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Review Article

The Regeneration of MEG as Recyclable Gas Hydrate Inhibitor: A Mini-Review from Laboratory to Machine Learning

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***Abstract** - This mini-review examines the latest advancements in Monoethylene Glycol (MEG) regeneration technologies, which are pivotal for sustaining efficiency in the oil and gas sector. MEG regeneration, essential for mitigating hydrate formations in subsea pipelines, has evolved significantly from traditional methods, predominantly methanol-based, to more sustainable MEG-based solutions. This paper delves into various experimental setups, from pilot plants to high-pressure reactors, then simulation approaches and machine learning applications, showcasing the nuanced understanding of MEG's behavior and the effectiveness of MEG during the regeneration process. Through a synthesis of recent studies, this review provides insights into the challenges of MEG regeneration, emphasizing the need for continuous innovation and optimization in hydrate management.*

***Keywords** - Flow assurance, Hydrate inhibition, MEG regeneration, MEG reclamation, Review study.*

1. Introduction

The burgeoning significance of Monoethylene Glycol (MEG) regeneration in the oil and gas industry is underscored by its indispensable role in mitigating hydrate formation within subsea pipelines and processing facilities. Hydrate blockages, known for their potential to inflict considerable operational and economic setbacks, necessitate implementing effective control strategies, among which MEG stands out for its efficacy and reusability.

The economic and environmental imperatives of MEG regeneration are highlighted by Teixeira, Medeiros and Araújo [1], who emphasize the critical need for high MEG injection rates to ensure adequate hydrate control, thereby underscoring the necessity for sustainable MEG recovery practices.

Historically, the progression of MEG regeneration technologies was somewhat stymied by the predominant use of methanol as a hydrate inhibition agent, as noted by Son, Kim [2]. However, the shift towards MEG-based solutions, driven by environmental and operational considerations, has catalyzed advancements in regeneration and reclamation methodologies. This transition is further evidenced by the common practice of MEG reconcentration since the 1990s, a process that Nazzer and Keogh [3] describe as crucial yet challenged by the adverse effects of formation water on regeneration units, including severe scaling and fouling. The technical nuances of MEG regeneration, particularly the distillation-based separation of MEG and water leveraging their distinct boiling points, are elaborated by Blackman and Gahan [4]. The array of recovery options, ranging from basic reconcentration to more sophisticated partial and complete reclamation techniques, illustrates the industry's endeavor to optimize MEG reuse while addressing the limitations posed by non-volatile contaminants and salts, as discussed by Brustad, Løken and Waalmann [5], and Teixeira, Medeiros and Araújo [1].

Eventhough the regeneration process of MEG is very important and widely applied in the field, no literature review has been published to summarize the related works, creating a research gap. In light of the evolving landscape of MEG regeneration, this paper aims to distil the essence of recent advancements and challenges in the field. By critically reviewing the literature, including pivotal studies by Alef, Gubner [6], Alef, Smith [7], Psarrou Psarrou, Jøsang [8], and others, this introduction sets the stage for a comprehensive exploration of contemporary and future trends in MEG regeneration, offering insights into the technological and operational dimensions of this critical aspect of hydrate management in the oil and gas sector.

2. Objectives

The objectives of this mini-review are illustrated as follows:

- To review the development of MEG regeneration strategies from basic lab experiments to advanced technologies.
- To determine the challenges/issues related to the process and suggest mitigations.
- To summarize the contributions of previous studies on this topic.

3. Selection Criteria

The studies selected for this mini-review are passing the following criteria:

- The study focuses on the process of MEG regeneration rather than the performance of regenerated MEG.
- The work is published in reputable journals.
- The study is well-designed and has clear objectives, methodology and results.

4. MEG Regeneration Strategies

The Monoethylene Glycol (MEG) regeneration process is a cornerstone in ensuring both the economic viability and environmental sustainability of operations within the oil and gas industries, especially given the necessity for high MEG injection rates for effective hydrate control [1]. Historically, the development of MEG regeneration and reclamation techniques was impeded by the prevalent use of methanol as a hydrate prevention agent [2]. However, since the 1990s, reconcentration has emerged as the standard approach for MEG regeneration despite the challenges posed by formation water, which can lead to significant salts and scale depositions and fouling, particularly in the reboilers units [3, 9]. These issues often result in operational downtimes, equipment failures, and safety hazards [10].

Distillation plays a crucial role in the MEG regeneration processes, leveraging the differential MEG boiling points (198 °C) and water (100 °C) at atmospheric pressure to facilitate component separation [4]. Within this context, three primary methodologies for MEG recovery have been identified [5] (See Figure 1):

(1) Regeneration or Reconcentration, where water is distilled from 'rich-MEG' under atmospheric conditions until a desired MEG concentration is reached, typically between 80-90 wt%. This method, however, does not address the removal of non-volatile chemicals and salts, which could pose a risk of corrosion if the formation water is present.

