The Influence of Wet Scrubber on the Performance Efficiency of Heat Exchanger at Gasification Based Waste to Energy Power Plants

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***Abstract*— This research investigates the influence of wet scrubber installation on the performance efficiency of a shell and tube heat exchanger operating in a gasification-based Waste-to-Energy (WtE) power plant located in Surakarta, Indonesia. The study was conducted using a quantitative comparative approach over a four-month operational period, comparing system performance before and after the application of a wet scrubber. Three key parameters such as heat exchanger effectiveness, fouling factor, and pressure drop were analyzed to determine the impact of the gas cleaning system on thermal performance. The results show that the fouling factor decreased from 0.003 to 0.002 J/h·m²·°C, indicating cleaner heat transfer surfaces. Meanwhile, the pressure drop on the tube side reduced from 130.374 Pa to 46.134 Pa, reflecting smoother gas flow and lower mechanical resistance. Consequently, heat exchanger efficiency increased dramatically from 34% to 83%, signifying a substantial improvement in heat transfer capability. These findings confirm that the wet scrubber effectively minimizes tar and fine particulate deposits in syngas, improving heat transfer efficiency, operational stability, and equipment lifespan. The integration of wet scrubbers is therefore proven to be a vital enhancement for optimizing gas cleaning and energy conversion processes in Waste-to-Energy systems.**

Keywords—Heat Exchanger, Efficiency, Energy, Gasification, Pressure Drop, Fouling Factor, Thermal

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I. INTRODUCTION

Human need for electrical energy is substantial and continuously increasing, driven by technological advancements that are key to national economic growth. For example, the per capita electricity consumption in Central Java province reached 807.39 kWh in 2024, with the government targeting further increases to support development and welfare. However, Indonesia remains highly dependent on non-renewable energy sources. The Ministry of Energy and Mineral Resources (ESDM) estimated in 2021 that Indonesia's oil reserves would only last for 9.5 years, while gas reserves would last for 19.9 years without new additions. Therefore, a crucial transition towards utilizing renewable energy is vital to ensure the sustainability of the national energy supply and mitigate the negative impact of carbon emissions. The Indonesian government is committed to accelerating the development of various renewable energy sources, including Solar, Wind, Geothermal, Hydro, and Waste-to-Energy Power Plants (WtE) or Pembangkit Listrik Tenaga Sampah (PLTSa). A concrete initiative is the target to build 12 PLTSa facilities in major cities between 2019 and 2022, projected to generate a total power of 234 Megawatts (MW) while simultaneously solving urban waste problems. This initiative is a follow-up to Presidential Regulation (Perpres) No. 35 of 2018 concerning the acceleration of waste-to-electricity facilities based on environmentally friendly technology [1], [2], [3].

PLTSa implements the Waste-to-Energy (WtE) concept, aiming to convert municipal solid waste (MSW) into electrical energy using efficient and environmentally sound gasification technology. The gasification process converts MSW into synthesis gas (syngas), which is then utilized as an energy source. This process begins with waste sorting and pyrolysis to produce syngas and a biochar residue. The syngas is used to drive a generator engine to produce electricity, with the combustion process typically occurring between 200°C and 1000°C. Syngas contains calorific components such as carbon monoxide (CO), hydrogen (H_2), and methane (CH_4), but it also contains inorganic contaminants (ammonia (NH_3), hydrogen cyanide (HCN), sulfur compounds like H_2S) and fine solid particles, dust, and organic impurities like tar [4], [5].

In actual operation, technical challenges arise, such

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as the irregular distribution of pressure and temperature within the gasifier reactor, leading to system leaks and reduced gasification efficiency. To address contamination, a High Temperature Filter Element (HTFE) is used to separate solid particles (dust) from the hot gas, protecting downstream equipment. Additionally, a wet scrubber (WS) is implemented as a complementary solution to eliminate tar and fine particles by spraying a liquid. The cleaned gas then flows to the heat exchanger (HE), where heat transfer occurs more efficiently without corrosion or pipe blockage risks. The performance of the heat exchanger significantly impacts the overall system efficiency. However, a major challenge in PLTSa operations is fouling (scaling or deposition) on the HE surfaces, caused by residual tar and dust that escape the gas cleaning system. Factors such as temperature and pressure imbalances, variations in waste composition, and moisture conditions primarily inhibit HE efficiency [6].

