Optimization of CO2 Capture Efficiency in a Flue Gas Treatment System: Assessing the Impact of Flow Rates, Absorbent Concentrations, Nanoparticles, and Temperature

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Abstracts: This study focuses on improving the efficiency of flue gas purification systems for carbon dioxide (CO_2) capture. The researchers investigated various factors, including flow rates, absorbent concentrations, nanoparticles, and temperature, to optimize the CO_2 capture process. They conducted experiments using a polytetrafluoroethylene (PTFE) hollow fiber membrane contactor to separate CO_2 from nitrogen. The presence of titanium dioxide and silica nanoparticles in a potassium carbonate solution facilitated the separation process. The findings indicate that optimizing flow rates and absorbent concentrations can enhance CO_2 capture efficiency. The use of nanoparticles in the absorbent solution was found to improve material capture effectiveness. The study also revealed that higher temperatures contribute to increased CO_2 capture efficiency. The research aims to advance CO_2 capture techniques to mitigate the release of industrial greenhouse gases, particularly in flue gas treatment systems. The researchers determined optimal settings for CO_2 capture in these systems, emphasizing the importance of absorbent concentration for stability and absorption, as well as the role of nanoparticles in enhancing reaction kinetics and CO_2 collection. The objective of the analysis is to maximize removal efficiency, although specific lower and upper bounds and a target value were not provided. The proposed solution suggests specific values for the independent variables, including temperature, gas flow rate, liquid flow rate, and the concentrations of K_2CO_3, PZ, SiO_2, and TiO_2, to optimize CO_2 capture.

Keywords: CO2 Capture, Flue Gas Treatment, Optimization, Flow Rates, Absorbent Concentrations, Nanoparticles, Temperature, Capture Efficiency, Greenhouse Gas Emissions, Industrial Processes.

1. INTRODUCTION

The utilization of potassium carbonate (K_2CO_3) for the adsorption of carbon dioxide (CO_2) is a noteworthy and adaptable approach within the domain of carbon capture and storage (CCS) technologies. The significance of this lies in its capacity to alleviate the discharge of carbon dioxide into the atmosphere, thereby tackling climate change and diminishing emissions of greenhouse gases [1]. This methodology exhibits extensive utility across diverse domains and fields. The utilization of K_2CO_3 for CO_2 absorption finds significant application in power generation facilities, particularly those that depend on non-renewable energy sources [2]. The process of K_2CO_3 absorption involves capturing CO_2 from the flue gas emissions of power plants, thereby preventing its release into the atmosphere. This results in a reduction of the carbon footprint associated with the energy generation process. Furthermore, it has the potential to be utilized in sectors characterized by significant CO_2 emissions, such as the production of cement, steel, and chemicals. The benefits associated with the utilization of K_2CO_3 for the purpose of CO_2 adsorption are significant as indicated in reference [4]. Primarily, potassium carbonate demonstrates a notable inclination towards CO_2, facilitating proficient and potent sequestration of the gas. The significant absorption capacity exhibited by K_2CO_3 renders it a desirable absorbent for CO_2 capture applications on a large scale. In addition, K_2CO_3 is easily accessible and comparatively affordable, thereby enhancing its cost-efficiency in comparison to alternative absorbents. An additional benefit is the simplicity in renewing the K_2CO_3 solution and reclaiming the trapped CO_2, as stated in reference [5]. Upon subjecting the potassium bicarbonate solution to thermal energy, the carbon dioxide is liberated in its gaseous form, thereby facilitating its segregation and subsequent retention or application. The process of regeneration renders the absorbent reusable, thereby augmenting the overall efficiency and sustainability of the system designed for capturing CO_2 [6][7].

Nonetheless, the utilization of K_2CO_3 for CO_2 adsorption entails specific factors to be considered and possible drawbacks to be considered. An area of concern pertains to the energy demands associated with the process of regeneration. The process of liberating the sequestered CO_2 from the solution necessitates an energy input, which, if sourced from fossil fuels, may counterbalance the ecological advantages accrued from CO_2 capture. Consequently, the incorporation of renewable energy sources into the regeneration process is imperative to optimize the potential for carbon reduction [8]. An additional factor to be considered is the corrosive properties exhibited by solutions containing potassium carbonate. The corrosive potential of K_2CO_3 due to its highly alkaline nature can result in equipment corrosion during the process of CO_2 capture and storage [9]. The significance of potassium carbonate (K_2CO_3) in carbon capture and storage (CCS) technologies is considerable, particularly in relation to its ability to adsorb CO2 [10]. Potassium carbonateis an alkaline compound possessing a strong attraction towards CO_2. The formation of a stable compound: the potassium bicarbonate ($KHCO_3$) can occur through the reaction of CO_2 and potassium, as evidenced by sources [5] [11].

$$K_2CO_3 + CO_2 + H_2O \rightarrow 2KHCO_3 \quad (1)$$

The chemical process takes place within a liquid medium, commonly employing either an absorption column or a packed bed reactor. During this process, a CO_2 stream is introduced to the K_2CO_3 solution, facilitating the dissolution and chemical reaction of CO_2 molecules with potassium carbonate. Consequently, the concentrate ion of CO_2 in the gas stream is effectively decreased due to its removal. The efficacy of carbon dioxide (CO_2) adsorption through the utilization of potassium carbonate (K_2CO_3) is contingent upon a multitude of variables, encompassing temperature, pressure, concentration of the K_2CO_3 solution, and duration of interaction between the gaseous and liquid phases. In general, the process of adsorption is enhanced by higher temperatures and lower pressures. Furthermore, an increased concentration of K_2CO_3 within the solution has been shown to enhance the efficiency of CO_2 capture, as reported in reference [12].[13].

The incorporation of nanoparticles (NPs) in conjunction with potassium carbonate (K_2CO_3) has been found to improve the efficacy of carbon capture processes. Nanoparticles (NPs) provide a multitude of benefits, such as enhancing surface area and catalytic effect, that can enhance the absorption capacity and kinetics of carbon dioxide (CO_2) capture, as indicated by previous research [14]. The enhanced surface area of nanoparticles facilitates improved interaction between the absorbent and CO_2 molecules, thereby promoting increased CO_2 uptake. This has been reported in literature [11]. The utilization of specific nanoparticles (NPs) can potentially enhance the catalytic activity, thereby promoting the reaction between CO_2 and K_2CO_3. This, in turn, can expedite the production of potassium bicarbonate and augment the overall efficiency of CO_2 sequestration, as reported in references [15] and [10].

Furthermore, the utilization of nanoparticles (NPs) can aid in reducing mass transfer limitations through the promotion of CO_2 diffusion into the absorbent solution. The inclusion of nanoparticles (NPs) within a K_2CO_3 solution has been observed to have a positive impact on the solubility of CO_2, leading to a reduction in mass transfer resistance[14]. This, in turn, has been shown to improve absorption kinetics and overall efficiency. The primary benefit of utilizing nanoparticles in conjunction with potassium carbonate lies in their capacity to stabilize and impede the deterioration of the absorbent solution, as noted in reference [16]. The efficacy of CO_2 capture process may be impacted by the deterioration of K_2CO_3 because of ancillary reactions or contaminants present in the flue gas. The inclusion of nanoparticles (NPs) has the potential to impede the degradation reactions and increases the durability of the absorbent solution, thereby guaranteeing its sustained efficacy. It is crucial to acknowledge that the effective integration of nanoparticles (NPs) in carbon dioxide (CO_2) capture procedures necessitates meticulous contemplation of several aspects, such as the suitable NPs' choice, their dispersion in the solution, and their congruity with K_2CO_3 [17]. The selection of NPs ought to be predicated upon their adsorption characteristics, stability, and cost-efficiency. It is crucial to employ accurate methods of characterization and optimize the concentration of nanoparticles to acheive the intended improvements in the efficiency of carbon capture. This has been highlighted in previous research [4],[16].

