International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048
Volume 10, Issue 6, pp 283-293, June-2026
https://doi.org/10.47001/IRJIET/2026.106036

Pinch Analysis and Simulation on the Utilization of Exhaust Gas as a Gas Fuel Heater for Energy Evaluation of Gas Turbine at Various Operating Loads

[1]Achbar Fauzi, [2]*Marcelinus Christwardana, [3]Berkah Fajar Tamtomo Kiono

[1,2]Master Program of Energy, School of Postgraduate Studies, Diponegoro University, Pleburan, Semarang 50241, Indonesia
[2]Department of Chemistry, Faculty of Science and Mathematics, Diponegoro University, Tembalang, Semarang 50275, Indonesia
[3]Department of Mechanical Engineering, Faculty of Engineering, Diponegoro University, Tembalang, Semarang 50275, Indonesia
*Corresponding Author's E-mail: marcelinus@lecturer.undip.ac.id

Abstract **- This study examines the use of exhaust-gas heat to preheat the gas fuel in the GE 09HA.02 gas turbine. The objective is to evaluate heat recovery potential, pinch point characteristics, and improvements in system energy performance at operating loads of 50%, 75%, and 100%. Pinch analysis and process simulation with DWSIM are employed. In the current configuration, exhaust gas is discharged without heat recovery. In the simulated system, exhaust gas heat is recovered via HX-1 to raise natural gas temperature from 17°C to 215°C before combustion. Results demonstrate that higher operating loads increase recoverable heat, with $Q_{recovered}$ rising from 7.34 MW at 50% load to 9.93 MW at 75% load, and reaching 13.00 MW at 100% load. Pinch point values remain relatively stable at 125.5°C, 126.5°C, and 126.3°C. Implementing the preheater increases turbine power, cycle work, and thermal efficiency across all load conditions. At 100% load, turbine power rises from 999.56 MW to 1016.84 MW, cycle work from 520.36 MW to 538.20 MW, and thermal efficiency from 42.064% to 43.506%. These findings indicate that utilizing exhaust gas heat as a fuel gas heater enhances internal energy efficiency and reduces heat loss in the gas turbine system.**

Keywords: pinch analysis, DWSIM simulation, waste heat recovery, fuel gas pre-heater, GE 09HA.02 gas turbine.

I. INTRODUCTION

Indonesia's national electricity generation system remains in a transitional phase, shifting from the dominance of fossil-fueled power plants toward increased adoption of new and renewable energy sources. Data from the Ministry of Energy and Mineral Resources indicate that, in the first semester of 2025, the installed capacity of national power plants reached approximately 105 GW, with new and renewable energy-based power plants accounting for only 15.2 GW, or 14.5% of the total capacity (Kementerian ESDM, 2025). This demonstrates that fossil-based power plants, including gas-fired units, continue to play a critical role in ensuring electricity system reliability. According to PLN's 2025–2034 RUPTL, gas-fired power plants are planned to remain integral to the power generation system, primarily to support operational flexibility and meet power supply requirements during the energy transition (PT PLN, 2025).

Gas-fired power plants offer operational flexibility, faster start-up times than coal-fired plants, and greater responsiveness to load fluctuations (Gonzalez-Salazar *et al.*, 2018). These attributes make gas turbines particularly suitable for supporting electricity systems that are integrating intermittent renewable energy sources. Despite these advantages, gas turbine operation is challenged by energy efficiency limitations, as a portion of combustion energy is not converted into power but is lost as high-temperature exhaust gas (Kittijungjit *et al.*, 2025). This exhaust gas retains substantial thermal energy, which can be recovered through waste heat recovery systems.

A viable strategy to enhance energy utilization in gas turbines involves using exhaust heat to preheat the fuel gas prior to its entry into the combustion chamber. Preheating the fuel gas increases its temperature, promoting more stable mixing and combustion processes (Hodge *et al.*, 2025). Utilizing exhaust heat in this manner reduces reliance on external energy sources and recovers energy that would otherwise be lost to the environment, thereby improving overall system performance. This approach is consistent with energy conservation principles, as it aims to increase thermal efficiency, lower the heat rate, decrease specific fuel consumption, and potentially reduce carbon emissions (Cerza *et al.*, 2022).

Despite the significant potential of waste heat utilization, effective heat recovery system design requires more than consideration of exhaust gas temperature alone. It is essential to evaluate the compatibility between the temperature profiles of the hot and cold streams to ensure efficient heat transfer. A

International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 10, Issue 6, pp 283-293, June-2026

https://doi.org/10.47001/IRJIET/2026.106036

small temperature difference can require a substantially larger heat exchanger surface area, while an excessive difference results in suboptimal heat recovery and continued energy loss (Kharaji, 2022). Consequently, a systematic approach is required to determine the minimum temperature difference, identify the pinch point, establish minimum utility requirements, and maximize heat recovery potential within the system.

Pinch analysis is an effective method for systematically analyzing heat integration based on thermodynamic principles (Yuan & Mao, 202). By constructing hot and cold composite curves, pinch analysis illustrates the relationship between heat flow from turbine exhaust gas and the cold stream, such as fuel gas or a heat recovery circulation medium. The identified pinch point provides a basis for determining the minimum temperature difference, the direction of heat transfer, and the thermally feasible heat-recovery potential (Jin *et al.*, 2020). Therefore, pinch analysis functions not only as an energy calculation tool but also as a baseline for establishing a rational preheater system configuration before process simulation.

For gas turbines, analyzing several load conditions is essential, as exhaust gas temperature, mass flow, fuel use, and heat recovery potential change with operating load (Motamed *et al.*, 2024). For instance, at lower loads such as 50%, available exhaust heat and fuel heating needs differ from those at medium (75%) or high (100%) loads. As a result, focusing on only one operating point complicates the design of heat recovery systems. Therefore, this study applies pinch analysis at three load levels: 50%, 75%, and 100%, to provide a clearer understanding of system behavior under different loads.

The results of process simulation model must be translated into a pinch analysis to assess the impact of preheater implementation on system performance. DWSIM software facilitates the modeling of thermodynamic systems, process flows, heat exchangers, and fluid state changes within heat recovery systems (Sreemahadevan *et al.*, 2024). Employing DWSIM enables comparison between baseline scenarios without waste heat recovery and modified scenarios incorporating a preheater at 50%, 75%, and 100% loads. These simulations enable quantitative analysis of parameters such as compressor work, turbine expander power, cycle work, and thermal efficiency (Alnaimi *et al.*, 2021).

