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Original Research Article

Optimization of Heat Recovery Steam Generator (HRSG) for Reducing Exhaust Flue Gas Temperature

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Abstract

This study presents the optimization of a Heat Recovery Steam Generator (HRSG) system with integrated low-temperature heat recovery to enhance thermal efficiency and promote sustainable energy utilization in a combined cycle gas turbine (CCGT) power plant. The research addresses key industrial challenges, including high exhaust flue gas temperatures (~200°C), dependence on electric heating, and underutilization of waste heat. A secondary heat exchanger (Preheater-2) is introduced downstream of the Make-Up Water Heater (MUWH) to reduce the flue gas exit temperature to 60°C while recovering energy for potable water heating. The system was modeled and optimized using Aspen Plus. Results show that the proposed configuration can offset approximately 550 units of 3 kW electric heaters, resulting in a daily energy saving of 11.55 MWh. Thermodynamic performance improved, with HRSG heat duty increasing from 2.546 MW to 3.711 MW and overall thermal efficiency rising from 61.25% to 64.76%. Sensitivity analysis identified an optimal potable water flow rate range of 60,000–70,000 kg/h, yielding stable outlet temperatures of about 80°C. Exergy analysis confirmed reduced system irreversibility. The low sulphur content of Nigerian natural gas supports safe low-temperature heat recovery without corrosion risk. The system offers a scalable solution for industrial waste heat recovery, with applications in process heating, domestic hot water generation, and energy cost reduction.

Keywords: Combined Cycle Gas Turbine (CCGT), Heat Recovery Steam Generator (HRSG), Waste Heat Recovery, Thermal Efficiency, Aspen Plus, Energy Optimization.

1.0 INTRODUCTION

Traditional waste heat utilization practices have long existed in African households, particularly in Southern Nigeria, where a single heat source such as firewood is used to perform multiple thermal tasks including cooking, drying, and food preservation. These indigenous practices reflect the principles of heat cascading and energy maximization, which are consistent with the operational philosophy of modern Heat Recovery Steam Generators (HRSGs). Both systems emphasize efficient utilization of available thermal energy to reduce fuel consumption and enhance sustainability.

Historically, HRSG technology has evolved significantly since its introduction in the 1960s. Early single-pressure systems have been progressively replaced by multi-pressure configurations, offering improved thermal efficiency and operational flexibility. Advances in materials and manufacturing techniques have enabled the development of compact and high-performance HRSG units. Despite these improvements, studies indicate that further optimization is required to reduce exhaust flue gas temperatures and improve overall energy recovery (Li *et al.,* 2020).

The increasing demand for sustainable and reliable energy, driven by population growth and industrialization, has intensified the need for efficient energy systems. Environmental concerns also necessitate the adoption of cleaner and more energy-efficient technologies (Ighodaro & Osikhuemhe, 2019). However, a significant portion of thermal energy in combustion-based systems is still lost through high-temperature exhaust gases, reducing efficiency and contributing to environmental pollution (Shi & Che, 2009).

HRSG systems provide an effective solution by recovering waste heat from gas turbine exhaust and converting it into useful energy, typically in the form of steam for power generation (Sharma & Singh, 2016). In combined cycle gas turbine (CCGT) plants, HRSGs play a crucial role in enhancing overall plant efficiency by utilizing exhaust heat for secondary power production (Rezaie *et al.,* 2018). These systems achieve higher efficiencies compared to conventional power plants due to improved energy utilization.

Despite this advantage, exhaust flue gas temperatures in HRSG systems often remain around 200°C, indicating incomplete heat recovery and potential energy loss. This highlights the need for further optimization of heat exchange processes to maximize energy extraction under varying operating conditions (Jong & Sang, 2008).

In the Nigerian context, the use of low-sulphur natural gas ("sweet gas") provides favorable conditions for low-temperature heat recovery by minimizing sulphur oxide (SO_x) formation and corrosion risks. This creates an opportunity to extend heat recovery to lower temperature levels without compromising system integrity.

Therefore, this study focuses on optimizing HRSG performance by reducing exhaust flue gas temperature from approximately 200°C to 60°C through the integration of an additional heat exchanger. The recovered energy is utilized for heating potable water, thereby replacing conventional electric heaters, improving energy efficiency, reducing operational costs, and supporting sustainable energy utilization.

The operation of Heat Recovery Steam Generators (HRSG) in combined cycle power plants is still associated with significant inefficiencies due to high exhaust flue gas temperatures of approximately 200°C, indicating substantial unrecovered thermal energy. This limitation reduces overall system efficiency and contributes to unnecessary energy losses and environmental impacts.

Despite the importance of HRSG optimization, there is limited implementation of integrated approaches aimed at reducing exhaust gas temperatures while simultaneously recovering usable low-grade heat. In particular, achieving a target reduction to 60°C remains a technical challenge within existing configurations.

Furthermore, a large amount of recoverable thermal energy from HRSG exhaust is currently underutilized and replaced by electrically powered heaters across industrial facilities. This results in increased operational costs and higher energy demand. There is therefore a need to develop an improved waste heat recovery strategy that enhances HRSG performance, reduces dependence on electric heaters, and supports sustainable energy utilization within industrial complexes.

The aim of this study is to optimize a single-pressure Heat Recovery Steam Generator (HRSG) system using Aspen Plus simulation to enhance thermal efficiency and improve waste heat recovery through low-temperature energy utilization. Reduce the exhaust flue gas temperature from approximately 200°C to 60°C through HRSG system optimization.

Evaluate the recovery of waste heat for potable water heating and assess its capability to replace approximately 550 units of 3 kW electric heaters within the plant. Improve overall HRSG thermal performance by enhancing heat recovery effectiveness and increasing system efficiency.

This study provides a practical and scalable approach to improving energy recovery in combined cycle gas turbine (CCGT) plants through optimized Heat Recovery Steam Generator (HRSG) performance. By integrating a secondary heat exchanger, the research demonstrates the possibility of reducing exhaust flue gas temperature from approximately 200°C to 60°C, thereby significantly improving low-grade heat utilization.

A key outcome of the study is the recovery of waste heat sufficient to offset approximately 550 units of 3 kW electric heaters, resulting in a daily energy saving of about 11.55 MWh. This reduction in electrical heating demand translates directly into lower operational costs and improved overall plant energy efficiency.

The proposed system also enhances thermal performance by increasing HRSG heat duty and improving system efficiency, making it suitable for industrial-scale implementation. In addition, the approach supports environmental sustainability by reducing fuel-based electricity consumption and associated emissions.

The findings are particularly relevant to industrial facilities such as Eleme Petrochemicals and similar energy-intensive complexes, where waste heat recovery can be integrated into existing infrastructure for process heating, potable water production, and future expansion needs. Overall, the study contributes to improved energy management, operational efficiency, and sustainable industrial development.

This study focuses on the optimization of a single-pressure HRSG system through the integration of a secondary heat exchanger (Preheater-2) to enhance low-temperature heat recovery. The analysis is limited to conventional shell-and-tube heat exchanger configurations in gas turbine HRSG applications.

The work evaluates thermodynamic performance, temperature profiles, and heat transfer behavior using Aspen Plus simulation for system modelling and assessment.

The scope excludes advanced heat exchanger technologies and non-power applications, and is restricted to simulation-based analysis without experimental or prototype validation.

This study advances HRSG optimization by demonstrating effective low-temperature waste heat recovery in combined cycle gas turbine systems through the integration of a secondary heat exchanger (Preheater-2).

The configuration reduces flue gas temperature from about 200°C to 60°C, improving overall thermal and exergy performance. It also shows that recovered heat can be effectively used for potable water heating, reducing reliance on electric heaters in industrial applications.

Overall, the findings provide practical design and operational insights for engineers and manufacturers, supporting improved energy efficiency, lower operating costs, and enhanced sustainability in gas turbine-based power plants.

2.0 RESEARCH METHODOLOGY

Modeling Techniques

This study presents a systematic methodology for reducing HRSG exhaust flue gas temperature from 200°C to 60°C through thermodynamic modeling, Aspen Plus simulation, and parametric analysis of key operating variables. The recovered low-grade heat is further evaluated for useful energy recovery, displacing approximately 550 portable electric heaters (3 kW each) operating at MCR for 7 hours per day. This demonstrates significant potential for improved plant energy efficiency through thermal energy recovery and cascading applications, including hot water generation and auxiliary industrial heating.

Assumption:

The HRSG system was modeled under the following thermodynamic assumptions to simplify analysis and enable reliable simulation:

i. The system operates under steady-state conditions, with constant mass flow rate, temperature, and pressure over time.
ii. The working fluid is treated as an ideal gas, governed by the ideal gas relationship ($PV = nRT$).
iii. Heat losses to the surroundings are considered negligible, and the system is assumed to be adiabatic.
iv. Specific heat capacities of the working fluids are assumed constant over the operating temperature range.
v. Thermodynamic properties are assumed uniform within each control volume, indicating local equilibrium conditions.

