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Optimizing CO_2 Capture Efficiency: Harnessing IoT and Industry 4.0 for Precise Temperature Analysis in Packed Absorption Columns

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Abstract. The deployment of various technologies to mitigate climate change is crucial for developing techniques that advance climate action. Climate change is exacerbated by rising levels of carbon dioxide (CO_2) and other greenhouse gases, deforestation, and the use of fossil fuels. Urgent measures are needed to enhance CO_2 capture efficiency, in alignment with the Sustainable Development Goals (SDGs) and climate action initiatives. This study investigates the influence of temperature variations in a packed absorption column on CO_2 capture efficiency. By employing Internet of Things (IoT) and Industry 4.0 principles, it facilitates precise data acquisition to monitor temperature fluctuations during experiments. Comparative evaluations under steady-state and saturation conditions provide critical insights for optimizing CO_2 capture in post-combustion processes. Conducting exploratory analyses enhances system understanding and informs design and operational strategies for effective and sustainable CO_2 capture. This research delves into the technical aspects of temperature optimization, emphasizing its significance for sustainable practices and the urgency of addressing climate change through innovative, technology-driven solutions.

Keywords: CO_2 capture, Temperature Analysis, Absorption Column, Greenhouse Gas Emissions, IoT, Industry 4.0, Data Analysis.

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1 Introduction

The escalating concern about global warming, fueled by rising concentrations of greenhouse gases, particularly carbon dioxide (CO_2), in the atmosphere, has intensified the search for innovative strategies to mitigate climate change [1]. As we enter the era of Industry 4.0 and witness the proliferation of Internet of Things (IoT) technologies, the importance of leveraging these advancements in the fight against climate change becomes increasingly evident. The fourth industrial revolution, characterized by the integration of digital technologies into various sectors, plays a pivotal role in shaping new approaches to climate action.

Amidst the escalating challenge of climate change, carbon dioxide (CO_2) capture stands out as a crucial element in mitigating greenhouse gas emissions. Among the promising technologies, packed absorption columns have proven to be indispensable in carbon capture systems. This essay explores the optimization of CO_2 capture efficiency, with a specific emphasis on the detailed analysis of temperature variables in a packed absorption column. The powerful Sankey Diagram is employed to visually represent these analyses, providing clear insights into the energy balance and performance of the process.

The most recent report from the Intergovernmental Panel on Climate Change (IPCC) outlines various strategies for reducing greenhouse gas emissions and adapting to the climate change induced by human activities. [2, 3]. In the backdrop of this environmental challenge, the industrial landscape is undergoing transformative changes, aligning with the principles of Industry 4.0. The impact of climate change is particularly pronounced in regions where almost half of the world's population resides, experiencing greater vulnerability to climate-related disasters such as floods, droughts, and storms [4, 5, 6]. Reducing the effects of CO_2 emissions from fossil fuel burning remains a paramount goal, and carbon capture and storage (CCS) technologies play a crucial role in achieving this objective [7, 8, 9]. The current form of energy generation relies heavily on fossil fuel combustion [10, 11], a primary source of CO_2 emissions, as outlined in government institutions reports [12, 13]. Against this backdrop, the development of CO_2 capture technologies, especially in post-combustion processes, has emerged as a key strategy for both climate change mitigation and economic development [14]. This initiative is supported by various national and international organizations, recognizing the vital role of CO_2 capture across industries such as steel, iron, cement, natural gas processing, and refineries, as reported by the Elcano Royal Institute [15]. In the pursuit of sustainable solutions, various technological pathways have been explored for converting CO_2 into commercial products, ranging from catalytic and electrochemical processes to mineralization, biological methods using microorganisms and enzymes, as well as photocatalytic and photosynthetic processes [16, 17, 18]. Post-combustion CO_2 capture processes encompass a variety of technologies, including absorption, adsorption, membrane separation, and cryogenics [19],[20]. Among these options, chemical absorption processes stand out as the most widely used methods in the industry for separating CO_2 from gas streams, with a focus on optimizing efficiency. [21]. The present research focuses on optimizing CO_2 capture efficiency by analyzing the impact of temperature variations within a packed absorption column that utilizes MEA as an absorbent at low concentrations due to its high corrosion at higher concentrations. Notably, this study emphasizes the importance of advancing data acquisition and analysis processes in steady-state absorption and saturation experiments. In this context, a data acquisition system based on the principles of IoT with Arduino was implemented to measure temperatures, representing a significant technological advancement to enhance efficiency in CO_2 capture processes within the framework of Industry 4.0 and IoT technologies.

2 Methodology

Packed absorption columns stand out as fundamental devices in CO_2 capture systems. They act as crucial interfaces for mass transfer between the feed gas and the absorbing solvent. CO_2 capture efficiency is directly linked to operational variables, and among them, temperature emerges as one of the most influential. Optimization of this variable presents itself as a crucial research path to improve the overall effectiveness of the process.

The aim of this work is to provide the user with a tool that allows them to interpret and make decisions based on the obtained results. This section outlines the methodology developed to achieve the objective.

2.1 Concept diagram

Fig. 1 describes the methodology employed to optimize CO_2 capture, with a focus on temperature analysis within the absorption column. The process unfolds through six outlined stages, commencing with the selection of materials and crucial measuring instruments for temperature acquisition during absorption. Subsequently, the development of a program facilitates temperature acquisition through a user-friendly graphical interface designed for seamless user interaction. Before temperature data acquisition, it involves precise calibration and integration of temperature sensors into the absorption system.

Experimental tests within the absorption system follow a design of experiments methodology. The collected data undergoes meticulous analysis with the aim of optimizing CO_2 capture efficiency. This comprehensive methodology, aligned with the principles of IoT and Industry 4.0, ensures a systematic approach to temperature analysis, emphasizing the enhancement of CO_2 capture processes.

