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DEVELOPMENT OF A CONTINUOUS DUAL-STAGE PURIFICATION SYSTEM FOR PYROLYSIS EXHAUST GAS

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Abstrak.

Sampah plastik merupakan salah satu masalah lingkungan terbesar di Indonesia karena sifatnya yang sulit terurai. Salah satu metode pengolahannya adalah pirolisis, yang mampu mengubah plastik menjadi minyak pirolisis, arang, dan gas buang. Namun, gas buang pirolisis masih mengandung CO_2 dan H_2S dalam kadar tinggi sehingga menurunkan nilai kalor dan membahayakan penggunaannya. Penelitian ini bertujuan merancang dan mengembangkan sistem purifikasi gas buang pirolisis berbasis absorber–adsorber kontinyu. Absorber menggunakan larutan NaOH, sedangkan adsorber terdiri atas steel wool, zeolit, arang aktif, dan silika gel. Hasil penelitian menunjukkan bahwa sistem purifikasi kontinyu mampu meningkatkan konsentrasi CH_4 dari 50% menjadi 89%, menurunkan CO_2 dari 50% menjadi 17%, dan menurunkan H_2S dari 50% menjadi 19%. Peningkatan kualitas gas ini menjadikan gas buang pirolisis layak digunakan kembali sebagai bahan bakar alternatif atau substitusi LPG dalam proses pirolisis. Dengan demikian, sistem purifikasi ini terbukti efektif, ekonomis, dan berpotensi diterapkan pada skala industri pengolahan limbah plastik.

Kata kunci: pirolisis, gas buang, purifikasi, absorber, adsorber.

Abstract.

Plastic waste is one of the most pressing environmental problems in Indonesia due to its non-biodegradable nature. Pyrolysis is a promising method to convert plastic waste into pyrolysis oil, char, and exhaust gas. However, pyrolysis exhaust gas contains high levels of CO_2 and H_2S, which reduce its calorific value and pose safety risks. This study aims to design and develop a continuous absorber–adsorber purification system for pyrolysis exhaust gas. The absorber employed NaOH solution, while the adsorbers consisted of steel wool, zeolite, activated carbon, and silica gel. The results showed that the continuous purification system increased CH_4 concentration from 50% to 89%, reduced CO_2 from 50% to 17%, and decreased H_2S from 50% to 19%. This improvement in gas quality makes pyrolysis exhaust gas suitable for reuse as an alternative fuel or LPG substitute in the pyrolysis process. Therefore, the purification system proved to be effective, economical, and has strong potential for application in industrial-scale plastic waste management.

Keywords: *pyrolysis, exhaust gas, purification, absorber, adsorber.*

Introduction.

Plastic waste has become one of the most challenging environmental problems worldwide due to its resistance to natural degradation and the continuous growth of plastic consumption [1]. In Indonesia, plastic accounts for a large fraction of municipal solid waste, reaching millions of tons annually, with improper disposal methods contributing to soil and water pollution [2]. Traditional approaches such as landfilling and open burning are not sustainable, as they cause secondary

pollution, release toxic gases, and occupy valuable land resources. Therefore, alternative treatment methods that not only reduce plastic waste volume but also recover energy are urgently required.

Pyrolysis has been identified as a promising thermochemical route for plastic waste conversion. It involves thermal decomposition at high temperatures under oxygen-limited or oxygen-free conditions, producing liquid fuel oil, char, and syngas [3]. The pyrolysis-derived oil can be used as a substitute for fossil-based fuels, while the non-condensable gases, which mainly consist of CH_4, CO, CO_2, and light hydrocarbons, have potential as supplementary fuel for sustaining the pyrolysis reactor itself [4]. However, one of the main obstacles in utilizing the pyrolysis exhaust gas is the presence of impurities, especially CO_2 and H_2S. These components lower the calorific value of the gas and can cause corrosion and environmental hazards if released untreated [5].

To enhance the usability of pyrolysis gas, purification technologies are essential. Absorption and adsorption are the two most widely studied methods for gas purification. Chemical absorption using alkaline solutions such as NaOH or amine-based solvents has been widely applied in natural gas sweetening and post-combustion CO_2 capture due to its high removal efficiency [6]. Farooqi et al. [7] reported that hybrid solvents combining monoethanolamine (MEA) and N-methyl-2-pyrrolidone (NMP) improved CO_2 and H_2S removal while reducing energy requirements. Such findings indicate that alkaline absorption is suitable for reducing acidic components from mixed gas streams, including pyrolysis exhaust.