Incorporating piperazine as an adjunct in carbon sequestration techniques involving potassium carbonate (K_2CO_3) has the potential to yield substantial advantages and augment the efficacy of CO_2 capture. The cyclic organic compound known as Piperazine can function as a promoter or activator in the process of CO_2 absorption, thereby resulting in an enhanced performance of carbon capture, as reported in reference [18],[4],[19]. Piperazine functions as a reactive solvent, facilitating the reaction between carbon dioxide and potassium carbonate, ultimately leading to the production of potassium bicarbonate. The enhancement in the reaction rate facilitates the efficacy of CO_2 assimilation, thereby enabling elevated CO_2 sequestration rates and diminishing the duration of contact necessary for proficient capture [12]. Piperazine has been found to possess not only promotional effects on CO_2 absorption but also the ability to alleviate the degradation of K_2CO_3 resulting from side reactions or impurities present in the flue gas. [14]. The maintenance of stability is of utmost importance for the sustainable functioning and financial feasibility of the carbon capture mechanism over an extended period. Nevertheless, it is crucial to consider the possible obstacles linked to the utilization of piperazine [20][21]. An area of concern pertains to the possible instability and vapor pressure exhibited by piperazine, which may lead to its dissipation via evaporation while undergoing the capture procedure. It is recommended that appropriate control measures and system design be employed in order to mitigate any potential losses of piperazine and optimize its efficacy, as per source [6].

This project intends to promote an innovative and efficient carbon capture technology, by using potassium carbonate (K_2CO_3), piperazine, and nanoparticles to create a novel carbon sequestration blend in a polytetrafluoroethylene (PTFE) hollow fiber membrane contactor (HFMC) and perform a parametric analysis to assess its performance. Gas and liquid flow rates, K_2CO_3 concentration and temperature manipulation will dominate the study. By examining how the effect of these operational factors determine carbon capture efficiency.

Parametric analysis evaluates many performance metrics. CO_2 absorption rate, removal efficiency, and solvent stability. The experimental results will be analyzed to determine the synergistic effects of K_2CO_3, piperazine, and nanoparticles and their sensitivity to temperature and flow rates. Parametric analysis can help identify optimum operating parameters that enhance carbon capture efficiency while balancing energy needs and system stability.

2. EXPERIMENTAL WORK

The process of absorbing carbon dioxide involves the utilization of a PTFE membrane module manufactured by Nanjing Junxin Environmental Technology Co., Ltd. for the purpose of CO_2 sequestration using blend of potassium carbonate (K_2CO_3), piperazine, and nanoparticles. The aim of this study is to conduct a parametric analysis on the performance of the mixture, with a specific focus on the manipulation of gas and liquid flow rates and temperature. Initially, a solution of 10% wt. concentration is prepared by dissolving potassium carbonate (K_2CO_3) in distilled water. The solution is subjected to magnetic stirring at ambient temperature for a duration of 30 minutes to attain uniformity. The solution's pH was measured to be pH: 10. Nanofluids are produced by incorporating nanomaterials, such as titanium dioxide and silica nanoparticles, into the underlying fluid. The nanomaterials were homogenously dispersed in the base fluid through a combination of magnetic stirring for a duration of 30 minutes, followed by sonication in a water bath sonicator for a duration of 60 minutes. This guarantees a homogeneous dispersion of the nanomaterials within the solution. Piprazine of 2% is also prepared for experimental purposes. Figure 1 depicts the experimental apparatus.

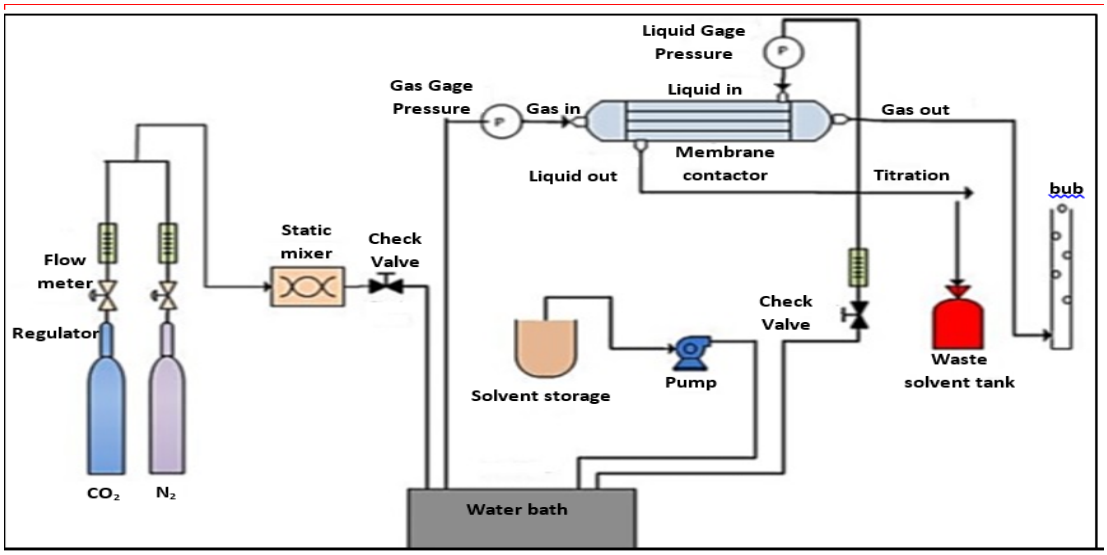

Fig 1a. Rig setup.

The process of absorbing carbon dioxide involves the utilization of a PTFE membrane module. The experimental setup comprises a module of a membrane contactor with hollow fibers, along with flow meters for both gas and liquid, pressure indicators, regulators, a static mixer for gases, a temperature controller, and a water bath. The transfer of absorbent from the solvent container to the internal lumen of the membrane module is facilitated by means of a peristaltic pump. A mixture of carbon dioxide and nitrogen gas is generated by a static mixer and subsequently passed through a water bath for temperature control, than it is directed towards the tube side of the membrane module. The coiled tube is supplied with an absorbent solvent which is then directed in a counter-current flow configuration towards the shell side of the membrane contactor module. The experimental assessments were carried out under a differential pressure of 0.2 atm between the gaseous and liquid phases along the investigation. We prevent the occurrence of bubbles within the mass transfer layer situated on the membrane surface, in order to uphold a consistently even mass transfer layer. After 15 minutes, the system attains its steady state. Following each testing cycle, the membrane module and pipes undergo a cleaning process utilizing distilled water, followed by drying with nitrogen gas to eliminate any remaining moisture. To mitigate membrane wetting and condensation effects , a valve is inserted into the liquid stream to impede the generation of gas bubbles. To avoid condensation , it is necessary to maintain a slightly higher pressure on the liquid side of the system compared to the gas side. Furthermore, the estimation of mass transfer and the amount of carbon dioxide assimilated from the surroundings is conducted through appropriate equations. The mixture liquid with K_2CO_3, incorporating piperazine (PZ), and the nanofluid with nanoparticles are prepared in following way:

- The initial step involves the preparation of the basic solution. To obtain a desired concentration, the necessary quantity of K_2CO_3 is dissolved in distilled water at ambient temperature. The pH of the solution is controlled to verify if it falls within the specified range, if relevant.
- The preparation of the PZ solution uses PZ powder wich is incorporated into the base fluid acquired in the first step.
- The suspension is mixed by magnetic stirrer for a duration of 10 minutes.
- To prepare the nanofluid, at the desired concentration of titanium dioxide or silica nanoparticles in the base fluid. The nanoparticles are incorporated into the base fluid under continuous stirring with a magnetic stirrer for a duration of 30 minutes to ensure a homogeneous dispersion. The nanofluid suspension is introduced in an ultrasonicator apparatus for a duration of 30 minutes. As cited by [66, 98], by this way the dispersion is stabilized and the agregation nanoparticle is avoided.

