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Research Article

Evaluation of Heat Loss Effect on Package Boiler Performance (5007-U) in the Utility Unit of Urea Fertilizer Industry

Evaluasi Pengaruh Kehilangan Panas Terhadap Performa Package Boiler (5007-U) Pada Unit Utilitas Industri Pupuk Urea

Rizka Wulandari Putri[1*], M. Fabian Merdeka[1], Rona Alisya[1], Rahmatullah[1], Muhammad Haviz[2]

[1]*Universitas Sriwijaya, Chemical Engineering Department, Faculty of Engineering, Indonesia*

[2]*King Fahd University Petroleum and Mineral, Department of Chemical Engineering, King Saudi Arabia*

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*Corresponding Author.
Email: rizkawulandariputri@unsri.ac.id

Abstract

Package boiler (PB) is a utility unit essential for producing steam by heating Boiler Feed Water (BFW) through the combustion of natural gas with air. Therefore, this study aimed to investigate the effect of heat loss on PB efficiency. To achieve this, direct and indirect methods were adopted, with data collected between 4 July and 29 August 2023. The results showed that PB efficiency in the fertilizer industry during this period ranged from 76.06% to 80.71%. On August 29, 2023, under optimal conditions, an efficiency of 80.71% was achieved, while a significant drop to 65.44% occurred during the 6th week on August 8, 2023, due to low oxygen (O_2) levels. Flue gas analysis on August 29, 2023, obtained 3.64% excess O_2, 11.17% carbon dioxide (CO_2), and 0.04% carbon monoxide (CO). PB performance was influenced by heat loss from the dry flue gas, hydrogen (H_2) content on flue gas, moisture in air and fuel, incomplete combustion, as well as radiation and convection phenomena.

Keywords: excess O_2; flue gas; heat loss; natural gas flow; package boiler

Abstrak

Package boiler merupakan salah satu unit utilitas yang berperan dalam menghasilkan steam dengan memanaskan boiler feed water dari panas hasil pembakaran natural gas dengan udara. Tujuan dari penelitian ini adalah untuk menyelidiki kehilangan panas pada package boiler, yang cenderung dapat menurunkan efisiensinya. Penelitian ini menggunakan dua metode untuk mengevaluasi efisiensi package boiler, yaitu metode langsung dan tidak langsung yang datanya dikumpulkan dari minggu 1- 9 (4 Juli – 29 Agustus 2023). Berdasarkan data yang didapatkan dari bulan Juli hingga Agustus, efisiensi package boiler di industri pupuk berada dalam rentang 76,06% hingga 80,71%. Package boiler industri pupuk urea mengalami kondisi optimal di pekan ke 9 pada tanggal 29 Agustus 2023 dengan efisiensi sebesar 80,71% dan penurunan efisiensi secara drastis di pekan ke 6 pada tanggal 08 Agustus 2023 dengan efisiensi sebesar 65,44%. Hasil analisa flue gas pada tanggal 29 Agustus 2023 didapatkan O_2 excess 3,64%, CO_2 content 11,17%, dan CO content 0,04%. Kinerja package boiler dipengaruhi oleh panas yang hilang karena flue gas kering, kadar H_2, kelembaban di udara dan bahan bakar, pembakaran tidak sempurna, radiasi dan konveksi.

Kata kunci: e*xcess O_2; flue gas; heat loss; natural gas flow; package boiler*

1. Introduction

The utility unit is responsible for producing steam, which serves as a driving force for turbines and pumps. Meanwhile, an ammonia plant operates its steam generator for production purposes. The utility unit produces steam using Waste Heat Boiler (WHB) and Package Boiler (PB) [1]. WHB utilizes exhaust gases from the combustion of natural gas and air from the Gas Turbine Generator (GTG), while PB uses heat from the combustion of natural gas with air, and is designed with excellent heat transfer capabilities through radiation, convection, and high conduction.

PB is a key component of the utility unit and the primary steam supply unit in the Urea Fertilizer Industry (UFI). It functions by raising the water temperature until reaching the steam point through direct contact with the flame generated by natural gas combustion. PB is fed with Boiler Feed Water (BFW) [2] and heat transfer occurs from the combustion of natural gas to water, resulting in the generation of steam used in the production process. However, its operation leads to heat loss due to various factors, including incomplete combustion [3]. Significant heat loss can result in reduced efficiency, thereby impacting performance [4].

