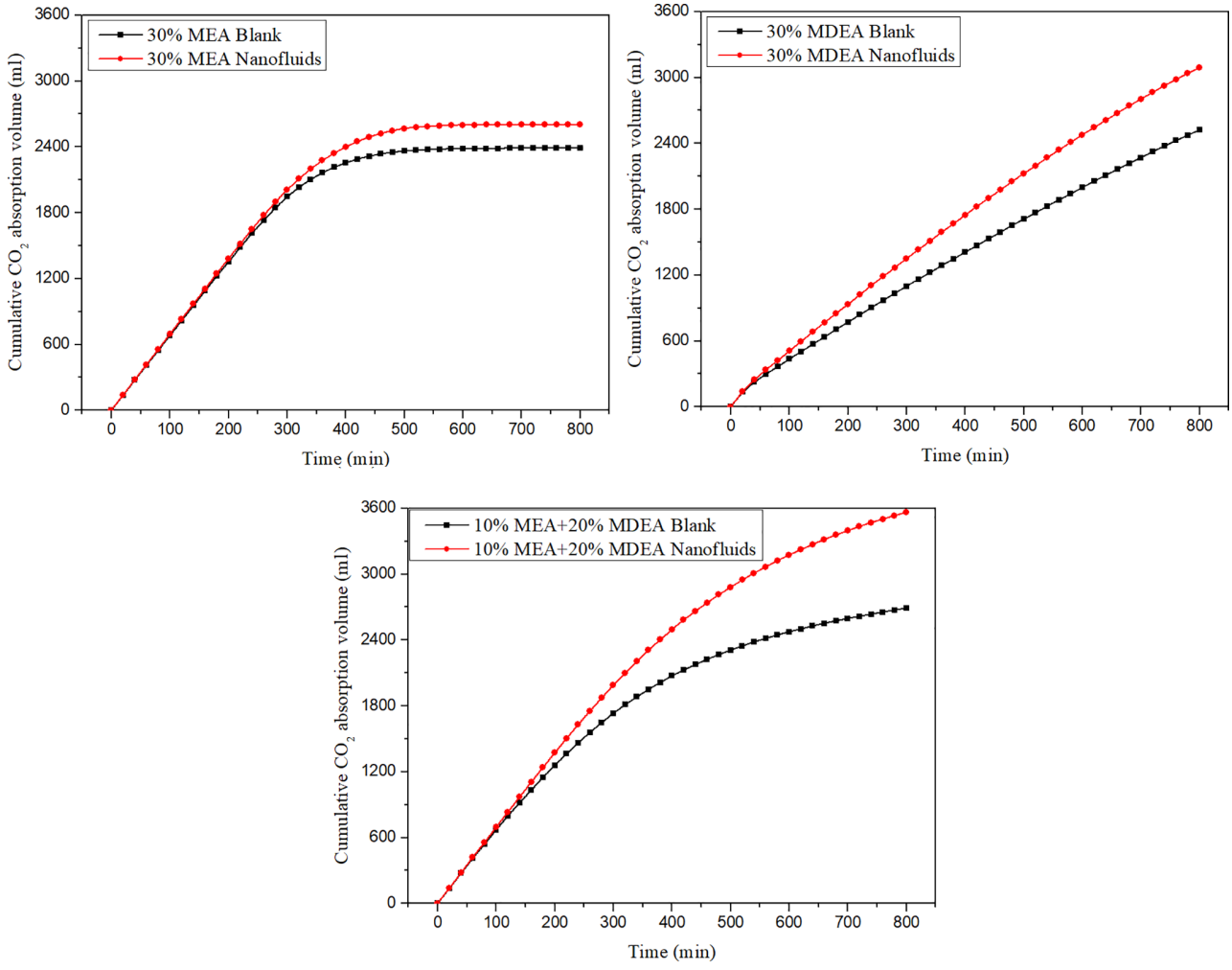


**FIGURE 4** Comparison of cumulative $CO_2$ absorption volume between blended amines and single-component amines (absorbent of 50 g, absorption time of 800 min)

longer; thus, the gap between nanofluids and blank absorbents is still increasing after 700 min.

