IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Impact Factor 8.066 ⁘ Peer-reviewed & Refereed journal ⁘ Vol. 12, Issue 4, April 2025

DOI: 10.17148/IARJSET.2025.12443

Optimized Heat Exchanger Design for Waste Heat Recovery in Offshore Gas Turbine Heating Systems: Case Study of NEPL Facility, Port Harcourt

Ahmad Habib Mohammed[1], Samuel Mary[2], Samaila Umar[3]

Department of Mechanical Engineering, Nigerian Defence Academy, Kaduna, Nigeria [1]

Department of Mechanical Engineering, Nigerian Defence Academy, Kaduna, Nigeria [2]

Department of Mechanical Engineering, Ahmadu Bello University, Zaria, Nigeria [3]

Abstract: This study presents the successful design and simulation of a waste heat recovery system (WHRS) tailored for reactivating the heating medium in an offshore gas turbine at the Nigerian National Petroleum Company Exploration and Production Limited (NNPC E&P Ltd) Production Facility. The research is driven by the ongoing pursuit of enhanced energy efficiency and sustainability in offshore operations. A standard modeling approach was employed, utilizing process flow diagrams (PFDs) for system integration and Computational Fluid Dynamics (CFD) analysis, coupled with Aspen HYSYS simulations to assess system performance under operating conditions. Flue gas composition analysis was conducted to determine input parameters for the WHRS design. Optimization techniques were implemented to establish the optimal heat exchanger design configuration. The heat exchanger was designed as a shell-and-tube system with 130 tubes of 20 m length and 0.025 m outer diameter. Simulations were conducted to evaluate the heat exchanger performance, determining a heat duty of 648,985 W, an overall heat transfer coefficient of 112.66 W/m²K, and a corrected Log Mean Temperature Difference (LMTD) of 281°C. Aspen HYSYS simulations validated system performance, yielding a tube-side outlet temperature of 130°C and a shell-side outlet temperature of 335.5°C. The results indicate improved energy recovery throughout the simulated process, confirming the feasibility of implementing waste heat recovery in crude oil preheating operations, contributing to improved energy management in offshore production facilities.

Keywords: Waste Heat Recovery (WHR), Simulation, Aspen HYSYS, Heat Exchanger Design, Offshore Gas Turbine, Shell-and-Tube Heat Exchanger, Computational Fluid Dynamics (CFD), Energy Recovery
.

I. INTRODUCTION

The recovery of heat from relatively clean waste hot flue gases offers a significant opportunity to enhance energy efficiency in industrial processes, enabling the generation of high temperature air, steam, or water for use in various equipment [1]. As a ubiquitous byproduct of energy-intensive operations and machinery [2]. Flue gases, particularly those discharged from gas turbines and internal combustion engines often possess thermal energy that, while at a lower temperature than the original source and above ambient conditions, is frequently underutilized [3]. Waste heat recovery (WHR) presents a crucial strategy to harness this thermal energy for practical applications before its release into the environment, thereby paving the way for eco-friendly power generation and facilitating the transition from wasted energy sources [4]. In contrast to more complex and costly alternatives like molten salt solutions, WHRS can be effectively implemented for heating media processes and even power generation [5]. Consequently, waste heat recovery systems (WHRS) have gained substantial importance in recent years as a vital means of improving fuel utilization in thermal engines and within the oil and gas industry for heating media, electricity generation, and broader energy transition initiatives [6]. The implementation of WHRS not only contributes to a reduction in pollution but also leads to a notable increase in the overall efficiency of energy systems. WHR encompasses a diverse range of methods, with its effectiveness significantly influenced by various parameters and variables related to heat exchangers, Rankine cycles, and thermoelectric generators [7]. Heat exchangers, a core component of many WHR systems, can be categorized based on several criteria. [8] classified these devices by flow path configuration (parallel flow, counter flow, single-pass cross flow, and multipass counter flow), contact type (direct contact involving immiscible fluids versus indirect or surface heat exchangers), and construction features (tabular/shell and tube, plate, plate-fin, tube-fin, and regenerative) [9]. In the context of this study, a waste heat recovery system utilizing a heat exchanger is specifically chosen due to its potential

IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Impact Factor 8.066 ⁜ Peer-reviewed & Refereed journal ⁜ Vol. 12, Issue 4, April 2025

DOI: 10.17148/IARJSET.2025.12443

for high recovery rates and relatively lower installation costs. The primary objective of this system is to generate a heating medium for the oil production process within the specific operational environment of an offshore gas turbine facility.

II. METHODOLOGY

This section details the activities undertaken for the design and simulation of the waste heat recovery system intended to reactivate a heating medium for preheating crude oil at the Nigerian National Petroleum Company Exploration and Production Limited production facility in Port Harcourt, Nigeria.