These assumptions idealize the HRSG system to facilitate thermodynamic modeling and performance evaluation. The resulting simulation provides a consistent basis for comparative and parametric analysis, enabling validation of system behavior through empirical and graphical correlation of results.

System Description:

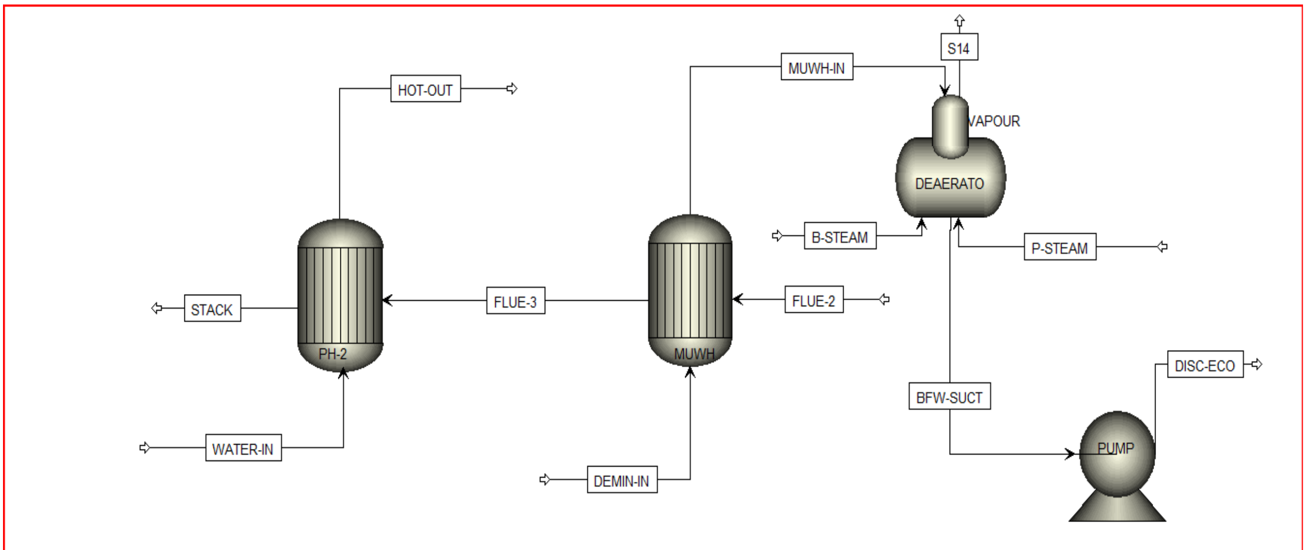


Figure 3.1: Schematic diagram of Deaerator Process Flow

The Heat Recovery Steam Generator (HRSG) recovers thermal energy from gas turbine exhaust to generate steam, thereby improving combined-cycle efficiency through utilization of otherwise wasted heat. The system operates on a counterflow configuration to enhance temperature gradients and maximize heat transfer effectiveness across heat exchange sections.

Gas turbine exhaust enters the HRSG at 520°C, with a mass flow rate of 25.28**kg/s** and pressure of 0.190kg/cm². The flue gas sequentially flows through the primary and secondary superheaters, HP evaporator (boiler bank), HP economizer, and Make-Up Water Heater (MUWH/Preheater-1) before exiting the stack at approximately 200°C and 0.0528kg/cm². Gas routing is controlled by a diverter damper system, including a guillotine damper, which enables mode switching between combined-cycle and bypass operation while preventing backflow during transients.

Boiler feedwater enters the system as demineralized water at 45°C, 16kg/cm², and 45,000 kg/h. In the MUWH, residual flue gas heat increases the water temperature to approximately 90°C, reducing external steam demand in downstream processes.

The preheated water is then directed to the deaerator, where its temperature is raised to 117°C using flash steam from Continuous Blowdown (CBD), pegging steam, and startup auxiliary steam. Under normal operation, pegging steam demand is significantly reduced due to MUWH preheating.

The deaerated feedwater is pressurized using an 8-stage centrifugal pump (1.3–85kg/cm², 63.93 A) and routed through the economizer (50.3kg/cm²) to the steam drum at approximately 260°C. In the evaporator section, saturated steam is generated and subsequently superheated through primary and secondary superheaters.

Final steam conditions at the plant header are:

- Temperature: 400°C
- Pressure: 48kg/cm²
- Flow rate: 50,000 kg/h

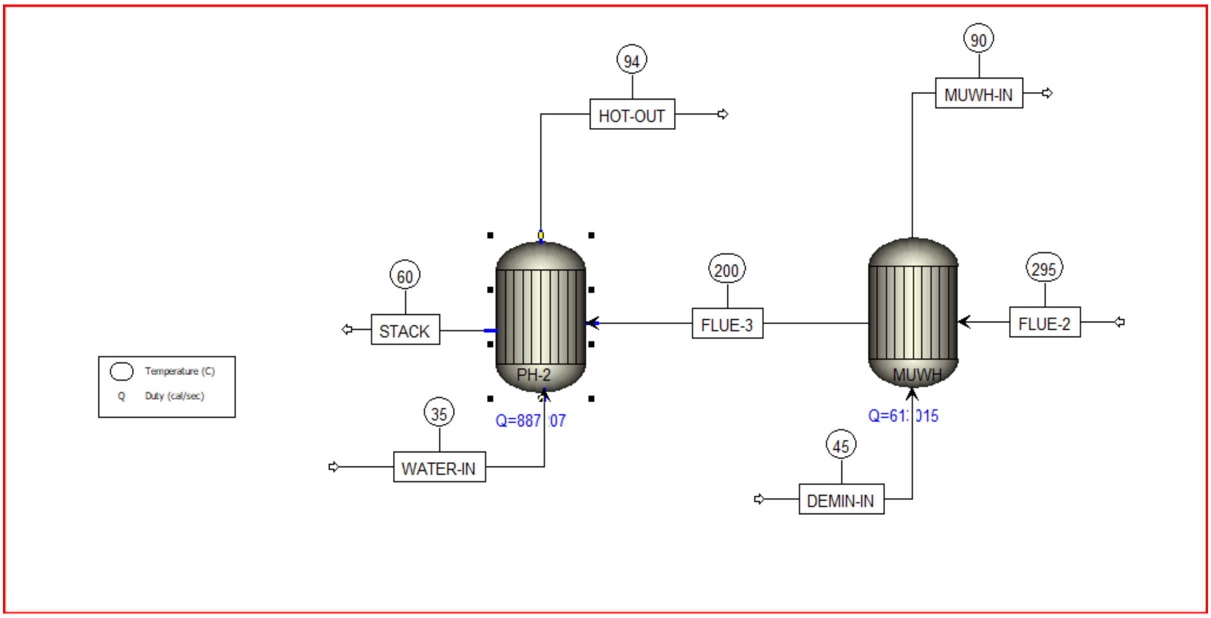


Figure 3.2: Schematic diagram of Preheater-2 Process Flow

Thermodynamic Analysis of Gas Power Cycle

In the gas turbine topping cycle, data used in computing the work output and thermal efficiency were obtained from the research work on power station.

Using the states in Figure the turbine work (WT) in the gas power cycle is given by:

The compressor work of the gas turbine (W_{cg})

$$W_{cgt} = M_a C_{pa}(T_6 - T_7) \quad (3.1)$$

$$T_6 = T_5\left\{1 + \frac{(r_p{}^{\beta}-1)}{\eta_c}\right\} \quad (3.2)$$

The gas turbine work in the gas power plant (W_{Tg})

$$W_{Tg} = M_g C_{pg}(T_7 - T_8) \quad (3.3)$$

$T_8 = T_8$Network output in the gas power plant (W_{netg})

$$W_{net} = W_{tg} - W_{cg} \quad (3.4)$$

Heat supply(Q_g) in the combustor of the GT

$$Q_g = m_g C_{pg} T_7 - M_a C_{pa} T_6 \quad (3.5)$$

The system efficiency (η_{gt}) (combine cycle)

$$\eta_{gc} = \frac{W_{netg}}{Q_g} \quad (3.6)$$

In figure 3.13 Thermodynamic analysis of the HRSG A single pressure HRSG is installed to replace the boiler in the steam power plant. The HRSG is expected to reduce the exhaust gas temperature of the gas power cycle before it exhausts to the atmosphere while generating superheated steam for the steam power plant operation.

$$HRSG = M_{,w}(h_6 - h_7) = M_g C_{pg} \quad (3.7)$$

Steam turbine $M_w(h_6 - h_7) = W_{st}$ (3.8)

The heat recovered from the exhaust gases (Q_r) is given by:

$$Qr = m_{ex}cp_{ex}(T_8 - T_9) \qquad (3.9)$$

The portion of the recovered heat transferred in the HRSG which is used to generate steam is given by:

$$Q_s = \varepsilon Q_r \qquad (3.10)$$

Data Collection

Operational Parameters:

Operational data were collected from key HRSG sections, including inlet and outlet temperatures, mass flow rates, and pressure drops. These parameters were used to validate the Aspen Plus simulation model and ensure accuracy of the predicted thermodynamic performance.