3. ANALYSIS METHODOLOGY

To determine the percentage of carbon dioxide removal, we compare the quantity of carbon dioxide that has been eliminated to the inlet concentration of carbon dioxide. The carbon dioxide removal percentage can be computed using the subsequent formula.:

$$Carbon\ Dioxide\ Removal\ \% = \frac{(Initial\ CO2\ Concentration - Final\ CO2\ Concentration)}{Initial\ CO2\ Concentration} \times 100 \quad (1)$$

The methodological protocol elucidated above exemplifies the procedure for ascertaining the initial concentration of carbon dioxide and its subsequent sequestration via conduction employing K_2CO_3, piperazine, and a solution of nanofluid. Concentration measurements are conducted using analytical techniques such as gas chromatography or spectrophotometry. The discrepancy between the initial and final concentrations is quantified, and the proportion of carbon dioxide elimination is assessed utilizing Equation (1).

In order to explore the impact of variables such as the percentage of K_2CO_3, NPs, Q_L, Q_g, and T on the process of carbon dioxide removal, we employ the Minitab software for sophisticated statistical analysis. The empirical observations are meticulously collected and organized in a systematic manner, while the requisite calculations of descriptive statistics are performed to elucidate the dataset's measures of central tendency and dispersion. Regression analysis, specifically employing multiple linear or polynomial regression techniques, is employed to evaluate the influence of various parameters on the process of carbon dioxide removal. The selection of a suitable model holds utmost importance in the process of determining the optimal regression model, wherein metrics such as R-squared, p-values, and ANOVA results play a pivotal role.

The parameter estimates derived from the regression analysis offer valuable insights into the intricate interplay between variables and the process of carbon dioxide removal. Minitab's optimization tools facilitate the determination of optimal parameter configurations that maximize the elimination of carbon dioxide, taking into account various constraints and objectives. The statistical analysis findings are duly interpreted, and a thorough examination is conducted to discern their implications for the process of carbon dioxide sequestration. A sensitivity analysis quantifies the resilience of the outcomes to variations in parameter values, thereby addressing potential limitations or ambiguities.

4. RESULTS AND DISCUSSION

4.1 The Effect of Liquid and Gas Flow Rates

The data that was observed indicates a distinct pattern where an increase in the rates of liquid flow rate (Q_L) results in an increase in the efficiency of CO_2 removal, as illustrated in Figures 2. The liquid volumetric flow rate varied from 53ml/min to 82 ml/min. It is shown that removal efficiency increased by 72%, 78%, 93%, 95% for (K_2CO_3), (K_2CO_3/PZ), (K_2CO_3/PZ/SiO_2), and (K_2CO_3/PZ/TIO_2) respectively. The mass transfer enhancement in the nanofluids caused is due to the grazing effect, Brownian motion and Micro convection. According to the grazing effect, the nanoparticles adsorbed the molecules of dissolved gas in a small film, and moving right through the concentration boundary layer, at last desorb the adsorbed molecules into the liquid bulk [22]. The presence of nanoparticles also can causes micro convection due to the nanoparticles Brownian motion; in fact, the micro convection can enhance the mass diffusion in the nanofluid. Because of the higher absorbing rate between CO_2 and K_2CO_3, K_2CO_3/ TiO_2/PZ nanofluids outperformed K_2CO_3/SiO_2/PZ nanofluids in terms of CO_2 absorption. Because TiO_2 adsorbed more CO_2, the concentration gradient of CO_2 increasing, and the absorption enhancement grew accordingly. It was shown that K_2CO_3/PZ/TiO_2 nanofluids offered a greater rate of enhancement, Where efficiency has increased from 35% to 95%. Similarly slanted findings to those of this research were also reported by [39]. Conversely, the CO_2 removal efficiency decreased from 86% to 63% when the gas volumetric flow rate was increased from 250 ml/min to 500 ml/min, as shown in fig.3

By increasing the gas flow rate concentration, CO_2 removal efficiency for all nanoparticles type reduces. The CO_2 residence time inside the fibers decreases and therefore lower amount of CO_2 can be absorbed through membrane into solvent [23].

The findings of this research are consistent with ref. [24][25][26]. Furthermore, the CO_2 removal efficiency for all nanoparticle types decreases as the gas flow rate increases. The increase of gas flow rate would accumulate the CO_2 Intensity. This phenomenon may results in a reduction in the efficacy of carbon dioxide removal. In situations where flow rates are elevated, the liquid contact time is so short on the shell side of the membrane contactor, to acheive substantial sequestration of CO_2 molecules, [27].

In order to ascertain the optimal range of flow rates, further investigation can be carried out through the utilization of experimental design methodologies like response surface methodology or factorial design. The present experiments investigates various flow rates for both the liquid and gas phases. Through a systematic manipulation of flow rates and the monitoring of CO_2 removal efficiency, it is possible to generate a response surface or contour plot that visually represents the relationship between flow rates and CO_2 capture efficiency. The present analysis conducts to the most favorable flow rate conditions, in our operating conditions, that can improve the efficiency of CO_2 removal [5],[11]. Furthermore, it is noteworthy to state that the inclusion of TiO_2 nanoparticles as additives resulted in a 43% increase in capture efficiency, whereas the incorporation of SiO_2 led to a 36% improvement. The incorporation of used additives has the potential to enhance the overall efficiency of the CO_2 capture procedure. When adding PZ to solution leads to increase CO_2 loading, the incorporation of piperazine results in a marginal increase in the capture efficiency across diverse liquid flow rates. According to the experimental results, the incorporation of piperazine results in a marginal increase of 2% in the capture efficiency across diverse gas and liquid flow rates. The aforementioned observations imply that the existence of piperazine results in a marginal enhancement in the efficacy of CO_2 sequestration. The utilization of piperazine as a solvent additive in CO_2 capture procedures is prevalent owing to its capacity to augment the absorption characteristics of the solvent. The facilitation of the reaction between carbon dioxide (CO_2) and the solvent can lead to an enhancement of the capture efficiency [18].