In order to visually compare the general $CO_2$ absorption performance of nanofluids and blank solutions within the same absorption time, the cumulative $CO_2$ absorption volume for 800 min was calculated, as shown in Figure 5. The total absorption volume of 30% MEA is the lowest, and the enhancement after adding nanoparticles is also the worst. The absorption capacity of MDEA is much greater than that of MEA, and its strengthening effect of nanoparticles is also more significant. The blended amine system not only has the highest absorption capacity, but it also has the largest increase of nanofluids. Therefore, it is feasible to use blended amine nanofluids to improve the $CO_2$ absorption system.

## 3.2 | Effect of MDEA concentration

In order to further determine the influence of MDEA concentration on the absorption of $CO_2$ by blended amine nanofluids, $TiO_2$ (0.6 g/L, 40 nm) blended amine nanofluids were prepared. The blended amine system adopts the method of controlling the concentration of MEA and changing the concentration of MDEA, and compares them with the blank group without adding nanoparticles, while the total mass of absorbent is still controlled at 50 g. The changes of cumulative $CO_2$ absorption volume and absorption enhancement factor E after the nanofluids' bubbling absorption for 800 min are shown in Figures 6 and 7.

It can be seen from Figure 6 that as the concentration of MDEA in the blended amine system increases, the total absorption of $CO_2$ also increases. Moreover, the absorption of $CO_2$ by the nanofluids absorbent is significantly higher than that of the amine solution without adding nanoparticles, which indicates that the nanofluids have a strengthening effect on the absorption of $CO_2$. When MEA and MDEA work together, the key to controlling this system is the reaction between MEA and $CO_2$. Therefore, changing the concentration of MDEA has little effect on $CO_2$ absorption.[39]

In addition, it can be found from Figure 7 that the absorption enhancement factor of blended amine nanofluids is markedly higher than that of MEA nanofluids. Moreover, the higher the concentration of MDEA in blended amine, the larger the enhancement factor E, and the more evident the enhancement effect of the nanoparticles on $CO_2$ absorption. Although MDEA has a limited effect on the absorption of blended amine solutions, after adding nanoparticles, MDEA has an obvious positive effect on nanofluids. Increasing the concentration of MDEA in a blended amine system can effectively improve the absorption capacity of nanofluids.

## 3.3 | Effect of MEA concentration

In the same way, in order to confirm the effect of MEA in the blended amine system, $TiO_2$ (0.6 g/L, 40 nm) blended amine nanofluids were prepared. The two amine solutions were mixed by controlling the concentration of MDEA and changing the concentration of MEA, and were then compared with the blank group without adding nanoparticles. The changes in total $CO_2$ absorption volume and absorption enhancement factor after the nanofluids' bubbling absorption for 800 min are shown in Figures 8 and 9.

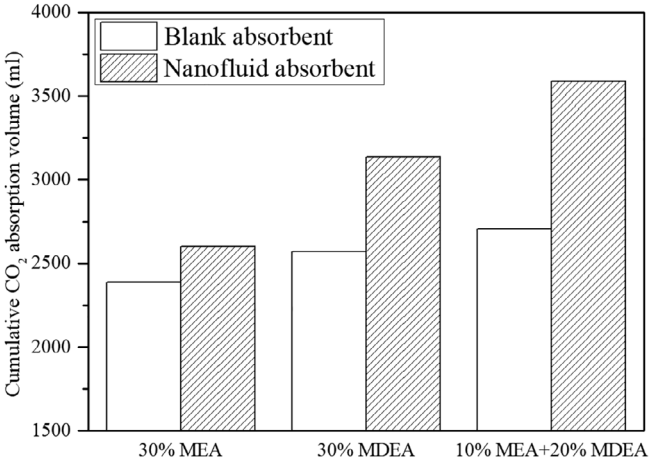


FIGURE 5 Total $CO_2$ absorption volume of blended amines and single amines in 800 min