Detailed temperature measurements were also taken at the HRSG exhaust to evaluate flue gas cooling behavior and heat recovery effectiveness. Thermocouples and calibrated sensing instruments were employed to obtain accurate temperature profiles, enabling assessment of heat transfer performance and identification of potential optimization opportunities.

Design Parameters & Optimization Strategic

The design of the shell-and-tube heat exchangers was optimized to enhance heat recovery performance while minimizing pressure losses. Material selection was based on thermal conductivity, mechanical strength, and high-temperature resistance. Carbon steel (45–60 W/m·K) and stainless steel (14–16 W/m·K) were selected for the shell and tube components due to their structural integrity and thermal suitability under flue gas conditions. In sections requiring enhanced heat transfer, aluminum fins (≈205 W/m·K) were incorporated to increase effective heat transfer surface area.

In addition, the tube bundle arrangement and flow configuration were optimized to improve heat transfer efficiency and reduce hydraulic resistance, thereby enhancing overall system performance.

Control Systems and Calibrations (Aspen Plus Control Logic)

The HRSG Preheater-2 uses a multi-loop PID control system to maintain stable and efficient operation. The primary loop regulates flue gas outlet temperature at 60°C by adjusting water flow.

Supervisory loop prevents overheating by limiting hot water temperature to 80°C, while a bypass loop provides protection under high-load conditions, though it remains inactive in this study.

Overall, the system ensures stable performance, safety, and efficient heat recovery.

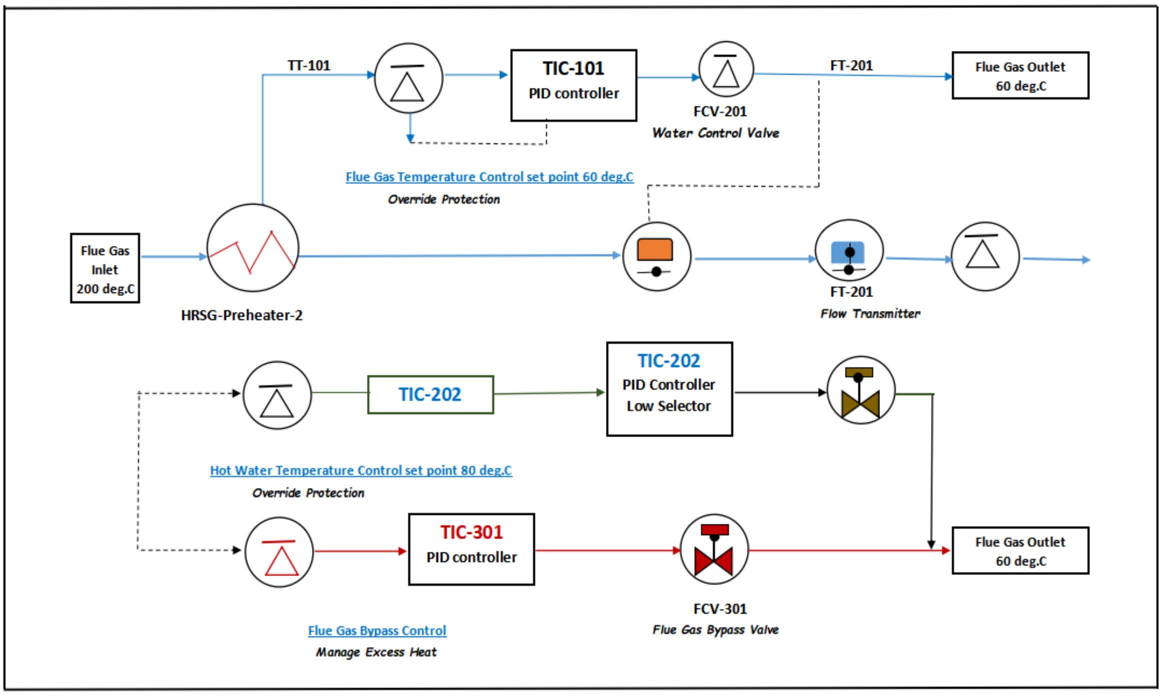


Figure 3.3: Schematic diagram of Preheater-2 Control Systems and Calibrations Logic

3.0 RESULTS AND DISCUSSION

Baseline HRSG Performance (Before Optimization)

The baseline performance of the HRSG was evaluated using Aspen Plus under steady-state conditions to represent the plant's existing configuration without the proposed Preheater-2. This assessment establishes a reference for identifying unused thermal energy and measuring potential improvements.

In the current setup, gas turbine exhaust flows through the economizer, evaporator, superheater, and

MUWH. While the MUWH recovers heat to preheat make-up water and improve cycle efficiency, the flue gas still exits at 190–200°C, indicating significant unrecovered low-grade heat that is discharged to the atmosphere.

The simulation, based on real plant data, confirms this inefficiency and highlights the absence of any downstream heat recovery for auxiliary applications such as potable water heating.

Baseline operating conditions:
Gas Turbine Output: 686.30 MW
Steam Turbine Output: 786.38 MW
Natural Gas Consumption: 244,400 KSm³/day
Thermal Efficiency: 61.25%

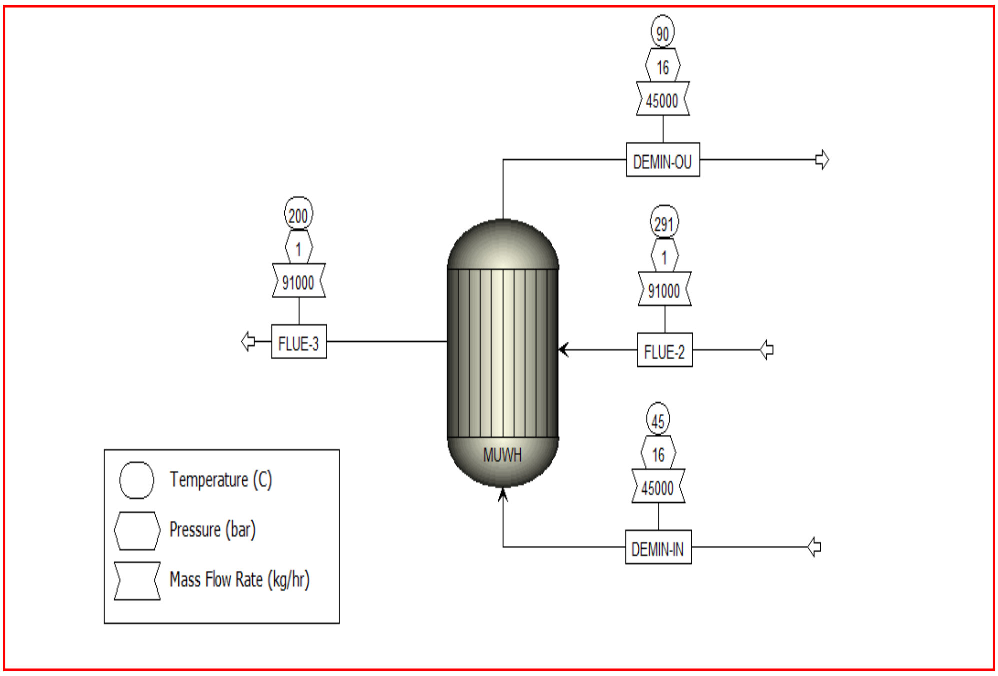
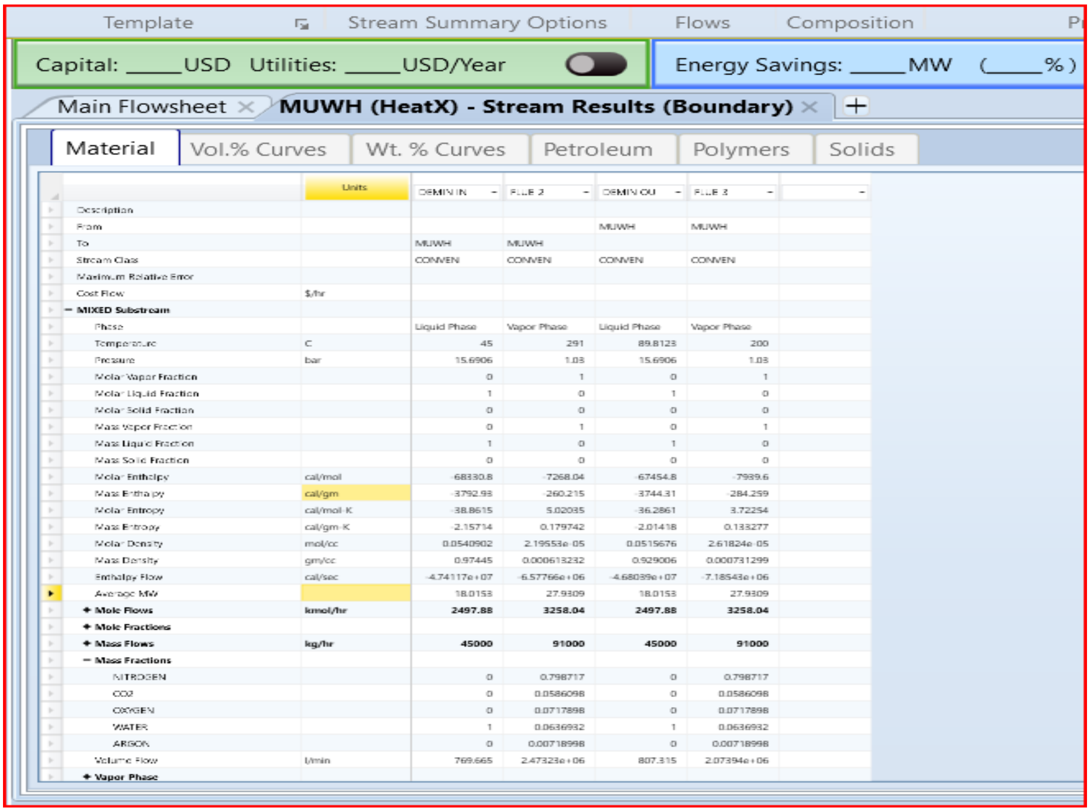