In parallel, adsorption methods using porous solids are being increasingly explored because of their simplicity, low energy demand, and regenerability [8]. Activated carbon, zeolites, and silica gel are among the most established adsorbents, while advanced materials such as metal–organic frameworks (MOFs) show remarkable capacity and selectivity for CO_2 and H_2S capture [9]. Sethupathi et al. [10] demonstrated that biochar-based adsorbents could efficiently capture CO_2 and H_2S from biogas, enhancing methane concentration. Similarly, Luo et al. [9] developed hybrid adsorbents with improved selectivity toward H_2S, which is particularly useful for improving the quality of syngas and pyrolysis gas.

Despite these advances, limited studies have investigated the integration of absorber–adsorber systems in a continuous configuration specifically for pyrolysis exhaust gas purification. In theory, combining absorption and adsorption could exploit the advantages of both methods: absorption effectively removes bulk CO_2, while adsorption provides additional polishing by capturing H_2S and residual CO_2. This dual-stage approach has been applied in natural gas treatment but has not been widely adapted for small-scale pyrolysis systems [6]–[8].

Therefore, the aim of this research is to design and develop a purification system for pyrolysis exhaust gas that integrates absorber and adsorber stages in a continuous manner. The proposed system employs NaOH solution as the absorber, followed by steel wool, zeolite, activated carbon, and silica gel as adsorbents. The main objectives are to (i) increase the concentration of combustible CH_4, (ii) reduce CO_2 and H_2S levels, and (iii) enhance the overall quality of pyrolysis gas for reuse as supplementary fuel in the pyrolysis reactor.

Research Methods.

The research methodology was divided into four main stages: design, construction, implementation, and testing of the purification system. The overall workflow is presented in Fig. 1.

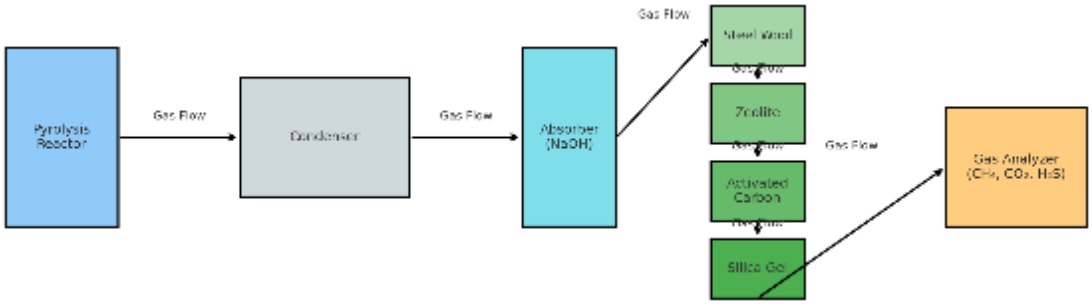

Figure 1. Research process scheme

A. Materials and Components

The materials and components used for the system included:

1. Absorber unit: A water filter housing filled with NaOH solution (1,177.5 cm^3). NaOH was selected due to its high reactivity toward acidic gases such as CO_2 and H_2S [6].
2. Adsorber units: PVC pipes (3-inch diameter, 60 cm length) packed sequentially with steel wool (565.2 cm^3), zeolite (282.6 cm^3), activated carbon (423.9 cm^3), and silica gel (282.6 cm^3). Each material was chosen based on its adsorption affinity:
   - Steel wool: oxidation of H_2S [8].
   - Zeolite: enhancement of CH_4 concentration by CO_2 capture [9].
   - Activated carbon: high surface area for CO_2 and H_2S adsorption [10].
   - Silica gel: effective CO_2 removal due to polarity and pore structure [5].
3. Gas connection system: PVC pipes, rubber hoses, and couplings for gas flow.
4. Measuring devices: A BX615 multi-gas detector to monitor CH_4, CO_2, and H_2S concentrations before and after purification.

B. System Design

The system was designed as a continuous dual-stage purification unit, where the pyrolysis gas from the condenser was first directed to the absorber (NaOH solution) and then sequentially passed through the adsorber media (steel wool → zeolite → activated carbon → silica gel). This layout was intended to maximize CO_2 absorption and provide stepwise removal of residual CO_2 and H_2S.

C. Pyrolysis Process

The feedstock consisted of shredded low-density polyethylene (LDPE) plastic waste. The pyrolysis reactor was heated to 250–550 °C under oxygen-free conditions. Non-condensable gases from the condenser outlet were channeled into the purification system.