Research has established the importance of gas cleaning systems in gasification technology for mitigating contaminants. The study by Tuomi et al. in 2015 investigated the behavior of biomass tar during filtration with High Temperature Filter Elements (HTFE) at approximately 800°C. This research provided critical insights into the interaction between tar and filter elements and its impact on the efficiency of solid particle filtration within HTFE during biomass gasification. Their findings underscored the protective role of HTFE for downstream equipment and highlighted improvements in syngas quality. The integration of HTFE and wet scrubbers in gasification systems has thus become pivotal for optimizing syngas purification prior to its further utilization in heat exchangers [7].

Research on wet scrubbers has gained increasing importance in the advancement of gasification technology due to their role in reducing tar and fine particulate content, which can damage system components. Several studies, including Abdulwahid (2019), have examined heat and mass transfer mechanisms in wet scrubber systems through experimental methods, thermodynamic analysis, and detailed studies on liquid bubble interactions. These investigations concluded that innovative wet scrubber designs can extend filter lifespan and enhance process efficiency. Mohd Yusoff et al. (2020) introduced an integration of wet scrubbers with membrane distillation (MD), offering highly efficient heat and water recovery solutions from flue gases, which present integrated energy management benefits [8], [9].

Experimental research by Supriyadi et al. (2021) confirmed that the design of wet scrubber filters significantly reduces syngas temperature and tar content. Moreover, Santoso et al. (2022) demonstrated that optimizing water spray flow rate and direction in wet scrubbers effectively minimizes tar concentration while maintaining thermal efficiency of the gasification process. Recent advancements by Mestemaker et al. (2024) modeled centrifugal scrubbers using dynamic droplet and heat transfer approaches, providing accurate predictions that assist industrial design optimization. Lastly, Thelin et al. (2025), through CFD simulations, validated that optimized wet scrubber designs enhance heat recovery in biomass power generation facilities significantly [10], [11], [12], [13].

While numerous studies have evaluated wet scrubber effectiveness in lowering gas temperature and tar levels, few have addressed heat exchanger performance before and after wet scrubber installation in commercial PLTSa systems operating on municipal solid waste (MSW) syngas in Indonesia. This study aims to fill that gap by quantitatively comparing the wet scrubber's operational impact on heat exchanger efficiency, thus offering novel contributions to the field through this research initiative.

II. Method

The research was conducted utilizing operational data obtained from the Waste-to-Energy Power Plant (PLTSa) in Surakarta City, Central Java, Indonesia. The study is executed through a quantitative, comparative method focusing on the thermal performance of a specific Shell and Tube Heat Exchanger (HE). The operational data analysis consist a period of 4 months, started on April 1, 2025 and ended on July 1, 2025, which comparing results derived from two distinct operating conditions: without the Wet Scrubber (WS) and with the WS system fully engaged. Three key parameters are selected to evaluate the WS impact on the HE's operational performance: HE Effectiveness, Fouling Factor, and the Pressure Drop.

A. *Gasification*

Gasification is a key thermochemical process in WtE, that converting biomass or municipal solid waste (MSW) into a gas fuel called syngas (synthesis gas). Unlike combustion, which aims for full oxidation, gasification involves partial oxidation (or reduction) at temperatures ranging from 600 to 1000. The syngas composition is highly dependent on the feedstock, operating temperature, and gasifying agent, primarily consisting of carbon monoxide, hydrogen, methane, carbon dioxide, and nitrogen [14].

The electricity generation process at the Waste-to-Energy (WtE) Power Plant begins with the thermal conversion of Municipal Solid Waste (MSW). The syngas production and cleaning chain follows a precise sequence to ensure optimal gas quality before entering the power generation unit. The raw syngas, produced within the Gasifier reactor, initially proceeds to a Junction Box where the stream is stabilized and directed toward the cleaning units. The first cleaning stage involves a Cyclone, which utilizes centrifugal force to remove large and medium-sized pollutant, thus protecting the subsequent high-efficiency filters. Following the cyclone, the gas stream enters the Wet Scrubber (WS), where it undergoes cooling and primary cleaning. In the WS, water sprays capture condensable organic compounds, primarily tar, and further fine particles through heat and mass transfer. The cooled and partially cleaned gas then passes through the High-Temperature Filter Element (HTFE), a specialized unit designed to capture any remaining fine dust particles that escaped the cyclone. This highly demanding step is critical for minimizing erosion and fouling downstream.