(2) Partial Reclamation involves diverting a portion of the regenerated MEG to a reclamation unit to sustain acceptable contaminants and salts, thus preserving valuable non-volatile additives like pH stabilizers and corrosion inhibitors for reuse within the MEG loop.

(3) Complete Reclamation, suitable for scenarios with significant formation water production, involves using a vacuum separator to remove non-volatile substances and univalent salts from the 'rich-MEG', followed by regeneration to achieve the optimal MEG concentration. These strategies underscore the complex interplay between operational efficiency, chemical integrity, and environmental considerations in managing MEG regeneration and reclamation processes.

5. Common Issues during MEG Regeneration and Proposed Solutions

In the context of hydrate control within the oil and gas industries, recycling Monoethylene Glycol (MEG) through regeneration and reclamation processes is a critical practice due to its extensive usage. The regeneration process primarily involves heating the water-saturated MEG solution, known as "rich-MEG," in the distillation column at approximately 120°C to vaporize the majority of the water content, resulting in "lean MEG" with an approximate purity of 90 wt% MEG. This phase, however, is susceptible to contamination by salts and other impurities. Conversely, the reclamation process aims to purify the rich or lean MEG mixture by evaporating it to eliminate contaminants and salts, usually under vacuum conditions at temperatures varying from 120 to 150°C [6].

The degradation of MEG during these processes poses significant challenges, as identified in the studies by Psarrou, Jøsang [8], and Rossiter Jr, Godette [11]. Both studies highlighted the formation of glycolic and formic acids as primary degradation products due to oxidation, with air ingress during processing being a plausible causative factor. This oxidative degradation not only compromises the efficiency of MEG as a thermodynamic hydrate inhibitor but also necessitates more frequent replacement, thereby increasing operational costs. Furthermore, scaling and fouling within the MEG system, predominantly due to iron, calcium, and magnesium salts from produced water, are prevalent issues that impact system efficiency and longevity. Haque [12] reported significant scaling in MEG reboiler and stripper columns, attributing the primary source of iron to produce water, which interacts with the MEG solution during heat exchange processes. Another concern is hydrocarbon carryover, which Haque [12] described as forming sludge within the MEG solution at low pH levels. This sludge can cause significant operational issues, including the erosion of mechanical components and the obstruction of filters, necessitating frequent maintenance and potentially leading to MEG loss. Pump seal leakage, particularly in plunger-type reciprocating pumps used for MEG injection, has been noted by Haque [12] as a recurrent issue contributing to MEG loss. Additionally, Son and Kim [2] highlighted that significant MEG losses occur during the centrifugation phase of reclamation, where liquid discharge is proportional to the salt content, and during reconcentration. However, the latter does not significantly vary across different operational scenarios.