Boiler efficiency represents the performance that is obtained by comparing the energy produced with the chemical energy from the fuel. The systems and components used in PB at the UFI utility unit have been operational for an extended period, necessitating an efficiency analysis. This analysis ensures that the steam produced reaches the appropriate temperature for use in the production process, requiring calculations of overall component flow rates [5] and heat absorbed in PB [6]. The efficiency of this boiler is below 84%, signifying the need for further evaluation. This study aims to investigate the effect of heat loss on PB efficiency.

2. Research Methods

Direct and indirect methods were adopted to evaluate PB performance (5007-U) in the utility unit of UFI. The evaluation of the direct method utilized actual data of heat input and output, calculated using equation 1.

$$\text{Efficiency} = Q_{input} / Q_{output} \quad \text{.............(1)}$$

$$\text{Efficiency} = 100\% - (L1 + L2 + L3 + L4 + L5 + L6) \quad \text{.............(2)}$$

$$L1 = \frac{m \times Cp \times (Tf - Ta)}{GCV\ Fuel} \times 100\% \quad \text{.....(3)}$$

$$L2 = \frac{9 \times H2 \times [584 + Cp\ (Tf - Ta)]}{GCV\ Fuel} \times 100\% \quad \text{.....(4)}$$

$$L3 = \frac{M \times [584 + Cp\ (Tf - Ta)]}{GCV\ Fuel} \times 100\% \quad \text{.....(5)}$$

$$L4 = \frac{AAS \times \text{humidity factor} \times Cp \times (Tf - Ta)}{GCV\ Fuel} \times 100\% \quad \text{.....(6)}$$

$$L5 = \frac{\%CO \times C}{\%CO + \%CO2} \times \frac{5744}{GCV\ Fuel} \times 100\% \quad \text{.....(7)}$$

$$L6 = 0{,}548 \times [(Ts / 55{,}55)^4 - (Ta / 55{,}55)4] + 1{,}957 \times (Ts-Ta)^{1{,}25} \times \text{sq.rt of } [(196{,}85\ Vm + 68{,}9) / (68{,}9)] \quad \text{.....(8)}$$

Descriptions:
Qinput = heat input (kJ)
Qoutput = heat output (kJ)
L1: Heat loss due to dry flue gas (%)
L2: Heat loss due to hydrogen in fuel (%)
L3: Heat loss due to moisture in fuel (%)
L4: Heat loss due to moisture in air (%)
L5: Heal loss due to carbon monoxide (%)
L6: Heat loss due to surface radiation and convection
m: Mass flow (kg/h)
Cp: Specific heat capacity (J/kg.K)
Tf: Final Temperature (°C)
Ta: Ambient Temperature (°C)
Ts: Entropy Temperature (°C)
GCV: Gross calorific value (KJ/kg)
AAS: Actual air supply (kg)

The indirect method used actual data, including sample quantities of independent variables such as flue gas components, flue gas temperature, natural gas components, steam flow, steam temperature, steam pressure, BFW pressure, BFW temperature, and airflow in PB at the utility unit. The evaluation comprised data collection, processing, boiler efficiency calculation, and analysis of the effect of heat loss on boiler performances [7]. PB efficiency was calculated using equation 2, while the effect of heat loss was analyzed by calculating losses from flue gas, hydrogen (H_2) content, moisture content on fuel, moisture on air, incomplete combustion, as well as radiation and convection using equations 3-8. The required data for this specific task, including actual input and output values of PB in UFI, were collected from the Utility Unit every Tuesday from 4 July to 29 August 2023 and symbolized with weeks1st to 9th.

3. Results and Discussion

3.1 The Effect of Total Heat Loss on PB Efficiency

The evaluation of boiler efficiency is conducted using an indirect method by calculating heat loss during the process. The direct method showed an average PB efficiency of 71,33% and did not present potential causes of inefficiency. Therefore, it requires actual calculations with the indirect method to accurately assess factors such as heat loss [8].