Previous studies have demonstrated that waste heat utilization in gas turbines can enhance energy performance and reduce emissions. Faqihi and Ghaith (2023) showed that integrating a heat recovery system into a gas turbine exhaust stack supports fuel gas heating, while subsequent research by Faqihi and Ghaith (2025) highlighted the potential for fuel savings and CO_2 emission reductions through waste heat utilization. Additional research on pinch analysis has confirmed its effectiveness in identifying heat recovery targets and opportunities for reducing energy consumption in industrial systems (Klemeš *et al.*, 2018). Nevertheless, studies that specifically combine pinch analysis at multiple operating loads with DWSIM simulations to evaluate the fuel gas preheater system in the GE 09HA.02 gas turbine remain limited.

This limitation constitutes a significant research gap, as gas turbines frequently operate under varying loads due to fluctuations in power demand, system dispatch requirements, and operational adjustments involving other plants. Consequently, evaluating waste heat recovery system performance across multiple load conditions is necessary to avoid restricting analysis to a single operating point. Analysis at 50%, 75%, and 100% loads is anticipated to yield insights into how the pinch point, heat recovery potential, and preheater effectiveness vary with gas turbine operating conditions.

This study analyzes the use of waste heat as a heat source in the gas fuel preheater system of the GE 09HA.02 gas turbine. The research begins with pinch analysis at 50%, 75%, and 100% loads to find the pinch point and assess heat use potential in the heat recovery circulation system. The results then shape a simulation model in DWSIM. Next, simulations compare scenarios with and without a preheater at every load to evaluate the effect of fuel heating on energy and exergy performance. The objectives are: (i) to identify the pinch point and waste heat use potential in the GE 09HA.02 system at 50%, 75%, and 100% loads; (ii) to develop and validate a simulation model of fuel heating based on waste heat use in the same turbine using DWSIM; (iii) to analyze the effect of a gas fuel preheater on energy and exergy efficiency at these load variations; and (iv) to compare system performance with and without a preheater. This comparison involves recovered heat, fuel temperature, heat rate, fuel use, and possible CO_2 emission reductions.

This approach is expected to help advance energy conservation strategies for gas-fired power generation systems. From a scientific perspective, this study enhances understanding of the integration between pinch analysis and process simulation for evaluating waste heat utilization systems. Practically, the findings offer a foundation for designing or assessing retrofitted preheater systems in gas turbines, with the aim of improving operational efficiency, minimizing energy losses, and supporting reduced fuel consumption in gas-fired power plants.

ISSN (online): 2581-3048
Volume 10, Issue 6, pp 283-293, June-2026
https://doi.org/10.47001/IRJIET/2026.106036

II. MATERIALS AND METHOD

Research Location and Object

The study was conducted on a GE 09HA.02 gas turbine unit in Karawang, West Java, focusing on exhaust gas heat utilization as a heat source for heating fuel gas. This unit was chosen for its potential to recover exhaust gas temperature through a heat recovery system. Three operating load conditions: 50%, 75%, and 100%, were examined to assess changes in heat utilization under low, medium, and high loads. Each condition was analyzed using a pinch approach, yielding results for DWSIM-based modeling and simulation that link the experimental basis to computational analysis.

Type of Research

This study employs a quantitative, simulation-based approach, processing numerical data such as temperature, pressure, mass flow rate, fuel composition, and gas turbine operating parameters under various load conditions. Building on the load-based investigation, the methodology follows two primary stages: pinch analysis and DWSIM simulation. Pinch analysis determines the pinch point and the potential for exhaust gas heat utilization for each load variation. The subsequent simulation model for the gas-fuel heating system in DWSIM is based on these findings, enabling a direct transition from analysis to simulation.

Process Description

In a conventional system (Figure 1a), air enters through the air inlet and is compressed to increase its pressure. The compressed air, referred to as compressor discharge, is directed to MIX-1, where it mixes with natural gas serving as fuel. This air-fuel mixture then enters the combustion chamber, where combustion occurs, producing high-pressure hot gas. The resulting gas is routed to the turbine expander via the TIT line, where its heat energy and pressure are converted into turbine power. Following expansion, the gas exits as GT exhaust and, in the conventional configuration, is discharged directly into the exhaust system without further heat recovery. This approach leaves residual heat energy in the exhaust gas unutilized. In contrast, the proposed configuration recovers heat from the GT exhaust to preheat the natural gas prior to mixing and combustion (Figure 1b). Instead of being discharged, the exhaust gas from the turbine expander is routed through a heat utilization line to SPL-1, with a portion directed as PH IN to the HX-1 heat exchanger. Within HX-1, heat from the exhaust gas is transferred to NG IN, resulting in natural gas exiting as NG OUT at an elevated temperature before entering MIX-1. The preheated natural gas is subsequently mixed with compressed air and introduced into the combustion chamber for combustion.