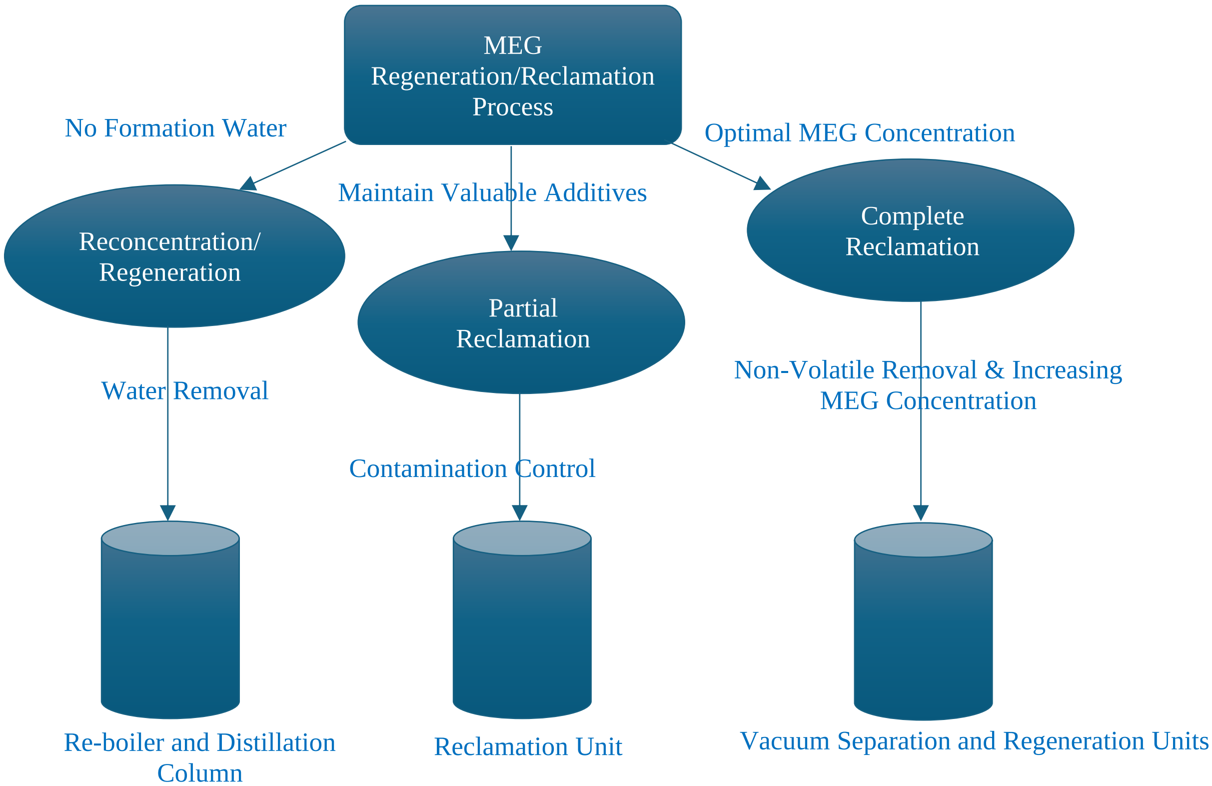

Fig. 1 Summary of the MEG regeneration/reclamation strategies

Addressing these challenges necessitates a multifaceted approach, focusing on both preventive measures to reduce the incidence of these issues and efficient maintenance strategies to mitigate their impact when they do occur. This comprehensive review underscores the intricate balance required in managing and recycling MEG in hydrate control applications, emphasizing the need for continuous innovation and optimization in process engineering and maintenance practices.

5.1. Issues Mitigation Methods

Mitigating the issues inherent in the dehydration and regeneration processes of Monoethylene Glycol (MEG) is pivotal for maintaining operational efficiency and ensuring uninterrupted plant performance. Several control measures have been successfully implemented to address common problems associated with MEG handling and processing, aimed at preventing these issues and enhancing the overall quality and efficiency of the MEG regeneration process [12].

The introduction of stripping gas into the reboiler or storage tank constitutes a significant step towards achieving higher MEG concentration levels, surpassing those attainable through standard regeneration techniques. The application of hot gas, which exhibits a natural affinity for water, facilitates the removal of residual water from the MEG solution, thereby concentrating the MEG beyond conventional limits [13, 14]. Regulating the reflux ratio in the stripper column is another critical control measure. By adjusting the reflux ratio, the temperature within the stripper column can be meticulously controlled to align with the water's boiling point, thereby optimizing the distillation process. In instances where a temperature controller in a three-way valve is not available, manual adjustment of the stripper column bypass valve has proven effective in achieving the desired control [13].

pH control stands out as a crucial aspect of maintaining MEG quality. The MEG solution's pH level indicates its acid content and potential degradation. Maintaining the pH within the optimal range of 7.4 to 8.5 is essential to prevent degradation and mitigate the associated increase in equipment corrosion rates [2].

Enhancing the separation efficiency at the Flash Separator is also paramount. Inadequate separation can lead to hydrocarbon carryover, which can be addressed by increasing the retention time within the separator. Adjusting the Rich MEG level at the Flash Separator and employing carbon filters as a secondary measure for hydrocarbon removal are practical steps towards improving separation efficiency [9].

These mitigation strategies underscore the importance of a proactive and comprehensive approach to managing the MEG regeneration process. By implementing these measures, it is possible to significantly reduce the prevalence of common issues and enhance the overall performance and reliability of the MEG regeneration system (see Figure 2).