D. Experimental Procedure

Baseline measurement: The composition of raw pyrolysis gas was recorded before purification. Single-stage purification: Each adsorbent medium and NaOH absorber was tested individually to evaluate its performance in gas quality improvement. Continuous dual-stage purification: The absorber–adsorber sequence was tested as an integrated unit. Data collection: Concentrations of CH_4, CO_2, and H_2S were measured in percentage (%) by volume using the gas detector. Analysis: Results were compared between untreated gas, single-stage purification, and continuous dual-stage purification.

E. Validation and Repetition

Each experiment was repeated three times to ensure reproducibility. The average values were reported as final results, while deviations were used to estimate experimental uncertainty.

Results and Discussion.

As shown in Fig. 2, the raw pyrolysis gas contained approximately 50% CH_4. After purification with different media, CH_4 concentration increased significantly. The NaOH absorber enriched CH_4 to 85%, while zeolite achieved the highest single-stage enrichment (87%). When all purification stages were combined in the continuous system, CH_4 concentration reached 89%, indicating that the dual-stage system was effective in enhancing fuel quality.

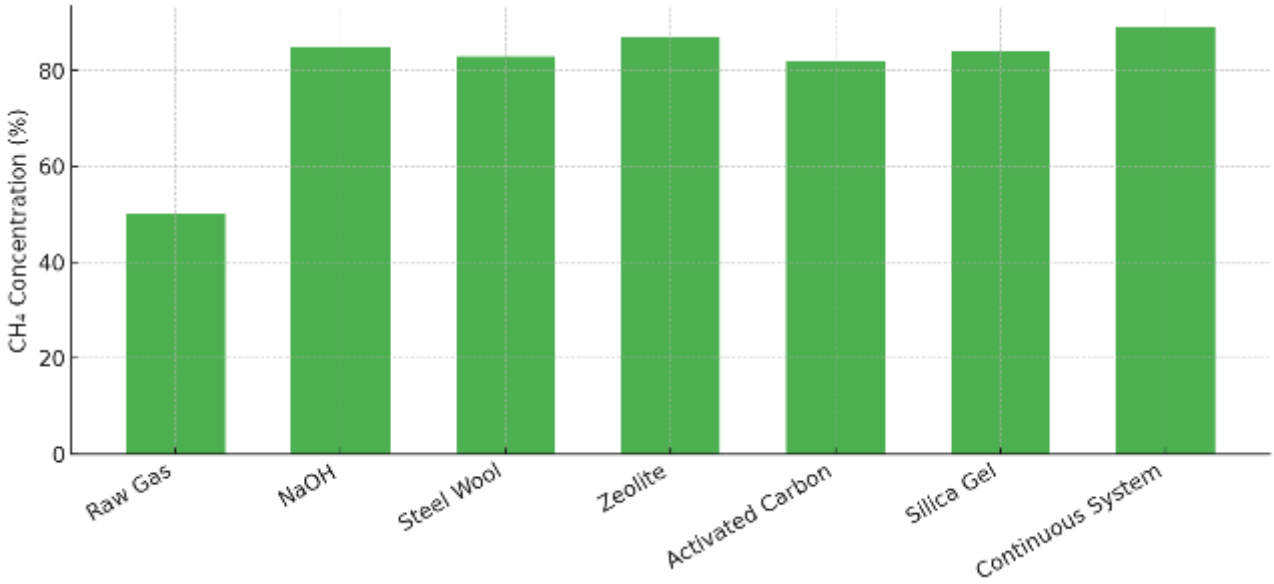

Figure 2. Methane (CH_4) Concentration in Gas Samples

Fig. 3 illustrates that CO_2 concentration in raw gas was around 50%. After treatment, all purification media reduced CO_2, with silica gel being the most effective single adsorbent (20%). The continuous system further reduced CO_2 to 17%, confirming that combining absorption and adsorption yields superior results compared to single-stage purification.