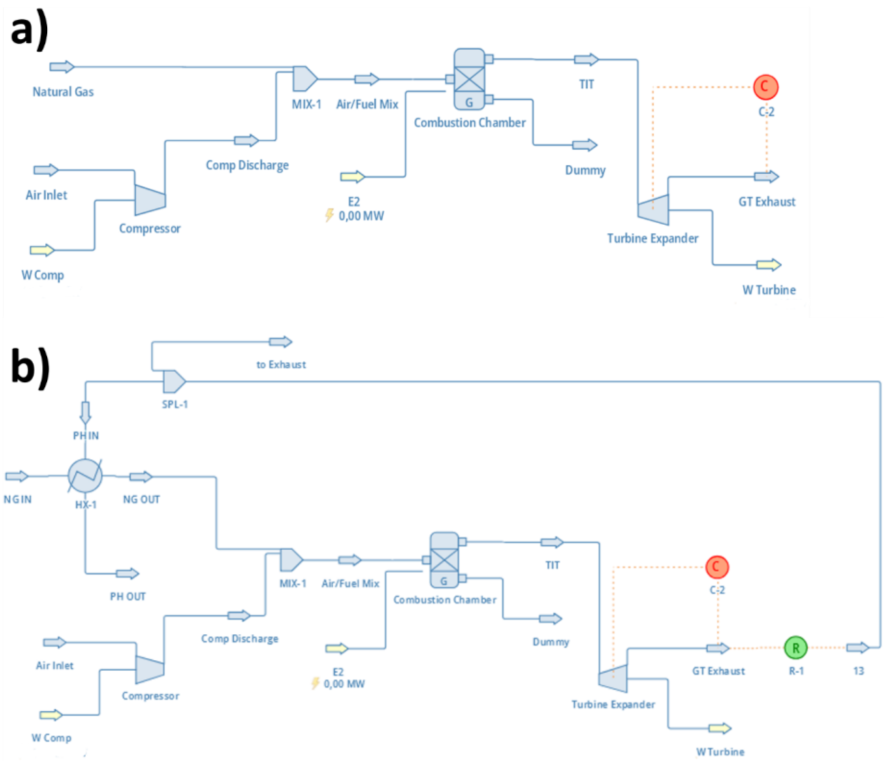

Figure 1: Gas turbine configurations: (a) conventional system without exhaust gas heat recovery and (b) proposed system with exhaust gas heat recovery for natural gas preheating

ISSN (online): 2581-3048
Volume 10, Issue 6, pp 283-293, June-2026
https://doi.org/10.47001/IRJIET/2026.106036

Research Stages

The research was conducted in four main stages, each logically following the previous. First, gas turbine operational data without pre-heater were collected at 50%, 75%, and 100% load, selecting steady-state data to avoid transient effects. Building on this foundation, stage two comprised a pinch analysis of the flue gas heat recovery system, designating the flue gas flow as the hot stream and the fuel gas flow or heating circulation medium as the cold stream transitioned to system modeling using DWSIM. Temperature profiles of the hot and cold streams were constructed to determine the pinch points at each operating load. Utilizing the pinch analysis results, including pinch point values, heating temperature limits, and potential heat recovery as model results. Finally, in the fourth stage, simulation results at each load condition were compared to evaluate existing system performance, providing a comprehensive assessment of the impact of exhaust gas utilization.

Simulations Using DWSIM

Simulations were performed using DWSIM software to model the utilization of exhaust gas as a heat source in a natural gas fuel preheater system. The simulation model leveraged actual operating data and analytical findings for each operating load. Primary conditions was simulated, as the modified condition, representing a system with an additional preheater that utilizes exhaust gas heat would be resulted on operating condition data for pinch analysis. In that scenarios, simulation parameters included the fuel temperature after the preheater, the amount of heat recovered, changes in exhaust gas flow conditions, and variations in key operating parameters. This approach enabled an effective comparison of the effectiveness of exhaust gas heat utilization across different load variations, thus building directly on prior research steps.

Pinch Analysis

Pinch analysis determines the limits of thermal utilization of exhaust gas heat. In the analysis approach, the gas turbine exhaust gas serves as the heat source, while the fuel gas or heating circulation medium serves as the heat-receiving stream. To maintain consistency, the analysis is performed at each operating load condition: 50%, 75%, and 100%. The process initiates by determining the inlet and outlet temperatures, the mass flow rate, and the heat capacity of each stream. Subsequently, heat transfer profiles for both streams are constructed. The minimum allowable temperature difference (ΔT_{min}) is applied between the streams. The pinch point, which is reached when the temperature difference is minimized, serves as a boundary for exhaust gas heat utilization. The outcomes from this step directly inform the target fuel gas heating temperature used in the DWSIM simulation model, ensuring a clear link between analysis and simulation.

Data Processing

Data from the pinch analysis based on DWSIM simulations were compared, focusing on the baseline condition and the condition with the preheater at each operating load. In processing, special attention was given to changes in fuel gas temperature, potential heat recovery, and the consistency of the simulation results with thermal limits established by pinch analysis. The results of data processing were then used to identify the operating load with the most effective exhaust gas heat utilization. This interpretation phase examined the relationships among the pinch point, fuel heating temperature, and DWSIM simulation results at 50%, 75%, and 100%loads, concluding the research sequence and connecting the analysis outcomes to the overall study objectives.

III. RESULTS AND DISCUSSION

Analysis of existing conditions

Under current conditions without a preheater for natural gas, increasing the load from 50% to 75% and 100% results in a consistent improvement in system performance (Table 1). Turbine expander power rises from 501.17 MW at 50% load to 718.91 MW at 75% load, and further to 999.56 MW at 100% load. This improvement is attributed to higher air and natural gas flow rates, which increase the energy of the combustion gas entering the turbine (Muñoz de Escalona *et al.*, 2012). Cycle work increases from 255.73 MW to 378.42 MW, reaching 520.36 MW at full load. Although compressor load also rises from 245.44 MW to 479.20 MW, the additional power generated by the turbine exceeds the increase in compressor work. Thermal efficiency improves from 36.572% at 50% load to 40.034% at 75% load and 42.064% at 100% load. These results demonstrate that the system operates more efficiently at higher loads; however, the heat from the gas turbine exhaust is not recovered, as the natural gas enters the combustion chamber without preheating (Du *et al.*, 2022).

Table 1: Operating parameters and performance results of the conventional gas turbine system at 50%, 75%, and 100% load conditions

Parameter	Unit	50%	75%	100%
Inlet air temperature	°C	31	31	31
inlet air pressure	bar	1.01325	1.01325	1.01325

International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 10, Issue 6, pp 283-293, June-2026

https://doi.org/10.47001/IRJIET/2026.106036

inlet air flow	kg/s	581.03	738.95	936.83
Compressed air temperature	°C	426.69	466.07	509.97
Compressed air pressure	bar	13.356	17.265	22.491
Natural gas temperature	°C	17	17	17
Natural gas pressure	bar	42	42	42
Natural gas flow	kg/s	14.073	19.024	24.897
Natural gas LHV	kJ/kg	49687	49687	49687
Flue gas temperature	°C	677	677.00	673
Flue gas pressure	bar	1.02511	1.03654	1.0528
Flue gas flow	kg/s	596.53	759.79	964.04
Compressor Work	MW	245.44	340.49	479.2
Turbine Expander Power	MW	501.17	718.91	999.56
Cycle Work	MW	255.73	378.42	520.36
Thermal efficiency	%	36.572	40.034	42.064