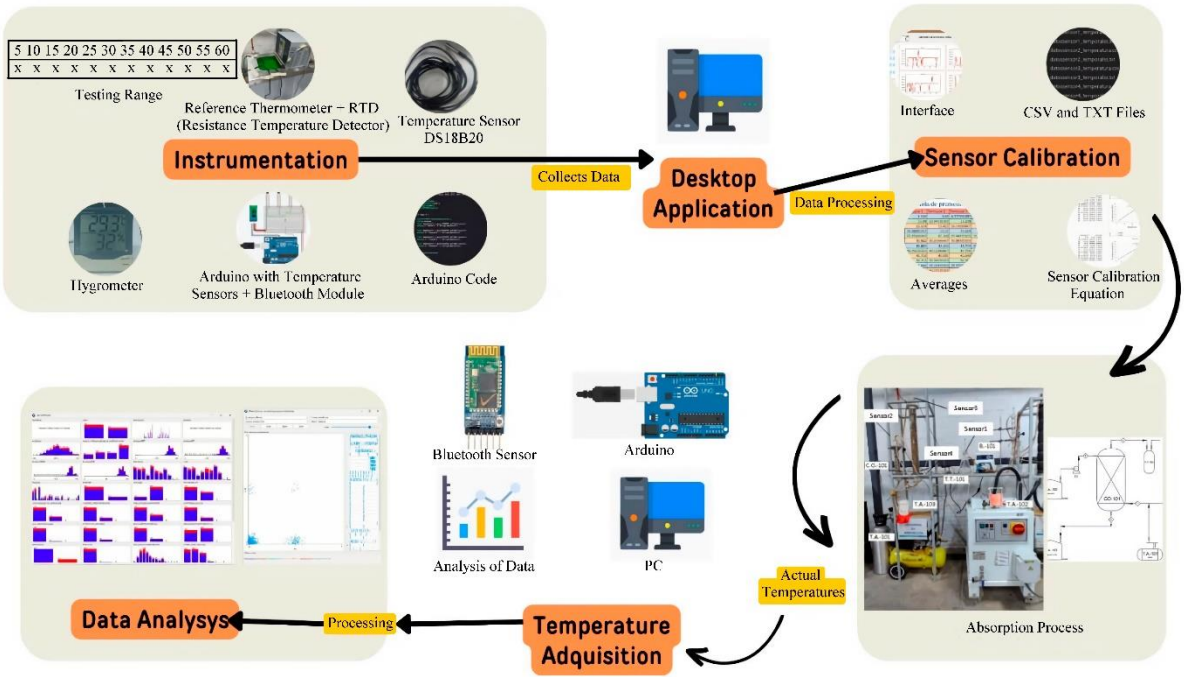

Fig. 1. Conceptual diagram of the methodology for the development of data acquisition optimization.

2.2 System description

Fig. 2 presents the detailed design of the absorption system described by Navarrete Procopio et al (2023) [22]:
The system is a column packed with ½-inch ceramic Berl saddles (PT-101). Tank 1 (TK-101) contains the CO_2 that mixes with the airflow supplied by the piston compressor (C-101). Tank 2 (TK-102) contains the MEA solution that feeds the ab-sorption column from the top (stream 1) through a peristaltic pump (P-101). The concentration of CO_2 in the gas stream is controlled with the rotameters (R-101, R-102). Tank 3 (TK-103) contains the MEA solution saturated with CO_2 that exits from the bottom of the absorption column (stream 6). The gas mixture is fed at the bottom of the column (stream 4). The purified gas is vented to the atmosphere from the top of the absorption column through a gas analyzer to determine the CO_2 concentration (stream 5).
The main difference between Navarrete Procopio's original study and this one is the replacement of thermocouples with DS18B20 sensors, located in the cur-rent streams 1, 4, 5, and 6.

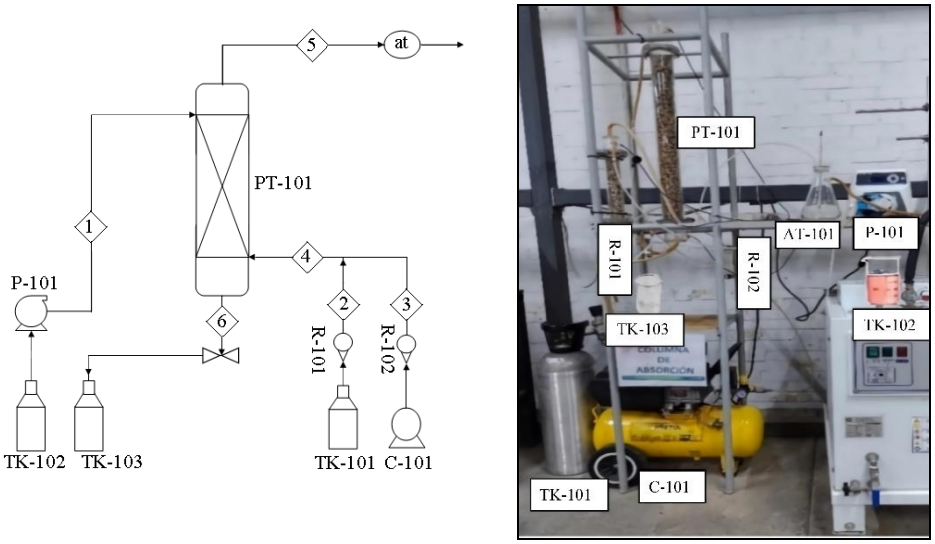

Fig. 2. Schematic diagram of the experimental absorption system.

2.3 Design of experiments

The absorption process, using Monoethanolamine (MEA) as the absorbent, is an essential technique in the industry for separating and purifying gases through the capture of specific components. Fig. 3 below shows an outline of the experimental design performed and the variables to be considered.

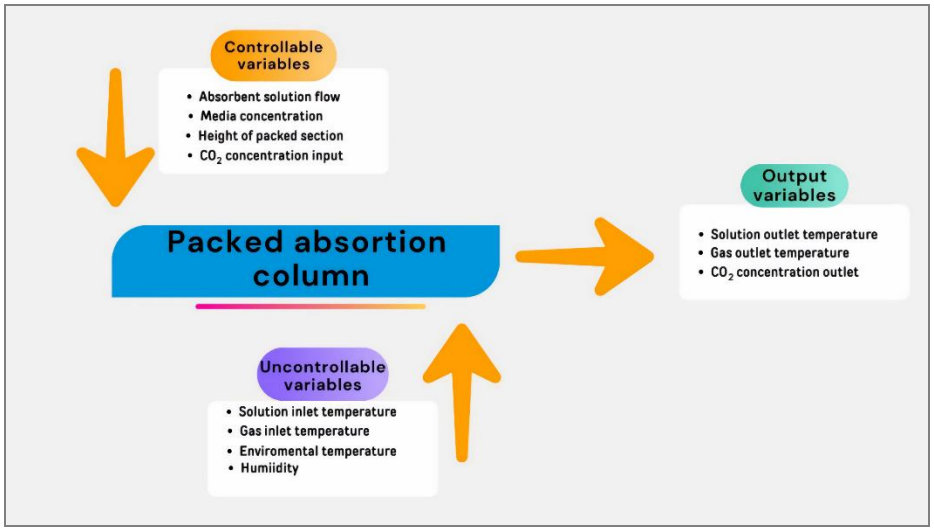

Fig. 3. Design of experiments diagram.

In this section, the work provide a detailed account of the experiments conducted to determine the saturation time and achieve a steady state. Table 1 presents the operating parameters used in these experiments.