A. *Collection of Process Data for Heat Exchanger Design*

Field data were obtained from NNPC Exploration and Production Limited (NEPL) OML 119 Field, using sensors and data logger. The parameters collected include:

i. Flue gas composition.
ii. Inlet and outlet temperatures of flue gas and water.
iii. Flow rates and pressures of both fluids.

The Data were collected over three months (February, April, and June, 2024) to account for seasonal variations.

B. *Development of Process Flow Diagram (PFD) for Waste Heat Recovery System*

Aspen Hysys V12 was utilized to develop the Process Flow Diagram (PFD) for the Waste Heat Recovery System, while EdrawMax V2.0.7 was employed for schematic illustration. The PFD effectively captured the flow of flue gas from the chimney to the heat exchanger, as well as the circulation of cooling water, and included detailed mapping of piping, valves, control elements, and temperature/pressure monitoring points to ensure comprehensive representation of the system.

C. *Design of Heat Exchanger Model*

A shell-and-tube heat exchanger type designed for flue gas heat recovery was meticulously modelled using SolidWorks V21. The software enabled detailed design of the tube bundle configuration, shell and tube layout, material selection, and dimensional tolerances. The design adhered to fundamental heat transfer principles, incorporating considerations for convective heat transfer, log mean temperature difference (LMTD), and overall heat transfer coefficient (Uo) calculations to ensure efficient heat recovery from the flue gas.

i) Design Consideration:

According to [10],[11] & [12], the main considerations for designing heat exchangers to effectively handle different operating conditions, ensuring optimal performance and longevity, are:

- Temperature Range: Heat exchangers must be designed to withstand fluctuations temperature while maintaining thermal efficiency.
- Pressure Levels: Consideration of pressure drops and resistance is crucial to prevent leakage and ensure safe operation.
- Flow Rates: Proper sizing and configuration are essential to accommodate varying flow rates and prevent flow-related issues

ii) Design parameters:

The design parameters for the effective design of the heat exchanger are presented in Table 1.

Table 1: Properties of the Working Fluids (Water and Exhaust Gas)

S/N	Parameter	Value	Unit
1.	Flue gas inlet temperature	360	ºC
2.	Flue gas outlet temperature	335.5	ºC
3.	Flue gas flow rate	1271	kgmol/h
4.	Specific heat of flue gas (CP)	1.0539	kJ/kgk
5.	Water inlet temperature	105	ºC
6.	Mas flow rate of water	499.6	kgmol/h
7.	Water outlet temperature	130	ºC
8.	Water Thermal conductivity (κ)	650	10-3 W/mK
9.	Flue gas Thermal conductivity (κ)	47.31	10^{-3} W/mK
10.	Specific heat of water (CP)	4.184	kJ/KgK
11.	Water Density (ρ)	985.2	kg/ m^3
12.	Flue gas Density (ρ)	0.5774	kg/ m^3
13.	Dynamic viscosity of water (μ)	486	10^{-6} kg/ms
14.	Dynamic viscosity of flue gas (μ)	30	10^{-6} kg/ms

IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Impact Factor 8.066 ⁑ Peer-reviewed & Refereed journal ⁑ Vol. 12, Issue 4, April 2025

DOI: 10.17148/IARJSET.2025.12443

iii) Simulation of the Designed Heat Exchanger:

The simulation process was carried out using ASPEN HYSYS V.12, and the results obtained from the analysis were used as input data for the simulation. CFD was recognized as a highly useful tool that was extensively employed to assess the thermal-hydraulic behaviour of heat exchangers. The heat exchanger simulation was a rigorous and high-fidelity mathematical process model that provided a realistic steady-state, static, and dynamic response for the heat exchanger. It helped to avoid the high costs associated with experimental testing. In this study, it was used to perform a thermal-hydraulic simulation of a high-pressure natural circular water tube heat exchanger. Thermal analysis was generally applied to determine temperature distribution, temperature gradients, and heat flow within the model, as well as the heat exchange between the model and its environment. Thermal simulation was the dynamic analysis of the energy performance of products using computer modeling and simulation techniques.

iv) Simulation of the Waste Heat Recovery System:

The designed heat exchanger was seamlessly integrated into a comprehensive waste heat recovery system (WHRS) within the Aspen Hysys V12 environment. This allowed for dynamic simulation of the system's performance under various operating conditions, evaluating key metrics such as heat recovery rate, thermal efficiency, and potential energy savings.

v) Validation of the Design

The result of the designed heat exchanger that was integrated into a waste heat recovery system (WHRS) within the Aspen Hysys V12 environment was compared with the process operating parameters of the real existing system.

III. RESULTS AND DISCUSSION

A. Collection of Process Data for Heat Exchanger Design

The composition of flue gas as presented in Table 2 will serve as the input data for the heat exchanger design. Table 3 on the other hand, present the data collected from the operation manual of the facility.