The cleaned syngas subsequently enters the thermal recovery stage, passing through two sequential heat exchangers: HE 1 and HE 2. These units are responsible for extracting thermal energy from the gas. Finally, before reaching the prime mover, the gas passes through a Fine Filter for final polishing to ensure the highest possible quality. The clean syngas is then fed into the Gas Engine to drive the generator and produce electricity.

B. *Wet Scrubber*

A wet scrubber is an important component in a gas cleaning system that functions to remove pollutants from dirty gas streams using liquid. In this system, before gas containing particles or hazardous gases enters the wet scrubber, the gas will pass through a cyclone as an initial dry cleaning process, then flow to the wet scrubber and on to the High Temperature Filter Element (HTFE) before entering the heat exchanger. Inside the wet scrubber, synthetic gas (syngas) is mixed with water through spraying, where the main elimination process of particles occurs by capturing them in liquid droplets or particles, while gas pollutants are absorbed into the liquid.

The working principle of a wet scrubber is based on direct contact between the dirty gas stream and the washing liquid, which is carried out through various methods such as spraying, flowing, or other forms of contact. In this process, solid particles are captured by liquid droplets or grains, and gaseous pollutants are absorbed or neutralized by the liquid. The efficiency of particle removal, especially very small particles, is highly dependent on the energy available in the system. Low-energy devices such as spray towers are effective for removing large particles, while high-energy devices such as venturi scrubbers or condensation scrubbers are needed to remove very small particles. Wet scrubbers are also known to have the advantage of being able to operate at high temperatures and humidity, capable of cooling exhaust gases so that the device can be designed smaller, removing both gaseous and solid pollutants, and neutralizing corrosive gases that have the potential to damage the unit. In general, a wet scrubber system consists of several main components, namely a water spray nozzle, a venturi scrubber, a scrubbing vessel, and a water tank. These components work together to ensure that exhaust gases are optimally cleaned before being fed into the next system. The illustration of wet scrubber application in PLTSa presented in Figure 1.

C. *Heat Exchanger Specification*

The heat exchanger used is a shell and tube type, where the shell contains syngas and the tube contains cooling water. The material used on the shell side is CS (MS, IS 2062 Gr B), and the material used on the tube side is SS (SA-179, Seamless). The specifications of the heat exchanger installed at the Waste-to-Energy Power Plant (PLTSa) are as follows in Table 1.