Table 1. Experimental operating parameters

Parameter Data	
Packing Type	Ceramic Berl saddles, 1/2"
Absorber Diameter (m)	0.08
Packed Absorber Height (m)	0.7 y 0.25
Gas Flow Rate (L/min)	16 y 5.7
MEA Concentration (w/w. %)	10 y 15
Pressure (kPa)	80

2.3.1 Saturation tests

When the MEA solution reaches its saturation point, it loses the ability to ab-sorb more gas molecules, indicating that it has reached its maximum retention capacity. Knowing the saturation time is essential to optimize the adsorption process and to ensure a flow rate for maximum MEA adsorption capacity. During the experimental tests, two MEA concentrations, one at 10% and the other at 15%, were evaluated to analyze their influence on the adsorption capacity and the saturation time. The gas flow is continuous at the CO_2 concentration set under the operating conditions, while the liquid to be saturated is a quantity of sorbent solution loaded in the sorption column.

2.3.2 Continuous testing

The continuous tests performed with 10% and 15% w/w MEA solutions were designed to operate the sorption column continuously to achieve a steady state condition. Consequently, achieving and maintaining a controlled steady state guarantees the maximum sorption capacity of the sorbent solution.

2.4 Importance of the Sankey Diagram in Optimization

The Sankey Diagram emerges as an invaluable tool for visualizing and under-standing the energy flow in the CO_2 capture system. By graphically representing energy inputs and outputs, the Sankey Diagram is instrumental in identifying critical areas for improvement and enables a comprehensive assessment of system performance. Its value lies in simplifying complex data representations and offering a clear visualization of the energy balance within the process.

2.5 Software development

A tool was developed to assist the user in interpreting and making decisions based on temperatures acquired through an Arduino circuit by automating the calculations and generating the graphs in real time, the waiting time was reduced, allowing early detection of potential errors in the experimental test. Table 2 describes the applications and programming language used in the development of this software. The choice of these tools is essential to ensure the efficiency and functionality of the data processed by the software.

Table 2. Description of the tools used and programming language for software development

Tools	Description	Version
Programming Language	Python	3.8.10
Pandas Library	Library for handling and analyzing tabular data	1.3.0
Matplotlib Library	Library for generating charts and visualizations	3.4.2
User Interface	QT5 Designer	5
Arduino IDE	Integrated Development Environment for programming Arduino	1.8.13
Excel	Microsoft spreadsheet application for data export	2019, 365, etc.

2.5.1 Acquisition interface of the absorption system

Fig. 4Fig. 4. Main GUI Interface for Absorption Process Experiments with Data Acquired from Each Sensor Located in the Absorption Column. shows the main interface used for the absorption process experiments, with data acquired from each sensor in the absorption column. The interface is divided into specific sections: in section (a) is where the Arduino port is configured to acquire data, the start button to begin temperature acquisition and allows to set the configuration and duration of the experiment is (b), on (c) has a tooltip with information about process experiments. Section (d) is responsible for calculating the saturation time based on the parameters entered in the form. The time of each test is displayed in section (e), and the acquired temperatures during the specified time in seconds are visualized in section (f).

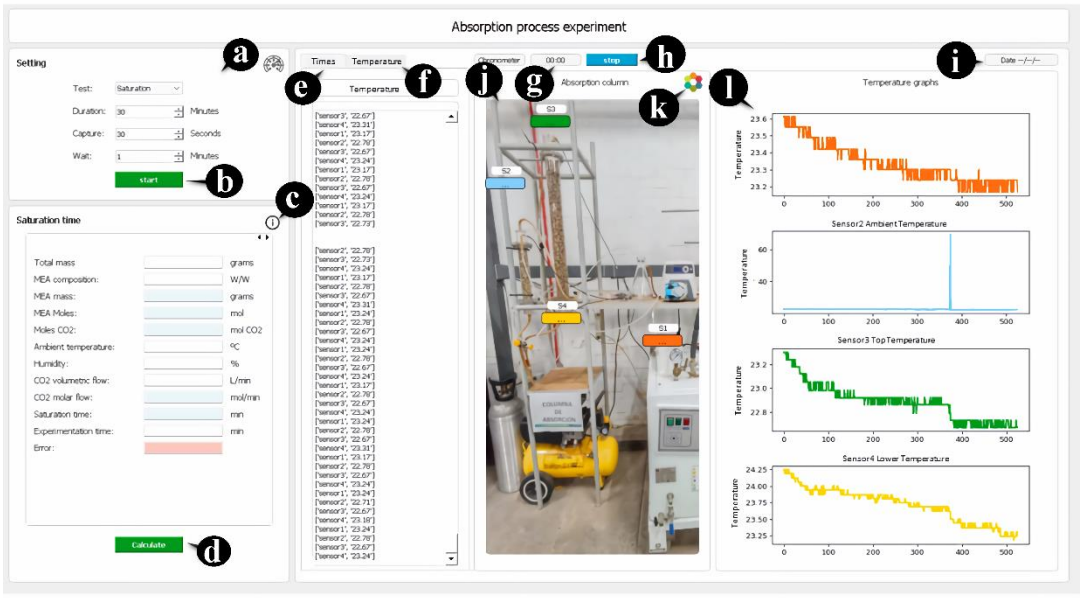

Fig. 4. Main GUI Interface for Absorption Process Experiments with Data Acquired from Each Sensor Located in the Absorption Column.

The interface also includes a timer in section (g), which continues to run even after data acquisition has been completed. (h) it's a button to stop the timer and thus the ongoing experiment. The actual computer date is displayed in section (i), providing a time stamp of the tests performed. Section (j) includes an illustrative picture of the absorption column, with colors representing the location of each sensor. The button (k) generates a graph representing the indicated capture time, calculating the average of the acquired temperatures. Finally, section (l) graphically displays the acquired temperatures, with each sensor represented by a different color for easy identification.

Fig. 5 shows a graphical user interface (GUI) displaying the average temperatures over the waiting time, based on data obtained from the four sensors.

