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Enhancement of Natural Gas Sweetening Performance Using Amine-Based Nanofluids

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تحسين أداء إزالة الحموضة من الغاز الطبيعي باستخدام الموائع النانوية القائمة على الأمينات

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Abstract:
The Mellitah gas plant in Libya faces persistent operational challenges in its Acid Gas Removal Unit (AGRU), including high energy consumption for solvent regeneration and limited absorption efficiency. Previous optimization studies identified an effective blend of 39 wt% MDEA and 1 wt% DEA as the optimal amine formulation.
This study investigates further performance enhancement by converting this hybrid solvent into a nanofluid containing multi-walled carbon nanotubes (MWCNTs) and silicon dioxide (SiO_2) nanoparticles at concentrations between 0.01 and 0.1 wt%.
A validated Aspen HYSYS V11 simulation model of the Mellitah AGRU was used to evaluate the impact of these nanoparticles on absorption efficiency and energy requirements. The MWCNT-based nanofluid achieved an 84.9 % CO_2-removal efficiency, compared with 77.7 % for the base case, and reduced reboiler duty by 21.5 % ($\approx 4.0\times10^4$ kW). The SiO_2-based nanofluid provided 81.8 % removal with 11.8 % energy savings.
The performance improvement is attributed to enhanced heat and mass transfer within the nanofluid. These findings highlight the technical feasibility and strong potential of nanofluid-formulated amine solvents for significant energy reduction and process intensification in industrial gas-sweetening systems.

Keywords: Gas Sweetening, Nanofluids, MDEA, DEA, Aspen HYSYS, Energy Efficiency, CO_2 Capture.

الملخص
يواجه مصنع الغاز مليته في ليبيا تحديات تشغيلية مستمرة في وحدة إزالة الغاز الحمضي (AGRU) بما في ذلك الاستهلاك العالي للطاقة لتجديد المذيبات وكفاءة الامتصاص المحدودة. حددت دراسات التحسين السابقة مزيجا فعالا من 39٪ بالوزن من MDEA و1٪ بالوزن من DEA باعتباره التركيبة الأمينية المثلى.
تبحث هذه الدراسة في تحسين الأداء بشكل أكبر عن طريق تحويل هذا المذيب الهجين إلى سائل نانوي يحتوي على أنابيب كربون نانوية متعددة الجدران (MWCNTs) وجزيئات نانوية من ثاني أكسيد السيليكون (SiO_2) بتركيزات تتراوح بين 0.01 و0.1٪ بالوزن.
تم استخدام نموذج محاكاة Aspen HYSYS V11 معتمد لوحدة إزالة الغاز الحمضي في مليته لتقييم تأثير هذه الجزيئات النانوية على كفاءة الامتصاص ومتطلبات الطاقة. حقق السائل النانوي القائم على MWCNT كفاءة إزالة CO_2 بنسبة 84.9٪ مقارنة بـ 77.7٪ للحالة الأساسية وخفض استهلاك إعادة التسخين بنسبة 21.5٪ ($\approx 4.0\times10^4$ كيلوواط) وحقق السائل النانوي القائم على SiO_2 إزالة بنسبة 81.8٪ مع توفير في الطاقة بنسبة 11.8٪.
يعزى تحسن الأداء إلى تحسين نقل الحرارة والكتلة داخل السائل النانوي. تسلط هذه النتائج الضوء على الجدوى التقنية والإمكانات القوية للمذيبات الأمينية المصنوعة من السوائل النانوية في تحقيق تخفيض كبير في الطاقة وتكثيف العمليات في أنظمة تحلية الغاز الصناعية.

الكلمات المفتاحية: تحلية الغاز، السوائل النانوية، MDEA، DEA، Aspen HYSYS، كفاءة الطاقة، احتجاز ثاني أكسيد الكربون.

Introduction.

Natural gas remains one of the world's most vital energy sources, yet it often contains undesirable acidic impurities such as carbon dioxide (CO_2) and hydrogen sulfide (H_2S). These components corrode pipelines, lower the gas's calorific value, and pose environmental and safety risks during processing [1].

Consequently, the removal of these contaminants commonly referred to as *gas* sweetening is a critical step in gas treatment operations.

Aqueous alkanolamines are the industry standard for acid-gas removal because of their chemical reactivity, selectivity, and regenerative capacity. Among them, methyldiethanolamine (MDEA) has proven especially attractive due to its low regeneration energy, minimal corrosion, and preferential absorption of H_2S over CO_2 [2].

However, MDEA's relatively slow reaction with CO_2 limits its efficiency; therefore, it is often blended with faster-reacting amines such as diethanolamine (DEA) or piperazine (PZ) [3].

Optimization work at the Mellitah gas plant demonstrated that a mixture of 39 wt% MDEA and 1 wt% DEA achieved an excellent balance between absorption capacity and energy requirement [5].

Despite these improvements, the regeneration of the solvent remains energy-intensive because of the substantial reboiler duty. Recent developments in nanotechnology offer a promising solution: nanofluids, which are base liquids containing finely dispersed nanoparticles that enhance both thermal and mass-transfer characteristics [6].

