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Original Research

DEVELOPMENT OF MIST MAKER TECHNOLOGY FOR ACID MINE DRAINAGE TREATMENT IN THE COAL INDUSTRY

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ABSTRACT

Development of mist maker technology for acid mine drainage treatment in the coal industry. *Acid mine drainage (AMD) is a major environmental problem characterized by low pH and high concentrations of dissolved metals, particularly iron (Fe), requiring effective and rapid treatment methods. This study aimed to analyze the effectiveness of a combination of a mist maker and lime in increasing pH and reducing Fe concentration in AMD. This study employed an experimental method with a pre-test and post-test design using three treatments: mist maker only, lime neutralization, and a combination of both. The experiment was conducted using 5 liters of AMD sample with a contact time of 30 minutes and three replications. The parameters analyzed were pH and Fe concentration. Data were analyzed descriptively and inferentially using a paired t-test. The results showed that the combination of lime and mist maker achieved the best performance, with a pH increase of 2.32 ± 0.21 (from 3.59 ± 0.21 to 5.91 ± 0.03) and a reduction in Fe concentration of 2.03 ± 0.61 mg/L, with an efficiency of 94.4%, which was statistically significant ($p < 0.05$). Lime neutralization increased pH by 1.81 ± 0.04 ($p < 0.05$), but the Fe reduction of 0.64 ± 0.57 mg/L was not statistically significant ($p > 0.05$). Meanwhile, the mist maker alone showed no significant change in pH (-0.11 ± 0.10; $p > 0.05$) and a non-significant Fe reduction of 0.64 ± 0.42 mg/L ($p > 0.05$). The combination of mist maker and lime significantly improves the efficiency of AMD treatment in terms of pH and Fe removal through the synergistic effects of aeration, neutralization, and precipitation processes, making it a promising rapid and effective alternative treatment method.*

INTRODUCTION

Mineral and coal mining is a major revenue-generating industry; however, several environmental impacts arise from mining activities [(1)]. The majority of coal mining in Indonesia utilizes the open-pit mining system, which removes the land surface and organic matter [(2)]. The open-pit coal mining process generally includes land clearing, topsoil stripping, excavation, loading, and transportation of overburden, as well as the excavation, loading, and transportation of coal [3]. Open-pit mining causes environmental impacts such as Acid Mine Drainage (AMD) [4]. One of these impacts is the generation of AMD containing pollutants such as TSS, Manganese (Mn), Iron (Fe), and low pH [5]. AMD is an acidic solution containing significant concentrations of dissolved metals, typically resulting from the oxidation of sulfide minerals, with characteristically very low to moderately low pH levels. Management of AMD generally involves increasing the pH through neutralization using alkaline materials alongside the formation of metal hydroxide/oxide precipitates via co-precipitation and/or adsorption mechanisms [6–10]. Literature reviews indicate that rapid pH elevation and higher Fe^3 concentrations consistently promote the formation of iron hydroxide precipitates and the co-precipitation of other metals such as aluminum (Al), manganese (Mn), and arsenic in neutralized AMD [8–12]. AMD represents a severe environmental issue resulting from mining activities, characterized by low pH and high dissolved metal content [13]. According to the Decree of the Minister of Energy and Mineral Resources No. 1827K/30/MEM/2018 regarding Guidelines for the Implementation of Good Mining Engineering Principles (Appendix VI), Acid Mine Drainage must undergo remediation and water quality management in accordance with established environmental quality standards [4].

Alternatives for AMD management are generally divided into active technologies and passive technologies [1]. Various AMD remediation technologies have been developed, ranging from active methods such as lime addition to passive methods such as constructed wetlands [14]. However, these conventional methods present limitations in terms of efficiency, operational costs, and the potential for secondary pollution [15]. Ultrasonic technology has demonstrated significant potential in water and environmental remediation. In water pollution control, ultrasonic treatment is highly advantageous for organic wastewater treatment and drinking water purification due to its ability to eliminate the need for additional chemicals and prevent secondary pollution [16]. Ultrasonic mist devices operate on the piezoelectric principle, wherein piezoelectric crystals generate ultrasonic waves at frequencies of 1–3 MHz, producing a fine mist from bulk water [17]. This technology has been successfully applied across various fields, including water purification, disinfection, and wastewater treatment [18,19]. An intriguing innovation in ultrasonic water treatment is its capacity for in-situ hydrogen peroxide (H_2O_2) generation. Furthermore, ultrasonic cavitation can degrade organic pollutants and assist in the oxidation process of heavy metals in AMD [16].