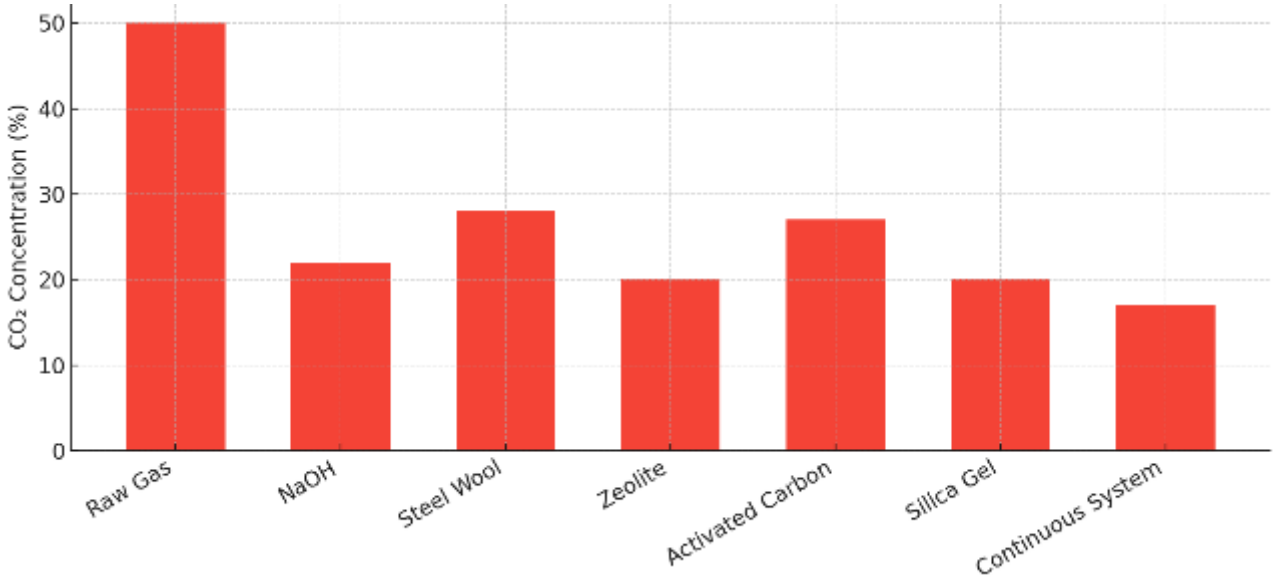

Figure 3. Carbon Dioxide (CO_2) Concentration in Gas Samples

As depicted in Fig. 4, the raw gas contained approximately 50% H_2S, which is highly undesirable due to toxicity and corrosive properties. Among the single adsorbents, steel wool was the most effective, reducing H_2S to 21% through oxidation and adsorption mechanisms. When integrated in the continuous system, H_2S concentration decreased further to 19%, which is within a safer range for fuel gas applications.