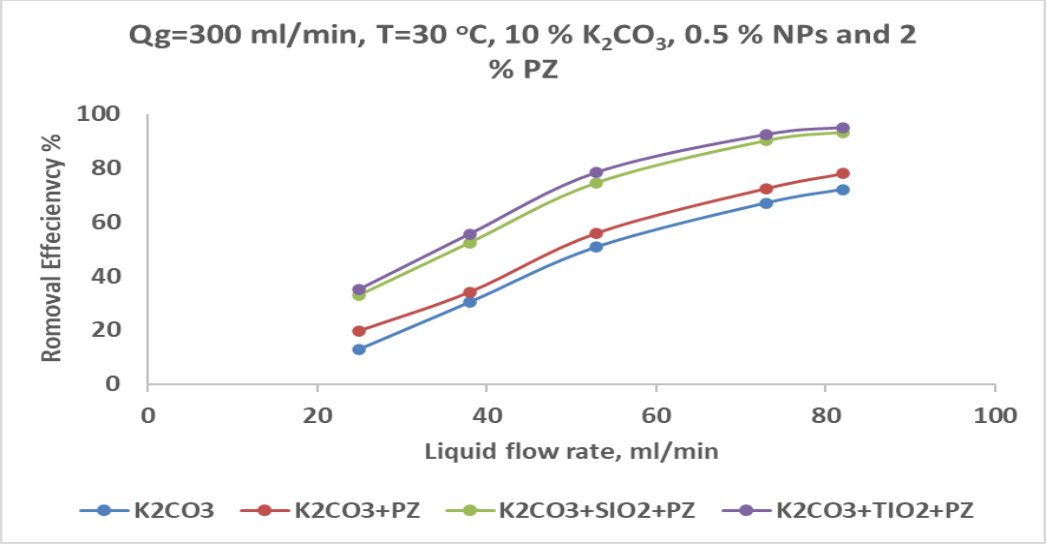

Fig 2: The impact of Liquid flow rate on CO_2 removal efficiency.

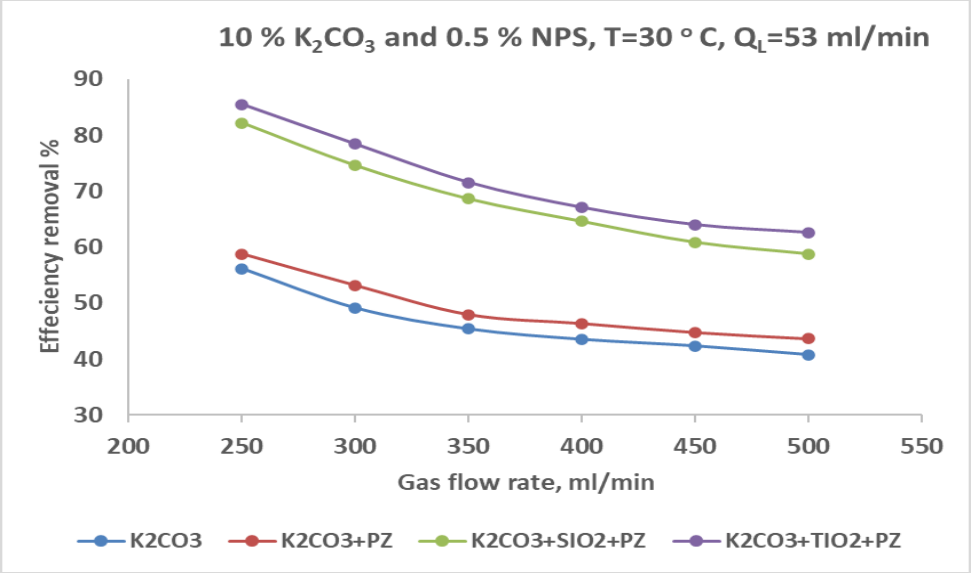

Fig 3: The impact of Gas flow rate on CO_2 removal efficiency.

4.2 The Impact of K_2CO_3 Concentration.

The findings depicted in Figure 4 indicate that there is a significant correlation between the percentage of K_2CO_3 and the efficiency of CO_2 removal, whereby an increase in the former from 6.0% to 14.0%wt. K_2CO_3 ,results in a noteworthy improvement in the latter. The nanofluid volumetric flow rate and gas volumetric flow rate were fixed at 53 ml/min and 300 ml/min, respectively, the CO_2 removal efficiency increased from 51% to 92%. The CO_2 capture process experiences a notable enhancement as the concentration of K_2CO_3 in the base fluid rises, leading to an increase in removal efficiency. This, in turn, facilitates a more efficient absorption of CO_2. As a consequence, the efficiency of CO_2 removal is enhanced [8][28]. It is noteworthy that there exists a potential upper threshold for the concentration of K_2CO_3, beyond which any subsequent increments may not yield a substantial improvement in the efficacy of CO_2 sequestration. The observed phenomenon may be attributed to various factors, including limitations in CO_2 solubility or the possibility of side reactions that could arise at elevated concentrations.

Incorporating the impact of K_2CO_3, can facilitate an enhanced comprehension of the molecular interplay between CO_2 and K_2CO_3, and its consequent influence on the efficacy of CO_2 elimination. In conclusion, the data demonstrates a distinct indication that increasing the concentration of K_2CO_3 in the base solution has a positive effect on the efficiency of CO_2 removal. The aforementioned phenomenon can be attributed to the increased availability of reactive sites for the absorption of carbon dioxide, which exhibits a direct correlation with the concentration of potassium carbonate (K_2CO_3). However, further investigation is required to determine the optimal K_2CO_3 concentration that maximizes CO_2 capture, while considering practical limitations and system constraints. The augmentation of K_2CO_3 concentration from 6% to 14% exerts a noteworthy influence on amplifying all the systems, namely K_2CO_3 alone, in conjunction with PZ, SiO_2 NPs, and TiO_2 NPs, to the extent of reaching a high enhancement rate.

The augmentation of K_2CO_3 concentration leads to an improvement in the solvent's ability to assimilate and interact with CO_2 molecules. As a consequence of this phenomenon, the elimination of CO_2 from the gaseous phase is enhanced, leading to an increase in the overall capture efficacy. The incorporation of additives, namely PZ (piperazine), SiO_2 NPs (silicon dioxide nanoparticles), and TiO_2 NPs (titanium dioxide nanoparticles), in conjunction with the augmented concentration of K_2CO_3, results in a heightened capture efficacy. these additives play a role in enhancing the mass transfer kinetics or the overall absorption characteristics of the solvent [12]. The observed increase in the CO_2 removal efficiency by twice time in the best conditions suggests that the system has a capacity to achieve a significantly higher level of performance in comparison to the baseline conditions.