Pinch Point and $Q_{recovered}$ Analysis from Simulation

The analysis demonstrates that increasing the operating load from 50% to 100% results in a corresponding increase in heat recovered by the preheater system. At 50% load, $Q_{recovered}$ is 7.34 MW with an actual pinch point of approximately 125.5°C. At 75% load, $Q_{recovered}$ rises to 9.93 MW with a pinch point of 126.5°C. At 100% load, $Q_{recovered}$ reaches approximately 13 MW with a pinch point of 126.3°C. These results indicate that higher operating loads enable greater utilization of flue gas heat for preheating natural gas prior to combustion (Zhao *et al.*, 2022). Table 2 summarizes the relationship between load, pinch point, and $Q_{recovered}$. The increase in $Q_{recovered}$ is not accompanied by a significant change in the pinch point, which remains within a narrow range of 125.5°C to 126.5°C. The minimal difference of about 1°C between loads suggests that the heat exchanger system maintains stable heat transfer characteristics across varying operating conditions. Therefore, the observed increase in heat recovery is primarily attributed to the increased heat capacity of the streams, particularly the flue gas and natural gas, rather than to a reduction in the pinch point or a narrowing of the minimum temperature difference (Al-Ani & Linke, 2018).

Table 2: Heat recovered and actual pinch point of the preheater system at different load conditions based on simulation

Load condition	$Q_{recovered}$(MW)	Actual pinch point (°C)
50%	7.34	125.5
75%	9.93	126.5
100%	13.00	126.3

The heat cascade analysis, with ΔT_{min} set to 20°C, shows that both the minimum hot and cold utility requirements are 0 MW for this heat exchanger system. This outcome demonstrates that the heating demand for natural gas is fully met by the flue gas waste heat, eliminating the need for additional external heaters or coolers within the minimum energy analysis limits (Hafizan *et al.*, 2019). Figure 2 illustrates the heat utilization pattern between the hot and cold streams from various electricity loads. The composite curve in Figure 2 confirms that the hot stream has sufficient heat capacity to raise the natural gas temperature from 17°C to 215°C. The absence of minimum hot and cold utility requirements indicates that the heat-exchange process meets the minimum energy target (Mohsenpour *et al.*, 2024). However, the temperature gap between the hot and cold composite curves remains substantial, reflecting an actual pinch point value significantly greater than the design ΔT_{min} of 20°C.

At 50% load, a $Q_{recovered}$ of 7.34 MW indicates that the flue gas provides sufficient heat to preheat the natural gas prior to combustion (Figure 2a). The actual pinch point of 125.5°C is substantially higher than the design ΔT_{min}, indicating a large temperature driving force for heat transfer (Wang et al., 2020). Operationally, this facilitates efficient heat transfer, but from an energy optimization standpoint, it suggests that the heat exchanger is not operating near a tight pinch condition. At 75% load, $Q_{recovered}$ increases to 9.93 MW due to the greater availability of waste heat from the flue gas, while the actual pinch point rises only slightly to 126.5°C (Figure 2b). This minimal change in pinch point indicates that additional heat recovery does not result in a narrower temperature approach, and the system has not reached the minimum thermodynamic limit defined by ΔT_{min} of 20°C. At 100% load, $Q_{recovered}$ reaches 13 MW with an actual pinch point of 126.3°C, demonstrating the system's capacity to utilize maximum waste heat under full load (Figure 2c). The pinch point remains nearly constant across all loads, indicating

ISSN (online): 2581-3048
Volume 10, Issue 6, pp 283-293, June-2026
https://doi.org/10.47001/IRJIET/2026.106036

that the increase in $Q_{recovered}$ at higher loads is primarily due to increased available heat energy rather than an improved interstream temperature approach (Akbari *et al.*, 2022).

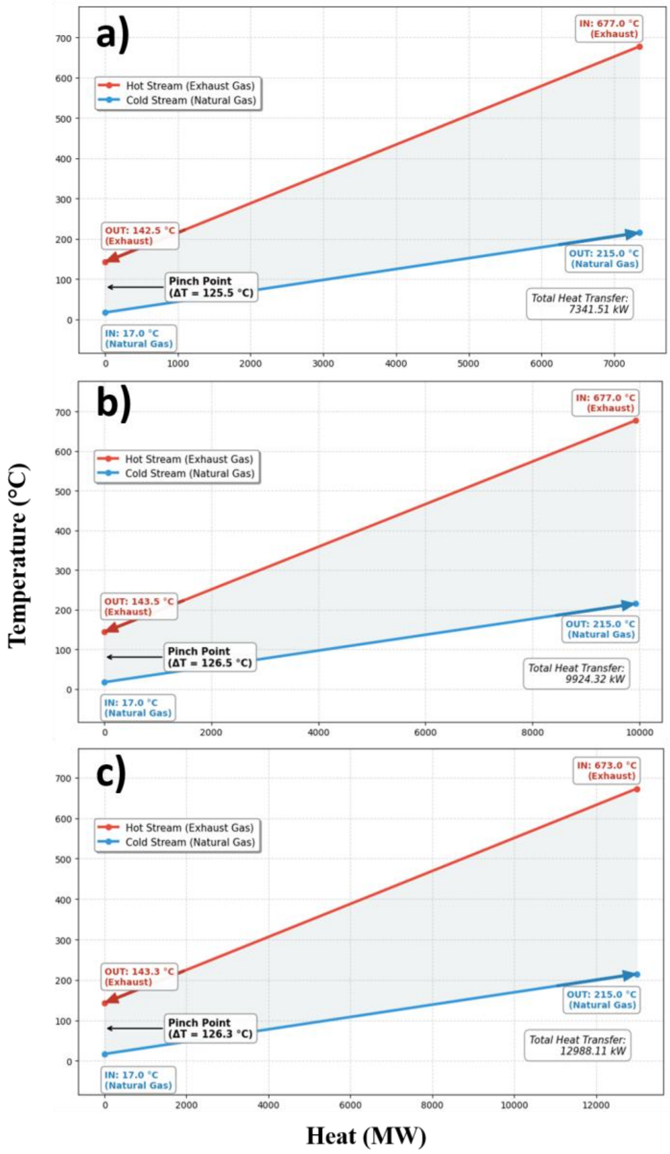

Figure 2: Composite curves of exhaust gas heat recovery for natural gas preheating at different gas turbine loads: (a) 50%, (b) 75%, and (c) 100%