When incorporated into amine systems, nanoparticles can intensify gas–liquid interaction and accelerate diffusion processes [7, 8].

Nonetheless, few studies have addressed the use of hybrid amine-based nanofluids under realistic plant conditions. The present work aims to evaluate the potential benefits of introducing nanoparticles into a DEA/MDEA solvent system, focusing on improving CO_2 removal and reducing energy consumption using a validated Aspen HYSYS simulation based on Mellitah plant data.

2. Process Description and Simulation Methodology.

2.1. Base Case Simulation.

The AGRU of the Mellitah gas plant was simulated in Aspen HYSYS V11 using the **Acid Gas Property Package**, which accurately models amine systems. Feed composition, pressure, temperature, and flow rate were derived from actual plant records and prior studies [5].

The absorber and regenerator configuration reflected standard design practice: sour gas contacts a lean amine solution containing 39 wt% MDEA, 1 wt% DEA, and 60 wt% H_2O, while the regenerator strips the absorbed gases using heat.

Table 1. Feed Gas Conditions and Composition.

Condition		
Parameter	**Value**	**Unit**
Temperature	30	°C
Pressure	3950	kPa
Molar Flow	14388	kgmol/h

Composition	
Component	**Mole Fraction**
H_2O	0.0002
Nitrogen	0.0459
CO_2	0.1571
H_2S	0.0129
Methane	0.7012
Others (C_2-C_7)	0.0815

Model predictions of CO_2 removal and reboiler duty deviated by less than 5 % from operational data, confirming the model's validity. The base case achieved 77.7 % CO_2 removal at a reboiler duty of 1.86×10^5 kW, serving as the reference for subsequent comparisons.

2.2 Nanofluid Modeling Approach.

ecause Aspen HYSYS cannot directly simulate nanoparticles, their effects were represented by modifying process parameters that correlate with nanoparticle behavior, mainly the **mass-transfer coefficient** and **thermal conductivity**.

- **Mass-transfer enhancement** was introduced by scaling the absorber tray efficiency using the semi-empirical correlation [8]:

$$E = 1 + A(\emptyset)^{B}$$

where ϕ is the nanoparticle volume fraction, and A and B are constants derived from literature (A=4.5, B=0.4 for MWCNTs; A=2.5, B=0.35 for SiO_2).

Thermal conductivity improvement was calculated with the Maxwell model [6]:

$$\mathrm{k_{nf}} = \mathrm{k_b}\left[\frac{\mathrm{k_p} + 2\mathrm{k_b} + 2\emptyset(\mathrm{k_p} - \mathrm{k_b})}{\mathrm{k_p} + 2\mathrm{k_b} - \emptyset(\mathrm{k_p} - \mathrm{k_b})}\right]$$

where k_{nf}, k_b, and k_p represent the thermal conductivities of the nanofluid, base amine, and nanoparticles, respectively.

MWCNTs and SiO_2 were tested in concentrations from 0.01 to 0.1 wt%. Nanofluid stability was assumed to remain constant throughout the simulation.

3. Results and Discussion.

3.1 Base-Case Performance

The validated hybrid-amine system achieved a CO_2 outlet mole fraction of 0.035 (77.7 % removal) and a reboiler duty of 1.86×10^5 kW. These results aligned closely with Mellitah plant data, confirming the reliability of the computational model.
This benchmark served to quantify subsequent improvements achieved through nanoparticle addition.

3.2 Effect of Nanofluids on Absorption Performance

Introducing nanoparticles markedly enhanced CO_2 absorption.
At the optimal concentration of 0.08 wt%, the MWCNT-based nanofluid achieved **84.9 % CO_2 removal**, whereas the SiO_2-based nanofluid achieved **81.8 %** removal, both exceeding the base case (Table 2).

Table 2. Performance Comparison at Fixed Amine Flow Rate ($3.5\text{x}10^4$ kgmol/h).

Scenario	CO_2 Outlet (mol frac.)	CO_2 Removal (%)	Reboiler Duty (kW)	Duty Reduction (%)
Base Case	0.0350	77.7	$1.86\text{x}10^5$	-
+ 0.08% SiO_2	0.0285	81.8	$1.64\text{x}10^5$	11.8
+ 0.08% MWCNT	0.0237	84.9	$1.46\text{x}10^5$	21.5

The improvement stems from increased interfacial turbulence and micro-convection caused by nanoparticle Brownian motion, which enhances the liquid-phase mass-transfer coefficient and promotes faster gas diffusion. H_2S removal remained above 99.9 % in all cases, confirming that the modified solvent maintained its selectivity.

3.3 Energy Requirement in Regeneration

Energy analysis revealed substantial reductions in reboiler duty.
For the MWCNT nanofluid, the energy demand decreased from 1.86×10^5 kW to 1.46×10^5 kW, corresponding to a 21.5 % saving.
For SiO_2, the duty dropped to 1.64×10^5 kW (11.8 % saving).
These results indicate that enhanced thermal conductivity allows more efficient heat transfer within the reboiler and lean/rich heat exchangers, reducing steam consumption and operational costs.