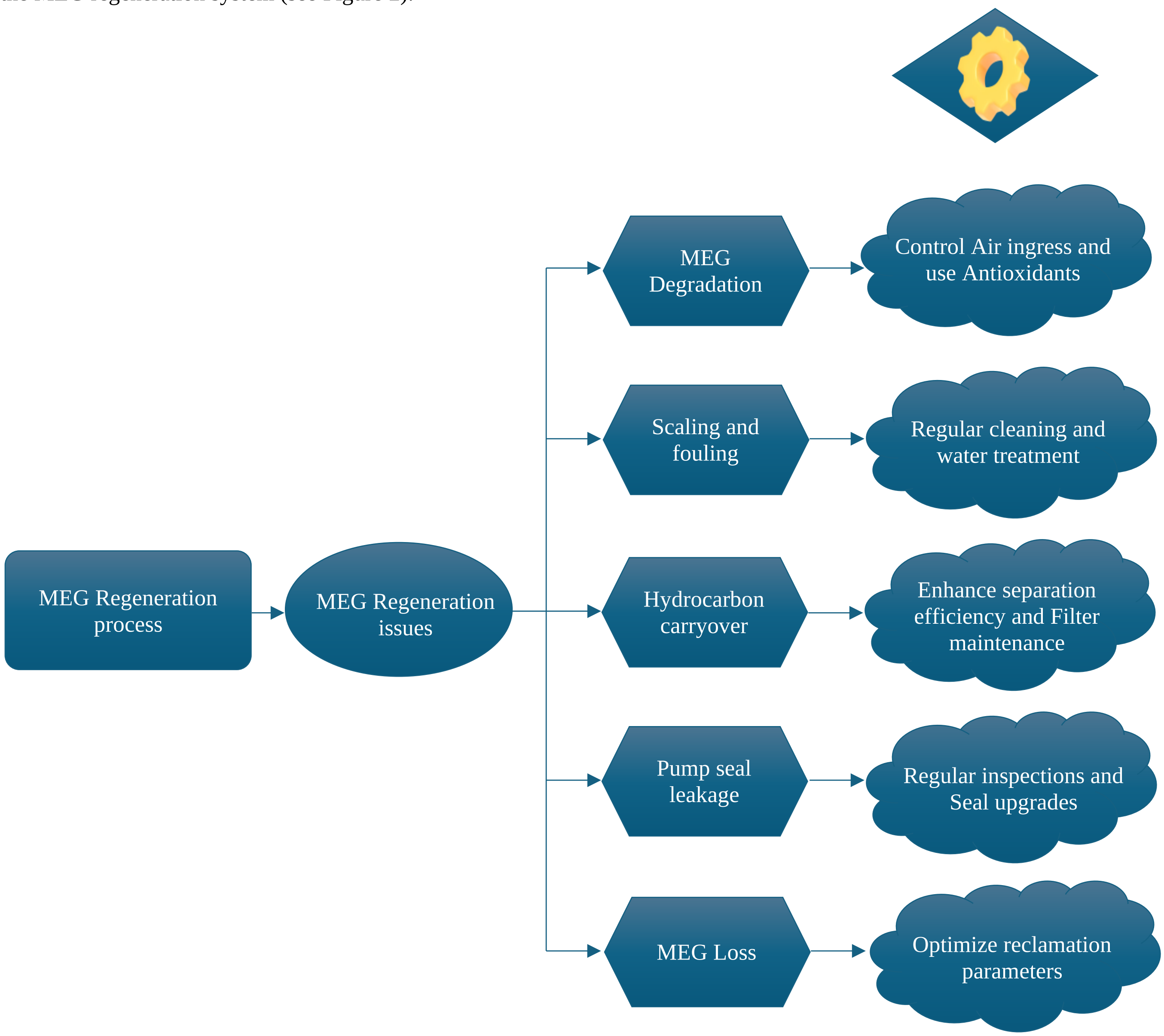

Fig. 2 Summary of MEG regeneration issues and corresponding mitigations

6. MEG Regeneration Experimental Sets

The exploration of Monoethylene Glycol (MEG) regeneration processes has been a focal point of recent research, particularly in the context of mitigating scaling and corrosion challenges associated with hydrate control in oil and gas operations. This section delves into the experimental setups and findings from key studies that have contributed significantly to understanding MEG's behavior under various treatment conditions and the efficacy of different inhibitors in the regeneration process (see Table 1 and Figure 3).

Table 1. Summary of experimental studies related to the MEG regeneration process

Study	Methods and Numerical Details	Key Findings and Contributions
[6]	- Conducted MEG regeneration experiments in a pilot plant simulating switchover from pH stabilization to FFCI.	- MEG viscosity increased to 1430.53 mPa-s; MEG became dark brown due to FFCI and MDEA accumulation.

	- pH optimization studies: pH > 8 used in pretreatment to remove divalent salts; acid injection before regeneration.	- The optimum pH for effective chemical removal could not be achieved due to varying needs across the process.
	- PVT cell (High-pressure) used to test reclaimed MEG's hydrate inhibition implementation.	- Reclaimed MEG showed reduced hydrate inhibition performance compared to pure MEG.
[15]	- ScaleSoftPitzer software used to predict salt deposition and scale formation in MEG pretreatment.	- Scale formation is more severe with scale inhibitors than with corrosion inhibitors.
	- Experimental setup: 50 mL rich MEG solutions treated with inhibitors; pH adjusted to 9.6 at 80°C; solids filtered out.	- Mixing corrosion and scale inhibitors increased scaling severity due to synergistic effects.
	- Scaling severity measured: experimental results matched software predictions, confirming reliability.	- Reclamation section highly affected by scaling due to high TDS; management needed to improve safety and reliability.
[16]	- MEG regeneration simulations conducted using Aspen Plus, modeling regeneration from 25 wt% to 70 wt% MEG concentration.	- Reducing MEG concentrations from 80 wt% to 70 wt% decreased life cycle cost by $5.98 million.
	- Experimental evaluation of KHI effectiveness in a high-pressure stirred-tank reactor under shallow water conditions.	- Suggested a hybrid approach: using KHI during regular operations and MEG injection during transient events.
	- Thermodynamic predictions used for hydrate equilibrium conditions; high-pressure simulation at 10 MPa, 10°C.	- Detailed phase equilibrium and hydrate risk analysis provide insights for optimizing hydrate inhibition systems.