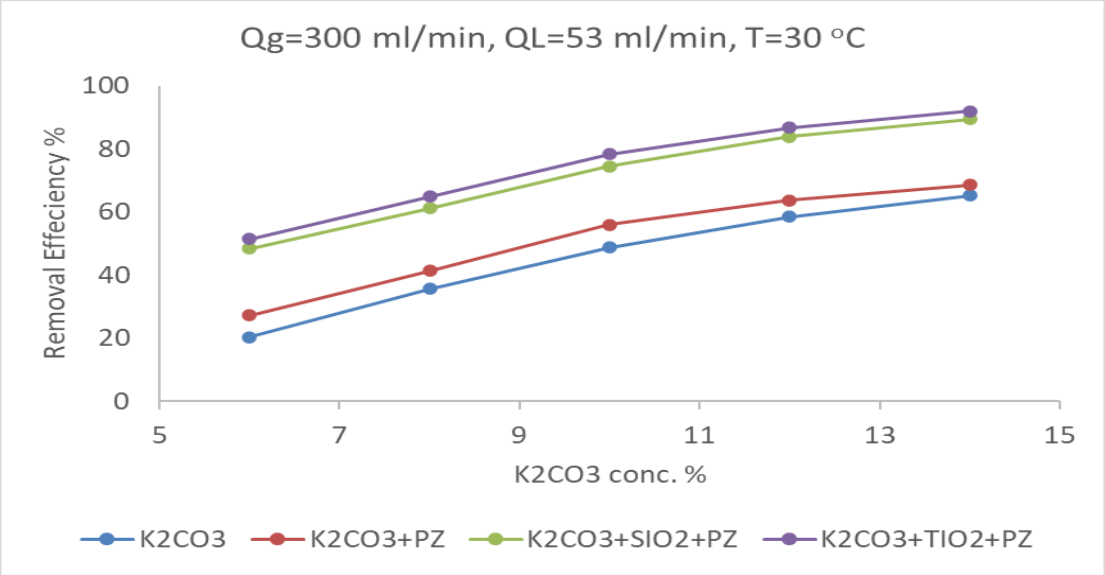

Fig. 4. The impact of K_2CO_3 on removal efficiency.

4.3 The Impact of Nanomaterials

Figure 5 provides insights into the impact of silica (SiO_2) and titanium oxide (TiO_2) nanoparticles on the efficiency of carbon dioxide (CO_2) removal. The investigated concentrations of TiO_2 and SiO_2 nanoparticles are 0.1 wt.%, 0.2 wt.%, 0.3 wt.%, 0.4 wt.%, 0.5 wt.%, 0.6 wt.%, and 0.7% wt with 2% piperazin (PZ).The volumetric flow rate of gas was 300 ml/min . The data suggests that the efficiency of CO_2 removal peaked when at used nanoparticles concentration of 0.5%wt. and was shown to be optimal for CO_2 absorption by these nanofluides as compared with other concentrations that studied and thereafter declined for both Nano fluids. At liquid flow rate of (53 ml/min) the removal efficiency was enhanced by 78%, 74% for K_2CO_3/PZ/TiO_2 , K_2CO_3/PZ/SiO_2 respectively, the addition of TiO_2 nanoparticles increased capture efficiency by 43%, while SiO_2 enhanced it by 36%. The efficacy of nanoparticles depends on various factors, including their dimensions, surface properties, and interactions with the surrounding fluid [14].

it can be noticed that K_2CO_3/PZ/TiO_2 nanofluid reveals better improved removal efficiency than K_2CO_3/PZ/SiO_2 nanofluids, which reached to 78%. on the other hand, the performance of CO_2

absorption decreased when nanoparticle concentration was higher than 0.5 Wt.%. Namely, there is an optimum concentration of nanoparticle for absorption of CO_2 performance. An augmentation in the concentration of nanoparticles (NPs) exceeding 0.5% leads to a marginal decline in the capture efficiency. This phenomenon can be ascribed to the manifestation of membrane fouling, resulting in a decrease in the efficacy of capturing. Here, the above- mentioned phenomenon can be explained as follows nanoparticle amount and mutual interference increase with increasing nanoparticle concentration, that can improve the mass transfer according to the boundary mixing effect.The presnce of the optimum concentration of nanofluids also observed by M.Darabi et al.[29]. In addition, an increase in the nanoparticles concentration may effect in the dispersion of the nanofluid and agglomeratiom of nanoparticles could take place. Therefore, the surface area of nanoparticles will be decreased. Furthermore, the nanoparticles movement will be hocked in the nanofluid by adjacent nanoparticles. Therefore, nanofluid absorption rate will decrease[26][30]. As mentioned earlier, the Brownian motion and shuttle effect of nanoparticles are two prominent machanisms that explain the mass transfer enhancement in the nanofluides. Increasing the concentration of nanoparticle is expected to increasing both shuttle effect and micro convection that lead to improve mass transfer rate.

The previous works consistent the trend of this results [31][32][33]. When adding PZ to the absorbents leads to increase CO_2 absorption in solvents due to its molecular structure. It is an attractive carbon dioxide adsorbent, because two carbon dioxide molecules can be attached to a single piperazine molecule through two amine groups in the piperazine, thus improving absorption [34][35].

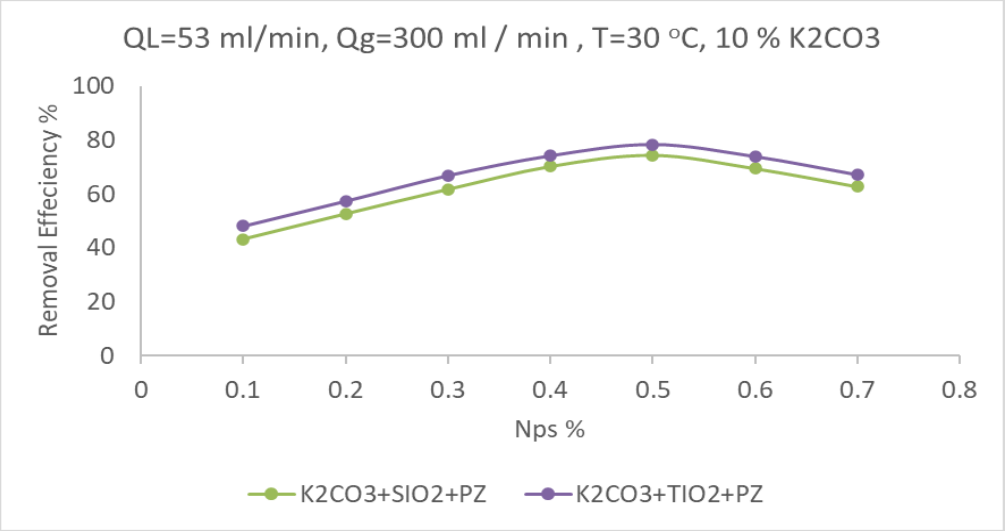

Fig. 5: The impact of nanoparticle conc. on removal efficiency.

The results of this investigation possess the potential to offer guidance for the progression of nanoparticle-based methodologies with enhanced efficacy. The examination of the available data suggests that the incorporation of isolated silica or titanium oxide nanoparticles at a concentration of 0.5% significantly impact the efficiency of CO_2 removal. Additional investigation is imperative to explore the potential of silica and titanium oxide nanoparticles and to optimize their concentration and properties with the aim of augmenting CO_2 capture [10].