As an alternative, Mist Maker technology, which utilizes ultrasonic principles to produce a fine mist, offers an innovative solution. The mist expands the contact surface area between water and air, accelerating the oxidation of Fe^{2+} ions into Fe^{3+}, which then precipitate as iron hydroxide, thereby reducing dissolved heavy metal levels. Furthermore, this technology is modular, energy-efficient, and has the potential to be integrated from small to large scales in mining areas. The problem addressed in this research is that the application of Mist Makers in AMD treatment in Indonesia remains very limited. Therefore, this study is essential to evaluate the potential of using Mist Makers as an innovative, effective, and environmentally friendly solution to address acid mine drainage issues, support sustainable mining operations, and improve environmental quality.

MATERIALS AND RESEARCH METHODS

Research Design

This study utilized an experimental design with a pre-test and post-test control group approach. This design was selected to directly evaluate the effect of mist maker technology on the efficiency of the acid mine drainage (AMD) neutralization process .

Three treatment groups were established: Control group (conventional neutralization using quicklime), Combination treatment group (quicklime + mist maker), Chemical-free treatment group (mist maker only). Each treatment group was observed prior to and following the treatment process to assess changes in water quality parameters, specifically pH and Fe concentration.

Study Location

Sampling was conducted in a coal mining area located in Tapin Regency, South Kalimantan. This location was selected due to its representative AMD characteristics, featuring low pH levels and relatively high metal concentrations. Sample testing and analysis were performed under controlled laboratory conditions to ensure consistent results and minimize external confounding variables.

Study Duration

The research was conducted in several stages, including sampling, equipment testing, laboratory experimentation, and data analysis, spanning a total duration of 2–3 months,

Research Procedure

The experimental procedure was carried out sequentially as follows:
The first stage was the collection of acid mine drainage samples from the study site. The samples were then brought to the laboratory to analyze their initial characteristics, including pH and Fe concentration as the primary parameters. The second stage was the preparation and testing of the ultrasonic mist maker device. In this stage, the device was tested for its ability to generate micro-mist sized around 1–5 microns, aiming to increase the contact surface area between the water and the neutralizing agent. The third stage was the execution of laboratory experiments involving three treatment scenarios. In the first scenario, neutralization was carried out using quicklime (CaO) as a conventional method. In the second scenario, a combination of quicklime and a mist maker was used. In the third scenario, only the mist maker was used without the addition of chemicals. Each treatment was performed with the same sample volume under controlled conditions. The experiments were conducted using 5 liters of AMD sample with a 30-minute contact time and three repetitions.

Research Sample

The samples used in this study were acid mine drainage collected directly from a coal mining site. The sampling technique was conducted using grab sampling, which involves collecting samples at a specific point representing the water conditions at that location. Each treatment utilized the same sample volume to maintain consistency and the validity of comparisons among treatments. The samples were then divided into several experimental units corresponding to the number of treatments tested.

Data Analysis

The data obtained from the measurements were analyzed descriptively and comparatively. The analysis was conducted by comparing the changes in pH values and Fe concentrations before and after treatment for each scenario. Furthermore, the reduction efficiency of Fe concentration was evaluated using the percentage decrease from the initial condition. The data are also presented in tables and graphs to illustrate the comparisons among treatments.

RESEARCH RESULTS AND DISCUSSION

The study began with a simple design of an acid mine drainage treatment system integrating aeration technology via a mist maker and a neutralization process using lime. The mist maker unit was designed using a 12-head ultrasonic device placed in a container holding a 5-liter volume of acid mine drainage. This system functions to generate micro-sized droplets to expand the contact surface area between water and oxygen, thereby accelerating the oxidation process of dissolved iron. Meanwhile, lime was added as a neutralizing agent to elevate the pH and provide the hydroxide ions (OH^-) required for the metal precipitation process. The treatment system was operated with a 30-minute contact time across three treatment variations: mist maker alone, lime alone, and a combination of mist maker and lime. The combination of these two methods is expected to produce a more effective treatment system through synergy between the aeration and neutralization processes, as reported in various previous studies indicating that the integration of aeration and alkaline materials can significantly enhance the efficiency of acid mine drainage treatment. Water quality results before and after treatment across variations are presented in Table 1 and Table 2:

Table 1. Experimental Results for Variations in Fe Concentration

No.	Method	Pre (Mean ± SD)	Post (Mean ± SD)	Fe (Mean ± SD)	Efficiency (%)	p-value	Remarks
1	Mist Maker Only	2,45 ± 0,65	1,80 ± 0,28	0,64 ± 0,42	26,5	0,12	Not significant
2	Lime Neutralization	1,74 ± 0,66	1,10 ± 0,14	0,64 ± 0,57	36,8	0,19	Not significant
3	Netralisasi Lime Neutralization + Mist Maker	2,15 ± 0,63	0,12 ± 0,02	2,03 ± 0,61	94,4	0,03	Significant

Based on Table 1, all treatments exhibited a reduction in Fe concentration, albeit with varying degrees of effectiveness. The initial Fe concentration values across all treatments displayed relatively uniform variation, averaging between 1.74 and 2.45 mg/L. This indicates that the baseline condition of the samples remained within a comparable range for each treatment. Following the treatments, a decrease in Fe concentration occurred across all methods, though with differing efficiency levels. The mist maker-only treatment showed a relatively minor Fe reduction, with a mean final concentration of 1.80 ± 0.28 mg/L, a reduction value of 0.64 ± 0.42 mg/L, and an efficiency of 26.5%. Despite the observed decline, statistical analysis revealed that this change was not significant ($p > 0,05$), indicating the limited effectiveness of this method when used alone.

The neutralization treatment using lime demonstrated slightly better performance, yielding a mean final concentration of 1.10 ± 0.14 mg/L, a reduction of 0.64 ± 0.57 mg/L, and an efficiency of 36.8%. However, statistical testing also indicated that this reduction was not significant ($p > 0,05$), uggesting substantial data variation among replicates. The most significant decrease occurred in the combined lime and mist maker treatment, where the final Fe concentration reached a mean of 0.12 ± 0.02 mg/L with a reduction value of 2.03 ± 0.61 mg/L and an efficiency of 94.4%. Statistical analysis confirmed that this combined treatment had a significant effect on reducing Fe concentration ($p < 0,05$). The relatively small standard deviation in the final concentration reflects a consistent and stable process. These findings indicate that integrating aeration via a mist maker with lime neutralization exerts a synergistic effect, enhancing Fe removal efficiency. Aeration increases dissolved oxygen levels to accelerate the oxidation of Fe^{2+} to Fe^{3+}, while the addition of lime elevates the pH, thereby promoting the formation of $Fe(OH)_3$ precipitates through the precipitation process.

Conceptually, this phenomenon aligns with the synergy between Fe^2 to Fe^3 oxidation and the neutralization process, which triggers the formation of iron hydroxide precipitates more efficiently. In scientific terms, oxidation enhances the availability of Fe^3 , which more readily forms $FeOH^3$ precipitates as pH increases during neutralization, resulting in faster and more extensive precipitation. Literature indicates that combining oxidation (whether via aeration or supplementary oxidants such as $H^2(O^2)$ with lime neutralization enhances Fe removal through the formation of $Fe(OH)^3$ precipitates, which in turn accelerates the co-precipitation of iron and other dissolved elements in AMD solutions [(11,20–23)]. Nevertheless, several studies show that lime neutralization alone or isolated oxidation can also be effective depending on solution conditions, such as initial Fe concentration, background metal composition, and baseline pH. Consequently, maximum efficiency remains highly context-dependent and heavily reliant on operational parameters, including oxidation rate, contact time, optimal lime dosage, and the fluid dynamics of the mist cloud (mist maker) that enhances aeration within practical systems (11,20,22).