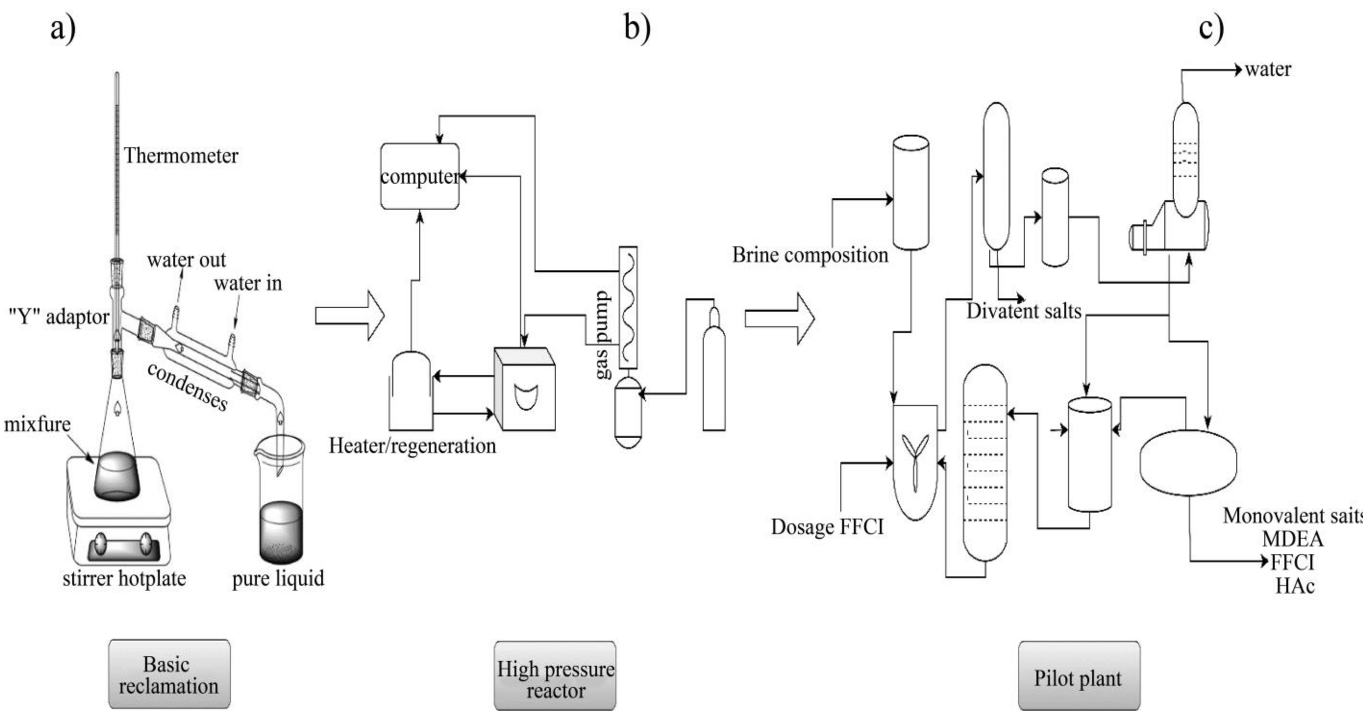

Fig. 3 The evolution of MEG reclamation investigation techniques

Yong and Obanijesu [15] embarked on a comprehensive study to assess the impact of three corrosion inhibitors and a scale inhibitor on scaling tendencies within the pretreatment and reclamation stages of MEG regeneration, as depicted in Figure 3(a). Initial experiments utilized the ScaleSoft Pitzer software to simulate salt deposition risks at the pretreatment phase, followed by empirical testing at inhibitor concentrations of 250 ppm and 1000 ppm. Subsequent trials incorporated scale inhibitors alongside corrosion inhibitors to gauge their combined effects on scaling. Rich MEG samples subjected to reconcentration and vacuum distillation revealed that the software's predictions closely mirrored the experimental outcomes, highlighting the contributory role of corrosion inhibitors in scaling while underscoring the scale inhibitor's propensity to exacerbate such issues. In a separate endeavour, Alef, Gubner [6] introduced a pilot plant, illustrated in Figure 3(b), designed to replicate the intricacies of MEG interaction with production fluids and chemical additives under conditions more akin to real-world applications than standard benchtop experiments. This facility, with a lean MEG processing capability ranging from 1 to 4 kg/h, encompasses a series of operational stages, including preparation of produced water, rich MEG formulation, MEG treatment for divalent salt elimination, followed by reclamation and regeneration phases, thereby providing a holistic view of the MEG lifecycle within industrial settings. Lee, Kim [16] further expanded the scope of experimental research by employing a stirred-tank reactor (high-pressure) to simulate hydrate formation and dissociation dynamics, as shown in Figure 3(c). This setup, capable of exerting pressures up to 15 MPa and mixing fluids at speeds varying from 0 to 800 rpm, offers invaluable insights into the physicochemical interactions during hydrate formation under pressurized conditions, thereby enriching the understanding of MEG's performance as a hydrate inhibitor across a spectrum of operational scenarios.