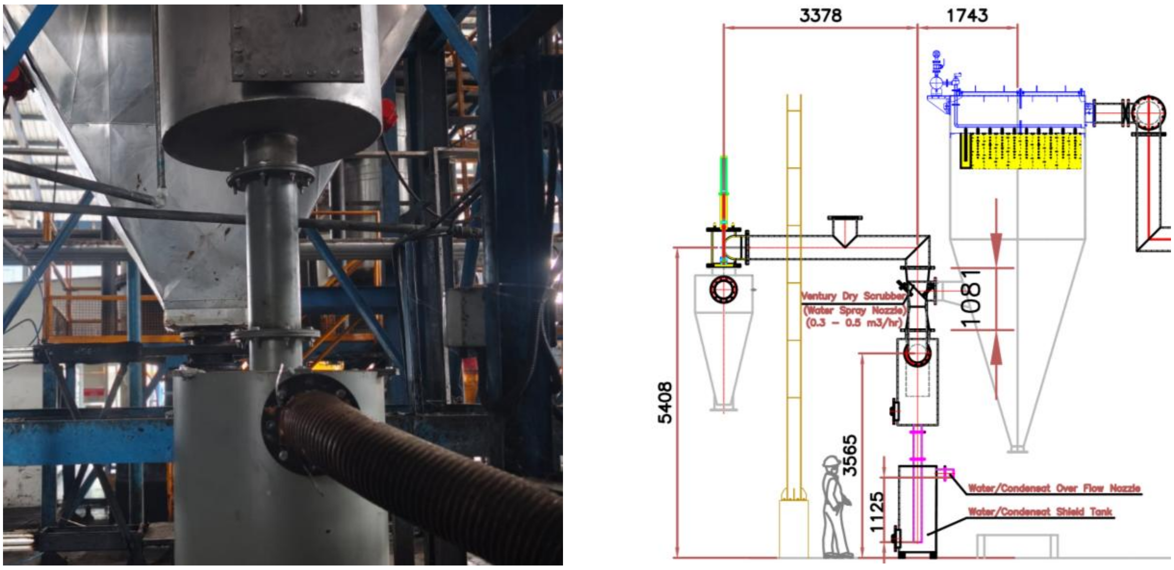

Figure. 1. Wet Scrubber

TABLE 1.
HEAT EXCHANGER SPECIFICATION

Nomenclature	Value	Units
Shell Outer Diameter (OD_s)	1.082	m
Shell Inner Diameter (ID_s)	1.075	m
Shell Length (L_s)	2.867	m
Number of Shell Baffles (N_s)	2	-
Distance Between Baffles (B)	2.5	m
Shell Passes (n_s)	1	-
Shell Flow Area (A_s)	0.791319	m^2
Tube Outer Diameter (OD_t)	0.03175	m
Tube Inner Diameter (ID_t)	0.02875	m
Tube Length (L_t)	2.50	m
Number of Tubes (N_t)	428	-
Tube BWG	14	-
Tube Pitch (P_t)	0.045	m
Tube Clearence (C)	0.015	m
Tube Passes (n_t)	1.00	-
Tube Flow Area (A_t)	0.25490	m^2

D. *Heat Exchanger Efficiency*

To calculate the efficiency of the HE's, it is stated as follows at Equation (1) [15]. Where Q is the heat transfer rate (Joule/h).

$$\eta HE = \frac{Q_{tube}}{Q_{shell}} \cdot 100\% \tag{1}$$

E. *Fouling Factor (Rd)*

To calculate fouling factor, it is stated as follows at Equation (2). Where Where UC is the Clean Heat Transfer Coefficient (J/h·m²·°C), and UD is the Dirty Heat Transfer Coefficient (J/h·m²·°C).

$$Rd = \frac{UC - UD}{UC \cdot UD} \tag{2}$$

F. *Pressure Drop*

To calculate pressure drop, it is stated as follows at equation (3). Where Where UC is the Clean Heat Transfer Coefficient (J/h·m²·°C), and UD is the Dirty Heat Transfer Coefficient (J/h·m²·°C).

$$Rd = \frac{UC - UD}{UC \cdot UD} \tag{3}$$

G. *Statistical Test*

In this study, data processing was carried out systematically to ensure the validity and reproducibility of the analysis results. Heat exchanger operating temperature and pressure data was collected from the operating period before and after the installation of the wet scrubber and the wet scrubber conditions in the PLTSa system. All collected data first underwent a cleaning process, including verification of missing data, checking for duplicates, and identifying and handling outliers that could potentially interfere with statistical analysis. The software used for statistical testing was IBM SPSS, Microsoft Excel, and Tecplot 360.

1) Normality Saphiro Wilk's Test

The Shapiro-Wilk test is a statistical method used to test whether data is statistically normally distributed. This method has high sensitivity and power in detecting deviations from normal distribution, and is particularly effective for small to medium sample sizes (usually $N < 50$). The null hypothesis in this test states that the data is normally distributed, and decisions are made based on the resulting p-value (significance). If the p-value is greater than the significance threshold (e.g., 0.05), then the assumption of normality is accepted; conversely, if the p-value is less than 0.05, the assumption of normality is rejected [16]. The results of normality Saphiro Wilk's test shown in Table 2.

Based on the results of normality testing using the Shapiro-Wilk method, it can be seen that not all data groups in the research variables show a normal distribution. Interpretation of the p-value for each operational parameter before and after the installation of the wet scrubber indicates that some data have a p-value greater than 0.05, namely HE GAS IN, HE GAS OUT, HE WATER IN, and PG FLOW RATE before the installation of the wet scrubber, as well as HE WATER OUT and PG FLOW RATE after the installation of the wet scrubber. So that in this group, the assumption of normal distribution can be accepted. However, for data with p-values less than or equal to 0.05, such as HE WATER OUT, PG PRESSURE, and HE PRESSURE before installing the wet scrubber, as well as HE GAS IN, HE GAS OUT, HE WATER IN, PG PRESSURE, and HE PRESSURE after installing the wet scrubber, it can be concluded that the data does not meet the assumption of normality. These findings indicate that most of the measured variables in this study are not normally distributed, especially the pressure and temperature parameters after the application of the wet scrubber.