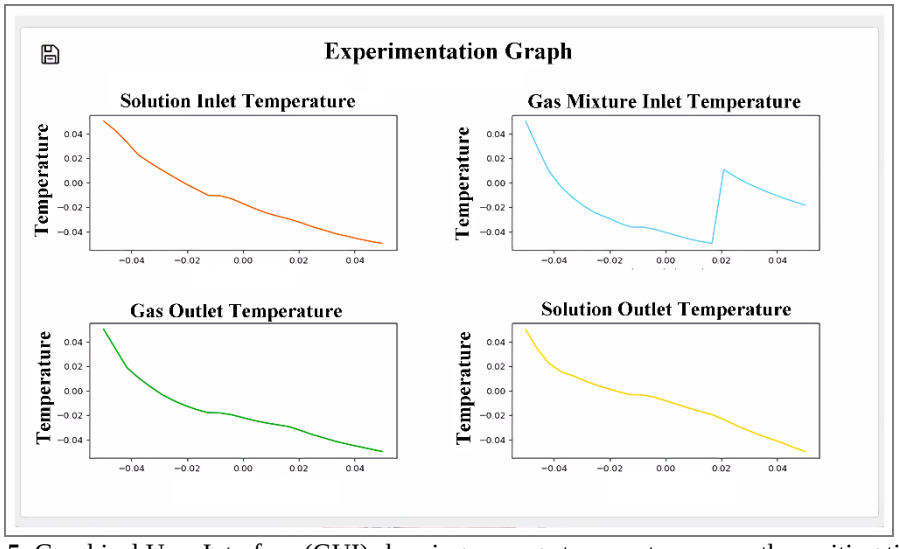

Fig. 5. Graphical User Interface (GUI) showing average temperatures over the waiting time.

3 Results

Throughout the development of this project, was optimized data acquisition from temperature sensors in the absorption column using custom-designed software. Integrated with Arduino, this software enhances real-time monitoring of experimental success and allows users to analyze temperature behavior based on the collected data.

The primary objective is the efficient capture of CO_2 during the absorption process, employing Monoethanolamine (MEA) as the absorbent. The study takes into consideration various controllable variables, such as solution flow, MEA concentration, and packed section height, along with uncontrollable variables like solution and gas inlet temperature. As a result, temperature measurements were gathered for both the solution and gas outlet under diverse experimental conditions, including saturation assessments and ongoing experiments.

This integrated approach, coupled with Arduino technology, aligns with the principles of IoT and Industry 4.0, ensuring the optimal utilization of real-time data capture for enhanced analysis of temperature dynamics during the CO_2 capture process.

The analysis of temperature variables is at the heart of CO_2 capture efficiency optimization. The relationship between the temperature of the feed gas and that of the absorbent solvent, as well as the temperature variation along the column, play a crucial role in CO_2 capture efficiency. This in-depth analysis allows the identification of optimal temperature points that maximize capture while minimizing the associated operating and energy costs.

3.1 Visual Representation through the Sankey Diagram

The Sankey Diagram becomes an essential tool to visually represent the complexities associated with temperature variables in the packed absorption column. Each energy flow is captured as a weighted arrow, providing an intuitive representation of how temperature variation directly affects process efficiency. From the inlet of the feed gas to the release of the captured CO_2, the Sankey diagram shown in Fig 6 provides a detailed view of how energy is distributed and trans-formed throughout the system.

Fig. 6. Absorption process experimentation Sankey diagram

3.2 Temperature

The paper presents absorption test results under steady-state and saturation conditions, examining the temperature behavior of gas outlet and solution under different experimental settings.

The data collected by the software shows the results of experimental tests performed at 10% MEA in both the continuous and saturation stages. The saturation test indicates when the system has reached its maximum gas absorption capacity, while the continuous test involves an increase in temperature to reach a stable equilibrium point. However, the equilibrium cannot be fully observed due to the short duration of the experimental test. This trend can be seen in Fig. 7.

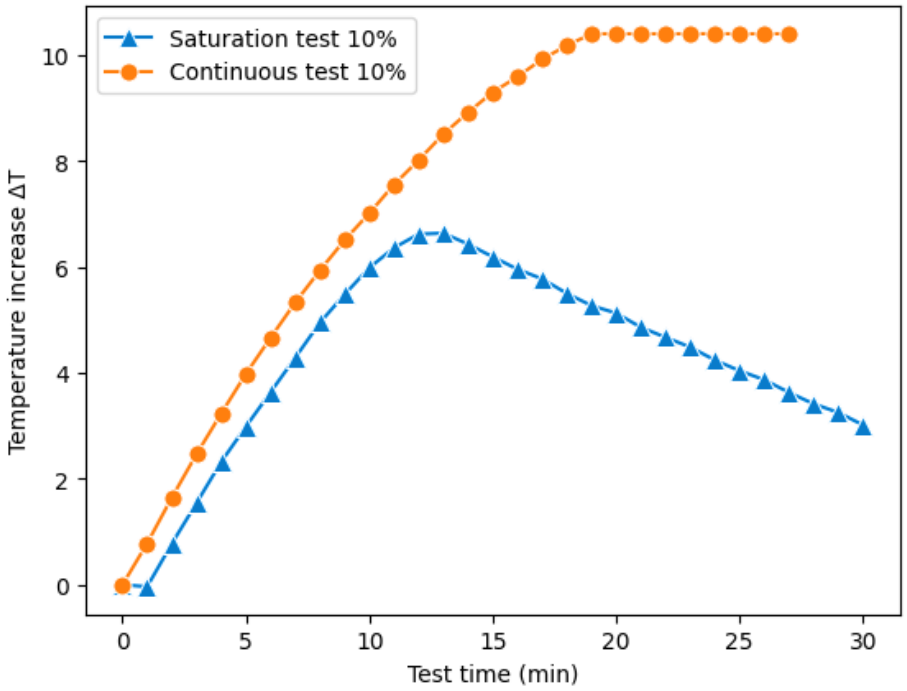

Fig. 7. Experimentation of experimental tests of MEA at 10% saturation and continuous.

An additional experiment was conducted using a 15% MEA solution. The obtained temperatures during the experiment are displayed in Fig. 8, illustrating the establishment of a steady state once equilibrium was reached. Subsequently, the continuous state indicated temperature stabilization, due to ongoing adsorption of MEA molecules. This explains the temperature maintenance. In saturation experiments, the temperature rises initially, reaches a peak, and then declines.

