ENHANCEMENT WASTEWATER TREATMENT IN ALUMINIUM EXTRUSION PROCESS USING SINGLE-EFFECT DISTILATION WITH SPRAY ATOMIZATION

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Abstract - Improper discharge of industrial wastewater poses a significant environmental challenge, particularly in industries such as aluminium extrusion processes which generate effluents containing strong acids, alkalis, chromium, and heavy metals. These hazardous contaminants require effective treatment to prevent environmental pollution. This study investigates the feasibility of employing a Single-Effect Distillation (SED) system as an innovative solution for wastewater treatment. The SED process not only harvests clean water but also minimizes the reliance on external chemical agents, offering a more sustainable approach. A novel spray inlet mechanism was integrated into the SED setup to enhance performance. This mechanism atomizes the incoming wastewater stream, significantly improving heat transfer efficiency within the evaporation chamber. The resulting enhancement increased the freshwater production rate by up to 24%. The quality of the distilled water was rigorously analyzed to ensure compliance with municipal discharge regulations, demonstrating the system's capability to produce safe, high-quality effluent. This research highlights the potential of SED technology, augmented with spray atomization, as a promising and environmentally friendly method for treating wastewater from aluminium extrusion processes while contributing to water conservation and pollution mitigation efforts.

Keywords - Wastewater, Aluminium Extrusions, Vacuum Evaporator, Spray Evaporator, Water Quality

I. INTRODUCTION

The demand for aluminium extrusions is projected to continue its upward trajectory, with a forecasted global market size approaching $140 billion by 2030 [1]. This increasing demand correlates with a rise in waste production from aluminium extrusion manufacturers, as the manufacturing process relies on various chemicals to produce high-quality products. To maintain the quality of aluminium extrusions, it is essential to regularly clean the internal surfaces of extruder dies, typically after processing around 3,000 kg of material per cycle [2,3]. Surface treatment processes, such as anodization and powder coating, involve the use of potent acids, including sulphuric acid, nickel fluoride, and hexavalent chromium [4,5,6]. These processes generate toxic effluents that necessitate treatment prior to discharge. Adhering to health and safety regulations for industrial water discharges is critical to safeguarding human health and preventing environmental degradation [7].

Common method of wastewater treatment for industries involves the usage of a High-Density Sludge (HDS). HDS involves several stages to ensure effective wastewater management which involves neutralisation, precipitation and flocculation. However, this study proposes an alternative form of waste treatment – vacuum evaporation. Vacuum evaporation creates a low-pressure environment within a sealed chamber which reduces the boiling point of the liquid inside. This reduces the amount of heat energy required for heating the liquid [8]. Moreover, vacuum evaporators can often operate without the need for chemicals, reducing environmental impact and operational costs [9]. High purity distillate with a low total dissolved solids of lower than 20 ppm can be achieved using vacuum evaporators thus meeting strict water quality standards [10,11]. To test the feasibility of utilising vacuum evaporation, a lab-scale Single Effect Distillation (SED) system was used to test the quality of the distillate.

Drawing inspiration from fuel injection systems in automobiles, the atomization of incoming wastewater into a vacuum chamber using an orifice nozzle generates fine liquid droplets. These droplets, characterized by a high surface-to-volume ratio, efficiently absorb surrounding heat and subsequently evaporate. This study investigates a novel spray-assisted SED system and evaluates the performance enhancements it offers compared to conventional methods.

II. METHODOLOGY

A lab-scaled SED system was created by utilising a 1 Litre Jacketed Reactor (GR-1L, Shanghai Linbel Instrument Co., Ltd.). The jacketed reactor is heated via the hot water flow on the outer jacket, pumped and heated by a Constant Temperature Recirculating Water Heater (GSC-10L, Shanghai Linbel Instrument Co., Ltd.). Steam produced from the evaporation of the wastewater is cooled in the glass condenser which is cooled with flowing cold water, controlled by a Recirculating Water Chiller (DLSB-4/15, Shanghai Linbel Instrument Co., Ltd.). The system is evacuated

by a Vacuum Pump (SHZ-D(III), Shanghai Linbel Instrument Co., Ltd.) and vacuum is controlled with a vacuum regulator (VC-100).