Figure 4.1: Schematic diagram of MUWH Process Flow



	Units	DEMIN IN	FLUE 2	DEMIN OU	FLUE 3
Description					
From				MUWH	MUWH
To		MUWH	MUWH		
Stream Class		CONVEN	CONVEN	CONVEN	CONVEN
Maximum Relative Error					
Cost Flow	$/hr				
− MIXED Substream					
Phase		Liquid Phase	Vapor Phase	Liquid Phase	Vapor Phase
Temperature	C	45	291	89.8123	200
Pressure	bar	15.6906	1.03	15.6906	1.03
Molar Vapor Fraction		0	1	0	1
Molar Liquid Fraction		1	0	1	0
Molar Solid Fraction		0	0	0	0
Mass Vapor Fraction		0	1	0	1
Mass Liquid Fraction		1	0	1	0
Mass Solid Fraction		0	0	0	0
Molar Enthalpy	cal/mol	-68330.8	-7268.04	-67454.8	-7939.6
Mass Enthalpy	cal/gm	-3792.93	-260.215	-3744.31	-284.259
Molar Entropy	cal/mol-K	-38.8615	5.02035	-36.2861	3.72254
Mass Entropy	cal/gm-K	-2.15714	0.179742	-2.01418	0.133277
Molar Density	mol/cc	0.0540902	2.19553e-05	0.0515676	2.61824e-05
Mass Density	gm/cc	0.97445	0.000613232	0.929006	0.000731299
Enthalpy Flow	cal/sec	-4.74117e+07	-6.57766e+06	-4.68039e+07	-7.18543e+06
Average MW		18.0153	27.9309	18.0153	27.9309
+ Mole Flows	kmol/hr	2497.88	3258.04	2497.88	3258.04
+ Mole Fractions					
+ Mass Flows	kg/hr	45000	91000	45000	91000
− Mass Fractions					
NITROGEN		0	0.798717	0	0.798717
CO2		0	0.0586098	0	0.0586098
OXYGEN		0	0.0717898	0	0.0717898
WATER		1	0.0636932	1	0.0636932
ARGON		0	0.00718998	0	0.00718998
Volume Flow	l/min	769.665	2.47323e+06	807.315	2.07394e+06
+ Vapor Phase					

Fig. 4.2: Simulation Result of Baseline (MUWH)

Baseline Simulation Result Discussion.

The baseline Aspen Plus results indicate that the MUWH recovers 2.564 MW (613,015 Cal/s) of heat; however, the flue gas still exits at about 200°C, confirming substantial unrecovered low-grade thermal energy.

This aligns with Zhang *et al.,* (2025), who noted that conventional HRSG systems typically discharge significant residual heat due to limited recovery capacity in primary heat exchangers.

Therefore, the elevated stack temperature establishes a clear technical justification for introducing Preheater-2 downstream of the MUWH to further recover waste heat, reduce exhaust temperature, and improve overall system efficiency.

Optimized Configuration Results (With Additional Heat Exchanger)

The optimized HRSG configuration incorporates an additional low-temperature heat exchanger (Preheater-2) downstream of the MUWH to recover residual flue gas heat for potable water heating.

Simulation results show that flue gas enters Preheater-2 at approximately 200°C and is cooled to about 60°C at the stack outlet, confirming effective recovery of low-grade thermal energy.

This significant temperature reduction demonstrates improved heat utilization, enhanced system performance, and a reduction in thermal emissions, thereby improving overall HRSG efficiency and environmental performance.

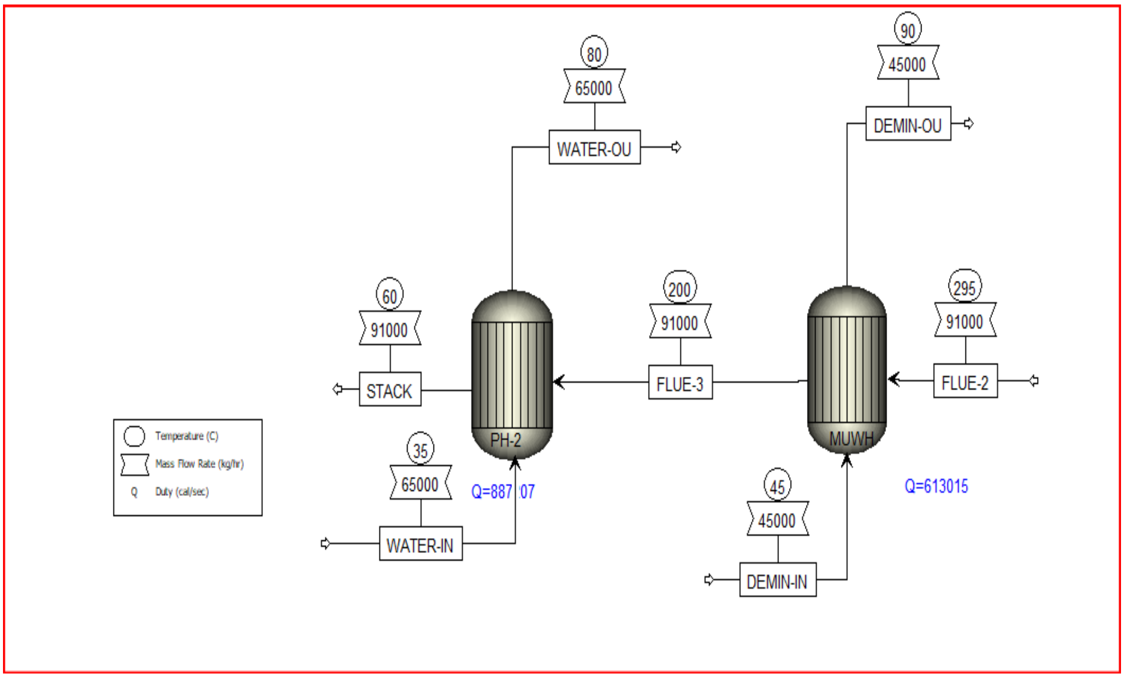


Figure 4.3: Schematic diagram of Optimized Preheater Process Flow

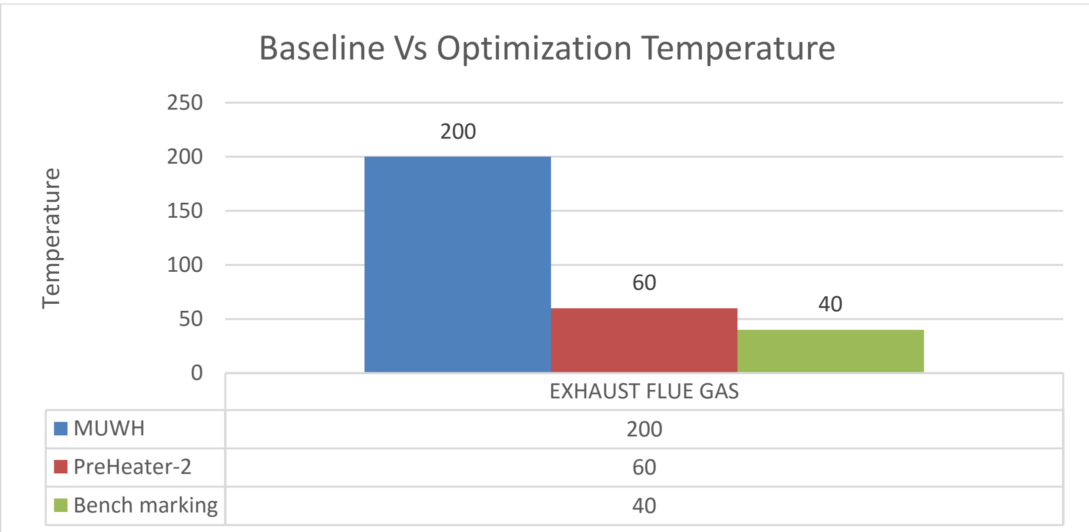


Figure 4.4: Flue Gas Baseline Vs Preheater Temperature

RESULT DISCUSSION

The integration of Preheater-2 reduces flue gas temperature from 200°C to 60°C, indicating significantly improved heat recovery and reduced stack losses. This confirms effective capture of previously wasted low-grade thermal energy.