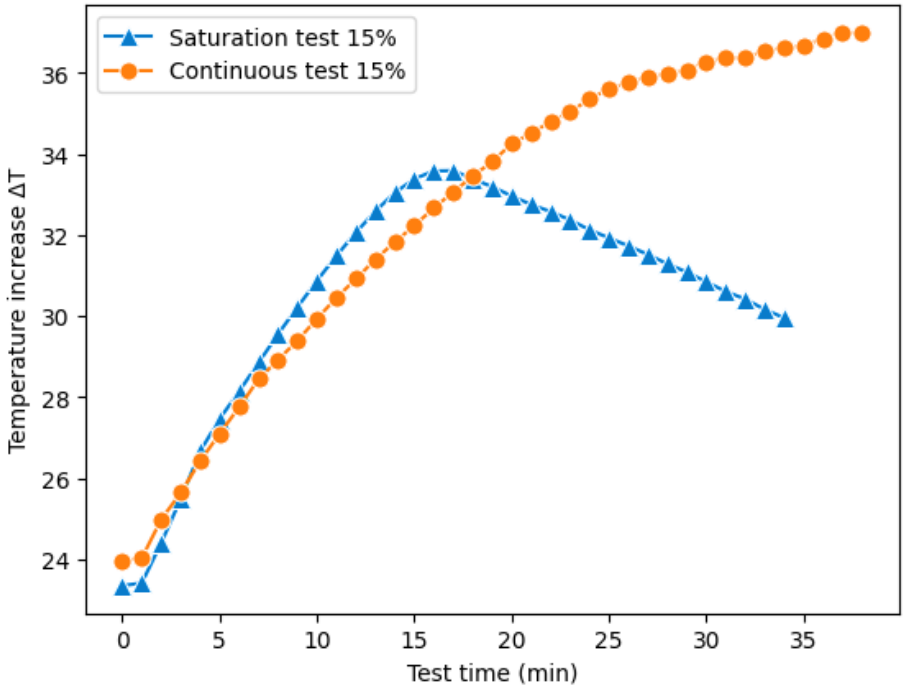

Fig. 8. Experimentation of experimental tests of MEA at 15% saturation and continuous.

Two additional experiments were conducted using a 15% MEA solution. In these tests, a column with a packed section height of 0.25 m was employed. The obtained results were compared with those from the 0.7 m column height, maintaining identical operating conditions in both columns. The main objective of these experiments is to analyze the saturation time when modifying the design parameters in the absorption column.

The temperatures recorded during the experiment in both columns are presented in Fig. 9.

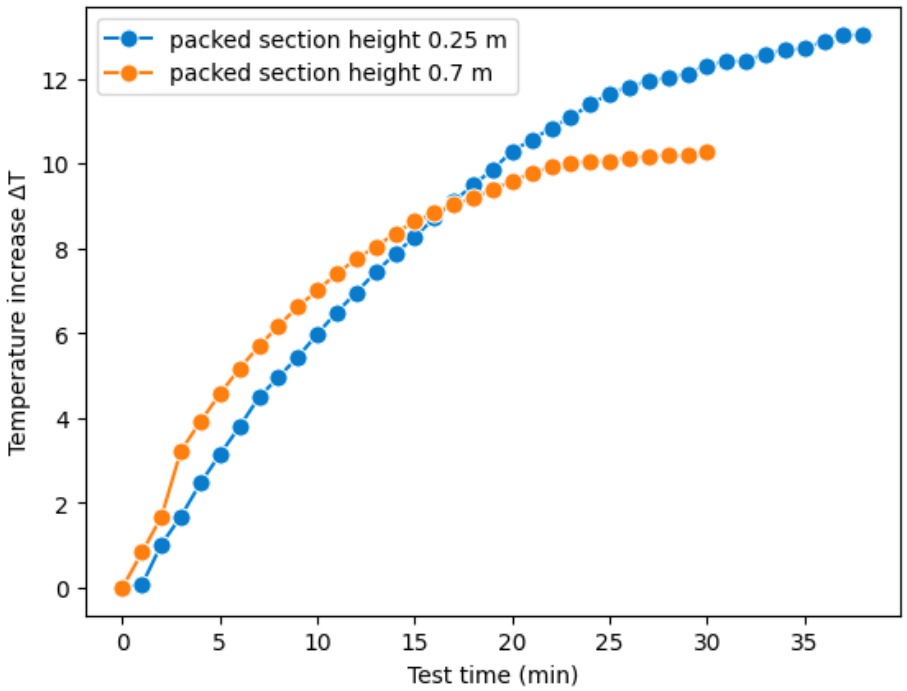

Fig. 9. Experimentation of experimental tests of MEA at 15% continuous.

Upon examining the previous experiments and comparing the heights of the packed sections, a similarity in the time required to reach equilibrium is observed. However, under saturation conditions, it is expected that the behavior of both experiments in the packed columns reflects an almost simultaneous de-crease in temperature, as at this point, the absorption of MEA molecules has ceased, as depicted in Fig. 10.

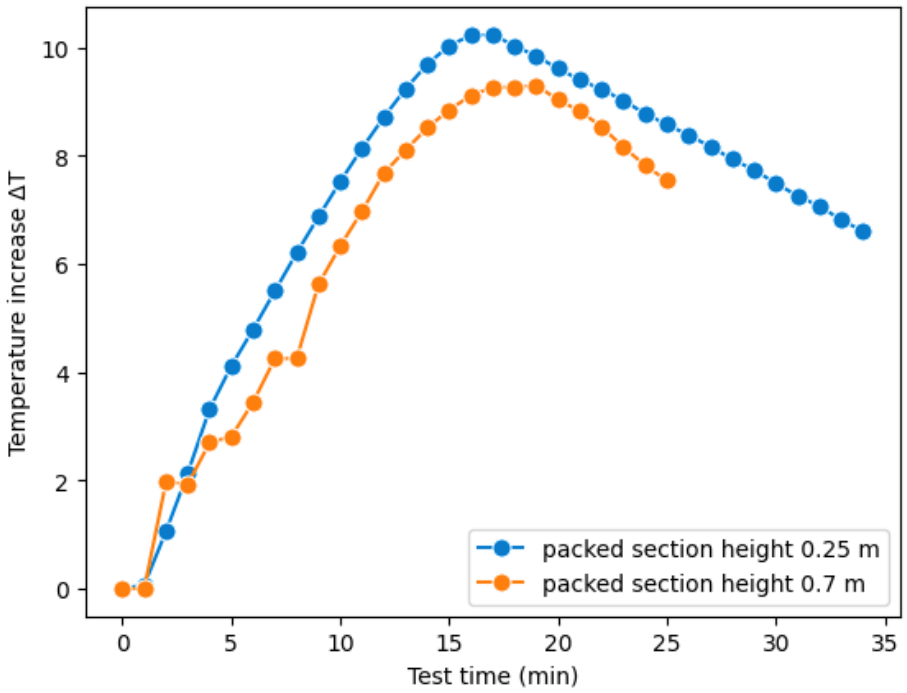

Fig. 10. Experimentation of experimental tests of MEA at 15% Saturation.

3.3 Data analysis

To identify correlations between variables, an exploratory analysis was performed on the experimental data. Fig. 11 illustrates a gradual temperature increase over time in Solution Outlet Temperature, Gas Mixture Inlet Temperature, and Gas Outlet Temperature.

Furthermore, an increasing Solution Outlet Temperature was found to be correlated with the abovementioned temperatures. However, an inverse relationship was noted between Solution outlet temperature and solution inlet temperature, indicating that as one increased, the other decreased.