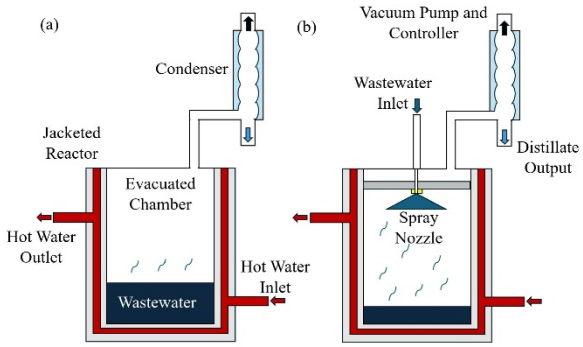


Figure 1: Schematic Diagram of (a) SED and (b) Spray Assisted SED

To evaluate the performance of the Spray-Enhanced Evaporation Device (SED), a baseline study was conducted by performing batch bulk boiling of 500 mL of wastewater over a duration of 600 seconds to determine the system's mass flow rate. The hot water temperature, which governs the heat input to the vacuum evaporator, was systematically varied between 70°C and 95°C in increments of 5°C. The condenser's cold-water temperature was maintained at 5°C, and the vacuum pressure was consistently set at 100 mbar to ensure controlled experimental conditions.

In the spray-assisted SED system, the wastewater was preheated to 50°C, corresponding to its saturation temperature at 100 mbar. The preheated wastewater was introduced into the system using a peristaltic pump (BT-100 equipped with a YZ15 pump head) at a flow rate of 100 mL/min for a duration of 10 minutes.

The wastewater samples utilized in this study were supplied by PMB AluminiumSdnBhd, originating from their Klang plant in Malaysia. Four distinct types of wastewater were provided for the experiments: Acidic, Alkaline, Heavy Metal, and Powder Coating wastewaters. The primary constituents of these wastewaters included sulfuric acid, sodium hydroxide, nickel fluoride, and hexavalent chromium, respectively. During the experimental process, the SED system was operated until 95% of the initial wastewater volume was evaporated, leaving behind a concentrated waste fraction equivalent to 5% of the initial volume.

The distillate produced from the wastewater during the SED process was subsequently passed through an activated carbon filter for post-treatment. The treated wastewater samples were then analyzed and characterized based on several parameters, including pH, Total Suspended Solids (TSS), Chemical Oxygen Demand (COD), as well as concentrations of nickel (Ni), hexavalent chromium (Cr^{6+}), and aluminum (Al). This systematic evaluation provided insights into the efficiency and efficacy of the SED in processing diverse industrial wastewater types.

III. RESULTS AND DISCUSSION

The mass flow rates of the SED are collected and compiled in the bar chart as shown in the figure below.

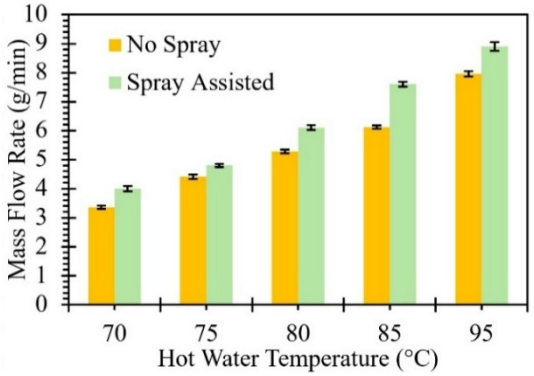


Figure 2: Mass Flow Rate of SED and Spray Assisted SED

The available data demonstrates that the spray-assisted SED consistently outperforms the conventional SED across all tested conditions. Specifically, improvements of 19.0%, 8.8%, 15.5%, 24.2%, and 11.8% were observed when the hot water temperature was set to 70° C, 75° C, 80° C, 85° C, and 95° C, respectively. This enhancement can be attributed to the fine water droplets introduced into the heated chamber by the spray-assisted mechanism. These droplets possess a larger surface area, allowing them to absorb ambient heat more efficiently and evaporate at an accelerated rate. The increased rate of evaporation directly contributes to a higher overall efficiency of the SED, offering significant potential for energy savings.

The superior performance of the spray-assisted SED can also be linked to its ability to create a more uniform temperature distribution within the chamber. This uniformity ensures optimal heat transfer, reducing thermal gradients and enhancing the evaporation process. Additionally, the rapid evaporation of fine droplets may help suppress heat losses typically associated with bulk water heating as in the case of the SED, further boosting system efficiency.