Table 2. Experimental Results for Variations in pH Value

No.	Method	Pre (Mean ± SD)	Post (Mean ± SD)	pH (Mean ± SD)	Effectivenes s (%)	p-value	Remarks
1	Mist Maker	3,37 ± 0,07	3,26 ± 0,13	-0,11 ± 0,10	-3,3	0,18	Not significant
2	Netralisasi Kapur	3,49 ± 0,03	5,30 ± 0,04	+1,81 ± 0,04	51,9	0,01	Significant
3	Kapur + Mist Maker	3,59 ± 0,21	5,91 ± 0,03	+2,32 ± 0,21	64,6	0,01	Significant

Based on Table 2, the initial pH values across all treatments exhibited a relatively uniform baseline, with mean values ranging from 3.37 to 3.59. This demonstrates that all samples were in a comparable acidic state prior to treatment. Following the treatment process, variations in pH values were observed across all methods, albeit with differing degrees of increase. The mist maker-only treatment showed a relatively minor change in pH, yielding a mean final value of 3.26 ± 0.13, representing a decrease of -0.11 ± 0.10. The resulting effectiveness of -3.3% indicates that aeration alone is insufficient to elevate pH and, in fact, tends to slightly lower it. Statistical analysis confirmed that this change was not significant ($p > 0,05$), suggesting that the effect of the mist maker alone on pH elevation is limited.

The neutralization treatment using lime demonstrated a significantly higher increase in pH, reaching a mean final value of 5.30 ± 0.04 with an increase of 1.81 ± 0.04. The pH elevation efficiency reached 51.9%, indicating that lime serves as an effective neutralizing agent in reducing the acidity of acid mine drainage. Statistical analysis indicated that this increase was significant ($p < 0,05$), , with relatively small data variance reflecting consistent results. The highest pH elevation occurred in the combined lime and mist maker treatment, which achieved a mean final value of 5.91 ± 0.03 and a net increase of 2.32 ± 0.21. Reaching an efficiency of 64.6%, this treatment exhibited the most optimal performance among all tested conditions. Statistical testing also confirmed that this increase was significant ($p < 0,05$). The relatively small standard deviation in the final pH reflects a stable and reproducible process. These findings indicate that integrating aeration via a mist maker with lime neutralization exerts a synergistic effect in elevating the pH of acid mine drainage. The mist maker enhances mixing and oxygen distribution within the solution, thereby accelerating chemical reactions, while lime increases alkalinity to support the neutralization process. The combination of these two mechanisms yields a faster and more effective pH elevation than either individual treatment.

Oxidation and neutralization promote the formation of iron hydroxide precipitates and the co-precipitation of other metals in acidic environments. Several studies have demonstrated that the oxidation of Fe^{2+} to Fe^{3+}, coupled with pH elevation via lime, systematically enhances the capacity of $Fe(OH)^3$ precipitates to bind other metals [11,20,22,23]. The oxidation of Fe^{2+} to Fe^{3+} prior to or during lime neutralization increases the potential for $Fe(OH)^3$ precipitate formation. Under conditions of elevated pH driven by Ca(OH)2, Fe^{3+} forms $Fe(OH)^3$, which precipitates rapidly and acts as nucleation sites for the co-precipitation of other metals (e.g., Al, Mn) through co-precipitation and adsorption processes on the surface of the iron hydroxide precipitate. This mechanism is supported by AMD studies utilizing strong base neutralization (NaOH, Ca(OH)2), which demonstrate the formation of Fe(III) hydroxide precipitates accompanied by a significant pH increase and secondary metal co-precipitation mechanisms. Overall, the pH increase resulting from the coupled oxidation–neutralization step alters the kinetic pathways and thermodynamic precipitation boundaries for dissolved iron, which is reflected in the overall enhancement of Fe precipitation efficiency [11,20,22]. This highlights the role of the mist maker as an effective aeration and oxidation-enhancing agent. Aeration increases the rate of Fe^{2+} to Fe^{3+} oxidation and elevates the proportion of Fe^{3+} species in solution; thus, when pH is raised by lime, the formation of $Fe(OH)^3$ precipitates becomes substantially more efficient. Evidence suggests that enhancing aeration via misting/air-carrier droplets can influence water chemistry dynamics; notably, agricultural misting studies have shown alterations in soil chemical properties such as pH, Ca, Mg, and base saturation following misting treatments [24,25]. pecifically, agricultural research indicates that liming treatments become more effective when combined with aeration and fertilization, as the combined effects of pH elevation and nutrient availability are optimized through surface-solution interface dynamics [25]. Deploying a mist maker alongside lime accelerates the rate of pH elevation and consequently enhances $Fe(OH)^3$ precipitation and secondary metal co-precipitation more effectively than either treatment applied individually. This phenomenon aligns with AMD literature showing that simultaneous oxidation and neutralization significantly alter the formation pathways of iron and associated metal precipitates, resulting in higher removal efficiencies for Fe and related metals compared to single treatments [11,20,22,23]. he highly significant pH increase observed during the combined mist maker and lime treatment may be heavily reliant on operational parameters, such as oxidation rates, lime dosage, contact time, and the fluid dynamics of the mist cloud within the system. Literature demonstrates that the pH response to lime is highly context-dependent, influenced by environmental factors and system design parameters [23, 26]. To optimize the precipitation efficiency of Fe and other metals in acidic solutions, a system design that integrates an oxidizer/aerator with an alkaline source ($Ca(OH)^2$) offers a superior approach compared to utilizing either step independently. This is corroborated by reports demonstrating rapid pH elevation and Fe^3 hydroxide precipitate formation when neutralization is integrated with oxidation/co-precipitation processes [11, 20, 22, 23]. Operational monitoring reveals that pH response and precipitation efficiency are highly sensitive to lime dosage, contact time, and aeration levels. Consequently, best practices necessitate dynamic control of operational parameters and adjustments based on real-time field data [9,23,26,27]. The implementation of a combined mist maker and lime system holds potential for improving treated AMD quality by enhancing pH elevation and fostering efficient iron hydroxide precipitation with opportunities for secondary metal co-precipitation. However, careful consideration must be given to sludge generation and waste management, warranting the adoption of alternative materials to improve sludge stability and minimize waste management costs [10, 11, 28]. Given that AMD typically exhibits high acidity and elevated Total Suspended Solids (TSS), the mist maker could be integrated with a filter box system to support AMD treatment efficacy and facilitate its development into a sustainable digital-based environmental monitoring instrument [29, 30]. Ultimately, AMD remediation efforts serve not only technical environmental objectives, but also vital public health and safety functions for communities and personnel operating in adjacent mining environments [31–33]. Sustainable waste management remains paramount to maintaining ecological balance and mitigating adverse impacts on human health and ecosystems [34].