2) Homogenity Levene's Test

Levene's Test is used to test the similarity of variances between data groups. This test is very useful in inferential statistical testing to ensure that the assumption of homogeneity of variances is met before conducting further analysis, such as the T-Test. The advantage of Levene's Test is that it is more robust against violations of normality assumptions than other tests, thus providing reliable results for data that may not always be perfectly normal [17]. The results of homogenity Levene's test shown in Table 3. In the table, the variables HE GAS IN, HE GAS OUT, PG PRESSURE, PG FLOW RATE, and HE PRESSURE all have p-values well below 0.05, so it can be concluded that the variance between groups for these parameters is not homogeneous. Meanwhile, the variables HE WATER IN (p= 0.285) and HE WATER OUT (p= 0.055) show p-values greater than 0.05, so it can be accepted that the data on these two variables have homogeneous variance.

3) Hypothesis One Way ANOVA Test

ANOVA was chosen to statistically determine whether there were significant differences in operational data averages on key metrics between the 'With Wet Scrubber' and 'Without Wet Scrubber' operation groups. This method works by comparing the variation that occurs between groups (variation caused by WS treatment) with the variation that occurs within groups (natural data variation), thus providing a robust assessment of the effectiveness of Wet Scrubber. The test was conducted at a significance level of p-value equals 0.05, where the rejection of the Null Hypothesis (H0), which states that there is no significant difference in average performance, would quantitatively prove that the application of the Wet Scrubber does indeed produce a real and measurable effect on the performance of the Heat Exchanger [18]. The results of hypothesis One Way ANOVA test shown in Table 4.

In the table contains very small p-values (all p-values are well below 0.05), this indicates that there are significant differences in variables such as HE GAS IN, HE GAS OUT, HE WATER IN, HE WATER OUT, PG PRESSURE, PG FLOW RATE, and HE PRESSURE. In general, ANOVA helps determine whether the variation between groups is greater than the variation within the group, so it can be said that the difference in means between groups does not occur by chance. If the p-value < 0.05, then the null hypothesis (that all groups have the same mean) is rejected, and it is concluded that at least one group is significantly different. With a very small p-value, it can be interpreted that the variables tested show a significant effect, such as differences in conditions before and after the installation of a wet scrubber or other conditions analyzed.

TABLE 2.
TEST OF NORMALITY

GROUP (VARIANCE)	P-VALUE	
	BEFORE WS	AFTER WS
HE GAS IN	6.878E-01	3.842E-02
HE GAS OUT	3.776E-01	1.433E-02
HE WATER IN	1.145E-01	2.782E-02
HE WATER OUT	4.031E-02	3.314E-01
PG PRESSURE	2.010E-03	1.402E-02
PG FLOW RATE	6.741E-02	6.599E-01
HE PRESSURE	9.825E-04	2.808E-02

TABLE 3.
TEST OF HOMOGENITY

VARIABLE	P-VALUE
HE GAS IN	2.549E-05
HE GAS OUT	1.137E-05
HE WATER IN	2.853E-01
HE WATER OUT	5.529E-02
PG PRESSURE	1.714E-03
PG FLOW RATE	1.107E-02
HE PRESSURE	3.148E-23

TABLE 4.
TEST OF HYPOTHESIS

VARIABLE	P-VALUE
HE GAS IN	1.969E-58
HE GAS OUT	1.712E-45
HE WATER IN	4.292E-13
HE WATER OUT	1.491E-16
PG PRESSURE	5.181E-16
PG FLOW RATE	9.694E-38
HE PRESSURE	2.303E-29

III. Results and Discussion

A. Heat Exchanger Fouling Factor Analysis

Based on Figure 1, the decrease in the fouling factor from 0.003 J/h·m²·°C before the installation of the wet scrubber to 0.002 J/h·m²·°C after installation indicates a significant improvement in the surface condition of the heat exchanger. A lower fouling factor signifies that the wet scrubber effectively reduces the deposition of dirt, tar, and other particulate matter on the heat exchanger's surface, which in turn decreases heat transfer resistance. This reduction in fouling directly contributes to enhanced heat transfer performance because a cleaner heat exchanger surface allows for more optimal thermal energy exchange between fluids. Additionally, the diminished fouling reduces maintenance requirements and mitigates the risk of unexpected operational downtime caused by frequent cleaning cycles.