Table 2: Composition of Flue Gas

COMPONENTS	kmol/hr
H_2O	989.413
CO_2	226.610
N_2	1809.36
SO_2	0.00000
O_2	22.3730

Table 3: Physical Properties

Physical Properties	Flue Gas	Water
Flow Rate (kgmol/h)	1271	499.6
Density (kg/m^3)	0.531	998
Heat Capacity (J/kg)	1195	4187
Kinematic Viscosity (Pa s)	0.00005345	8.66 x 10-07
Conductivity (W/m.c)	0.048	0.61
Inlet Temprature (°C)	360	105
Outlet Temprature (°C)	332.149555	130
Min. Vel. (m/s)	10	
Dynamic Viscosity(Ns/m^2)	0.00002849	0.000489
Heat Energy Req. (W)	648985	648985
PI	3.142	
Gravity (m/s^2)	9.81	
Ambient Temp. (°C)	28	
Correction Factor (F)	0.98	

Table 2 describes the composition and physical properties of a flue gas stream from a combustion system. The flue gas primarily consists of nitrogen (1809.36 kmol/hr), water vapor (989.413 kmol/hr), and carbon dioxide (226.610 kmol/hr), with a small amount of oxygen (22.373 kmol/hr) and no detectable sulfur dioxide, indicating efficient combustion of a low-sulfur fuel with excess air. The physical properties of the flue gas (flow rate: 19.5 kg/s, density: 0.531 kg/m³, heat capacity: 1195 J/kg°C, thermal conductivity: 0.048 W/m•°C, dynamic viscosity: 2.849 x 10-5 Ns/m², inlet temperature:

IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Impact Factor 8.066 ⋇ Peer-reviewed & Refereed journal ⋇ Vol. 12, Issue 4, April 2025

DOI: 10.17148/IARJSET.2025.12443

360°C, outlet temperature: 335.5°C) and water (flow rate: 85.68 kg/s, density: 998 kg/m³, heat capacity: 4187 J/kg•°C, thermal conductivity: 0.61 W/m•°C, dynamic viscosity: 4.89 x 10-5 Ns/m², inlet temperature: 105°C, outlet temperature: 130°C) are crucial for designing efficient waste heat recovery systems, with water's superior heat capacity and thermal conductivity enabling better heat absorption and transfer compared to the flue gas.

B. Process Flow Diagram (PFD) for Waste Heat Recovery System

Figures 1 to 3 describe and compare three Process Flow Diagrams (PFDs) related to heat exchange in industrial operations, specifically within the NNPC exploration and production limited (NEPL) OML 119 Field and a proposed waste heat recovery system. Fig. 1 shows the existing system, which uses an oil heater and a heat exchanger with a heating medium system, but it doesn't optimize waste heat utilization.

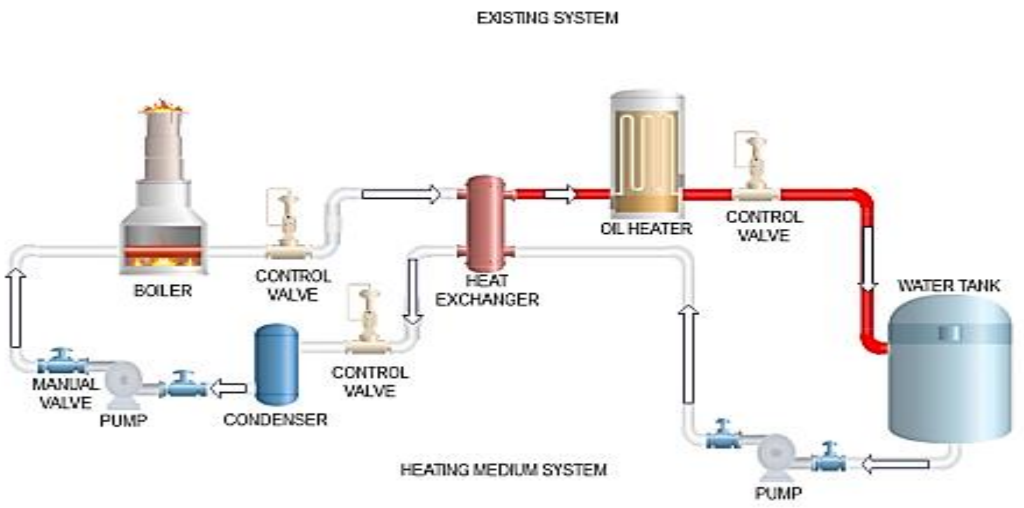

Fig. 1: Schematic representation of the NNPC exploration and production limited (NEPL) OML 119 field.

Fig.2 presents a proposed system that directly recovers heat from a gas turbine exhaust using a redesigned heat exchanger, eliminating the oil heater and improving energy recovery and overall system efficiency.