Collectively, these studies underscore the multifaceted nature of MEG regeneration and reclamation processes, highlighting the critical role of experimental research in navigating the complexities of hydrate control. Through these investigations, the industry gains valuable knowledge on optimizing MEG treatment protocols, enhancing operational efficiency, and mitigating environmental impacts, thereby paving the way for more sustainable and cost-effective practices in hydrate management.

7. Simulation and Modelling Studies

Exploring advanced simulation studies and cost analysis in Monoethylene Glycol (MEG) regeneration opens a new chapter in optimizing industrial processes for hydrate inhibition. This section delves into groundbreaking methodologies, from empirical models predicting MEG's performance over multiple regeneration cycles to machine learning algorithms forecasting operational inefficiencies, setting the stage for a detailed examination of cost-effective and efficient MEG regeneration strategies.

7.1. Modeling the Recycled MEG Performance

Alef, Smith [7] developed an empirical model grounded in equilibria data to enhance the understanding of Monoethylene Glycol (MEG) application in industrial settings. This model can predict the decline in MEG's hydrate inhibition efficacy through multiple regeneration cycles and factors in the equilibrium pressure and temperature of gauging MEG's degradation and diminishing efficiency. The model is finalized in Equation 1:

$$T = a\ ln\left(\frac{P}{b}\right) + c\ ln\left(\frac{P}{d}\right) n \quad (1)$$

Where n is the corresponding cycle, (T and P) are the dissociation conditions, and a, b, c, and d are the model constants: 8.117, 40.827, -0.06957 and 1710.7, respectively. The model has shown remarkable accuracy in reflecting experimental data, thereby proving its utility in optimizing MEG's application in hydrate inhibition. The T calculated using the model is compared with the T experimental for each cycle. Any disagreements between the *T calculated* and the *T experiment* are "represented by the relative difference as a percentage (RD%). Most calculations are within 0.1 - 0.2 °C of the corresponding experimental value and rarely differed by more than 2% with an average of 1.24%. It can be concluded that the developed model accurately represents the experimental data from which it was constructed".

7.2. Simulation Model for MEG Regeneration Process and Cost Analysis

In a comprehensive study by Lee, Kim [16], shallow water gas fields situated at an average depth of 60 meters below sea level were examined to understand the operational dynamics in similar conditions prevalent in Southeast Asia and the Middle East. These regions typically feature gas field developments extending down to 100 meters, with seasonal water temperatures fluctuating between 10 °C in winter and 30 °C in summer. The study notes that while the reservoir production pressure averages 15 MPa, subsea pipelines typically operate at a reduced pressure of 10 MPa from the subsea to the platform. To analyze the operational conditions within these parameters, Lee, Kim [16] employed the "Electrolyte Non-Random Two Liquid (ENRTL)-Redlich–Kwong (RK) models" integrated within the Aspen process simulation software to predict fluid properties and phase behaviors under varying conditions. One notable finding from this research was the economic impact of adjusting Monoethylene Glycol (MEG) concentration in the regeneration process; "a reduction from 80 wt% to 70 wt% in MEG concentrations was projected to decrease the life cycle cost (LCC) of the MEG regeneration process by approximately $5.98 million", primarily through savings on distillation column costs. This significant outcome underscores the necessity of incorporating rigorous experimentations and process models, particularly those including LCC analysis, to optimize hydrate inhibition systems for enhanced economic efficiency.

7.3. Model Development and Evaluation of Reclamation Unit

The MEG regeneration process's effectiveness in economic performance is significantly influenced by factors such as the losses of Monoethylene Glycol (MEG) and the energy requirements for the separation process. Highlighting the importance of maximizing MEG recovery while minimizing the disruptions caused by salts for sustainable process operations, Son, Kim [2] undertook a detailed investigation into the modelling and simulations of the salt and water elimination stages. This study aimed to forecast the need for hydrate inhibitors in subsea conditions and delineate systematic methodologies for identifying optimal process configurations and operational conditions that could enhance economic outcomes by reducing MEG loss and energy consumption. Utilizing process simulation tools such as Aspen Plus® and UniSim Design for model development, the research meticulously validated these models against real-world industrial data, ensuring their relevance and applicability. A notable achievement of this study was the attainment of a 99.42% recovery rate of hydrate inhibitors from the reclamation unit, a figure that aligns closely with the recovery rates observed in commercial operations, typically ranging from 99.4% to 99.5%.