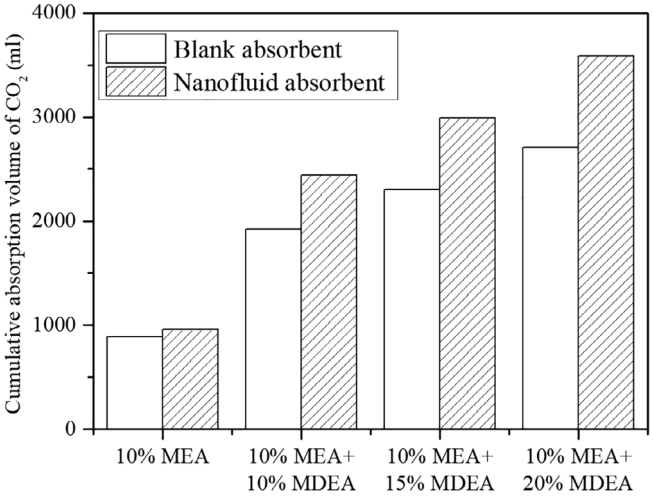


FIGURE 6 Effect of methyldiethanolamine (MDEA) concentration on cumulative $CO_2$ absorption volume (absorbent of 50 g, absorption time of 800 min)

According to Figure 8, as the concentration of MEA in blended amine increases, the $CO_2$ absorption capacity of nanofluids also increases. The nanofluids blended with MEA and MDEA in proportion have a stronger absorption capacity than ordinary amine solutions, which also confirms the strengthening effect of nanoparticles on gas–liquid mass transfer. After adding MEA, the $CO_2$ absorption of the blended amine system significantly improves, which is also due to the reaction mechanism of the blended amine absorbing $CO_2$. Changing the concentration of MEA in the blended amine can effectively improve the $CO_2$ absorption capacity.

However, in blended amine nanofluid systems, raising the concentration of MEA is not conducive to the strengthening effect of nanoparticles. Figure 9 shows that the absorption enhancement factor of blended amine nanofluids is generally higher than that of MEA nanofluids. However, as the concentration of MEA increases, the enhancement factor shows a downward trend, and the $CO_2$ absorption enhancement effect of nanoparticles lessens. This indicates that the chemical reaction rate is an important factor in nanofluid systems, which means the enhancement becomes weak when the reaction rate between the absorbent and $CO_2$ is very fast.[31] The chemical absorption process of $CO_2$ is divided into diffusion control and chemical reaction control. Nanoparticles show more obvious enhancement in the mass transfer process of diffusion control. Therefore, the addition of adsorbent nanoparticles cannot produce a good effect.

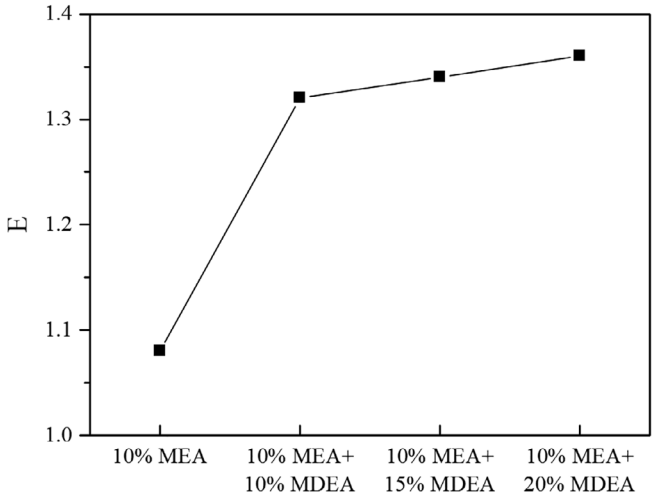


**FIGURE 7** Effect of methyldiethanolamine (MDEA) concentration on absorption enhancement factor

## 3.4 | Effect of blended amine ratio

In order to further visually verify the influence of the blended amine system on the nanofluids absorption experiment, $TiO_2$ (0.4–1.4 g/L, 40 nm) blended amine (25% MDEA + 5% MEA, 20% MDEA + 10% MEA, 15% MEA + 15% MDEA) nanofluids were prepared. The enhancement factor E of nanofluids at each solid content is obtained by comparison with the blank group without adding nanoparticles. The experimental results are shown in Figure 10.