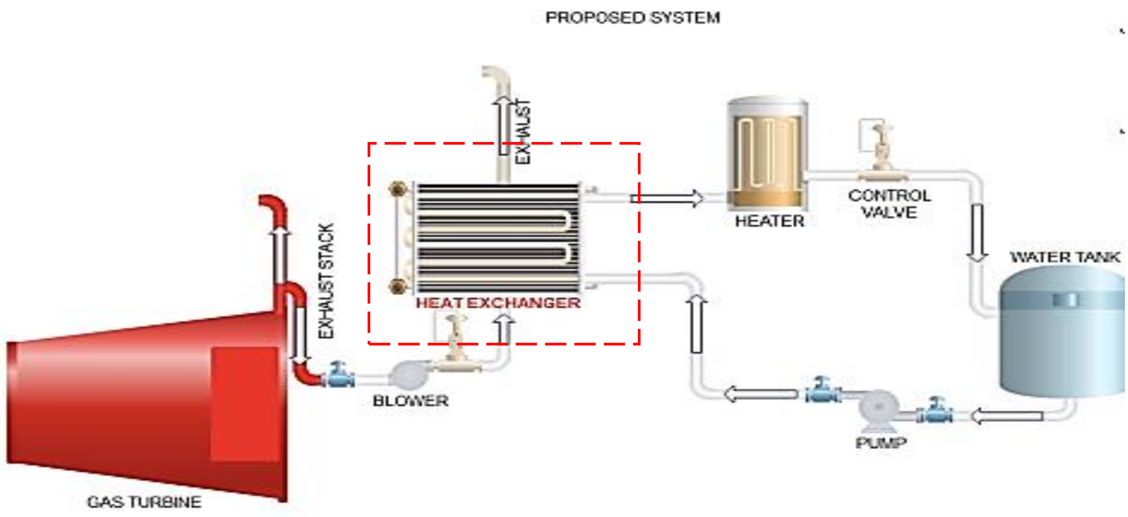

Fig. 2: 3D presentation of the proposed heat exchanger fully integrated into the NEPL system

Fig. 3, designed using ASPEN HYSYS V.12, illustrates a waste heat recovery system that utilizes flue gas from a turbine to heat water via a heat exchanger. This system includes a turbine, blower, and heat exchanger, water circuit with a tank and pump, and potentially an oil heater for supplementary heating. This design aims to maximize thermal energy recovery, enhance energy efficiency, and improve sustainability by efficiently transferring heat from waste gas to water.

IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Impact Factor 8.066 ⪤ Peer-reviewed & Refereed journal ⪤ Vol. 12, Issue 4, April 2025

DOI: 10.17148/IARJSET.2025.12443

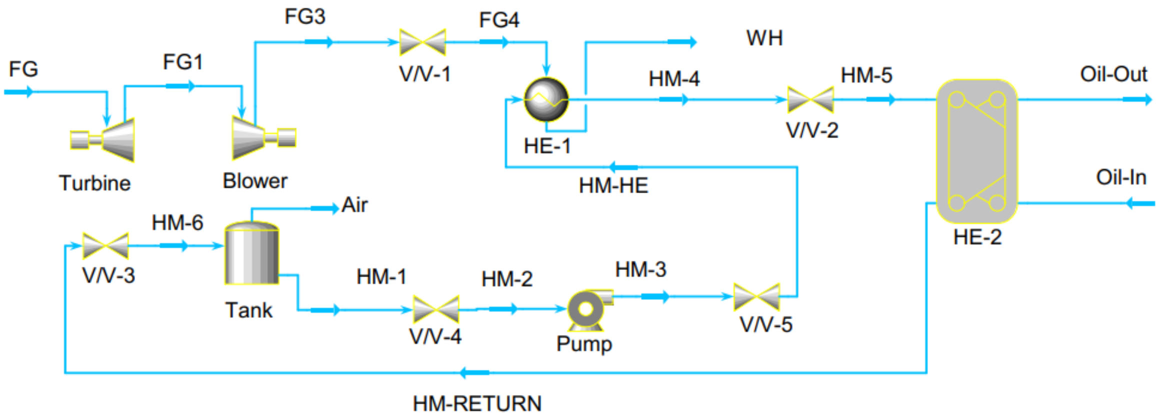

Fig. 3: Aspen Hysys Simulation of the designed heat exchanger fully integrated into the NEPL system

C. Design of the Heat Exchanger Model

The physical dimensions and design parameters of the heat exchanger used in the WHRS are provided in Tables 4 and 5 Table 4 outlines the physical dimensions: the tubes have an outer diameter of 0.025 m, an inner diameter of 0.023 m, and a thickness of 0.002 m. There are approximately 130 tubes, each 20 m long. The casing is 13.0514 m long and 2.64625 m wide. The tubes are arranged in a staggered configuration with both longitudinal (SL) and transverse (ST) pitch of 0.03 m, which optimizes fluid flow and heat transfer.