The results of the performance efficiency calculation for PB using an indirect method are presented in Figure 1. The average efficiency was in the range of 70-80%, except on August 8, 2023, where a significant decrease was observed. In week 6th, specifically on August 8, 2023, PB efficiency experienced a drastic decrease, reaching 65.44%. This phenomenon occurred due to heat loss caused by a relatively high level of incomplete combustion. In the same week, the flue gas analysis conducted showed that approximately 5.89% of carbon monoxide (CO) gas was contributing significantly to the sharp efficiency decrease. During the last week of July and the middle of August, UFI was shut down, leading to suboptimal operation of PB in the facility and contributing to an efficiency decrease. Various factors can contribute to heat loss, including high flue gas temperatures, hydrogen content in natural gas, moisture content in air as combustion feedstock, incomplete combustion of natural gas, and heat loss due to radiation.

Table 1. Collected data from PB (5007-U)

Data	Unit	Weeks								
		1st	2nd	3rd	4th	5th	6th	7th	8th	9th
Steam flow	ton/h	40.02	40.99	32.79	32.25	37.92	26.88	44.50	46.17	33.50
Steam pressure	kg/cm^3	42.11	43.07	42.68	42.48	42.37	42.90	43.28	43.64	43.17
Steam temperature	ºC	409.00	410.42	410.00	409.42	409.33	407.40	408.42	409.50	408.50
BFW pressure	kg/cm^3	57.99	58.29	59.67	58.40	37.92	59.53	58.75	59.09	56.47
BFW temperature	ºC	84.74	72.41	77.76	83.92	76.17	86.80	54.83	60.00	97.33
Natural gas flow	m^3/h	4,445	4,173	3,532	3,463	4,430	3,094	4,947	5,198	3,028
Airflow	kg/h	59,312	56,259	47,278	46,913	58,753	40,541	66,374	81,779	46,131

3.2 The Effect of Heat Loss Due to Dry Flue Gas on PB Efficiency

Heat loss due to dry flue gas represent a significant inefficiency, as the gas exiting boiler system still contains heat. This loss can be measured by the flue gas temperature, as recorded in UFI laboratory. The exiting gas carries away heat that should have been utilized for steam production or heating, thereby reducing efficiency.

Figure 2 shows a consistent loss of heat caused by dry flue gas each week. In week 6th, a significant loss was observed compared to other periods, as evidenced by the flue gas temperature, which reached 219°C. The flue gas temperature is directly proportional to heat released by PB. This case presents the effect of heat loss on efficiency reduction. An increase in temperature can be attributed to insufficient heat transfer and fouling caused by deposits from fuel or BFW [9]. However, the flue gas temperature should not be very low to prevent water vapor from condensing on the chimney walls [10].

3.3 The Effect of Heat Loss Due to H_2 Content in Fuel on PB Efficiency

H_2 content in fuel is typically in the form of hydrocarbons or pure H_2 gas and can impact boiler efficiency. A significant factor contributing to decreased efficiency is the evaporation of water due to H_2 content in the fuel. In the case of PB, water evaporation can occur due to the presence of H_2 in the natural gas used. Water is formed from the reaction between hydrogen and oxygen in the air during combustion [11]. It will turn into steam by absorbing heat from combustion, leading to a reduction in heat absorption for evaporating BFW and reduced efficiency [12].

Heat loss due to H_2 content in the fuel represents the largest, particularly because PB relies on natural gas, predominantly composed of methane. Figure 3 shows that the average heat loss due to H_2 in natural gas was approximately 11.8%. This loss is influenced by H_2 content in the mass component of natural gas fuel, leading to relatively stable heat loss over time. However, an increase was observed on week 6th (August 8, 2023), rising to 12.17%. The increase was traced to an imbalance in the air-fuel ratio, as evidenced by an excess small oxygen (O_2) level of 1.21%. This can lead to incomplete combustion, affecting heat generated [13].