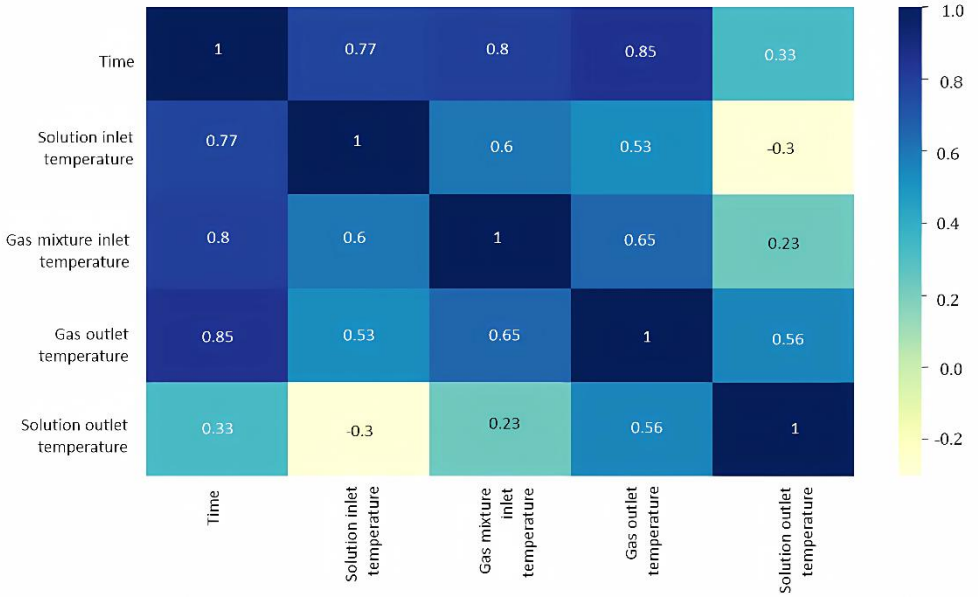

Fig. 11. Correlation of Variables in 10% MEA Saturation Test.

In Fig. 12, the relationships are more pronounced, with CO_2 gas temperature in-creasing over time, pointing to a faster absorption rate. Furthermore, a stronger negative correlation was observed between the concentrated solution temperature and the solution temperature, signifying higher sensitivity at greater concentrations.

Fig. 12. Correlation of Variables in 15% MEA Saturation Test.

Comparing the data obtained from the packed column of 0.2 m with the 0.7 m column, we can observe differences in variable correlations due to the relatively short experimentation time. However, the information provided remains valuable and promising.

In saturation experimentation, a strong positive correlation stands out between input and output temperatures for both the gas and the solution. Specifically, it is observed that the gas and solution outlet temperatures exhibit a significant correlation of approximately 0.92, indicating a direct relationship between them. Furthermore, the input temperatures for both gas and solution show even stronger correlations, around 0.94 and 0.99 respectively, signaling a highly positive relationship between these variables.

These findings suggest consistency in the thermal behavior of the system during the saturation process as depicted in Fig. 13.

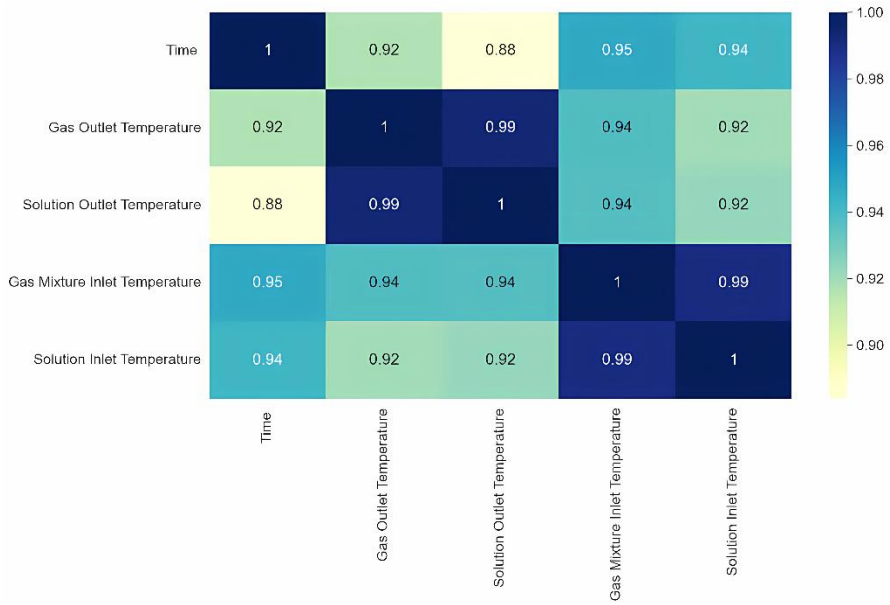

Fig. 13. Correlation of Variables in 15% MEA Saturation Test Packed column 0.2 m.

In experiments resulting from the 0.7 m packed absorption column, concentrating the MEA solution was found to be a more effective approach. The data show a positive relationship between time and temperature for CO_2 gas, indicating faster absorption at higher concentrations. Furthermore, the observed negative correlation between the temperature of the concentrated solution and the solution suggests a more efficient heat transfer from the gas to the solution.

In both continuous experiments using 10% and 15% MEA solutions, a significant negative correlation was discovered between time and temperatures of the variables being analyzed. This finding suggests a trend toward stabilizing or reducing temperatures as the experiment progressed.

Fig. 14 displays important negative correlations between the concentrated solution's temperature, the ambient and gas temperatures, illustrating the sub-stance's noteworthy influence on the surrounding temperatures. Notably, we observed strong and moderate negative correlations.

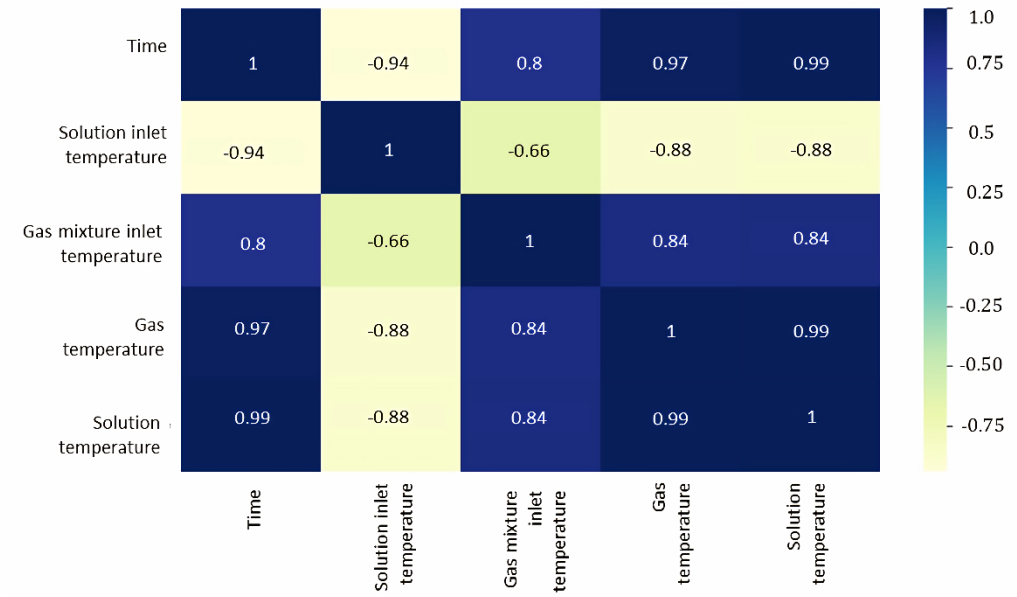

Fig. 14. Correlation of Variables in 10% MEA Continuous Test.