Figure 10 indicates that the enhancement factor E of 25% MDEA + 5% MEA nanofluids is the largest, which can reach up to 1.36 at 0.6 g/L. There is less MEA that controls the reaction rate, which leaves more space for nanoparticles. Under the same reaction conditions, the

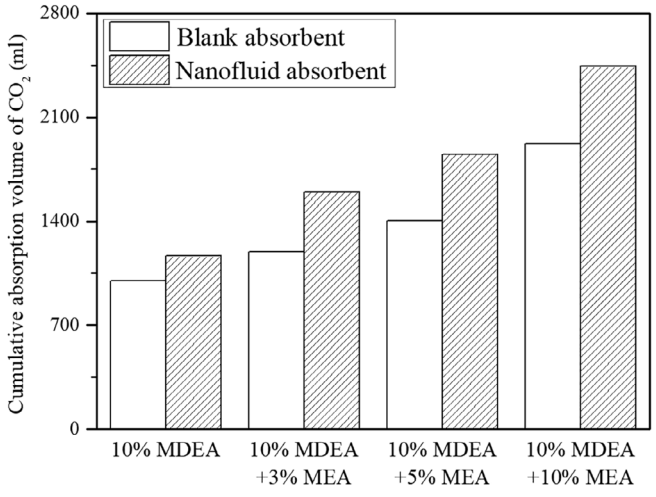


**FIGURE 8** Effect of monoethanolamine (MEA) concentration on cumulative $CO_2$ absorption volume (absorbent of 50 g, absorption time of 800 min)

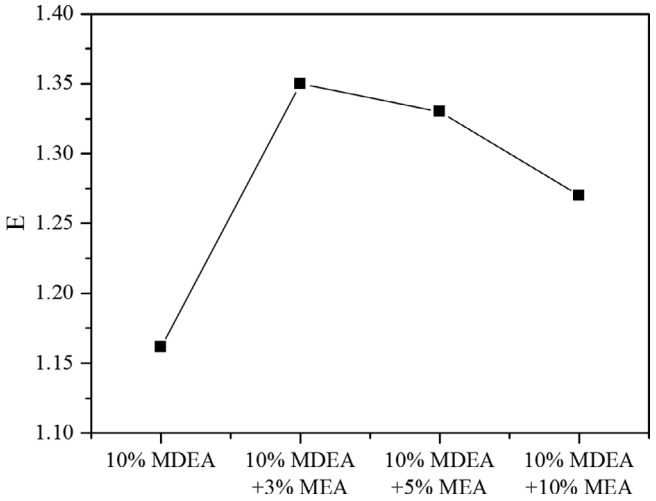


**FIGURE 9** Effect of monoethanolamine (MEA) concentration on absorption enhancement factor

absorption enhancement factor of MEA nanofluids is the lowest overall. Comparing the absorption capacity of five nanofluids, it can be found that the enhancement factor of blended amine nanofluids is higher than that of the single-component amines. Moreover, in a blended amine system, the lower the MEA concentration, the more obvious the absorption enhancement of nanoparticles.

Regardless of single-component amines or blended amine nanofluids, the absorption enhancement factor shows a trend of first increasing and then decreasing with the increase of particle solid content. Namely, there is an optimum solid content of nanoparticles for enhancing the $CO_2$ absorption rate, and the best solid content of $TiO_2$ nanoparticles in the 30 wt.% MDEA-MEA system is 0.6 g/L. This phenomenon can be explained by the change of nanofluid viscosity.[40] Raising the concentration of nanoparticles can strengthen the Brownian motion and promote mass transfer. However, as the concentration of nanofluids increases, the particles will agglomerate and settle, which not only weakens the Brownian motion of particles but also causes the viscosity of the absorbent to rise sharply. The increase of viscosity reduces the diffusion coefficient of $CO_2$ in the absorbent, thereby reducing the total liquid phase mass transfer coefficient, and the enhancement factor decreases remarkably.[41] Therefore, there is an optimal concentration of nanofluids to achieve the best absorption enhancement.