Table 4: Heat Exchanger Geometry

Geometry	**Values**	**Unit**
Tube Outer Diameter (OD)	0.025	m
Tube Inner Diameter (ID)	0.023	m
Pitch (SL)	0.03	m
Pitch (ST)	0.03	m
Length (L)	2	m
Thickness	0.002	m
Number of Tubes (Nc)	130	-
Number of Columns	13	-
Casing Length	2.2	m
Casing Width	1.825	m
Casing Area	4.015	m^2

Table 5 details the operational and performance parameters. The heat exchanger has a heat duty of 648,985 W and an overall heat transfer coefficient of 112.66 W/m^2K. The Log Mean Temperature Difference (LMTD) is 286.74°C, corrected to 281.00°C. The heat transfer area is 20.50 m^2, and the maximum flue gas velocity is 13.33 m/s. The shell-side and tube-side Reynolds numbers (6236.36 and 21767.7, respectively) indicate turbulent flow. The Prandtl numbers are 0.709 (shell-side) and 0.36 (tube-side). The Nusselt number is 58.68, the friction factor is 0.00453, and the adjusted Reynolds number is 2459.91. The heat capacity rate is 0.8837, and the discharge rate is 0.1923 m^3/s. These parameters collectively suggest that the heat exchanger is well-designed for efficient waste heat recovery due to its effective heat transfer and ability to handle the expected thermal loads under turbulent flow conditions.

D. 3D Model Design and Simulation of the Heat Exchanger

i). Design and simulation of a heat exchanger model

Figure 4 shows the 3D model of well-structured multi-pass tube bundles of the designed heat exchanger. Thus, Figure 5 depicts a shell and tube heat exchanger with the bundle of U-bent tubes enclosed within the rectangular shell.

IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Impact Factor 8.066 ⁜ Peer-reviewed & Refereed journal ⁜ Vol. 12, Issue 4, April 2025

DOI: 10.17148/IARJSET.2025.12443

Table 5: Heat Exchanger Design Parameters

Parameter	Value	Unit
Outlet Temperature - Flue Gas	332.1495548	°C
Heat Duty (Qe = Qw)	648985	W
LMTD	286.73593	°C
Corrected LMTD	281.0021114	°C
Heat Transfer Area (A)	20.50021963	m²
Number of Tubes (Nt)	130.4919	-
Reynolds Number - Shell Side	6236.3597	-
Maximum Velocity (Umax)	13.33333389	m/s
Overall Heat Transfer Coefficient (Uo)	112.6593187	W/m²K
Nusselt Number (Nud)	58.67656186	-
Prandtl Number - Shell Side (Pr1)	0.7092892	-
Heat Transfer Coefficient (ho)	112.6593187	W/m²K
Surface Area per Tube (At)	1.445m²	m²
Cross-sectional Area (Ac)	0.463772	m²
Velocity - Tube Side (Vt)	2.214	m/s
Power (P)	0.0004657	W
Reynolds Number - Tube Side	21767.7	-
Heat Transfer Coefficient - Tube Side (ht)	0.2479058	W/m²K
Friction Factor (f)	0.00453	-
Adjusted Reynolds Number (x 0.63)	2459.905	-
Prandtl Number - Tube Side (Pr)	0.36	-
Heat Capacity Rate	0.8836972	-
Discharge	0.1923077	m³/s

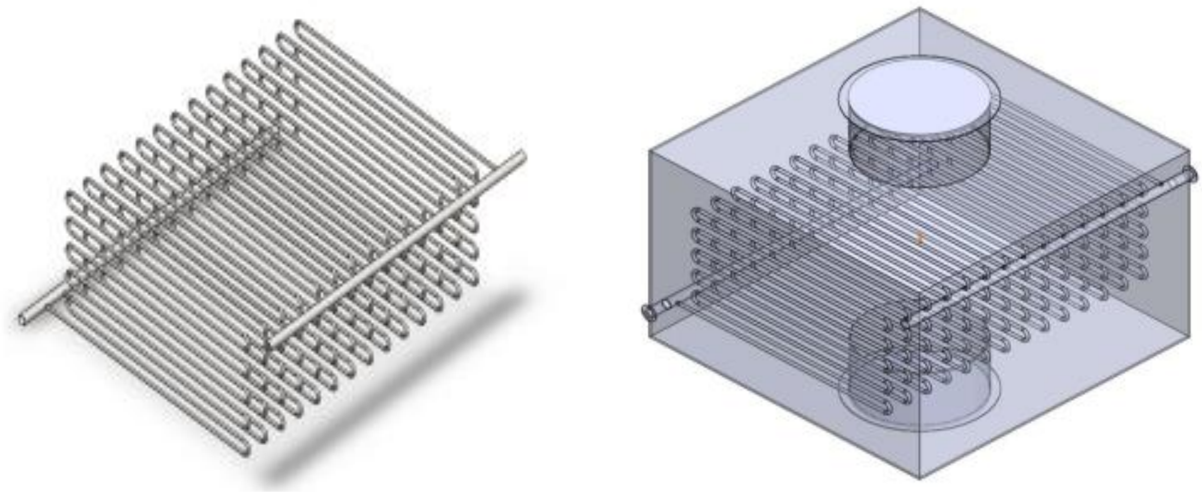

Fig. 4: 3D Model of the Heat Exchanger

Fig. 4 shows the 3D model of well-structured multi-pass tube bundles of the designed heat exchanger. Thus, the figure depicts a shell and tube heat exchanger with the bundle of U-bent tubes enclosed within the rectangular shell. The model is a robust and efficient shell-and-tube configuration, well-suited for maximizing thermal energy utilization in waste heat recovery. Additionally, the U-bend tube arrangement increases the heat transfer surface area while minimizing pressure drop and thermal stresses.