These effects align with fundamental principles that fouling imposes an additional thermal resistance layer on heat transfer surfaces, adversely affecting the overall heat transfer coefficient and efficiency. Fouling not only impairs thermal performance but also results in increased pressure drop within the heat exchanger, causing elevated operational costs and potential mechanical stresses. Therefore, mitigating fouling through wet scrubber application helps maintain optimal heat exchanger functionality by minimizing these adverse effects. Moreover, by reducing the fouling rate, the operational lifespan of the heat exchanger is extended, which contributes to lowering maintenance expenses and improving economic feasibility. This is crucial for industrial applications such as waste-to-energy (WtE) plants, where operational efficiency and reliability are paramount. The integration of wet scrubbers is thus deemed an effective strategy to ensure sustained performance and longevity of heat exchanger units in syngas cleaning processes.

B. Heat Exchanger Pressure Drop Analysis

Based on Figure 2, the effect of the wet scrubber is also evident in the pressure parameters on the tube side, where the pressure drop decreases dramatically from 130.374 pascals to 46.134 pascals. This significant decrease in pressure drop reflects a notable reduction in the resistance to syngas flow, primarily due to the effective removal of solid particles and tar that previously clogged the flow path. A smoother, less obstructed flow results in a more stable and lower pressure requirement, meaning that the pump or blower system needs to exert less power to maintain the operational flow rate. This reduction in mechanical power demand not only improves the thermal efficiency of the overall system but also contributes to lower operational energy consumption, which is particularly beneficial in industrial-scale applications where energy costs are substantial. The importance of reducing pressure drop extends beyond energy savings. A lower pressure drop on the tube side plays a vital role in maintaining the stability and reliability of heat exchanger operations by lessening the mechanical load on system components. Reduced mechanical stress helps diminish wear and tear on the heat exchanger's structural elements, prolonging equipment life and minimizing the frequency and cost of maintenance interventions. These benefits collectively enhance operational uptime and system availability, which are critical metrics in continuous industrial processes.

Conversely, the pressure drop on the shell side, which contains the cooling water, did not show any significant change and remained stable at 275.772 pascals. This stability indicates that the wet scrubber's primary function is directed toward the purification of gas stream contaminants, rather than affecting liquid side flow conditions. The relatively invariant flow and physicochemical properties of the cooling water contribute to this lack of change. Unlike the syngas carrying particulate matter and tar, the cooling water flow is more controlled and less prone to fluctuations caused by impurities. This differentiation underscores the wet scrubber's targeted impact on gas phase cleaning, which is crucial for optimizing heat exchanger performance by protecting the gas side from fouling while maintaining the integrity of the water side flow dynamics. In summary, this marked improvement in pressure conditions on the tube side due to wet scrubber installation highlights the critical role of effective gas cleaning in enhancing heat exchanger performance and operational sustainability. The selective influence on gas flow resistance and mechanical load reduction strongly supports the integration of wet scrubber technology in syngas purification processes in waste-to-energy plants.

C. Heat Exchanger Efficiency Analysis

Based on Figure 3, the increase in heat exchanger efficiency from 34% before the installation of the wet scrubber to 83% after installation represents a very significant improvement, emphasizing the critical role of wet scrubbers in enhancing heat transfer processes. This substantial increase in efficiency indicates that the heat exchanger can utilize heat energy more effectively, optimizing the heating or cooling of fluids with minimal heat loss. The main drivers behind this improvement are the combined effects of a reduced fouling factor and a lower pressure drop on the tube side, which together create far more favorable operating conditions for thermal exchange. Furthermore, the reduction in tar and fine particulate concentrations within the syngas flowing through the wet scrubber ensures that the heat transfer processes proceed uninterrupted, maintaining stable operation and preventing premature degradation of heat exchanger components due to corrosion or blockage. This uninterrupted flow is essential for preserving material integrity and sustaining long-term performance. Such findings are consistent with research that highlights the importance of effective gas cleaning systems, particularly wet scrubbers, in maintaining and enhancing heat exchanger efficiency within biomass gasification and waste-to-energy power plants.