In Fig. 15, the trend of temperature stabilization over time persisted. Finally, there were strong negative correlations observed between ‘gas outlet temperatures, and ‘solution outlet temperatures’, indicating a simultaneous decrease in these temperatures at higher concentrations.

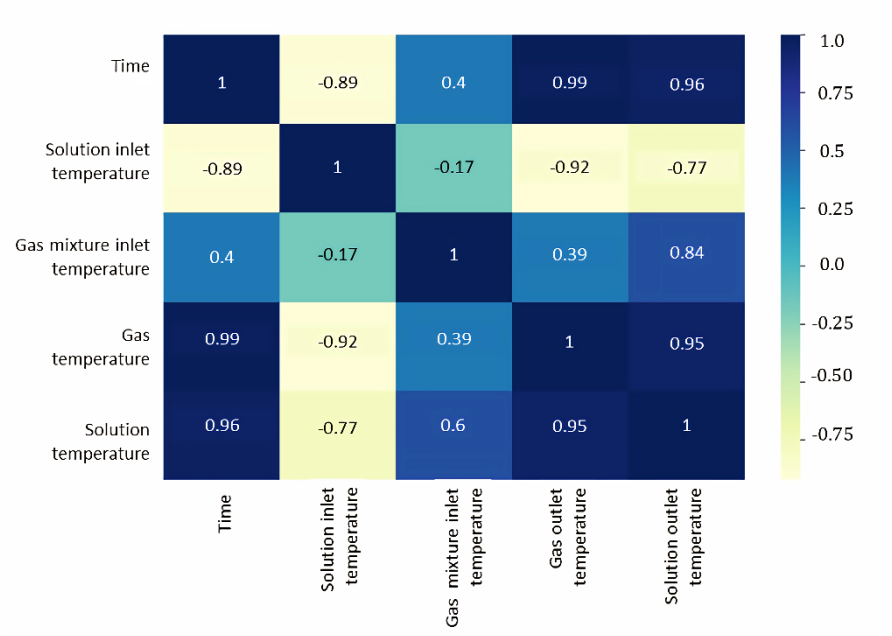

Fig. 15. Correlation of Variables in 15% MEA Continuous Test.

In continuous experimentation, there is notable thermal coherence, with significant positive correlations between input and output temperatures for both gas and solution, indicating a direct and consistent relationship throughout the process, as observed in Fig. 16.

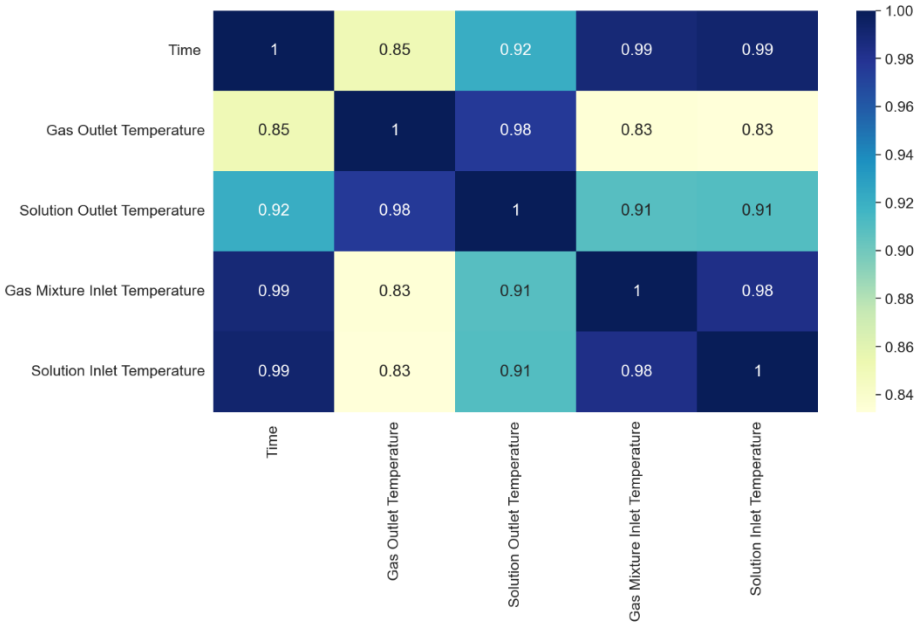

Fig. 16. Correlation of Variables in 15% MEA Continuous Test Packed column 0.2 m.

Both experiments in both columns emphasize the importance of maintaining a controlled steady state to maximize efficiency in the continuous absorption of CO_2 with MEA solutions. The higher concentration (15%) exhibited more pronounced correlations, suggesting increased thermal sensitivity and more efficient heat transfer compared to the 10% concentration. These findings are

crucial for industrial and environmental applications, ensuring an optimal CO_2 capture process and effective temperature management within the absorption system.

While it is true that the 0.2 m packed absorption column behaved similarly to the 0.7 m column, replicated data on a small scale suggests that the obtained in-formation is accurate and scalable for performance optimization, despite observed changes in correlations in the smaller column, attributed to the measured experimentation time.

4 Conclusions

In summary, the advancement of experimental processes through real-time da-ta collection and analysis, reliant on Industry 4.0 and Internet of Things (IoT) technologies, stands as a significant achievement. Specialized software has played a crucial role, ensuring meticulous data collection and accurate graph generation to understand error margins and sensor accuracy.

The integration of calibrated temperature sensors into the packed absorption column, coupled with an intuitive graphical interface for data acquisition, simplified temperature measurement across all four process streams. The experiments with 10% and 15% MEA contractions not only addressed corrosion concerns linked to concentrated solutions but also deepened insights into CO_2 capture efficiency.