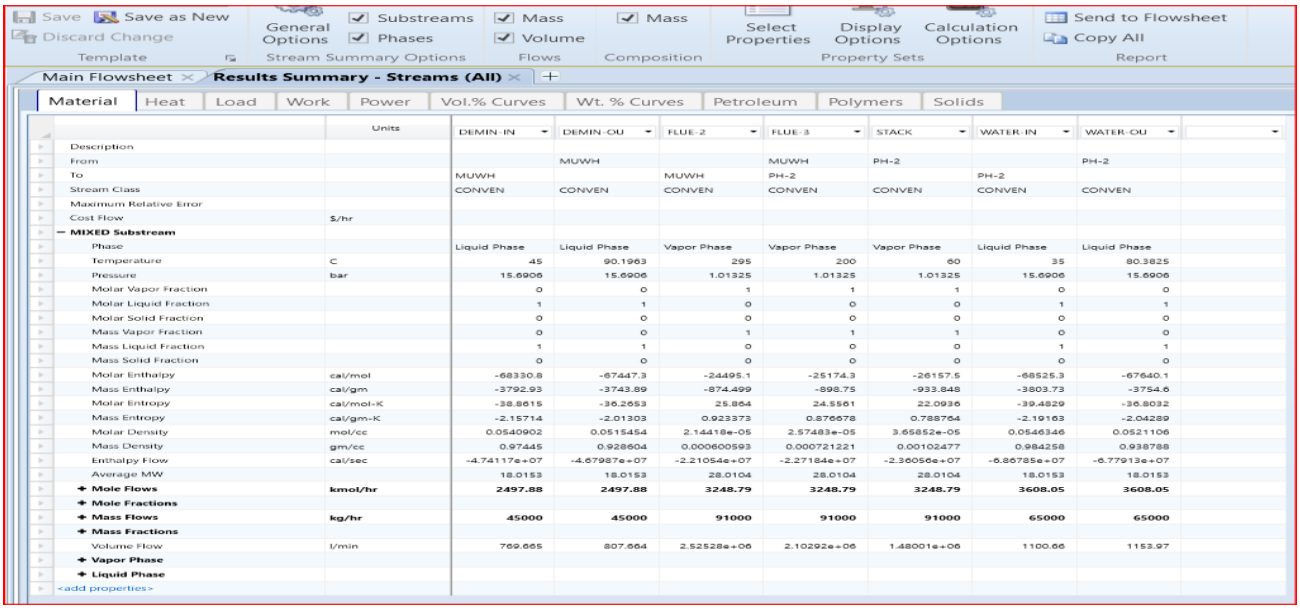
The result is consistent with Zhang et al. (2025), who reported improved efficiency through additional downstream heat recovery stages.

In this study, the recovered heat is applied to potable water heating, replacing about 550 electric heaters, thereby reducing electrical consumption and improving overall energy utilization while also lowering thermal emissions.

Table 4.1: Potable Water Heating Performance

System	Recovered Heat	Performance Impact
Benchmark (Zhang *et al.,* (2025)	District-heating/hot water supply via absorption heat pump	Increased Heating capacity and efficiency (12.18%)
Preheater-2	Portable water heating, replacing electric heaters	Reduced electrical demand and increased efficiency and heat utilization.

This demonstrates strong performance improvement in both cases through staged heat-recovery integration.



	Units	DEMIN-IN	DEMIN-OU	FLUE-2	FLUE-3	STACK	WATER-IN	WATER-OU
Description								
From			MUWH		MUWH	PH-2		PH-2
To		MUWH		MUWH	PH-2		PH-2	
Stream Class		CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN
Maximum Relative Error								
Cost Flow	$/hr							
− MIXED Substream								
Phase		Liquid Phase	Liquid Phase	Vapor Phase	Vapor Phase	Vapor Phase	Liquid Phase	Liquid Phase
Temperature	C	45	90.1963	295	200	60	35	80.3825
Pressure	bar	15.6906	15.6906	1.01325	1.01325	1.01325	15.6906	15.6906
Molar Vapor Fraction		0	0	1	1	1	0	0
Molar Liquid Fraction		1	1	0	0	0	1	1
Molar Solid Fraction		0	0	0	0	0	0	0
Mass Vapor Fraction		0	0	1	1	1	0	0
Mass Liquid Fraction		1	1	0	0	0	1	1
Mass Solid Fraction		0	0	0	0	0	0	0
Molar Enthalpy	cal/mol	-68330.8	-67447.3	-24495.1	-25174.3	-26157.5	-68525.3	-67640.1
Mass Enthalpy	cal/gm	-3792.93	-3743.89	-874.499	-898.75	-933.848	-3803.73	-3754.6
Molar Entropy	cal/mol-K	-38.8615	-36.2653	25.864	24.5561	22.0936	-39.4829	-36.8032
Mass Entropy	cal/gm-K	-2.15714	-2.01303	0.923373	0.876678	0.788764	-2.19163	-2.04289
Molar Density	mol/cc	0.0540902	0.0515454	2.14418e-05	2.57483e-05	3.65852e-05	0.0546346	0.0521106
Mass Density	gm/cc	0.97445	0.928604	0.000600593	0.000721221	0.00102477	0.984258	0.938788
Enthalpy Flow	cal/sec	-4.74117e+07	-4.67987e+07	-2.21054e+07	-2.27184e+07	-2.36056e+07	-6.86785e+07	-6.77913e+07
Average MW		18.0153	18.0153	28.0104	28.0104	28.0104	18.0153	18.0153
+ Mole Flows	kmol/hr	2497.88	2497.88	3248.79	3248.79	3248.79	3608.05	3608.05
+ Mole Fractions								
+ Mass Flows	kg/hr	45000	45000	91000	91000	91000	65000	65000
+ Mass Fractions								
Volume Flow	l/min	769.665	807.664	2.52528e+06	2.10292e+06	1.48001e+06	1100.66	1153.97
+ Vapor Phase								
+ Liquid Phase								
<add properties>								

Figure 4.5: Stream Summary Result of Temperature and Mass Flow

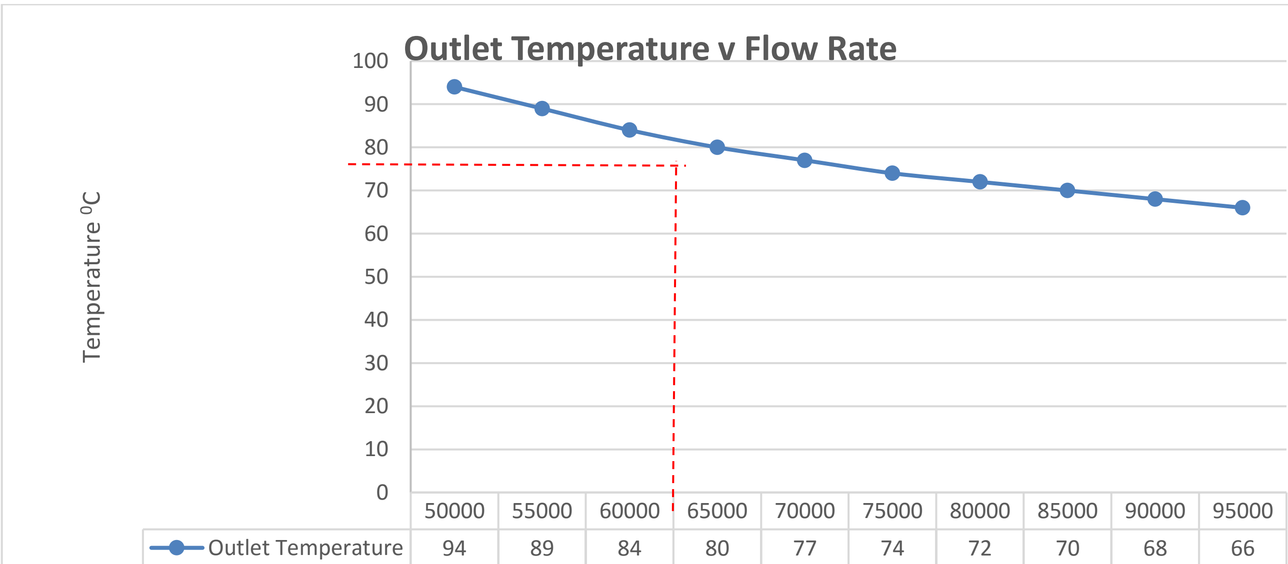


Figure 4.6: Outlet Temperature vs Portable Water Flow Rate Graph

The optimized HRSG system effectively recovers waste heat, increasing potable water temperature from 35°C to 66–94°C depending on flow rate. An inverse relationship is observed where higher flow rates reduce outlet temperature due to shorter residence time and lower heat transfer per unit mass.