## 3.5 | Model validation

Due to the similarity between mass transfer and heat transfer, Xuan[41] obtained the apparent mass diffusion coefficient of the binary nanofluids as Equation (7):

$$D_{nf} = D_0\left(1 + c\varphi^{m_1} Re_{nf}^{m_2} Sc_{nf}^{n}\right) \tag{7}$$

Therefore, the effective mass diffusion coefficient of the binary nanofluids can be expressed as Equation (8):

$$D_{ad} = c\varphi^{m_1} Re_{nf}^{m_2} Sc_{nf}^{n} D_0 \tag{8}$$

When other conditions are the same, the Reynolds number (Re) and Schmidt number (Sc) in the above formula are both related to solution viscosity and particle volume

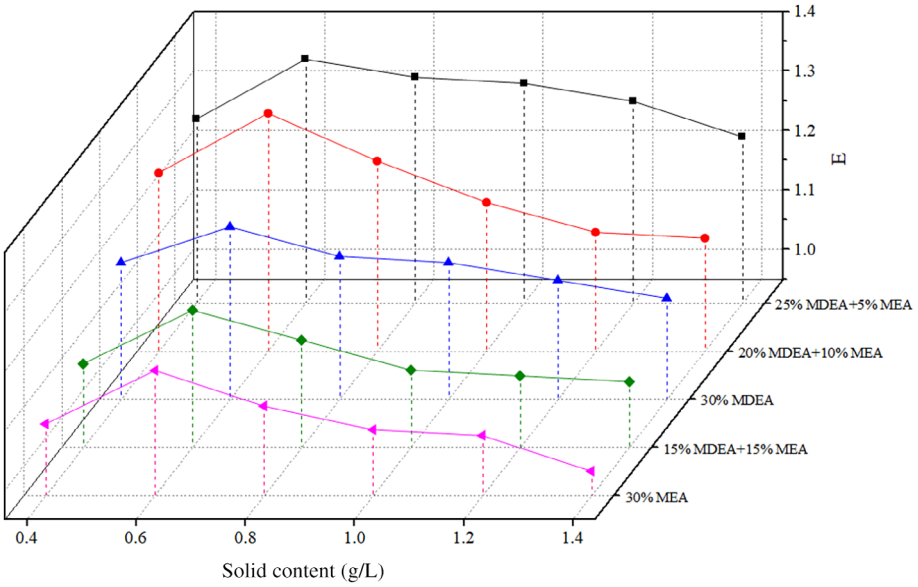


**FIGURE 10** Effects of blended amine ratio on enhancement factor

**TABLE 2** Equation fitting result

| Nanofluids | a | b | c | d | e | $R^2$ |
|---|---|---|---|---|---|---|
| 25% MDEA + 5% MEA | 2.850 | 2.627 | 89.872 | −0.052 | 0.009 | 0.923 |
| 15% MEA + 15% MDEA | 11.355 | 7.299 | 66.170 | −0.245 | 0.067 | 0.997 |
| 30% MDEA | 5.320 | 4.046 | 209.651 | −0.043 | 0.010 | 0.925 |
| 20% MEA + 10% MDEA | 15.292 | 10.638 | 39.575 | −0.515 | 0.153 | 0.982 |
| 30% MEA | 15.809 | 11.135 | 76.233 | −0.281 | 0.063 | 0.914 |

Abbreviations: MDEA, methyldiethanolamine; MEA, monoethanolamine.