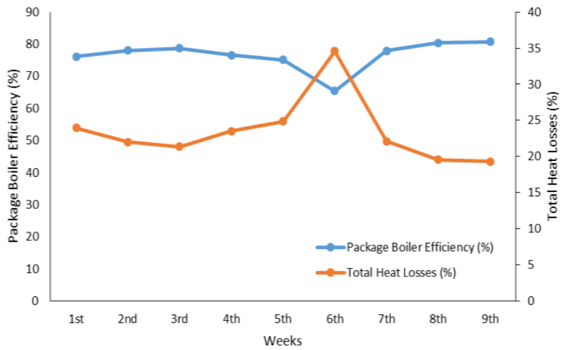

Figure 1. Effect of total heat loss on PB

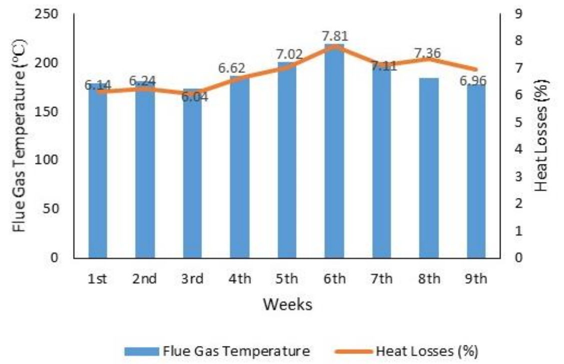

Figure 2. Effect of dry flue gas on heat loss

3.4 The Effect of Heat Loss Due to Moisture in Air and Fuel on PB Efficiency

Heat losses can be caused by the presence of moisture in both natural gas feed and air used in the combustion process. Moisture in the natural gas feed and air enter the boiler and leave as steam. Heat needed to warm BFW is consumed by moisture, leading to heat loss and a reduction in PB efficiency. The higher the moisture content in the fuel, the greater the heat loss, due to the reduction in the effective calorific value of the fuel [10]. Heat loss was attributed to sensible heat used to raise moisture to boiling point, latent heat for moisture evaporation, and excess heat to reach the flue gas temperature.

Figure 4 shows heat loss caused by the presence of moisture content in natural gas fuel. The analysis results from July-August present minimal moisture in the natural gas feed, leading to heat loss consistently measured at 0% for each week. However, the combustion air drawn from the ambient environment also contains moisture. During the combustion process, this water vapor did not participate in any reaction but mixed with the smoke gases produced. As a result, some of the heat generated during combustion is absorbed by moisture in the air, which reduces the energy available for evaporating moisture content [12].

Figure 4 shows heat loss caused by moisture content in the combustion air. A constant heat loss was observed until the 1st week of August, averaging approximately 0.32%, while in the 2nd week, it increased to 0.37%. This was attributed to an imbalance in the air and natural gas flow. In the 4th week of August, a significant difference was observed. On week 8th, exactly on August 22, 2023, the air and natural gas flows were 81,779.9 kg/h and 4,348.74 kg/h, respectively, which led to excess air and increased water vapor entering the boiler. On August 29th, 2023, the air supplied was at an average of 46,131.3 kg/h, but the natural gas flow decreased to 2,510.85 kg/h. Therefore, the excess air and water vapor entering the boiler was increased.

3.5 The Effect of Heat Loss Due to Imperfect Combustion on PB Efficiency

Incomplete combustion occurs as signified by the presence of CO content in the flue gas analysis. Furthermore, it results from insufficient O_2 to burn the fuel completely into carbon dioxide (CO_2) and water [13].