An optimal condition occurs at 65,000 kg/h, producing about 80°C, suitable for domestic hot water use and enabling replacement of electric heaters, resulting in notable energy savings.

Overall, a ~45°C temperature rise confirms strong thermal performance of Preheater-2 while maintaining stable flue gas conditions at 91,000 kg/h and a well-balanced system operation.

(ii) Heat Duty

The optimized system successfully recovers waste heat, increasing potable water temperature from 35°C to 66–94°C, with performance decreasing as flow rate increases due to reduced heat transfer per unit mass.

The optimal operating point of 65,000 kg/h yields about 80°C, suitable for domestic use and enabling displacement of electric heaters.

Overall, a ~45°C temperature rise confirms effective performance of Preheater-2 under stable flue gas conditions.

Calculation Summary
Baseline Heat Duty (MUWH only)
Given or calculated from plant data, e.g., 613,015 kcal/s
$Q_{baseline}$ = <u>2.564MW</u>
Optimization Heat Duty (MUWH & Preheater-2)

Calculated as
$Q = \dot{m} \times Cp \times \Delta T = [18.06 \times 1 \times (80-35)] = 887.207$ kcal/s
$Q_{optimized}$ = <u>3.711MW</u>

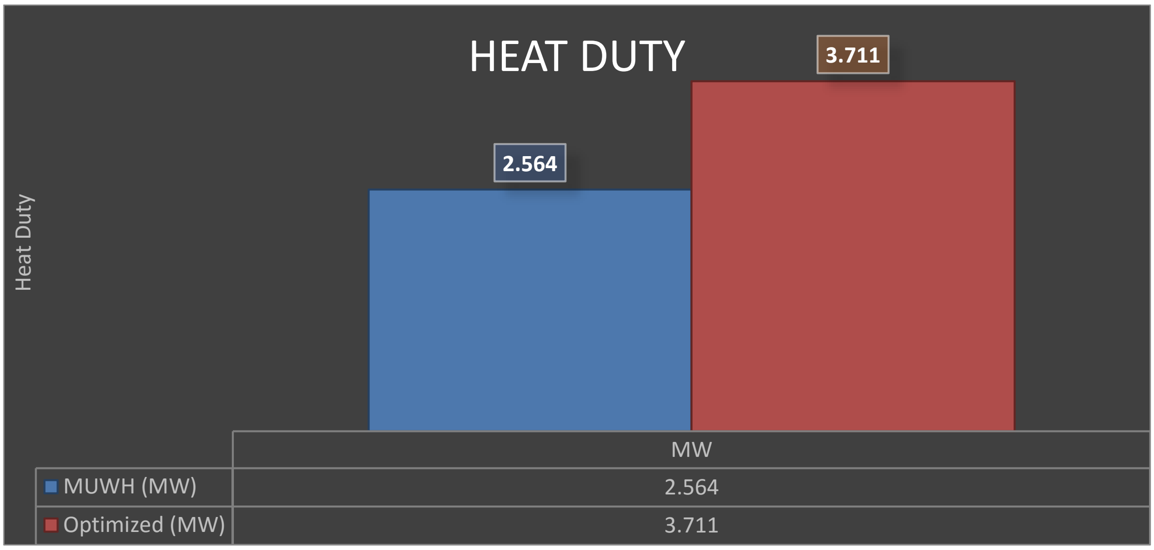


Figure 4.7: Heat Duty of MUWH vs Optimized Preheater Chart

Heat duty increases from 2.564 MW (baseline) to 3.71 MW (optimized), indicating a 45.76% improvement in waste heat recovery due to Preheater-2 integration.

This confirms effective utilization of residual flue gas heat (~200°C outlet from MUWH) for potable water heating, validating the additional heat exchanger's performance.

Overall, the system shows improved energy recovery, reduced losses, and enhanced HRSG efficiency.

$$Q_{in} = 244.400 \times 35.8 = 8750{,}720\ MJ/d$$

$$Q_{in} = 2430.78 \text{ Mwh.}$$

$$P_{optimized}d = 3.711 \times 24 = 89.06\ Mwh$$

Total Power Output = $P_T + P_S + P_{optimized}$

$$P_{Total=}686 + 786.38 + 89.064 = 1{,}561.744Mwh$$

Overall Thermal Efficiency (ŋ) $= \frac{1{,}561.744}{2430.76}\ Mwh$

$$\eta = 64.78\%$$

The integration of Preheater-2 reduces flue gas temperature from 200°C to 60°C, enabling recovery of 3.711 MW of low-grade heat and improving plant thermal efficiency from 61.25% to 64.76% (a 3.51 percentage-point or 5.73% relative increase). This recovered energy is used for potable water heating, replacing approximately 550 electric heaters and eliminating their electrical demand.

Compared with Zhang et al. (2025), which achieved deeper cooling to 40°C and a 12.18% efficiency gain via district heating, the present study applies the same waste-heat recovery principle but for potable water production, achieving meaningful efficiency improvement within HRSG operational limits.

Energy analysis shows that eliminating electric heaters reduces daily consumption from 2,823.37 MWh to 2,811.82 MWh, saving 11.55 MWh/day (0.41%). This recovered energy can be reallocated to auxiliary loads or operational support systems, improving overall plant energy management and flexibility.

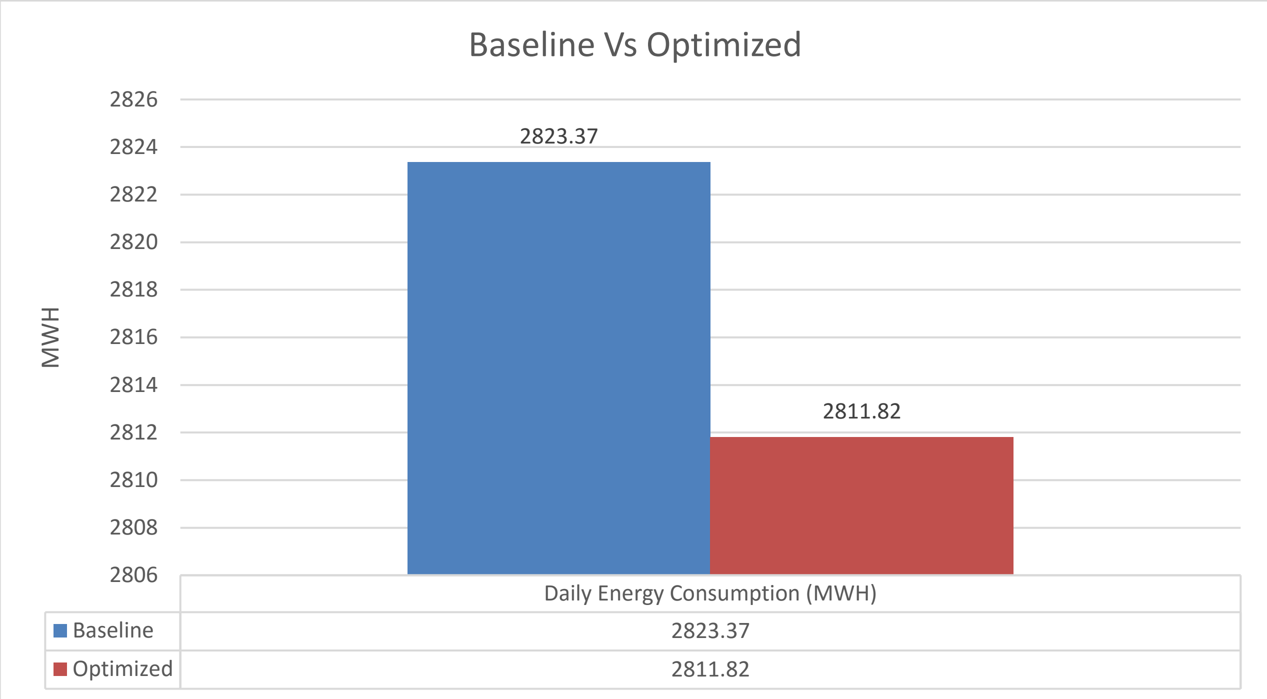


Figure. 4.8: Daily Energy Consumption of Baseline vs Optimized Chart

Exergy Analysis

Exergy analysis was conducted to evaluate the quality of the recovered heat from Preheater-2. The potable water is heated from 35°C to 80°C, using a reference environmental temperature of 25°C, a mass flow rate of 18.06kg/s, and a specific heat capacity of 4.18 kJ/kg·K.

The results show that the recovered 3.711 MW of thermal energy contains about 3.48 MW of useful exergy, indicating a high proportion of usable energy.

This confirms that the recovered heat is not only significant in quantity but also high in quality, making it suitable for replacing electric heaters and improving overall system efficiency.

Economic Savings / Cost Analysis

The integration of Preheater-2 provides significant economic benefits by replacing electric water heaters with recovered waste heat. The 550 electric heaters (3 kW each, 7 h/day) consume about 11,550 kWh/day, costing approximately ₦808,500 per day at ₦70/kWh.