4.4 The Effect of Temperature

Figure 6 provides explicit information about the influence of temperature (T) on the efficiency of CO_2 removal in solvent strengthened by nanoparticles and PZ. at different temperatures of 20, 30, 40 and 50°C. The nanofluid volumetric flow rate was 53 ml/min, and the gas volumetric flow rate was 300 ml/min. The removal efficiency increased from 70% to 78% for K_2CO_3/PZ/TiO_2 nanofluid when the temperature increased from 20°C to 30°C. However, the CO_2 absorption performance is dropped when the temperature raised more than 30°C. The trends of the results are consistent with previous published works [23][24][36]. Temperature influences the kinetics of chemical reactions involved in CO_2 absorption by the base fluid or the interaction of CO_2 with adsorbent materials. Changes in temperature alter the rate of CO_2 sequestration and affect the equilibrium state of the sequestration mechanism and increase diffusivity of the species and the reaction rate constant according to the Arrhenius expression beside the thermodynamics Negative Gibbs free energy increases by temperature increasing [37, 38]. On the other hand, an increase in temperature can also cause a decrease in CO_2 solubility which reduces the effectiveness of CO_2 capture. Vapor fills the membrane pores, thus results in capillary condensation which can increase the membrane resistance which leads to a lower driving force for CO_2 absorption increase in absorbent evaporation and increase in CO_2 back-pressure which are not favorable for the absorption process [2],[24]. By increasing temperature, the Brownian movement and the aggregation of nanoparticles in absorption solutions may affected by temperature. This manner is further passionate in solution containing nanostructure due to the enhancement in the heat transfer caused by nanoparticles [3][24]. On the other hand, both mass and heat transfers have direct relationship with temperature. For nanofluids, higher suspension temperature will make stronger Brownian motion of suspended nanoparticles. Also, more intense microconvection inside the nanofluid, which further magnifies energy and mass transfer processes inside the nanofluid [39].

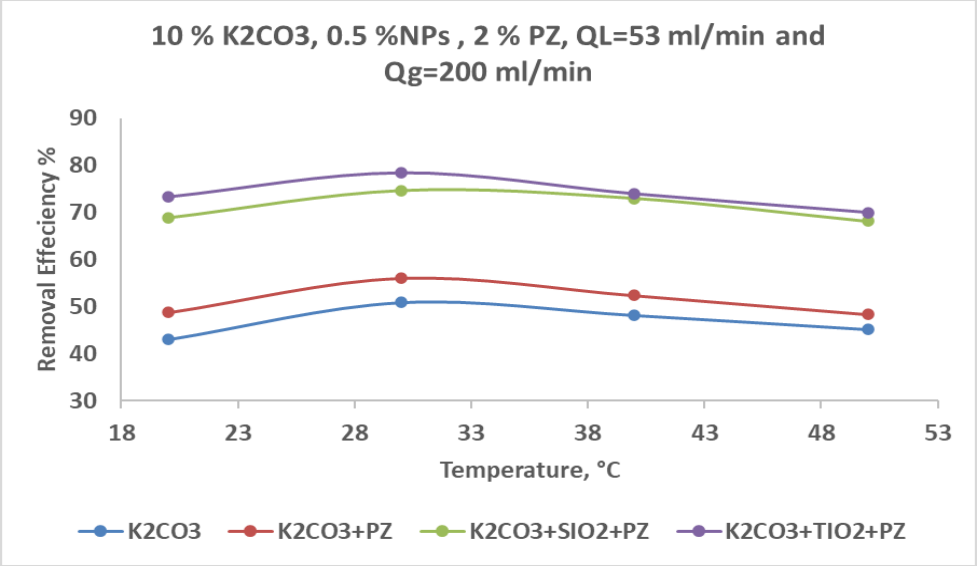

Fig. 6: The impact of Temp. on removal efficiency.

4.5. Statistics Analysis

The design of experiments (DOE) is a powerful approach used to systematically plan, conduct, and analyze experiments. It allows researchers to efficiently investigate the effects of multiple factors on a response variable while controlling for potential confounding variables. By carefully selecting the levels of each factor and replicating the experiment, DOE enables the identification of significant factors and interactions, leading to a comprehensive understanding of the underlying relationships.

Once the experimental data is collected, statistical methods such as Analysis of Variance (ANOVA) and regression are commonly employed for data analysis. ANOVA assesses the significance of differences among means of multiple groups and helps determine whether there are statistically significant effects of individual factors or their interactions on the response variable. It quantifies the variability between and within groups to make inference about the overall differences. Regression analysis, on the other hand, explores the relationship between a dependent variable (response) and one or more independent variables (predictors). It fits a mathematical model to the data and estimates the coefficients of the predictors, indicating the magnitude and direction of their influence on the response variable. Regression analysis is particularly useful for understanding the impact of continuous variables on the response and predicting outcomes based on the model. The regression table is an essential output of the regression analysis. It presents the estimated coefficients, their standard errors, t-values, p-values, and other statistical measures. The coefficients represent the expected change in the response variable associated with a one-unit change in each predictor while holding other factors constant. The standard errors provide a measure of the uncertainty in the coefficient estimates, and the t-values and p-values indicate the significance of each predictor. By functionalizing the regression table, researchers can gain valuable insights into the strength and significance of the relationships between the predictors and the response variable. It allows for a clear interpretation of the coefficients and helps identify which factors have a significant impact on the response. This functionalization also aids in making data-driven decisions and formulating effective strategies based on the study's results.

Table 1 presents the results of a statistical analysis that explores the relationship between various factors (T, Q_g, Q_L, K_2CO_3 %, PZ%, SiO_2 %, TiO_2 %) and CO_2 removal efficiency. The coefficients (Coef) in the table represent the estimated values of the regression model for each factor, indicating the expected change in CO_2 removal efficiency with a one-unit change in the corresponding factor while keeping other variables constant. The standard error of the coefficient estimates (SE Coef) provides a measure of uncertainty or variability associated with the estimated coefficients. The t-value measures the significance of each coefficient, with larger absolute t-values indicating stronger evidence against the null hypothesis of a zero coefficient. The p-value represents the probability of observing a t-value as extreme as calculated, assuming the null hypothesis is true. Lower p-values, typically below 0.05, indicate stronger evidence against the null hypothesis. The Variance Inflation Factor (VIF) assesses

multicollinearity between predictors, with values close to 1 indicating low multicollinearity. The constant term in the analysis represents the expected CO_2 removal efficiency when all other predictors are zero, which in this case is 74.19. The individual predictors (T, Q_g, Q_L, K_2CO_3%, PZ%, SiO_2%, TiO_2%) are examined in relation to CO_2 removal efficiency, and their coefficients indicate the expected change in CO_2 removal efficiency with a one-unit change in each factor. The associated p-values provide insights into the significance of each factor, where p-values less than 0.05 generally indicate a statistically significant relationship. Based on the provided information, it appears that Q_g, Q_L, K_2CO_3%, PZ%, SiO_2%, and TiO_2% have statistically significant effects on CO_2 removal efficiency. The non-zero coefficients associated with these factors suggest they have a meaningful impact on the response variable.

- Based on the provided information, it appears that Q_g, Q_L, K_2CO_3 %, PZ%, SiO_2 %, and TiO_2 % have statistically significant effects on CO_2 removal efficiency. The coefficients associated with these factors are non-zero, suggesting they have a meaningful impact on the response variable.

Overall, this analysis provides insights into the relationships between the examined factors and CO_2 removal efficiency. However, it's important to note that additional context and further analysis would be required to fully understand the significance and practical implications of these findings in the specific research context.

Table 1: coded coefficient analysis.