Figure 3 presents the composite curve for the clean natural gas case at 100% load, demonstrating the lower exhaust gas outlet temperature and the associated heat recovery profile. When clean natural gas with a sulfur content near zero is used, the exhaust gas outlet temperature can be reduced from 143.3°C to 65°C due to the minimal risk of sulfur or acid dew point occurrence. In contrast, fuels containing sulfur produce SO_2 during combustion, with a portion further oxidized to SO_3. SO_3 reacts with water vapor in the exhaust gas to form H_2SO_4 vapor (Jaworowski & Mack, 1979). If the exhaust gas temperature falls below the acid dew point, H_2SO_4 condenses on the heat exchanger surface, causing acid corrosion. Consequently, when operating with sulfur-containing fuels, the exhaust gas outlet temperature is typically maintained at higher levels, such as 143.3°C, to prevent acid condensation (Bahadori, 2011). In the case of clean LNG, the absence of sulfur prevents the formation of SO_x and H_2SO_4, so the minimum exhaust gas temperature is no longer constrained by the sulfur dew point. The exhaust gas can be cooled to 65°C, provided the water dew point and heat exchanger material limitations are considered. At 100% load, the total heat transfer with normal natural gas is approximately 13 MW, whereas with clean natural gas it is approximately 12.3 MW. The lower value for clean LNG is not attributed to reduced exhaust gas cooling potential, but rather to the limitation imposed by the cold stream side, specifically heating natural gas from 17°C to 215°C, and adjusting the hot stream mass to achieve a 65°C outlet. Therefore, clean natural gas primarily offers greater flexibility in reducing exhaust gas temperature and lowering corrosion risk, while the actual heat transfer is determined by the natural gas heat absorption capacity and the heat exchanger energy balance.

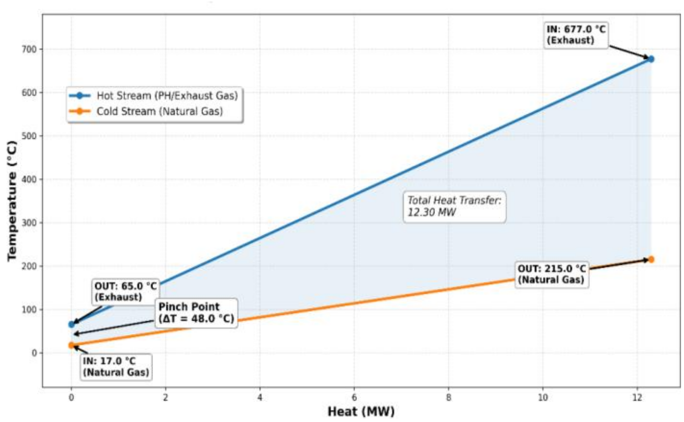

Figure 3: Composite curve of the fuel gas heater at 100% load with a "clean" natural gas as fuel sources

Figure 4 shows that increasing the operating load increases heat transfer from the hot fluid to the cold fluid. The maximum heat exchanged rises from 10.75 MW at 50% load (Figure 4a), to 14.69 MW at 75% load (Figure 4b), and reaches 19.36 MW at 100% load (Figure 4c). For preheater operation, the natural gas temperature is targeted to increase from 17°C to 215°C, so the actual $Q_{recovered}$ is determined at the point where the cold fluid reaches approximately 215°C, rather than at the end of the full profile. Interpolation of the heat exchanger profile data yields $Q_{recovered}$ values of approximately 7.34 MW at 50%, 9.93 MW at 75%, and 13 MW at 100%. At this stage, the hot fluid temperature remains around 142-143°C, resulting in a substantial temperature difference between the hot and cold fluids. This finding indicates that the increase in $Q_{recovered}$ is primarily attributable to the greater availability of heat energy at higher operating loads, rather than operation closer to the pinch limit (Gou *et*

International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 10, Issue 6, pp 283-293, June-2026

https://doi.org/10.47001/IRJIET/2026.106036

al., 2021). The heat exchanger profile thus corroborates the pinch analysis results, confirming that HX-1 recovers more heat as the load increases, while the system continues to exhibit a wide temperature driving force and has not yet operated under tight pinch conditions (Linnhoff & Hindmarsh, 1983).

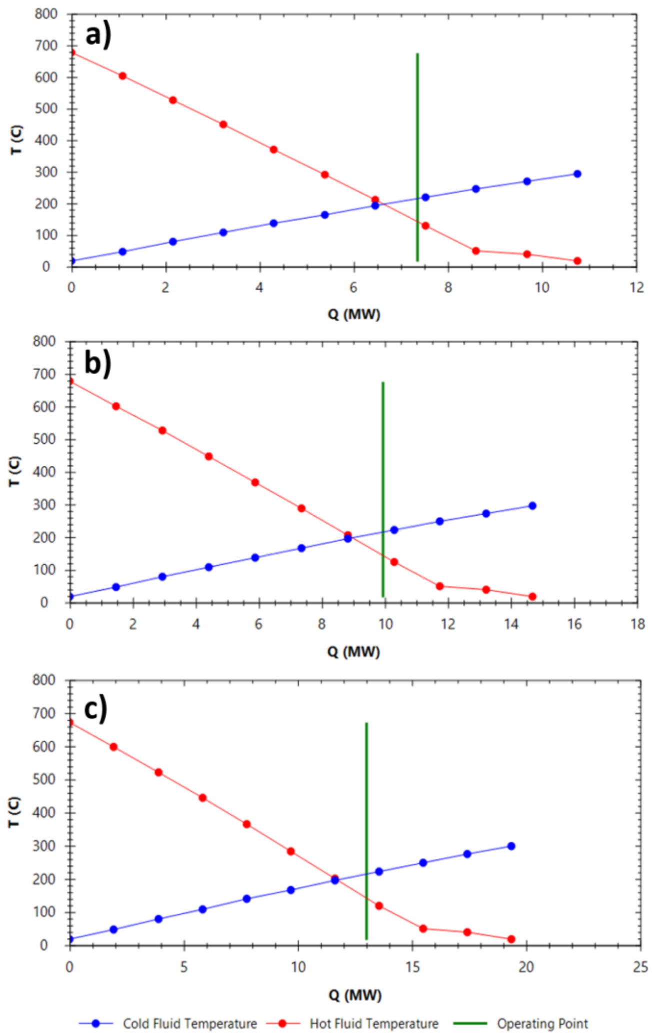

Figure 4: Heat exchanger temperature profiles for exhaust gas heat recovery at different gas turbine loads: (a) 50%, (b) 75%, and (c) 100%