ii). Simulation and Evaluation of the Designed Heat Exchanger

The cross-sectional heat flow profile views of the heat exchanger with fluid velocity at the inlet and outlet regions shown in Fig. 5.

IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Impact Factor 8.066 ⧖ Peer-reviewed & Refereed journal ⧖ Vol. 12, Issue 4, April 2025

DOI: 10.17148/IARJSET.2025.12443

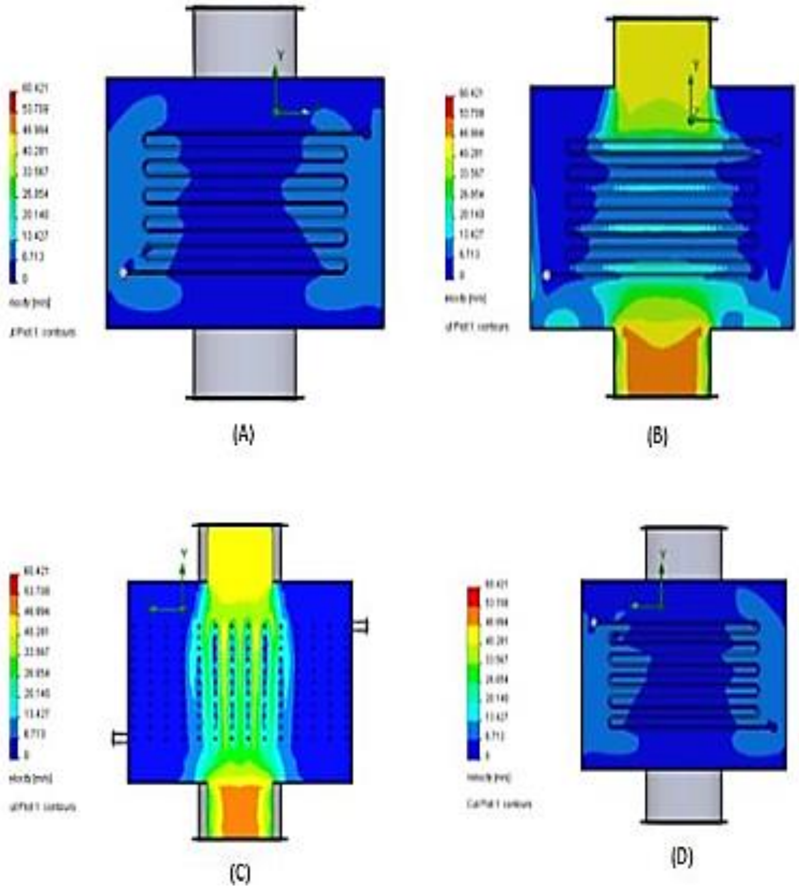

Fig. 5: Heat Profile Simulation for the Designed Heat Exchanger

The Simulations visualized in Fig. 5, illustrating velocity distribution in different shell-and tube heat exchanger configurations. Color gradients indicate velocity magnitudes, with red being highest and blue lowest. Fig. 5(A) shows a U-tube bundle with flow from left to right, exhibiting high velocities inside the tubes (good heat transfer) and low velocities with recirculation near the shell walls (potential inefficiency). Fig. 5(B) depicts a shell-and-tube exchanger with top inlet and bottom outlet, showing high velocities at these points (strong momentum flow) but potential velocity stratification and pressure losses. Fig. 5(C) presents a modified, possibly straight-tube, arrangement with more uniform fluid distribution and structured velocity contours, suggesting enhanced flow organization, minimized dead zones, and optimized performance with reduced pressure drops. Fig. 5(D), similar to 5(A) but from a different viewpoint, shows a U-tube configuration with low velocities and recirculation near the shell walls, indicating potential for poor fluid mixing and suggesting the need for enhancements like baffles to improve flow uniformity and heat transfer. The CFD simulations demonstrate that velocity distribution in shell-and-tube heat exchangers varies significantly with flow arrangement and tube configuration. High velocities within tubes promote convective heat transfer, while stagnant zones on the shell side can hinder efficiency, suggesting opportunities for design optimization.

iii) Simulation and evaluation of the complete waste heat recovery system (WHRS)

Fig. 6 illustrates the WHRS with the designed heat exchanger integrated in the system for the purpose of waste heat recovery from flue gas to produce hot water for consumption indicating all the streams and process conditions.