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	74.19	1.73	42.86	0.000	
T	-0.34	1.61	-0.21	0.836	1.01
Q_g	29.74	1.55	19.14	0.000	1.00
Q_L	-3.172	0.917	-3.46	0.001	1.01
K_2CO_3 %	21.26	1.63	13.01	0.000	1.00
PZ%	2.144	0.792	2.71	0.008	1.48
SiO_2 %	12.69	1.04	12.17	0.000	1.55
TiO_2 %	14.99	1.04	14.38	0.000	1.55

Table 2 provides a comprehensive analysis of variance (ANOVA) for the regression model employed to examine the relationship between the predictors (T, Q_g, Q_L, K_2CO_3 %, PZ%, SiO_2 %, TiO_2 %) and CO_2 removal efficiency. The table highlights key aspects of the analysis: the sources of variation including the Model, Linear predictors, Lack-of-Fit, and Pure Error; the associated degrees of freedom (DF); the Adjusted Sum of Squares (Adj SS) and Adjusted Mean Square (Adj MS) reflecting the variance adjusted for DF; the F-Value indicating the significance of predictor-response relationship; and the corresponding p-values. Interpretation of the results reveals that the overall model, encompassing all predictors, demonstrates a highly significant connection with CO_2 removal efficiency, substantiated by a substantial F-value of 140.09 and a minuscule p-value of 0.000. Among the individual predictors, except for T (p-value = 0.836), each exhibits a statistically significant association with CO_2 removal efficiency, evident from their low p-values. The Error term represents unexplained variation, while the noteworthy significance of the Lack-of-Fit term implies the potential presence of nonlinear relationships or unaccounted factors influencing CO_2 removal efficiency beyond the linear model. The Total variation represents the raw sum of squares for the response variable without adjustments.

Overall, the ANOVA results indicate that the model, including the predictors Q_g, Q_L, K_2CO_3 %, PZ%, SiO_2 %, and TiO_2 %, has a significant relationship with CO_2 removal efficiency. However, it's important to note that the lack-of-fit term suggests that the linear model might not fully capture all the variability in the data, indicating the need for further analysis or consideration of additional factors.

Table 2: ANOVA table.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	7	26199.2	3742.74	140.09	0.000
Linear	7	26199.2	3742.74	140.09	0.000
T	1	1.2	1.16	0.04	0.836
Qg	1	9788.8	9788.76	366.38	0.000
Q_L	1	319.5	319.53	11.96	0.001
K_2CO_3 %	1	4520.0	4520.03	169.18	0.000
PZ%	1	195.7	195.72	7.33	0.008
SIO_2 %	1	3959.0	3959.01	148.18	0.000
TiO_2 %	1	5524.9	5524.85	206.79	0.000
Error	86	2297.7	26.72		
Lack-of-Fit	76	2294.7	30.19	100.76	0.000
Pure Error	10	3.0	0.30		
Total	93	28496.9			

The regression equation provided is:

$$Removal\ efficiency\ \% = -56.41 - 0.022T + 1.0434Qg - 0.02115QL + 531.5K2CO3\% + 214.4PZ\% + 3625SiO2\% + 4282TiO2\% \quad (2)$$

Here's an interpretation of the statistical measures associated with the regression model:

- S: The estimated standard deviation of the residuals is 5.16891. It represents the average distance between the observed data points and the predicted values from the regression equation.

- R-squared (R-sq): R-squared is a measure of the proportion of the total variability in the response variable that can be explained by the regression model. In this case, the R-squared value of 91.94% indicates that approximately 91.94% of the variation in CO_2 removal efficiency can be explained by the predictors included in the model.

- R-squared adjusted (R-sq(adj)): The adjusted R-squared takes into account the number of predictors and the degrees of freedom in the model. It penalizes the inclusion of additional predictors that do not significantly contribute to the model's fit. The R-squared adjusted value of 91.28% suggests that the predictors in the model explain a substantial amount of the variability in CO_2 removal efficiency.

- R-squared predicted (R-sq(pred)): The R-squared predicted provides an estimate of how well the regression model can predict future observations. The R-squared predicted value of 90.63% indicates that the current model has a good predictive capability for CO_2 removal efficiency.

Overall, the regression model shows a high level of goodness-of-fit, as indicated by the high R-squared and R-squared adjusted values. It suggests that the predictors (T, Q_g, Q_L, K_2CO_3%, PZ%, SiO_2%, TiO_2%) included in the model collectively explain a significant portion of the variation in CO_2 removal efficiency. The R-squared predicted value suggests that the model can reasonably predict the CO_2 removal efficiency for new or future data points.

To create a Pareto chart for the given expression of the removal efficiency, we need to consider the magnitudes of the coefficients associated with each variable. The Pareto chart will help us identify the most significant factors contributing to the removal efficiency.

Here is the breakdown of the variables and their coefficients:

- T: Temperature coefficient = -0.022
- Q_g: Gas flow rate coefficient = 1.0434
- Q_L: Liquid flow rate coefficient = -0.02115
- K_2CO_3%: K_2CO_3 percentage coefficient = 531.5
- PZ%: PZ percentage coefficient = 214.4
- SiO_2%: Silica percentage coefficient = 3625
- TiO_2%: Titanium oxide percentage coefficient = 4282

Using these coefficients, we can construct the Pareto chart (Fig 7) by arranging the variables in descending order of their absolute values. The Pareto chart will have bars representing the absolute values of the coefficients for each variable. The tallest bar will represent the variable with the highest absolute coefficient value, indicating its significant influence on the removal efficiency. The bars will be arranged from left to right in decreasing order of their heights.

The cumulative percentage line in the chart will show the cumulative contribution of the variables to the total variability explained by the expression. It will start at zero and gradually increase as each variable is added, eventually reaching 100% at the end. By examining the Pareto chart, you can easily identify the variables with the largest bars, indicating their significant impact on the removal efficiency. Additionally, the cumulative percentage line will help you understand how much of the total variability in the removal efficiency is explained by including a certain number of variables.

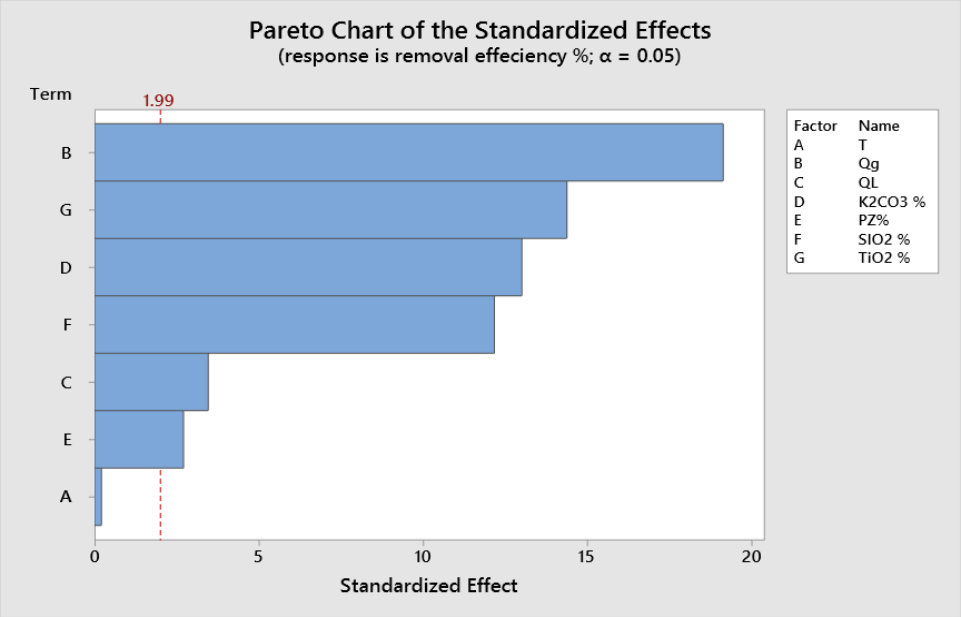

Fig. 7 Pareto chart of present work.