Moreover, the investigation revealed that a substantial portion of the total energy consumption, at least 60%, was attributed to the MEG-water separation process in the reconcentration unit, underscoring the critical need for energy optimization in the regeneration process. This comprehensive analysis serves as a pivotal reference for enhancing the economic and environmental efficiency of MEG regeneration systems.

8. Machine Learning

Machine learning has been widely applied in flow assurance as a powerful tool and advanced technology, but machine learning has not been utilized in the process of MEG regeneration yet, except in one study by [17]. The advent of machine learning techniques in addressing operational inefficiencies within subsea systems has marked a significant leap forward in predictive analytics, particularly in the context of scaling, fouling, and subsequent plugging in Monoethylene Glycol (MEG) Regeneration Units (MRUs). In the study by Hamidiy, Amir [17], supervised machine learning, specifically the Random Forest algorithm, was employed to forecast plugging risks within Indonesian subsea systems by analyzing the association between various operational parameters and total dissolved solids in lean MEG. This approach illuminated the intricate relationship between process variables and MRU performance and underscored the transformative potential of machine learning in bolstering operational decision-making and efficiency.

Table 2. Summary of Hamidi's machine learning study

Parameter	Description	Impact/Results	Recommendation
Plugging Issue	Caused by solid particle deposition in the MEG injection line	Increased risk of hydrate formation and loss of production	Use predictive monitoring and proactive maintenance strategies
Key Parameters	Flowing pressure, CO_2 content, produced water flow rate, gas flow rate	Significant predictors of plugging risk	Regular monitoring and adjustment based on these parameters
Machine Learning Algorithms	Various algorithms tested, including ANN, Random Forest, and SVM	ANN achieved the highest accuracy: 98.47%	Employ ANN for reliable plugging prediction
Model Performance	ANN model's accuracy: 89.28%; F1-score: 80.18%	Effective in real-time plugging prediction	Optimize the model further with additional data
Mitigation Strategies	Monitoring cleanliness level and ensuring proper equipment functionality	Reduces risk of MEG injection failure	Use methanol as a secondary safety measure
Future Enhancements	Incorporate additional parameters and actual field data	Improved model accuracy and broader applicability	Gather more comprehensive datasets for model training

The study's findings revealed that the Random Forest model, with initial accuracy values of 75.69% and an F1-score of 82.47%, emerged as the most efficacious predictor of plugging incidents. Further optimization of the model's hyperparameters enhanced its accuracy and F1-score to 89.02% and 92.02%, respectively. The refined model demonstrated an average accuracy of 77.89% when applied to test data, affirming a significant correlation between process parameters and MRU performance (see Table 2).

This revelation underscores the viability of machine learning models in enhancing predictive accuracy and operational insights within the MEG regeneration framework [18]. The application of such predictive models offers several tangible benefits to MRU operations, including a substantial reduction in manual labor associated with lean MEG sampling, testing, and analysis. Moreover, the ability to monitor the cleanliness of lean MEG in real-time and predict potential blockages due to contamination significantly enhances the responsiveness and precision of operational decisions. These advancements, facilitated by machine learning, not only contribute to the optimization of MRU operations but also herald a new era of efficiency and predictability in the management of subsea systems, ensuring that lean MEG specifications remain within desired thresholds and thereby mitigating the risk of operational disruptions [19].

9. Contributions to the MEG Regeneration Research

This mini-review encompasses a spectrum of studies focusing on the regeneration of industrial hydrate inhibitors, employing a variety of experimental setups and methodologies to address the complexities of Monoethylene Glycol (MEG) regeneration processes. For instance, Alef, Gubner [6] designed a pilot plant to mimic real-world conditions for studying MEG and chemical additives, thereby highlighting the significance of each stage in the regeneration process. In contrast, Lee, Kim [16] investigate hydrate formation and dissociation, providing insights into physical processes crucial for developing effective hydrate inhibition strategies. Yong and Obanijesu [15] examined the impact of corrosion and scale inhibitors on the scaling at pre-treatment and reclamation stages, using both software predictions and experimental analyses to determine the optimal inhibitor doses and combinations.

Further advancements in the field are demonstrated through the application of technology and modeling. Psarrou, Jøsang [8] delved into MEG degradation under regeneration conditions, identifying main degradation products and suggesting measures to minimize degradation.