The Aspen HYSYS V12 simulation (Fig. 6) illustrates a Waste Heat Recovery System (WHRS) designed to heat oil using flue gas. Hot flue gas (360°C, 100 kPa, 1271 kmol/h) enters a heat exchanger (HE) and exits at a lower temperature (335.5°C), transferring heat to a water stream that enters at 105°C and exits at 130°C. Oil enters the system at 60°C and 800 kPa (500 kmol/h) and is heated to 85.59°C with a slight pressure drop (790 kPa) after passing through the heat exchanger. A pump (PUMP-1) circulates the water, and a tank with venting provides safety and pressure regulation. Control valves manage flow and pressure for system stability. This simulation highlights the effectiveness of waste heat recovery in improving energy efficiency, reducing energy losses, and promoting cost savings and sustainability in industrial processes by repurposing excess thermal energy from flue gas to heat oil.

IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588
International Advanced Research Journal in Science, Engineering and Technology
Impact Factor 8.066 ⪤ Peer-reviewed & Refereed journal ⪤ Vol. 12, Issue 4, April 2025
DOI: 10.17148/IARJSET.2025.12443

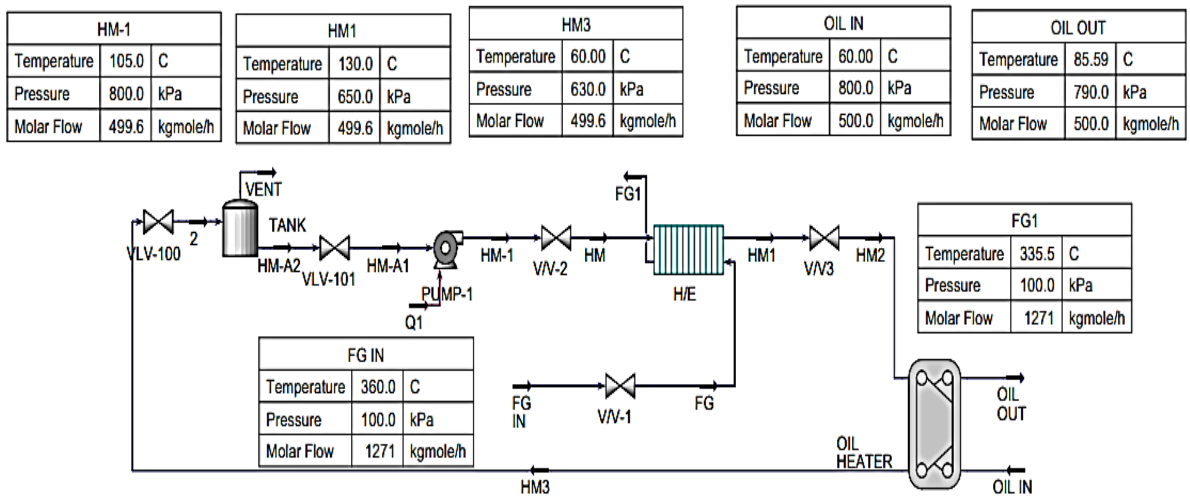

Fig. 6**:** Aspen Hysys simulation and evaluation of the complete WHRS with the designed heat exchanger

iv). Validation of the system using the field operating parameters

Table 6 compares the operating parameters of the existing and designed heat exchanger systems. For the water stream, the designed system maintains the same supply (130°C) and return (105°C) temperatures with no pressure loss and a stable flow rate (499.6 kmol/hr), confirming reliable heat transfer. For the crude oil stream, the designed system slightly lowers the supply temperature (from 65°C to 60°C) but achieves a slightly higher return temperature (from 85°C to 85.59°C), indicating improved heat recovery with a minor pressure drop (from 8 bar to 7.90 bar) and a constant flow rate (500 kmol/hr). These results validate the designed heat exchanger's effectiveness in optimizing energy utilization, reducing energy losses, and ensuring stable and sustainable crude oil preheating operations.

Table 6: Compares the operating parameters of the existing and designed heat exchanger systems

		Water Stream		**Crude Oil Stream**	
S/No.	**Parameters**	**(Existing System)**	**(Designed System)**	**(Existing System)**	**(Designed System)**
1	Supply Temperature (°C)	130	130	65	60
2	Return Temperature (°C)	105	105	85	85.59
3	Supply Pressure (bar)	6.5	6.5	8	7.90
4	System Flow Rate (kmol/hr)	499.6	499.6	500	500

IV. CONCLUSION

The study successfully designed and simulated a waste heat recovery system (WHRS) for preheating crude oil at the NNPC E&P Ltd Production Facility, aiming to improve energy efficiency and sustainability by recovering heat from flue gases.

i. Flue gas analysis revealed its composition, dominated by nitrogen, water vapor, and carbon dioxide, with no sulfur dioxide, indicating low-sulfur fuel use and environmental compliance. The oxygen content suggested optimal combustion.
ii. Process Flow Diagrams (PFDs) showed the evolution from a conventional heating system to an optimized WHRS that eliminates the oil heater and directly integrates a heat exchanger to maximize heat recovery from gas turbine exhaust.
iii. The designed shell-and-tube heat exchanger (130 tubes, 20 m length, 0.025 m outer diameter) operates with a heat duty of 648,985 W, an overall heat transfer coefficient of 112.66 W/m²K, and a corrected LMTD of 281.00°C. Turbulent flow conditions (shell-side Re = 6236.36, tubeside Re = 21767.7) ensure efficient convective heat transfer.