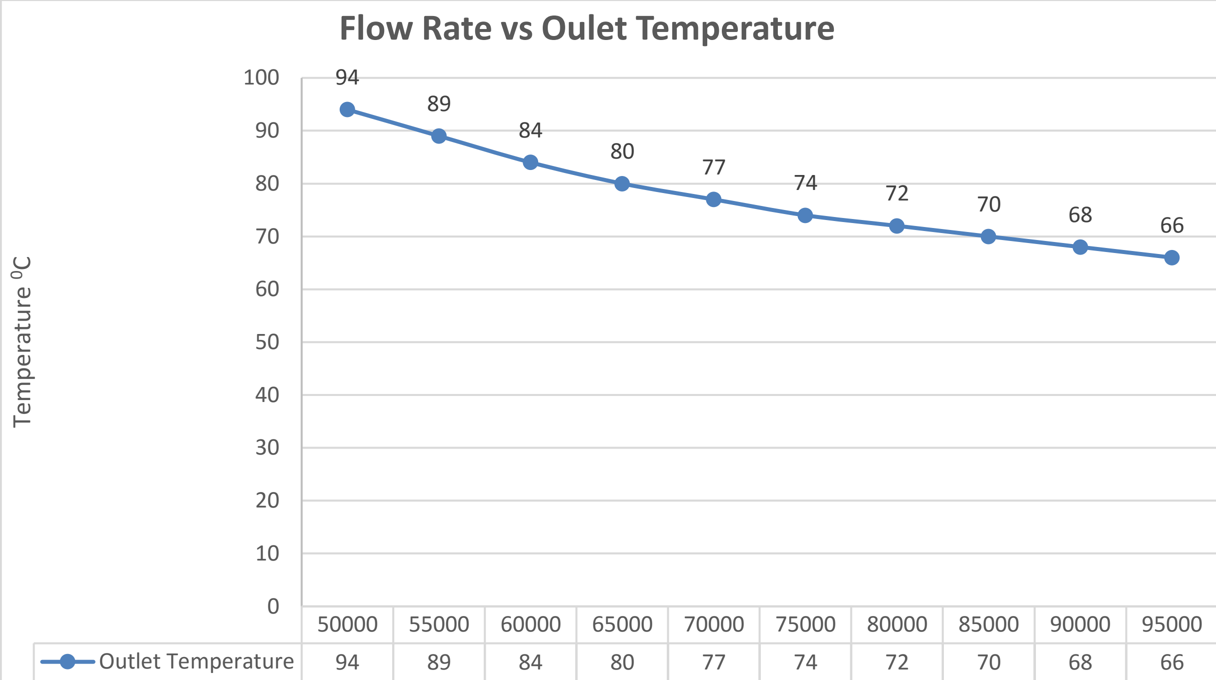
This translates to monthly savings of about ₦24.26 million and annual savings of approximately ₦294.1 million.

With these savings, the payback period is around 6 months, while the Levelized Cost of Heat is reduced by about 97% compared to electric heating.

Overall, the results confirm strong economic viability and justify full implementation of the HRSG waste heat recovery system.

Sensitivity Analysis

This section consolidates the results obtained from key sensitivity analyses conducted on the optimized HRSG configuration. The variables explored include potable water flow rate, outlet temperature, heat duty, thermal efficiency, and exergy recovery. The summary enables a clear visualization of how each parameter responds to variation in system conditions, and helps evaluate system performance optimization under different scenarios.



Water Flow vs Outlet Temperature:

Outlet temperature decreases as water flow rate increases due to reduced residence time and lower heat absorption per unit mass. At 50,000 kg/h, longer residence time allows heating up to about 94°C, while at 95,000 kg/h it drops to around 66°C.

The trend shows diminishing sensitivity at higher flow rates, confirming reduced thermal effectiveness as flow increases.

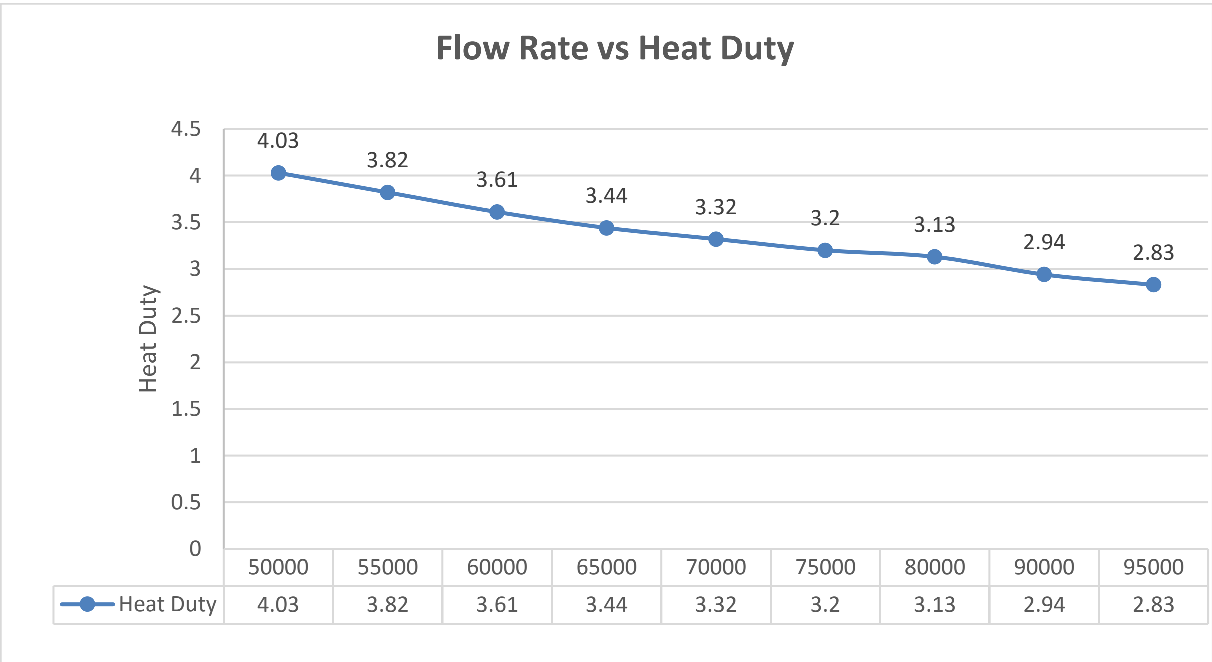


Figure 4.10: Water Flow vs Heat Duty Graph

Water Flow Rate vs Heat Duty:

Heat duty increases at low flow rates due to better residence time and heat transfer. Beyond about 65,000 kg/h, reduced residence time limits heat exchange, causing heat duty to level off or slightly decrease.

This indicates an operating limit where higher flow rates reduce thermal efficiency and overall heat recovery effectiveness.

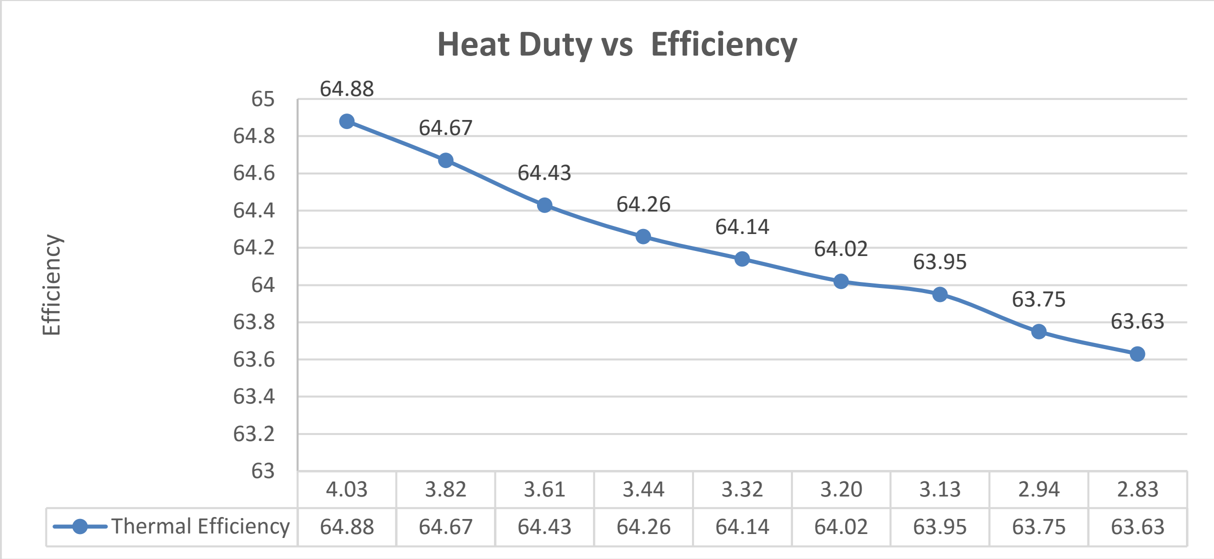


Figure 4.11: Heat Duty vs Thermal Efficiency Graph

Heat Duty vs Thermal Efficiency:

The relationship shows that thermal efficiency increases with heat duty, since higher heat transfer improves recovery of available thermal energy.