3.4 Sensitivity Analysis and Optimal Concentration.

A sensitivity analysis varying nanoparticle concentration from 0.01 to 0.1 wt% showed in figure 1 continuous improvement in CO_2 removal and energy savings up to approximately 0.08 wt%, beyond which performance gains plateaued.

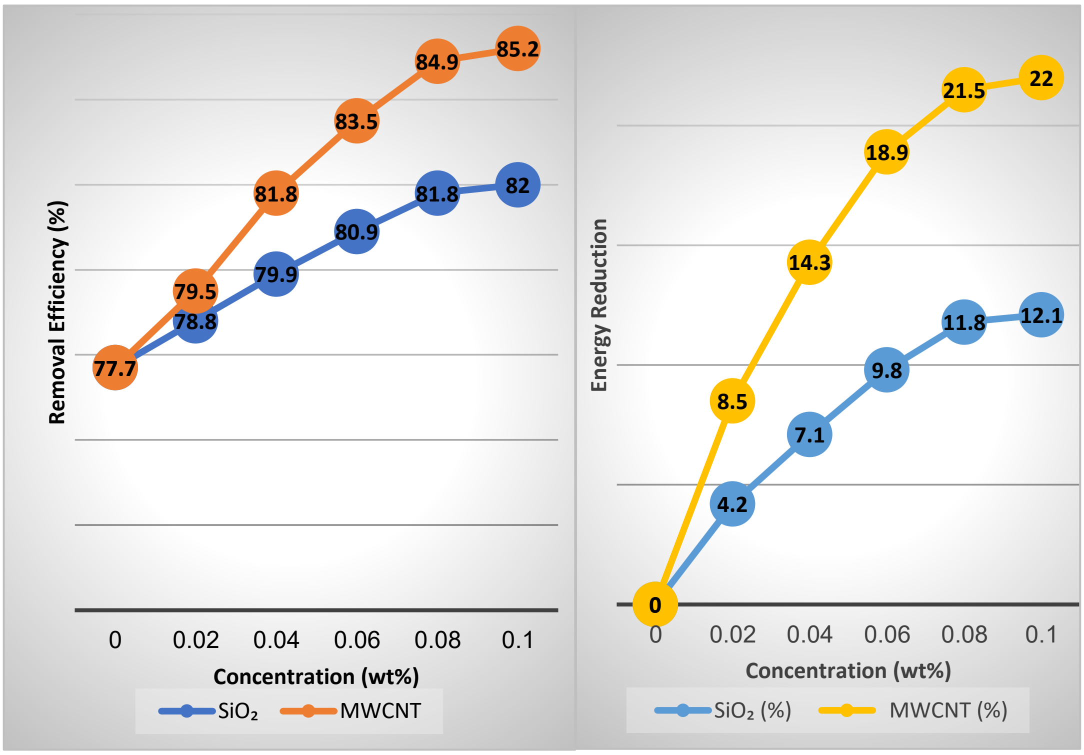

Figure 1. Impact of nanoparticle concentration on process performance.

Higher concentrations led to marginal benefits due to increased viscosity and possible nanoparticle agglomeration that hinder mass transfer.

Therefore, 0.08 wt% was identified as the optimal concentration, balancing performance enhancement with process stability, consistent with prior experimental findings [7, 9].

3.5 Overall Technical Discussion.

The simulation confirms that nanofluid incorporation can meaningfully intensify gas-sweetening performance. Even minimal nanoparticle additions deliver measurable improvements in absorption and energy efficiency. From an industrial standpoint, MWCNT-based nanofluids offer the greatest performance enhancement, while SiO_2 provides a cost-effective and safer alternative with slightly lower benefits. These findings demonstrate that nanofluid technology can be seamlessly integrated into existing amine systems, offering a practical route toward sustainable and energy-efficient natural-gas treatment.

4. Conclusion.

This work establishes that the inclusion of nanoparticles within a hybrid MDEA/DEA solvent can significantly enhance both CO_2-removal efficiency and energy performance in natural-gas sweetening. The MWCNT-based nanofluid achieved 84.9 % CO_2 removal with a 21.5 % reduction in reboiler duty, while the SiO_2-based nanofluid attained 81.8 % removal and 11.8 % energy savings at an optimal concentration of 0.08 wt%.

These outcomes are attributed to improved heat and mass-transfer properties within the nanofluid medium.

The study demonstrates that amine-based nanofluids present a technically viable and scalable strategy for upgrading existing gas-sweetening units, especially in Libyan gas-processing facilities where energy efficiency is a key operational concern.

Nomenclature.

Symbol	Description
H_2S	Hydrogen sulfide
CO_2	Carbon dioxide
DEA	Diethanolamine
MDEA	Methyldiethanolamine
MWCNT	Multi-walled carbon nanotubes
SiO_2	Silicon dioxide

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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