The relationship between the pinch point and $Q_{recovered}$ reveals a key pattern. In theory, a smaller pinch point indicates that heat recovery is approaching its maximum, as the temperature difference between the hot and cold streams decreases (Kim *et al.*, 2022). However, the actual pinch point observed in these results remains significantly larger than the design ΔT_{min}. Consequently, the increase in $Q_{recovered}$ from 7.34 MW to 13 MW is best attributed to higher operating loads and increased stream heat capacity, rather than to enhanced performance resulting from a narrower pinch point. The pinch-point analysis shows that the preheater system contributes positively to heat recovery across all load conditions. However, the relatively constant pinch-point value, which remains much higher than the design ΔT_{min}, suggests that the system is not yet constrained by pinch-point limitations (Bakar *et al.*, 2016). The large temperature driving force indicates that the current heat recovery performance is primarily determined by the operating load and the availability of flue gas heat.

Comparison of Thermodynamic Performance of Gas Turbine Systems without and With Pre-Heater

A comparison between the existing system without a preheater and the simulation system incorporating a preheater shows that adding HX-1 as a fuel gas heater enhances gas turbine cycle performance across all operating load conditions. The primary modification was an increase in natural gas temperature from 17°C in the existing system to 215°C in the simulation system. This result confirms that flue gas heat was effectively recovered to raise the fuel enthalpy prior to combustion. Notably, natural gas pressure, flow rate, and lower heating value (LHV) remained constant at each load, indicating that the observed performance improvement resulted from waste heat utilization rather than increased fuel input.

At 50% load, implementation of the preheater increased Turbine Expander Power from 501.17 MW to 510.19 MW, representing a gain of 9.02 MW. Compressor work decreased marginally from 245.44 MW to 244.57 MW, resulting in an increase in Cycle Work from 255.73 MW to 265.62 MW. This 9.89 MW improvement in cycle work was accompanied by a rise in thermal efficiency from 36.572% to 37.987%, an increase of 1.415 percentage points. These results indicate that preheating natural gas enhances the reactants' energy state prior to combustion, thereby increasing the effectiveness of heat conversion in the turbine expander. At 75% load, the preheater's impact remains evident: Turbine Expander Power increased from 718.91 MW to 732.04 MW, a gain of 13.13 MW. Compressor work remained constant at 340.49 MW, so the entire increase in turbine power was reflected directly in higher net cycle work, which rose from 378.42 MW to 391.55 MW. Thermal efficiency improved from 40.034% to 41.423%, an increase of 1.389 percentage points. This demonstrates that at medium loads, flue gas heat recovery directly increases net output without additional fuel consumption. At 100% load, the simulation system with a preheater achieved the largest absolute performance improvement. Turbine Expander Power increased from 999.56 MW to 1016.84 MW, a gain of 17.28 MW. Compressor work decreased slightly from 479.20 MW to 478.64 MW, resulting in Cycle Work increasing from 520.36 MW to 538.20 MW, a gain of 17.84 MW. Thermal efficiency rose from 42.064% to 43.506%, an increase of 1.442 percentage points. These findings confirm that higher operating loads yield greater absolute benefits from waste heat recovery due to increased thermal energy in the flue gas.

International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 10, Issue 6, pp 283-293, June-2026

https://doi.org/10.47001/IRJIET/2026.106036

Cycle work increases consistently across all load conditions, with gains of 9.89 MW at 50%, 13.13 MW at 75%, and 17.84 MW at 100%. This trend corresponds directly to the observed increases in turbine expander power, while compressor work remains largely unchanged. The compressor's stability indicates that the preheater does not impose additional load on it. Consequently, the improvement in net cycle work is primarily attributable to enhanced turbine expansion power resulting from improved combustion conditions due to natural gas preheating. Thermal efficiency also rises under all operating conditions, demonstrating that the preheated system converts fuel energy into net work more effectively than the existing configuration. Since the natural gas flow rate and LHV are constant across the two systems, the efficiency gains are derived from increased net-work output rather than from higher fuel energy input.

From the perspective of flue gas utilization, the HX-1 inlet flue gas temperature ranges from 673°C to 677°C, offering substantial heat recovery potential. The flue gas flow rate in the simulation system is marginally lower than in the existing system, with values decreasing from 596.53 kg/s to 595.174 kg/s at 50% load, from 759.79 kg/s to 758.041 kg/s at 75% load, and from 964.04 kg/s to 961.773 kg/s at 100% load. These minor reductions do not negatively affect system performance, as the available sensible heat remains sufficient to raise the natural gas temperature to 215°C. This outcome confirms that HX-1 functions effectively as a heat recovery unit for fuel heating. The findings are consistent with both the pinch point analysis and the recovered heat ($Q_{recovered}$).

In summary, the comparison between the existing and simulation systems demonstrates that integrating the preheater via HX-1 yields substantial thermodynamic advantages. The simulation system achieves higher fuel temperatures without increasing natural gas consumption, resulting in increased turbine power, greater net cycle work, and improved thermal efficiency across all operating loads. This performance enhancement is attributable to the recovery of exhaust heat, which is redirected into the cycle as preheating energy for the fuel. Consequently, the preheater configuration offers superior internal energy utilization and reduces exhaust heat losses compared to the existing system.