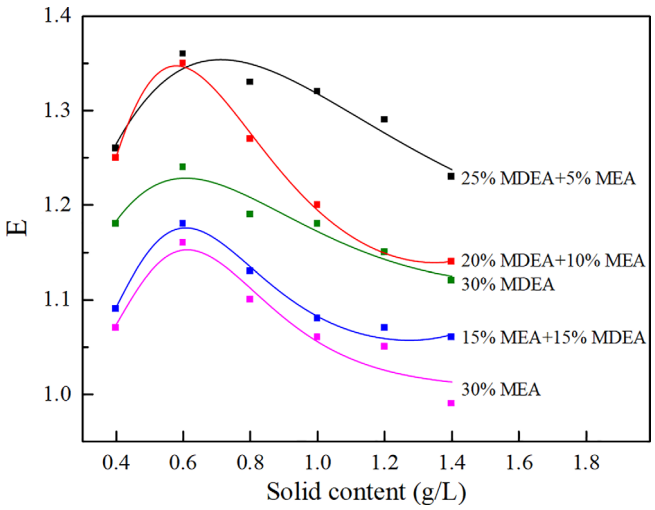


**FIGURE 11** Comparison of the measured enhancement factor with the proposed correlation

fraction. Viscosity is one of the most important thermophysical characteristics of nanofluids. The particle volume fraction and temperature are key parameters that affect the viscosity of nanofluids. Since the absorption temperature is constant at 25°C in this experiment, only the effect of solid content is considered. Therefore, by using the relations between particle volume fraction and viscosity of nanofluids, the equation of solid content and absorption enhancement factor can be derived.

Khanafer and Vafai[42] established an empirical model of the viscosity and volume fraction of nanofluids based on experimental data. The basic relationship between the solid content of nanoparticles and the viscosity of nanofluids can be expressed as Equation (9):

$$\frac{\mu_{nf}}{\mu_f} = 1 + 3.544\varphi + 169.46\varphi^2 \tag{9}$$

Based on the above theories, the following empirical equation for predicting the enhancement factor of $TiO_2$ -amine nanofluids in this experiment has been proposed:

$$E = exp\left[a + bln\varphi + cln\left(1 + d\varphi + e\varphi^2\right)\right] + 1 \tag{10}$$

where φ denotes the solid content of nanoparticles, and a, b, c, d, and e are constant values as shown in Table 2.

The limitations of this equation are as follows: (1) the absorption temperature is constant at 25°C and (2) the solid content of $TiO_2$ nanoparticles ranges between 0.4–1.4 g/L. Figure 11 shows the comparison between the enhancement factor obtained by the above correlation and those obtained from the experiments. It can be found that the equation is in good agreement with the experimental data. Therefore, it is feasible to predict the enhancement factor of $TiO_2$-amine nanofluid through the empirical formula.

## 4 | CONCLUSIONS

In this study, a bubbling reaction system was implemented to comprehensively study the $CO_2$ capture properties of MDEA-MEA blended amine nanofluids. $TiO_2$ nanoparticles and ASAP surfactant were adopted to develop a high-efficiency $CO_2$ absorption system. Compared with two single-component amines of MEA/MDEA, nanoparticles play a more significant absorption enhancement role in the MDEA-MEA blended amine system. Furthermore, the strengthening effect of nanoparticles becomes stronger with the increase of MDEA concentration, while increasing the concentration of MEA is not conducive to the enhancement. The absorption enhancement factor shows a trend of first increasing and then decreasing with the increase of solid content. Therefore, nanofluids have an optimum solid content, and in this system, the best solid content of $TiO_2$ nanofluids is 0.6 g/L. The enhancement factor E of 25% MDEA + 5% MEA nanofluids can reach up to 1.36 at the optimum solid content. At last, a correlation for predicting the enhancement factor of $TiO_2$-amine nanofluids was proposed, which was in good agreement with the experimental results.

Although several factors of MDEA-MEA nanofluids have been studied, future work should cover more key parameters, such as nanoparticle type, blended gas volume flow, and initial carbon dioxide concentration. Furthermore, the applicability of the proposed empirical equation is limited. Future research should be focused on identifying the major parameters which affect the enhancement process of $CO_2$ absorption and on establishing a more efficient nanofluids $CO_2$ capture system.

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## AUTHOR CONTRIBUTIONS

**Jiaxin Liang:** Data curation; formal analysis; investigation; writing – original draft. **Huiyu Han:** Data curation; formal analysis; investigation; validation. **Wenbo Li:** Data curation; investigation. **Xiaoxun Ma:** Funding

acquisition; methodology; project administration; resources. **Long Xu:** Formal analysis; funding acquisition; investigation; project administration; supervision; writing – review and editing.

## PEER REVIEW

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## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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