Given this insight, the scalability of spray-assisted SEDs for industrial applications could be explored. The boosted performance in large-scale wastewater treatment facilities could highlight its economic and environmental benefits.

The wastewater is then also characterized on their water properties and compared to the standard set by

the Malaysia's Department of Environment (DOE). Standard B of the Environmental Quality (Industrial Effluent) Regulations of 2009 has been used [13].

Based on the experimental data, it is evident that the effluents generally comply with the regulatory standards for industrial effluent discharge in Malaysia, with the exception of the pH value. To address this non-compliance, activated carbon treatment (ACT) was proposed as a viable solution to adjust the pH of the effluents. Specifically, the treatment aims to raise the pH of the initial effluent to within the acceptable range of 5.5–9.0 for the acid, heavy metal, and powder coating streams. However, for the alkali stream, an unexpected reduction in pH was observed, dropping from 6.6 to 5.5 after undergoing ACT. This phenomenon is likely attributable to the use of the same activated carbon filter previously employed for acidic streams, leading to a neutralization effect. Despite this reduction, it is noteworthy that the alkali stream's initial effluent already satisfies regulatory standards. Therefore, this stream can be discharged directly without requiring additional treatment.

An intriguing observation during the study was the sudden and pronounced increase in aluminum (Al) levels in the powder coating stream following ACT, a deviation not mirrored in other streams. Additionally, minor increases in chromium (Cr^{6+}) concentrations were detected in both the acid and alkali streams post-treatment. These anomalies are hypothesized to stem from the accumulation of Al and Cr^{6+} on the activated carbon from prior experimental runs, which were subsequently released during the current process. This underscores the critical need for regular replacement or regeneration of the activated carbon filter to prevent the release of adsorbed compounds. Failure to do so could compromise the effectiveness of the treatment process and potentially result in effluents exceeding permissible discharge limits.

Parameter	pH	Cr6+ (mg/L)	Ni (mg/L)	Al (mg/L)	COD (mg/L)	TSS (mg/L)
Alkali	6.6	0.008	0.008	0.059	0	10
Alkali ACT	5.5	0.013	0.000	0.038	0	13
Heavy Metal	4.4	0.050	0.000	0.071	13	13
Heavy Metal ACT	6.3	0.009	0.000	0.035	0	19
Powder Coating	3.6	0.021	0.000	0.022	44	11
Powder Coating ACT	6.4	0.008	0.000	0.965	0	12
Acid	3.2	0.014	0.000	0.093	7	13
Acid ACT	6.4	0.031	0.180	0.026	0	11
Regulatory Limit	5.5-9.0	0.050	1.000	15.000	200	100

** ACT = Activated Carbon Treated

Table 1: Treated Effluent Characterisation

Furthermore, the chemical oxygen demand (COD) of all streams post-treatment dropped to zero, demonstrating the efficacy of ACT in removing organic contaminants from the effluents. Conversely, a slight increase in total suspended solids (TSS) was noted in the alkali, heavy metal, and powder coating streams. However, this increase is negligible as the TSS levels remain significantly below the regulatory threshold of 100 mg/L. Overall, these findings emphasize the potential of ACT as a robust treatment method, while also highlighting areas for optimization to ensure consistent compliance with environmental standards.

IV. CONCLUSIONS

In conclusion, the spray-assisted SED demonstrates a clear advantage over conventional SEDs across a range of operating temperatures. Performance improvements of up to 24% at higher hot water temperatures highlight the effectiveness of the spray-assisted mechanism in enhancing evaporation efficiency. The introduction of fine water droplets with larger surface areas facilitates rapid heat absorption and accelerated evaporation rates, directly contributing to higher system efficiency and potential energy savings. To test the feasibility of implementing SED, wastewater samples from an aluminium extrusion manufacturing plant are processed and characterized. It was found that the water quality of the effluent from the SED has not met the regulatory requirements particularly in the pH value as the resulting effluents are too acidic. Hence, a secondary treatment process involving the passing the SED outputs thru an activated carbon filter results in higher water quality. The resulting effluents then

have met the discharge standards for industrial effluents (Standard B) set by the DOE in Malaysia.

ACKNOWLEDGMENTS

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