Table 3: Existing and simulated gas turbine performance at different load conditions

Parameter	Unit	Existing	simulation	existing	simulation	existing	simulation
		50%		75%		100%	
Inlet air temperature	°C	31	31	31	31	31	31
inlet air pressure	bar	1.01325	1.01325	1.01325	1.01325	1.01325	1.01325
inlet air flow	kg/s	581.03	581.03	738.95	738.95	936.83	936.83
Compressed air temperature	°C	426.69	429.204	466.07	465.183	509.97	509.984
Compressed air pressure	bar	13.356	13.356	17.265	17.265	22.491	22.491
Natural gas temperature	°C	17	215	17	215	17	215
Natura gas pressure	bar	42	42	42	42	42	42
Natural gas flow	kg/s	14.073	14.073	19.024	19.024	24.897	24.897
Natural gas LHV	kJ/kg	49687	49687	49687	49687	49687	49687
Flue gas temperature	°C	677	677	677.00	677.00	673	673
Flue gas pressure	bar	1.02511	1.02511	1.03654	1.03654	1.0528	1.0528
Flue gas flow	kg/s	596.53	595.174	759.79	758.041	964.04	961.773
Compressor Work	MW	245.44	244.57	340.49	340.49	479.2	478.64
Turbine Expander Power	MW	501.17	510.19	718.91	732.04	999.56	1016.84
Cycle Work	MW	255.73	265.62	378.42	391.55	520.36	538.2
Thermal efficiency	%	36.572	37.987	40.034	41.423	42.064	43.506

*existing = without pre-heater

**simulation = using exhaust gas as pre-heater

ISSN (online): 2581-3048
Volume 10, Issue 6, pp 283-293, June-2026
https://doi.org/10.47001/IRJIET/2026.106036

IV. CONCLUSION

The utilization of exhaust gas heat as a natural gas preheater enhances the energy performance of the GE 09HA.02 gas turbine across various load conditions. In the baseline configuration, natural gas enters the combustion chamber at 17°C without preheating, resulting in suboptimal use of exhaust gas heat. Simulation results demonstrate that implementing the HX-1 preheater system increases the natural gas temperature to 215°C without altering the fuel flow rate or lower heating value (LHV). This finding confirms that performance improvements are attributable to exhaust heat recovery rather than increased fuel consumption. Pinch analysis indicates that $Q_{recovered}$ rises with operating load, reaching 7.34 MW at 50% load, 9.93 MW at 75% load, and 13.00 MW at 100% load. The pinch point remains relatively stable between 125.5°C and 126.5°C. This trend suggests that enhanced heat recovery is primarily driven by increased heat capacity of the flue gas and natural gas streams at higher loads, rather than by a reduced minimum temperature difference. In the clean natural gas scenario, the flue gas outlet temperature can be lowered to 65°C with a pinch point of 48°C, provided the natural gas outlet temperature is maintained at 215°C and the dew point of air and heat exchanger material constraints are observed. The fuel gas preheater consistently improves performance across all operating loads. At 50% load, cycle work increases from 255.73 MW to 265.62 MW and thermal efficiency rises from 36.572% to 37.987%. At 75% load, cycle work increases from 378.42 MW to 391.55 MW and thermal efficiency from 40.034% to 41.423%. At 100% load, cycle work increases from 520.36 MW to 538.20 MW and thermal efficiency from 42.064% to 43.506%. Therefore, integrating HX-1 as a fuel gas heater demonstrably increases turbine power, net cycle work, and thermal efficiency without imposing a significant additional load on the compressor. This system should be considered as an effective energy conservation strategy for gas turbine-based power plants.

REFERENCES

[1] Al-Ani, O., & Linke, P. (2018). Power generation targets from hot composite curves. *Energies*, 11(2), 403. https://doi.org/10.3390/en11020403

[2] Akbari, H., Hosseinnia, S. M., Sorin, M., Reddick, C., & Laperle, D. (2022). Adapted time slice model of pinch analysis for direct-indirect heat recovery in buildings. *Journal of Energy and Power Technology*, 4(2), 013. https://doi.org/10.21926/jept.2202013

[3] Alnaimi, F. B. I., Jasbeer Singh, M. S., Al-Bazi, A., Al-Muhsen, N. F. O., Mohammed, T. S., & Al-Hadeethi, R. H. (2021). Parametric investigation of combustion process optimization for gas turbines at SJ Putrajaya. *Energy Reports*, 7, 5722–5732. https://doi.org/10.1016/j.egyr.2021.08.202

[4] Bahadori, A. (2011). Estimation of combustion flue gas acid dew point during heat recovery and efficiency gain. *Applied Thermal Engineering*, 31(8–9), 1457–1462. https://doi.org/10.1016/j.applthermaleng.2011.01.020

[5] Bakar, S. H. A., Hamid, M. K. A., Alwi, S. R. W., & Manan, Z. A. (2016). Selection of minimum temperature difference (ΔTmin) for heat exchanger network synthesis based on trade-off plot. *Applied Energy*, 162, 1259–1271. https://doi.org/10.1016/j.apenergy.2015.07.056

[6] Cerza, M., Meinster, B., & Blair, S. (2022). Implementation of a waste heat recovery combined cycle system employing the organic Rankine cycle for a gas turbine. *AIAA SCITECH 2022 Forum*. https://doi.org/10.2514/6.2022-1406

[7] Du, J., Guo, J., Zhang, Z., Li, M., Ren, F., & Liu, Y. (2022). A triple cascade gas turbine waste heat recovery system based on supercritical CO_2 Brayton cycle: Thermal analysis and optimization. *Energy Conversion and Management: X*, 16, 100297. https://doi.org/10.1016/j.ecmx.2022.100297

[8] Faqihi, B., & Ghaith, F. (2023). A novel design of heat recovery system from exhaust stacks' silencers in a simple cycle gas turbine. *International Communications in Heat and Mass Transfer*, 148, 107068. https://doi.org/10.1016/j.icheatmasstransfer.2023.107068

[9] Faqihi, B., & Ghaith, F. (2025). Enhancement of waste heat recovery from exhaust stack silencers in a simple cycle gas turbine. *International Journal of Thermofluids*, 27, 101237. https://doi.org/10.1016/j.ijft.2025.101237

[10] Gonzalez-Salazar, M. A., Kirsten, T., & Prchlik, L. (2018). Review of the operational flexibility and emissions of gas- and coal-fired power plants in a future with growing renewables. *Renewable and Sustainable Energy Reviews*, 82(1), 1497–1513. https://doi.org/10.1016/j.rser.2017.05.278