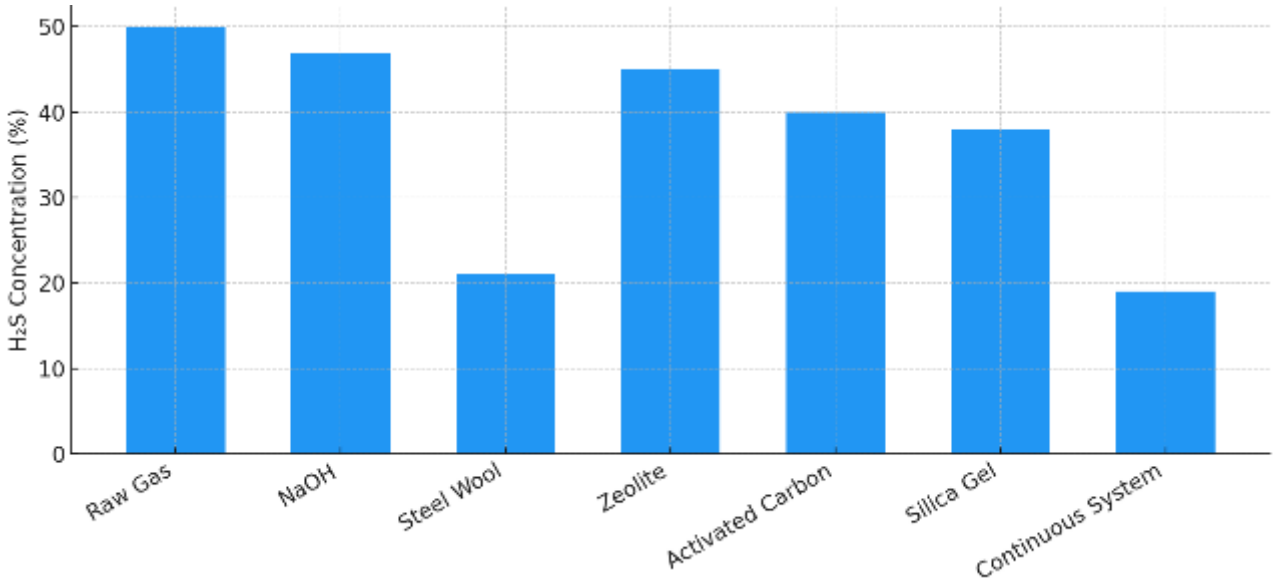

Figure 4. Hydrogen Sulfide (H_2S) Concentration in Gas Samples

The combined absorber–adsorber system demonstrated a synergistic effect. NaOH absorption effectively reduced bulk CO_2, while the adsorbers provided selective removal of residual CO_2 and H_2S. Consequently, methane concentration increased, making the purified gas more suitable as a substitute fuel for sustaining the pyrolysis reactor or replacing LPG. These findings are consistent with previous studies on biogas upgrading and natural gas sweetening [6]–[10], highlighting that hybrid absorption–adsorption systems are more efficient than single-stage processes.

Conclusion.

This research has demonstrated that the development of a continuous dual-stage purification system, integrating an NaOH-based absorber with sequential adsorbers (steel wool, zeolite, activated carbon, and silica gel), is highly effective in upgrading pyrolysis exhaust gas quality. The system significantly increased methane concentration from 50% in the raw gas to 89% after purification, thereby enhancing the calorific value and usability of the gas as an alternative fuel. At the same time, carbon dioxide was reduced from 50% to 17%, and hydrogen sulfide was lowered from 50% to 19%, ensuring both improved combustion quality and safer utilization. These results confirm that the hybrid absorber–adsorber approach provides a synergistic effect, where bulk acidic gases are efficiently removed by absorption while the adsorbers further eliminate residual CO_2 and H_2S. The outcome makes the gas suitable for reuse in sustaining the pyrolysis process or partially replacing LPG, offering both environmental and economic benefits.

For future work, further studies should focus on optimizing the composition and arrangement of adsorbent media to maximize selectivity and capacity. Testing the system on a larger scale, particularly in industrial or pilot-plant pyrolysis settings, would provide valuable insights into operational stability and cost-effectiveness. Additionally, investigating regeneration methods for adsorbent materials could improve long-term sustainability and reduce operational costs. By addressing these aspects, the system can be further refined and scaled up as a practical solution for waste-to-energy applications.

References.

[1] Das, “Advancements in adsorption based carbon dioxide capture: A review,” Heliyon, vol. 9, no. 9, pp. e19740, 2023.

[2] A. Pivato, A. Di Maria, G. Raga, and F. Sorlini, “Air-Polluting Emissions from Pyrolysis Plants: A Systematic Mapping,” Environments, vol. 11, no. 7, pp. 680, Jul. 2024.

[3] N. Sánchez-Bastardo, J. Schlögl, and R. R. den Otter, "Methane Pyrolysis for Zero-Emission Hydrogen Production," Ind. Eng. Chem. Res., vol. 60, no. 19, pp. 6953–6968, 2021.
[4] S. Li, "Reviewing Air Pollutants Generated during the Pyrolysis of Solid Waste for Biofuel and Biochar Production," Sustainability, vol. 16, no. 3, pp. 1215, 2024.
[5] M. Devi, S. K. Das, and A. Datta, "A comprehensive review on thermochemical conversion of plastic waste for energy recovery," Energy Convers. Manage., vol. 252, p. 115051, 2022.
[6] C.-H. Yu, C.-H. Huang, and C.-S. Tan, "A Review of CO_2 Capture by Absorption and Adsorption," Aerosol Air Qual. Res., vol. 12, no. 5, pp. 745–769, 2012.
[7] A. S. Farooqi, A. Ali, S. Bashir, et al., "Removal of Carbon Dioxide and Hydrogen Sulfide from Natural Gas Using Hybrid Solvents," ACS Omega, vol. 9, no. 1, pp. 451–462, 2024.
[8] L. H. de Oliveira, D. L. Silva, and R. L. Moreira, "Adsorption of H_2S, CO_2, CH_4 and their mixtures on activated carbon," J. Environ. Sci., vol. 82, pp. 71–82, 2019.
[9] L. Luo, X. Zhang, and Y. Wang, "Enhanced selective adsorption of H_2S from CO_2 by hybrid adsorbent materials," Chem. Eng. J., vol. 481, p. 149346, 2024.
[10] S. Sethupathi, K. N. Bin Sairan, et al., "Biochars as potential adsorbers of CH_4, CO_2 and H_2S," Sustainability, vol. 9, no. 1, pp. 121, 2017.