DOI: 10.17148/IARJSET.2025.12443

iv. CFD simulations of the U-tube bundle configuration showed optimal heat transfer within the tubes, with high velocities. Stagnation zones near the shell suggested potential for improvement with baffles or flow diverters.

v. The designed heat exchanger effectively maintains water stream temperatures (supply 130°C, return 105°C) with stable flow and no pressure loss. For crude oil, it slightly lowers the supply temperature (65°C to 60°C) while increasing the return temperature (85°C to 85.59°C) with a minimal pressure drop (8 bar to 7.90 bar) and constant flow rate, validating its ability to enhance heat recovery, minimize energy losses, and improve overall system efficiency for sustainable offshore production

REFERENCES

[1]. Thekdi, A., & Nimbalkar, S. U. (2015). *Industrial waste heat recovery-potential applications, available technologies and crosscutting r&d opportunities* (No. ORNL/TM-2014/622). Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States).

[2]. Tian, H., Shu, G., Wei, H., Liang, X., & Liu, L. (2012). Fluids and parameters optimization for the organic Rankine cycles (ORCs) used in exhaust heat recovery of Internal Combustion Engine (ICE). *Energy*, *47*(1), 125-136.

[3]. Ononogbo, C., Nwosu, E. C., Nwakuba, N. R., Nwaji, G. N., Nwufo, O. C., Chukwuezie, O. C., ... & Anyanwu, E. E. (2023). Opportunities of waste heat recovery from various sources: Review of technologies and implementation. *Heliyon*, *9*(2).

[4]. Rahbari, H. R., Elmegaard, B., Bellos, E., Tzivanidis, C., & Arabkoohsar, A. (2025). Thermochemical technologies for industrial waste heat recovery: A comprehensive review. *Renewable and Sustainable Energy Reviews*, *215*, 115598.

[5]. Uturi, N., Aronica, S., Bellini, L., & Salvati, A. (2019). Design and CFD analysis of an industrial low-pressure compressor for a concentrating high-temperature solar power plant. *International Journal of Thermodynamics*, *22*(4), 184–191. https://doi.org/10.5541/ijot.643311

[6]. O'Rielly, K., & Jeswiet, J. (2015). Improving industrial energy efficiency through the implementation of waste heat recovery systems. Transactions of the Canadian Society for Mechanical Engineering, 39(1), 125-136. https://doi.org/10.1139/tcsme-2015-0010

[7]. Mesfin, N., Ali, M. D. I., Ekanthaiah, P., Gupta, N. K., Kumbha, S., Srivastava, A. K., & Saxena, S. (2023). CFD modeling of waste heat recovery system to dry sand mold at G-7 Trading and Industry PLC. *Applied Mechanics and Materials*, *911*(1), 69–76.

[8]. Alsayah, A. M., Faraj, J. J., & Eidan, A. A. (2024). A review of recent studies of both heat pipe and evaporative cooling in passive heat recovery. *Open Engineering*, *14*, 20240012. https://doi.org/10.1515/eng-2024-0012

[9]. Vesely, L., Kapat, J., Bringhenti, C., Ribeiro, G. B., & Tomita, J. T. (2024). Innovative Design of Waste Heat Recovery Heat Exchangers. In *AIAA SCITECH 2024 Forum* (2757).

[10]. Elouardi, E., Yatim, F. E., & Chehouani, H. (2021). Temperature effect on thermal-hydraulic performance of one-pass counter-current flow shell-and-tube heat exchanger and upon its design. Thermal Science, 26(00), 349-349. https://doi.org/10.2298/TSCI210710349E

[11]. Zhuang, Y., Huang, N., & Jiang, Y. (2024). Effect of Volumetric Flow Rate on Heat Transfer Characteristics of Single-Fractured Rock with Different Surface Morphology and External Temperature. *Processes*, *12*(12), 2821. https://doi.org/10.3390/pr12122821

[12]. Hussein, A. K., & Sharma, K. V. (2024). Temperature effect on thermal-hydraulic performance of one-pass counter-current flow shell-and-tube heat exchanger and upon its design.*International Journal of Thermal Sciences*, *186*, 107451. https://doi.org/10.1016/j.ijthermalsci.2023.107451