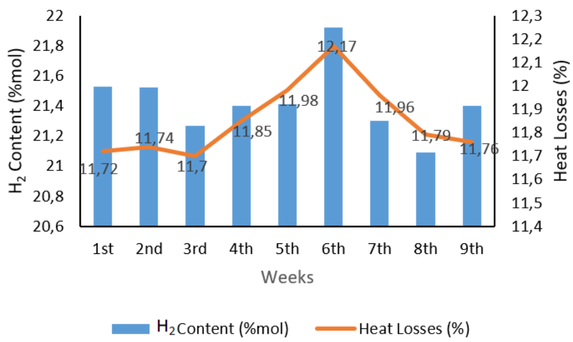

Figure 3. Effect of H_2 in fuel on heat loss

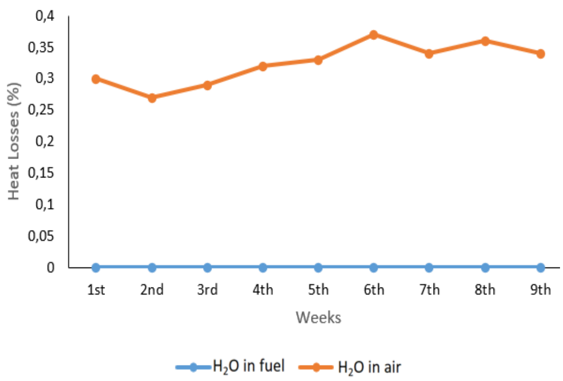

Figure 4. Graph of heat loss due to moisture in air and fuel

Figure 5 shows the weekly fluctuations in heat loss due to incomplete combustion, which is signified by the high CO component. On week 6th, exactly on August 8, 2023, the calculated losses were quite high, with CO content in boiler flue gas reaching approximately 5.89%. This percentage is relatively high when compared to other weeks. The increased levels were attributed to a lower combustion air rate of approximately 40,541.72 kg/hour. The reduced airflow resulted in uneven air distribution in the boiler, leading to incomplete combustion and higher CO production in the flue gas. Incomplete combustion occurs when there is not enough O_2 to burn the fuel completely into CO_2 and water [14].

On weeks 7th and 9th, heat loss decreased drastically because CO output in the flue gas analysis was small. During weeks 8th and 9th, CO content was 0, implying that all natural gas was completely burned. This was attributed to a change in the setting of combustion air operating conditions.

3.6 The Effect of Heat Loss Due to Radiation and Convection on PB Efficiency

Heat loss due to radiation and convection occurs when heat energy from PB is transferred to the environment instead of being utilized for steam production. The influencing factors include ambient temperature, natural gas flow, and the Gross Heating Value (GHV) of natural gas. The amount of heat loss depends on the temperature of the hot surface which is affected by the insulation (thickness, thermal conductivity, and condition) [15].

Figure 6 shows heat loss caused by convection and radiation phenomena. Heat loss due to radiation fluctuates weekly, and the amount depends on the surface area of PB. These losses become significant when PB operates at low loads [16]. Additionally, variations in natural gas flow during the combustion process can affect the air temperature in the system. On weeks 6th and 9th, exactly on August 8 and 29, the natural gas flow had the lowest value. This affects the thermal conditions and air humidity in the room or system, thereby influencing the temperature of the environment surrounding boiler.

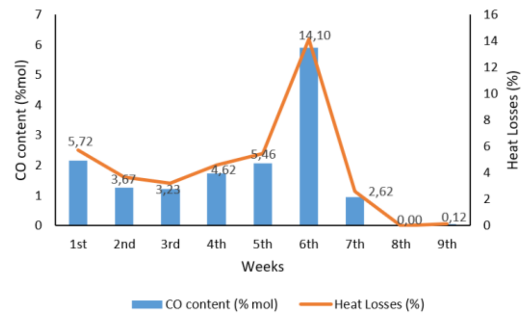

Figure 5. Heat loss due to imperfect combustion

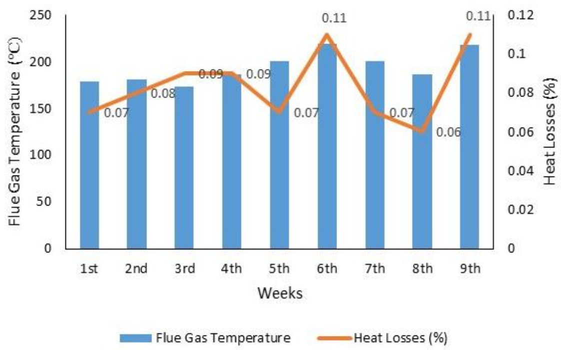

Figure 6. Heat loss due to radiation and convection

4. Conclusion

The best PB performance efficiency was obtained on week 9th (August 29, 2023), reaching 80.71%. This was attributed to optimal airflow settings and increased excess O_2 content, which facilitated complete combustion and minimized CO content. The value obtained approached the design data of 84%.

Meanwhile, the lowest efficiency of 65.44% was achieved on week 6th (August 8, 2023). The decrease in PB performance was caused by several factors, including heat loss carried by flue gas, H_2 content in fuel, moisture in the air, incomplete combustion, as well as radiation and convection from the boiler. The highest efficiency was achieved when excess O_2 in the flue gas reached an optimal limit. An excess O_2 of 3% was sufficient to ensure optimal heat production without losses due to incomplete combustion. The highest heat loss, which impacted efficiency, was caused by H_2 content in the natural gas. The highest total amount of heat loss signified the lowest PB efficiency.

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