The software's agility in delivering prompt results and supporting data-driven decision making has been pivotal in advancing CO_2 capture processes. Notable correlations between variables, particularly their association with temperature, have been identified through exploratory data analysis. While acknowledging the need for additional experiments to validate these observations, the results form a robust foundation for future integration of more advanced Artificial Intelligence techniques, aligning with the evolving paradigms of Industry 4.0 and IoT.

Furthermore, optimizing CO_2 capture efficiency by analyzing temperature variables within a packed absorption column emerges as a crucial research area in the ongoing fight against climate change. The application of the Sankey Diagram not only enhances system understanding but also serves as a guiding framework for designing and operating more effective and sustainable CO_2 capture processes.

Looking forward, future perspectives center on strategically integrating advanced control and monitoring technologies, in harmony with Industry 4.0 and IoT principles. This integration aims for continuous and adaptive optimization, dynamically responding to operational variations and environmental conditions a progressive leap toward promoting a more efficient, environmentally friendly, and technologically advanced CO_2 capture process.

Moreover, it is noteworthy that the behavior of the 0.2 m packed absorption column closely resembled that of the 0.7 m column. The replicated data on a small scale not only affirms the accuracy and scalability of the obtained information but also underscores the potential for performance optimization. Despite observed changes in correlations in the smaller column, these variations are at-tributed to the measured experimentation time, providing valuable insights for future investigations.

References

1. Organización Mundial del Comercio. (2009). *El comercio y el cambio climático*. Secretaría de la OMC, Suiza. https://www.wto.org/spanish/res_s/booksp_s/abstract_trade_climate_change_s.pdf
2. Intergovernmental Panel on Climate Change (IPCC). (2023). *Urgent climate action can secure a livable future for all*. Suiza. https://www.ipcc.ch/2023/03/20/press-release-ar6-synthesis-report/
3. Intergovernmental Panel on Climate Change (IPCC). (2023). *AR6 Synthesis Report Climate Change 2023*. IPCC. https://www.ipcc.ch/report/sixth-assessment-report-cycle/
4. Intergovernmental Panel on Climate Change (IPCC), Lee, H., & Romero, J. (2023). *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth*. Ginebra, Suiza. https://www.ipcc.ch/report/ar6/syr/
5. Iberdrola. (2020). *Países más afectados por el cambio climático*. https://www.iberdrola.com/sostenibilidad/paises-mas-afectados-cambio-climatico

6. United Nations. (2023). *Causes and effects of climate change*. https://www.un.org/en/climatechange/science/causes-effects-climate-change
7. Salaet Fernández, S., & Roca Jusmet, J. (2019). Agotamiento de los combustibles fósiles y emisiones de CO2: Algunos posibles escenarios futuros de emisiones. *Galega de Economía, 19*(1), 1-19. https://doi.org/10.1016/j.petlm.2016.11.003
8. Rosca Jusmet, J. (2022). La política climática y los combustibles fósiles: Una perspectiva desde la oferta. *Economía Crítica, 34*, 9-25. https://revistaeconomiacritica.org/index.php/rec/article/view/649
9. Díaz Cordero, G. (2012). El cambio climático. *Ciencia y Sociedad, 37*, 227-240. https://www.redalyc.org/pdf/870/87024179004.pdf
10. Laguna Monroy, I. (2002). La generación de energía eléctrica y el ambiente. *Gaceta Ecológica, 65*, 53-62. https://www.redalyc.org/pdf/539/53906504.pdf
11. Arango, M. A. A. (2016). Model risk assessment projects in thermal power generation [Modelo de proyectos de evaluación de riesgo en generación de energía térmica]. *Espacios, 37*(26). https://www.scopus.com/record/display.uri?eid=2-s2.0-84966604674&origin=inward&txGid=204221a32138ca1a4828c537cf5c2420
12. Samaniego, J., & Schneider, H. (2019). *Cuarto informe sobre financiamiento para el cambio climático en América Latina y el Caribe, 2013-2016*. Comisión Económica para América Latina y el Caribe (CEPAL). https://repositorio.cepal.org/bitstream/a4f2981d-840a-4923-92b1-ccdebf3ee95c
13. Olcina Cantos, J. (2015). Cambio climático y riesgos climáticos en España. *Investigaciones Geográficas, 49*, 197-220. https://www.redalyc.org/pdf/176/17617034010.pdf
14. Romeo, L., & Bolea, I. (2015). Overview post-combustion CO2 capture. *Boletín del Grupo Español del Carbón, 35*, 8-11. https://dialnet.unirioja.es/servlet/articulo?codigo=6241105
15. Pelegry, E. (2010). La captura y almacenamiento de CO2: Una solución eficiente para luchar contra el cambio climático. *Real Instituto Elcano*. https://www.realinstitutoelcano.org/documento-de-trabajo/la-captura-y-almacenamiento-de-co2-una-solucion-eficiente-para-luchar-contra-el-cambio-climatico/
16. Cámara, A., Santero, R., Martínez, M., & Jiménez, J. (2019). Desarrollos en tecnologías de aprovechamiento de CO2. *Energía Limpia, 3*(2), 85-100. https://www.redalyc.org/pdf/969/96949059004.pdf
17. Alper, E., & Yuksel Orhan, O. Y. (2017). Utilización de CO2: Desarrollos en procesos de conversión. *Petróleo, 3*(1), 109-126. https://doi.org/10.1016/j.petlm.2016.11.003
18. Chauvy, R., Meunier, N., Thomas, D., & De Weireld, G. (2019). Selecting emerging CO2 utilization products for short- to mid-term deployment. *Applied Energy, 236*, 662-680. https://doi.org/10.1016/j.apenergy.2018.11.096
19. Blanco, E. A., & Ortega, F. M. (2018). Tecnologías de captura de CO en procesos de postcombustión de gas natural. *MET&FLU, 14*, 22-33. https://www.cdtdegas.com/images/Descargas/Nuestra_revista/MetFlu14/7_CapturaCO2.pdf
20. Chao, C., Deng, Y., Dewil, R., Baeyens, J., X., & Fan, X. (2021). Post-combustion carbon capture. *Renewable and Sustainable Energy Reviews, 138*, 110-490. https://doi.org/10.1016/j.rser.2020.110490
21. Environment LIFE Programme. *LIFE-CO2-INT-BIO - CO2 emissions reduction by industrial integration and value chains creation*. Ministerio para la Transición Ecológica y el Reto Demográfico, Madrid, España. http://www.lifeco2intbio.eu/sites/default/files/2023-07/Laymans%20Report%20LIFE%20CO2IntBio%20digital%20eng.pdf
22. Navarrete Procopio, M., Urquiza, G., Castro, L., & Zezatti, V. (2023). Saturation of the MEA solution with CO2: Absorption prototype and experimental technique. *Results in Engineering, 19*, 101286. https://doi.org/10.1016/j.rineng.2023.101286