CONCLUSIONS AND RECOMMENDATIONS

This study demonstrates that the combination of a mist maker and lime is effective in improving the quality of acid mine drainage through a significant elevation of pH and reduction of Fe concentration. The combined treatment resulted in a pH increase of 2.32 ± 0.21, reaching a final pH of 5.91 ± 0.03, and a reduction in Fe concentration of 2.03 ± 0.61 mg/L with a removal efficiency of 94.4% within a 30-minute contact time, which was proven statistically significant ($p < 0,05$). In comparison to single treatments, the mist maker alone and lime neutralization showed non-significant effects on Fe reduction ($p > 0,05$), although lime significantly increased pH. This indicates that pH elevation alone is insufficient to optimize Fe precipitation without being supported by an intensive oxidation process. Mechanistically, the mist maker plays a role in enhancing oxygen transfer via micro-droplet formation that accelerates the oxidation of Fe^{2+} to Fe^{3+}, whereas lime elevates the pH to promote the formation of $Fe(OH)_3$ precipitates through the precipitation process. The synergy of these two processes yields higher, faster, and more stable treatment efficiency compared to single treatments. Consequently, this combined technology holds potential as an effective, rapid, and applicable alternative for acid mine drainage treatment.

Based on the research findings, future studies are recommended to optimize operational parameters such as variations in lime dosage, contact time, and reactor configuration and capacity to achieve more optimal conditions. Additionally, further studies on reaction kinetics are necessary to gain a deeper understanding of the rates of Fe oxidation and precipitation. Furthermore, pilot-scale field testing is required to evaluate system performance under real-world conditions, including the effects of environmental factors such as flow rate, temperature, and variations in acid mine drainage characteristics.

ETHICAL APPROVAL

This study received ethical approval from the Ministry Of Health Polytechnic Banjarmasin , with reference number No.260/KEPK-PKB/2026

CONFLICT OF INTEREST

The research team declares that this study was conducted objectively and independently and that there are no conflicts of interest, whether financial, commercial, or personal, that could have influenced the conduct of the research, data analysis, interpretation of the results, or reporting of the findings. The research team assumes full responsibility for the accuracy, integrity, and validity of all data, results, and conclusions presented in this study.

AUTHOR CONTRIBUTIONS

MIA: conceptualisation and study design; MJS and RMAS : data collection; SH,A and MI : statistical analysis; MIA and MS: manuscript writing and literature review. All authors read and approved the final manuscript.

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