At about 4.03 MW heat duty, efficiency reaches a maximum of ~64.88%, while at 2.83 MW it drops to ~63.63%. This indicates that improved heat recovery directly enhances system performance.

Overall, the trend confirms that maximizing heat duty leads to better HRSG efficiency, although the change in efficiency is relatively moderate across the range.

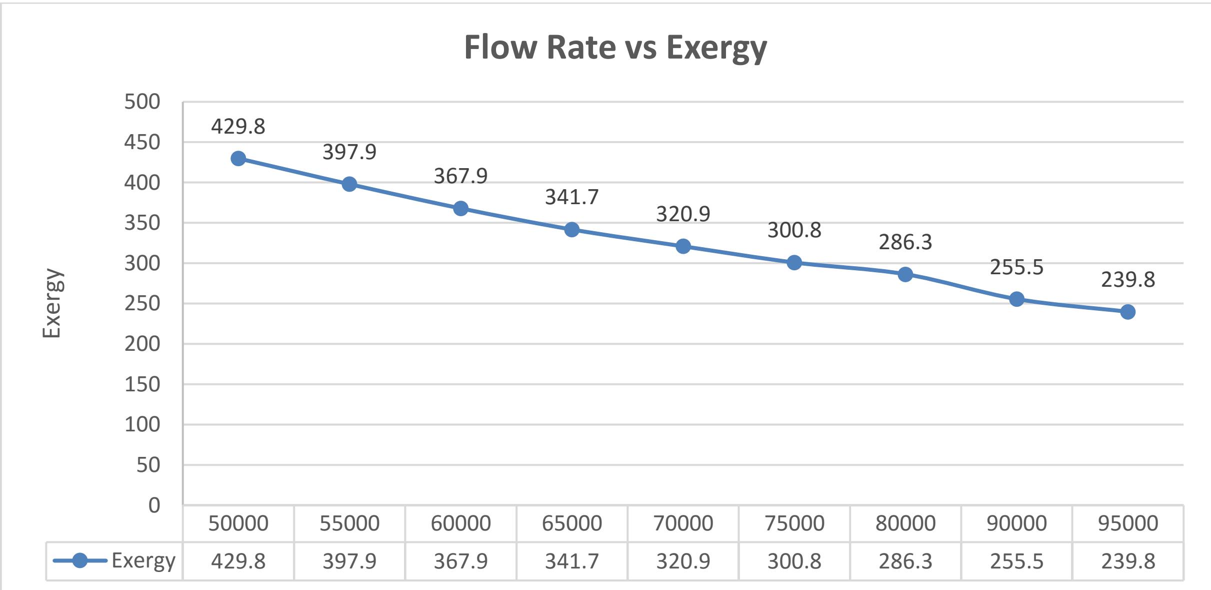


Figure 4.12: Flow vs Exergy Graph

Flow Rate vs Exergy Recovery:

Exergy recovery reduces with increasing flow rate. It is highest (~429.8 kW) at 50,000 kg/h and decreases to ~239.8 kW at 95,000 kg/h due to reduced residence time and lower heat transfer per unit mass.

5.0 CONCLUSIONS

The integration of a low-temperature heat exchanger (Preheater-2) into an existing HRSG significantly improved waste heat recovery by utilizing flue gas downstream of the MUWH. Simulation results showed a reduction in flue gas temperature from ~200°C to 60°C, a 32.7% increase in heat duty (2.546 MW to 3.711 MW), and an improvement in thermal efficiency from 61.25% to 64.76%.

The optimized system successfully heated potable water from 35°C to 60–90°C (optimal ≈80°C at 65,000 kg/h), enabling displacement of ~550 electric heaters and achieving ~11.55 MWh/day energy savings. Exergy analysis confirmed reduced irreversibility and improved energy quality utilization, while sensitivity analysis identified water flow rate as the key performance driver.

Overall, the study validates that secondary low-grade heat recovery in HRSG systems enhances efficiency, reduces energy consumption, and provides viable environmental and economic benefits.

Recommendations

Preheater-2 should be considered for full-scale HRSG integration following OEM validation. Electric heater usage should be progressively replaced to realize energy savings. Optimal operation is achieved by maintaining potable water flow at 60,000–70,000 kg/h.

Routine exergy-based monitoring is recommended to sustain performance improvements, while recovered energy should be integrated into auxiliary plant demand planning. Collaboration with OEMs is encouraged for design refinement.

The project should be extended to include plant-wide exergy assessment, seasonal performance variation, and life-cycle cost analysis to support long-term optimization and investment decisions.

REFERENCES

- Bianchi, M., & De Pascale, A. (2011). Bottoming cycles for electric energy generation: Parametric investigation of available and innovative solutions for low and medium temperature heat sources. *Applied Energy, 88*, 1500–1509.
- Chen, L., Li, Y., & Wang, Y. (2018). Numerical investigation of inlet guide vane on heat transfer in a heat recovery steam generator. *International Journal of Heat and Mass Transfer, 127*, 1241–1252.
- Franco, A., & Casarosa, C. (2002). Increasing efficiency of combined cycle power plants. *Applied Thermal Engineering, 22*(13), 1501–1518.
- H.G. Zhang, Wang, E. H., & Fan, B. Y. (2013). Dual-loop organic Rankine cycle for waste heat recovery. *Applied Energy, 102*, 504–513.
- Khan, M. N., & Tlili, I. (2018). Thermodynamic analysis of combined cycle power plants. *Case Studies in Thermal Engineering, 12*, 166–175.
- Li, H. K., Chen, J. H., Sheng, D. R., & Li, W. (2016). Thermoeconomic analysis of gas-steam combined cycles. *Journal of Zhejiang University (Engineering Science)*.
- Li, M., Wang, J., & Ding, Y. (2019). Optimization of HRSG inlet guide vane. *Energy Conversion and Management, 196*, 112075.
- Liu, T., Zhang, G., Li, Y., & Yang, Y. (2018). Off-design performance of combined cycle plants. *Energy Conversion and Management, 162*, 55–65.
- Macian, V., Serrano, J. R., Dolz, V., & Sanchez, J. (2013). Bottoming Rankine cycle design for waste heat recovery. *Applied Energy, 104*, 758–771.
- Njoku, I. H., Oko, C. O. C., & Ofodu, J. C. (2018). Combined cycle integrated with ORC and absorption cooling. *Cogent Engineering, 5*, 1451426.
- Pan, Z., Ting, M., Li, W.-D., Ma, G.-Y. (2018). High-temperature waste heat recovery heat exchanger design.
- Peris, B., Navarro-Esbri, J., & Moles, F. (2013). ORC waste heat recovery configurations. *Applied Thermal Engineering, 61*, 364–371.
- Polyzakis, A. L., Koroneos, C., & Xydis, G. (2008). Optimum gas turbine cycle selection. *Energy Conversion and Management, 49*, 551–563.
- Sipeng Zhu, Deng, K., & Qu, S. (2013). Exergy analysis of bottoming Rankine cycle. *Energy, 58*, 448–457.
- Taal, M., Bulatov, I., Klemeš, J., & Stehlík, P. (2003). Economic evaluation of retrofit projects. *Applied Energy, 23*, 1819–1833.
- Vaja, L., & Gambaro, A. (2010). ORC bottoming cycle for ICE waste heat recovery. *Energy, 35*, 1084–1094.
- Wang, Y., Li, Y., & Chen, L. (2020). IGV effects on HRSG heat transfer. *International Journal of Thermal Sciences, 147*, 106134.
- Wilcock, R. C., Young, J. B., & Horlock, J. H. (2005). Gas turbine blade cooling and efficiency. *Journal of Engineering for Gas Turbines and Power, 127*, 109–120.
- Yao, H., Sheng, D., Chen, J., Li, W., Wan, A., & Chen, H. (2013). Exergoeconomic analysis of combined cycle systems. *Applied Energy*.
- Young, J. B., & Wilcock, R. C. (2002a). Air-cooled gas turbine thermodynamics. *Journal of Turbomachinery, 124*, 207–213.
- Young, J. B., & Wilcock, R. C. (2002b). Gas turbine coolant flows and losses. *Journal of Turbomachinery, 124*, 214–221.
- Zhang, C., Wang, Y., Zheng, C., & Lou, X. (2006). Exergy cost analysis of coal-fired plants. *Energy Conversion and Management, 47*, 817–843.
- Zhang, G., Zheng, J., & Xie, A. (2016). Combined cycle thermodynamic analysis under design/off-design conditions. *Energy Conversion and Management, 126*, 76–88.
- Zhang, Y., Zhao, C., & Li, Y. (2013). Thermoeconomic cost analysis of combined cycle plants. *Journal of Nanjing Normal University*.
- Zheng, Y. (2015). Steam system optimization in advanced combined cycles. *Energy Construction*, 2, 46–50.
- Zhen, W., & Liqiang, D. (2021). Off-design thermoeconomic performance of gas turbine cycles. *Proceedings of CSEE*, 1–12.