Meanwhile, Hamidiy Suryodipuro [19] employed a machine learning model to predict potential plugging issues, showcasing the application of data analytics in operational decision-making. Lee, Kim [16] also conducted a Hysys simulation to evaluate the life cycle cost of the MEG regeneration processes, indicating the potential for cost reductions through optimal MEG concentration adjustments. Additionally, Son, Kim [2] focused on modeling and simulation to optimize the salt and water removal processes, highlighting the balance between energy consumption and hydrate inhibitor recovery for sustainable process efficiency.

These studies collectively contribute to the understanding and enhancement of MEG regeneration processes, emphasizing the importance of technological integration, precise chemical management, and systematic optimization for industry applications. These studies are summarized in (see Table 3).

10. Future Insights

As the oil and gas industry strides towards more sustainable and efficient practices, Monoethylene Glycol (MEG) reclamation and regeneration have emerged as focal areas of innovation and research. The transition from traditional hydrate prevention methods towards more environmentally friendly and cost-effective techniques underscores the significance of advancements in MEG regeneration technologies.

Table 3. Contributions to the MEG regeneration research

Study Reference	Experimental Setup	Key Findings	Recommendations
[6]	5-stage pilot plant: formation water, rich MEG, MEG pre-treatment, regeneration, reclamation.	Detailed analysis of the regeneration process, emphasizing stage importance.	Research specific pre-treatment methods for optimization.
[16]	High-pressure stirred-tank reactor for hydrate experiments.	Insights into gas hydrate behavior under varied conditions.	Develop efficient hydrate inhibition strategies.
[15]	Corrosion and scale inhibitor testing with ScaleSoft Pitzer and experiments.	Corrosion inhibitors increase scaling; scale inhibitors have adverse effects.	Adjust inhibitor doses and combinations for optimal results.
[8]	Study of MEG degradation under regenerations/reclamations condition.	Glycolic and formic acids are identified as the main degradation products.	Minimize air ingress and control environmental factors.
[19]	Machine learning (Random Forest) model predicting plugging in MEG units.	High accuracy in predicting plugging; the utility of machine learning noted.	Implement machine learning for real-time monitoring and maintenance.
[16]	Simulation of MEG regeneration in shallow water gas fields.	Lower MEG concentration reduces life cycle costs.	Optimize MEG concentration for cost-efficiency.

[2]	Modeling and simulation of MEG reclamation focusing on energy consumption.	High recovery rates; energy in separation significant to total consumption.	Evaluate configuration and conditions to minimize energy use and MEG loss.

Recent studies, such as those conducted by Alef, Gubner [6], Alef, Smith [7], have shed light on the impact of multiple regeneration cycles of the regenerated MEG as thermodynamic hydrate inhibitor and the evaluation of MEG reclamation during corrosion control switchover. These investigations provide critical insights into optimizing the reuse of MEG, thus contributing to more sustainable practices within the industry. Furthermore, the work by Psarrou, Jøsang [8] on carbon dioxide solubility and MEG degradation offers essential knowledge on maintaining the efficacy of MEG in hydrate inhibition under varying operational conditions.

The integration of advanced simulation tools and machine learning algorithms presents a promising avenue for enhancing the predictability and efficiency of MEG regeneration processes. The application of machine learning in predicting plugging risks in MRU systems, as explored by Hamidiy, Suryodipuro [19], exemplifies the potential of data-driven approaches in preempting operational challenges and optimizing system performance. The development and evaluation of models, such as those by Son, Kim [2], focusing on salt and water removal steps, further illustrate the trend towards more sophisticated analytical frameworks in the regeneration process.

Finally, the future of MEG regeneration and reclamation is poised to be shaped by a confluence of advanced computational techniques, a deeper understanding of chemical interactions within the regeneration process, and a continued emphasis on sustainability. Integrating empirical research findings with predictive analytics and simulation models will undoubtedly enhance the operational efficiency and environmental footprint of hydrate control practices in the oil and gas sector. As these technologies evolve, it is anticipated that they will play a pivotal role in meeting the industry's dual objectives of economic viability and environmental stewardship.

11. Conclusion

The regeneration of Monoethylene Glycol (MEG) stands at the forefront of enhancing operational sustainability in the oil and gas industry, addressing the critical challenge of hydrate formation in subsea pipelines. Through an extensive review of recent advancements, this paper underscores the transition from traditional to more environmentally friendly and efficient MEG regeneration technologies. Experimental research has been instrumental in overcoming challenges such as MEG degradation, scaling, and fouling, paving the way for innovative solutions that include the application of machine learning for plugging prediction and simulation models for cost analysis. The future of MEG regeneration is likely to be shaped by integrating computational tools and a deeper understanding of chemical interactions, focusing on sustainability. As the industry progresses, the evolution of MEG regeneration methodologies will be crucial in maintaining operational integrity and minimizing environmental impact, ensuring the dual objectives of economic viability and environmental stewardship are met.

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