[11] Gou, X., Zhang, H., Li, G., Cao, Y., & Zhang, Q. (2021). Dynamic simulation of a gas turbine for heat recovery at varying load and environment conditions. *Applied Thermal Engineering*, 195, 117014. https://doi.org/10.1016/j.applthermaleng.2021.117014

[12] Hafizan, A. M., Klemeš, J. J., Wan Alwi, S. R., Abdul Manan, Z., & Abd Hamid, M. K. (2019). Temperature disturbance management in a heat exchanger network for maximum energy recovery considering economic

ISSN (online): 2581-3048
Volume 10, Issue 6, pp 283-293, June-2026
https://doi.org/10.47001/IRJIET/2026.106036

analysis. *Energies,* 12(4), 594. https://doi.org/10.3390/en12040594

[13] Hodge, A. J., Shahin, T. T., Gejji, R. M., Philo, J. J., Lucht, R. P., & Slabaugh, C. D. (2025). Fuel temperature effects on combustion stability of a high-pressure liquid-fueled swirl flame. *Journal of Propulsion and Power*, 41(1), 53–63. https://doi.org/10.2514/1.B39592

[14] Jaworowski, R. J., & Mack, S. S. (1979). Evaluation of methods for measurement of SO_3/H_2SO_4 in flue gas. *Journal of the Air Pollution Control Association,* 29(1), 43–46. https://doi.org/10.1080/00022470.1979.10470750

[15] Jin, Y., Gao, N., & Wang, T. (2020). Influence of heat exchanger pinch point on the control strategy of Organic Rankine cycle (ORC). *Energy,* 207, 118196. https://doi.org/10.1016/j.energy.2020.118196

[16] Kementerian Energi dan Sumber Daya Mineral. (2025, August 13). Semester I tahun 2025, kapasitasterpasangpembangkitmeningkat 4,4 GW. *Kementerian Energi dan Sumber Daya Mineral Republik Indonesia*. https://www.esdm.go.id/id/media-center/arsip-berita/semester-i-tahun-2025-kapasitas-terpasang-pembangkit-meningkat-44-gw

[17] Kharaji, S. (2022). Heat exchanger design and optimization. In Heat Exchangers. *IntechOpen*. https://doi.org/10.5772/intechopen.100450

[18] Kim, Y., Lim, J., Shim, J. Y., Hong, S., Lee, H., & Cho, H. (2022). Optimization of heat exchanger network via pinch analysis in heat pump-assisted textile industry wastewater heat recovery system. *Energies,* 15(9), 3090. https://doi.org/10.3390/en15093090

[19] Kittijungjit, T., Klamrassamee, T., Laoonual, Y., &Sukjai, Y. (2025). Comprehensive study on waste heat recovery from gas turbine exhaust using combined steam Rankine and organic Rankine cycles. *Energy Conversion and Management: X,* 25, 100825. https://doi.org/10.1016/j.ecmx.2024.100825

[20] Klemeš, J. J., Varbanov, P. S., Walmsley, T. G., & Jia, X. (2018). New directions in the implementation of Pinch Methodology (PM). *Renewable and Sustainable Energy Reviews,* 98, 439–468. https://doi.org/10.1016/j.rser.2018.09.030

[21] Linnhoff, B., & Hindmarsh, E. (1983). The pinch design method for heat exchanger networks. *Chemical Engineering Science*, 38(5), 745–763. https://doi.org/10.1016/0009-2509(83)80185-7

[22] Mohsenpour, M., Pazuki, M. M., Salimi, M., &Amidpour, M. (2024). Optimized heat exchanger network design for a phthalic anhydride plant using pinch technology: A maximum energy recovery approach with economic analysis. *Results in Engineering*, 24, 103438. https://doi.org/10.1016/j.rineng.2024.103438

[23] Motamed, M. A., Genrup, M., & Nord, L. O. (2024). Part-load thermal efficiency enhancement in gas turbine combined cycles by exhaust gas recirculation. *Applied Thermal Engineering*, 244, 122716. https://doi.org/10.1016/j.applthermaleng.2024.122716

[24] Muñoz de Escalona, J. M., Sánchez, D., Chacartegui, R., & Sánchez, T. (2012). Part-load analysis of gas turbine & ORC combined cycles. *Applied Thermal Engineering*, 36, 63–72. https://doi.org/10.1016/j.applthermaleng.2011.11.068

[25] PT PLN (Persero). (2025). Rencanausahapenyediaantenagalistrik (RUPTL) PT PLN (Persero) 2025–2034. *PT PLN (Persero).* https://web.pln.co.id/statics/uploads/2025/06/b967d-ruptl-pln-2025-2034-pub-.pdf

[26] Sreemahadevan, S., Sivakumar, K. V., & Palanisamy, M. (2024). Evaluation of the open source process simulator DWSIM for bioprocess simulation. *PeriodicaPolytechnica Chemical Engineering*, 68(2), 195–202. https://doi.org/10.3311/PPch.23166

[27] Wang, B., Klemeš, J. J., Varbanov, P. S., & Zeng, M. (2020). An extended grid diagram for heat exchanger network retrofit considering heat exchanger types. *Energies,* 13(10), 2656. https://doi.org/10.3390/en13102656

[28] Yuan, T., & Mao, Y. (2024). A review of pinch analysis techniques and extended application in power systems. *Renewable and Sustainable Energy Reviews,* 202, 114684. https://doi.org/10.1016/j.rser.2024.114684

[29] Zhao, Y., Yu, G., Li, Y., Zhao, H., & Wang, F. (2022). Pinch analysis for heat integration of pulverized coke chemical looping gasification coupled with coke-oven gas to methanol and ammonia. *Processes,* 10(9), 1879. https://doi.org/10.3390/pr10091879

ISSN (online): 2581-3048
Volume 10, Issue 6, pp 283-293, June-2026
https://doi.org/10.47001/IRJIET/2026.106036

Citation of this Article:

Achbar Fauzi, Marcelinus Christwardana, & Berkah Fajar Tamtomo Kiono. (2026). Pinch Analysis and Simulation on the Utilization of Exhaust Gas as a Gas Fuel Heater for Energy Evaluation of Gas Turbine at Various Operating Loads. *International Research Journal of Innovations in Engineering and Technology - IRJIET*, 10(6), 283-293. Article DOI https://doi.org/10.47001/IRJIET/2026.106036

****