In addition to immediate performance benefits, improved heat exchanger efficiency can lead to significant operational advantages such as reduced fuel consumption, lower maintenance requirements, and increased equipment lifespan. The optimization of heat transfer directly impacts the overall energy efficiency of the power generation cycle, thereby contributing to reduced operational costs and environmental footprint. With ongoing advancements in wet scrubber design, including enhanced capture efficiency and heat recovery techniques, the integration of such systems is increasingly recognized as a key element of sustainable and high-performance waste-to-energy operations. This improvement also underscores the synergy between gas cleaning systems and heat exchanger performance, demonstrating that investments in upstream cleaning equipment like wet scrubbers can yield substantial returns in process efficiency and reliability downstream. Consequently, this study supports the continued development and adoption of wet scrubber technologies as an integral component in optimizing heat exchanger operation and advancing the economic and environmental sustainability of PLTSa facilities.

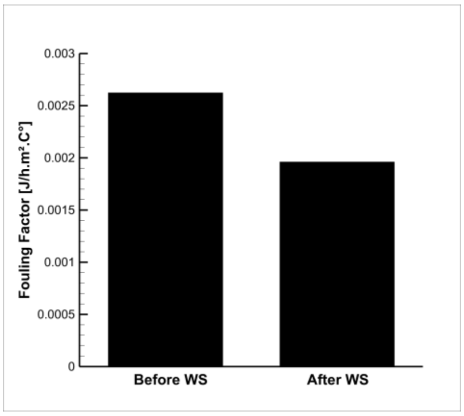

Figure. 1. Graph of fouling factor analysis results before wet scrubber application against after wet scrubber aplication

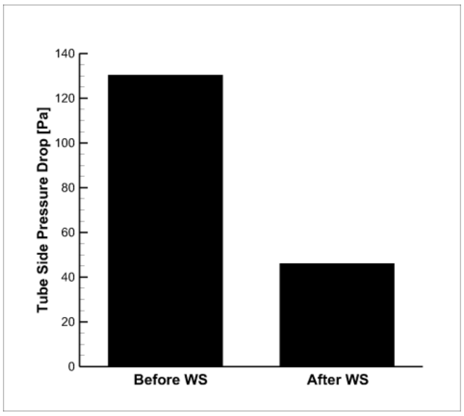

Figure. 2. Graph of tube side pressure drop analysis results before wet scrubber application against after wet scrubber aplication

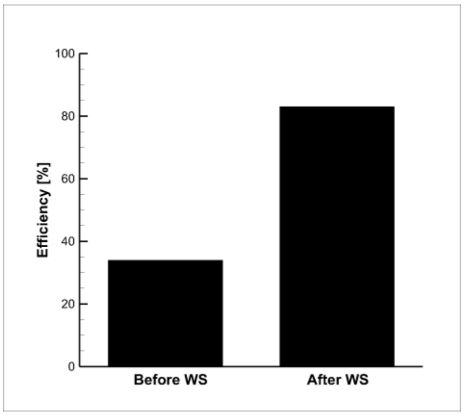

Figure. 3. Graph of heat exchanger efficiency analysis results before wet scrubber application against after wet scrubber aplication

IV. CONCLUSION

This study aimed to analyze the influence of wet scrubber installation on the performance of a heat exchanger in a gasification-based Waste-to-Energy power plant, and the results confirm that the wet scrubber significantly enhances system efficiency and reliability. The reduction of the fouling factor from 0.003 to 0.002 J/h·m²·°C and the decrease in tube-side pressure drop from 130.374 Pa to 46.134 Pa demonstrate that cleaner syngas flow reduces thermal resistance and energy loss, leading to a substantial increase in heat exchanger efficiency from 34% to 83%. These outcomes prove that the wet scrubber not only improves gas purity but also sustains optimal heat transfer performance, reduces maintenance requirements, and extends equipment lifespan. In response to the research purpose, it can be concluded that integrating a wet scrubber system is essential for optimizing heat exchanger operation and ensuring long-term energy efficiency in Waste-to-Energy facilities. Future work is recommended to focus on wet scrubber design optimization, water utilization management, and advanced monitoring methods to further enhance system performance and support sustainable power generation.

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