4.6 Optimization Analysis

We can assess the sensitivity of each parameter by examining their respective coefficients as shown in Fig 8:

- T (Temperature): The coefficient is -0.022. A negative coefficient indicates that as temperature increases, removal efficiency decreases. The magnitude of -0.022 suggests that temperature has a relatively small impact on removal efficiency compared to other parameters.
- Q_g (Gas flow rate): The coefficient is 1.0434. A positive coefficient indicates that as gas flow rate increases, removal efficiency increases. The magnitude of 1.0434 suggests that Q_g has a moderate impact on removal efficiency.
- Q_L (Liquid flow rate): The coefficient is -0.02115. A negative coefficient indicates that as liquid flow rate increases, removal efficiency decreases. The magnitude of -0.02115 suggests that Q_L has a relatively small impact on removal efficiency compared to other parameters.
- K_2CO_3 % (K_2CO_3 percentage): The coefficient is 531.5. A positive coefficient indicates that as the percentage of K_2CO_3 increases, removal efficiency increases. The magnitude of 531.5 suggests that K_2CO_3 % has a significant impact on removal efficiency.
- PZ% (PZ percentage): The coefficient is 214.4. A positive coefficient indicates that as the percentage of PZ increases, removal efficiency increases. The magnitude of 214.4 suggests that PZ% has a significant impact on removal efficiency.
- SiO_2% (Silica percentage): The coefficient is 3625. A positive coefficient indicates that as the percentage of silica increases, removal efficiency increases. The magnitude of 3625 suggests that SiO_2% has a substantial impact on removal efficiency.
- TiO_2% (Titanium oxide percentage): The coefficient is 4282. A positive coefficient indicates that as the percentage of titanium oxide increases, removal efficiency increases. The magnitude of 4282 suggests that TiO_2% has a substantial impact on removal efficiency.
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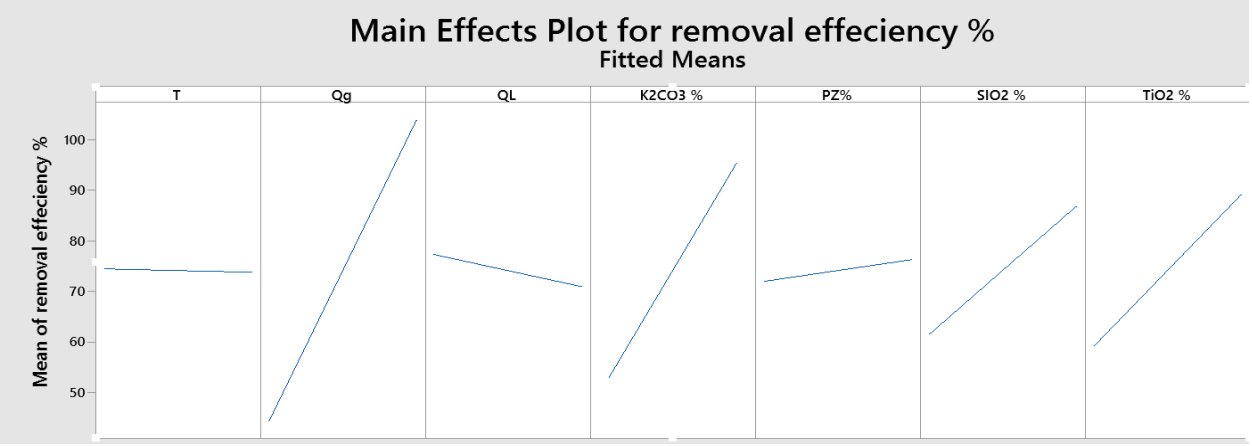

Fig 8: Factorial analysis for parameters sensitivity finding.

The objective with regards to the removal efficiency, as per the provided data, is to attain a maximal value. The absence of specified lower and upper bounds implies the lack of predetermined thresholds for the removal efficiency. The absence of the target value is also not specified. The removal efficiency has been assigned a weight of 1, signifying its paramount significance in the analysis.

The proposed solution encompasses a range of independent variable configurations, namely T, Q_g, Q_L, K_2CO_3 %, PZ%, SiO_2%, and TiO_2%. The corresponding removal efficiency is predicted through the application of a regression model.

Regarding the particular resolution:

- The temperature was set to 30 ^oC.

- The gas flow rate (Q_g) was established at a value of 200.
- The liquid flow rate, denoted as QL, was established at a value of 82.
- The K_2CO_3 percentage was established at 0.14.
- The PZ percentage is established at 2%.
- The silica percentage, denoted as SiO_2%, has been established at 0.7%.
- The percentage of titanium oxide (TiO_2%) has been established at 0.7%.

The removal efficiency anticipated from these parameters is 158.51, accompanied by a standard error of 3.79. The predicted removal efficiency is associated with a 95% confidence interval (CI) of (150.98; 166.05), while the 95% prediction interval (PI) is estimated to be (145.77; 171.26).

CONCLUSIONS

Based on the experimental results obtained in this investigation, it can be deduced that there is a direct correlation between the efficacy of carbon dioxide (CO_2) removal and the velocity of liquid flow (Q_L), while an inverse relationship is observed between the efficiency of CO_2 removal and the velocity of gas flow (Q_g). This observation implies the presence of a spectrum of flow rates that may enhance the efficiency of CO_2 sequestration. The effectiveness of carbon dioxide (CO_2) removal is directly influenced by the concentration of potassium carbonate (K_2CO_3) in the liquid, wherein higher amounts of K_2CO_3 lead to improved operational efficiency. The observed effectiveness of carbon dioxide (CO_2) elimination was found to be significantly impacted by the inclusion of titanium dioxide (TiO_2) nanoparticles at a concentration of 0.5% and 2%PZ as opposed to silica (SiO_2) nanoparticles. The inquiry further determined that the optimal temperature for CO_2 removal was observed to be 30°C. The statistical analysis reveals that the variables Q_g, Q_L, K_2CO_3%, PZ%, SiO_2%, and TiO_2% manifest noteworthy influences on the efficacy of CO_2 elimination. The ANOVA analysis has unveiled a chemically significant correlation between the efficiency of carbon dioxide (CO_2) elimination and the comprehensive model encompassing all predictors. Nevertheless, the existence of a deficiency-of-match constituent in the linear model implies the potential occurrence of unaccounted variability, thereby indicating the plausible impact of additional factors that have not been taken into account in the present model. Henceforth, it may be imperative to conduct additional scrutiny or incorporate supplementary variables to enhance comprehension and apprehension of the comprehensive panorama pertaining to CO_2 elimination efficacy. In order to maximize the efficiency of CO_2 elimination, it is imperative to optimize the flow rates, concentration of K_2CO_3, and characteristics of the nanoparticles. The objective of the analysis is to optimize the removal efficiency, as indicated by the weight assigned to this parameter. The lack of well-defined lower and upper thresholds, along with an absence of a specified desired value for the elimination efficacy, was observed. The proposed methodology involves the determination of exact numerical values for the independent variables, specifically temperature (T) set at 30°C, gas flow rate (Q_g) maintained at 250, liquid flow rate (Q_L) set at 82, K_2CO_3% at 0.14, PZ% at 2%, SiO_2% at 0.7%, and TiO_2% at 0.7%.

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