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Research Paper

Technical and Economic Analysis of Installing Plate Heat Exchangers and Waste Heat Boilers for Catalytic Reforming Units in Refineries

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Abstract: For the Catalytic Reformer Units, a feasibility study and the replacement of Combined Feed/Effluent Exchangers, which are currently shell and tube type, with PACKINOX Plate type have been considered. The study must include the potential for operational enhancements of the fired heaters connected to the PACKINOX heat exchangers. Catalytic Reformer Unit: Adding a convection heat recovery steam generator (HRSG) to the Fired Heaters. The high-level objectives of this project are as follows: energy savings, optimizing fired heaters, reducing environmental concerns, and increasing steam production within the refinery network. In this study, the impact of the fuel gas/fuel oil ratio on IRR, NPV, and payback, considering both subsidy prices and international prices, has been investigated. Summarizing the feasibility study results of this project, achieving up to 14.01% IRR with a payback period of 6.74 years for the project investment makes the installation of PACKINOX and HRSG feasible for the refinery. Notably, typical heat recovery projects with more than 10% IRR are generally recognized as attractive for revamping projects. Therefore, significant gross fuel prices in the future will increase the aforementioned IRR.

keywords: Catalytic Reforming Unit, Plate Heat Exchanger, Waste Heat Recovery.

1. Introduction

Reducing energy consumption in energy-intensive industries in a special way can lead to profitability as well as reducing the production of environmental pollutants. As one of the most important industries in the world, the crude oil refining industry consumes a lot of energy. Various studies have been conducted to reduce energy consumption in refineries. With energy and economic analysis, the researchers discussed the possibility of producing power and electricity, water and hydrogen, and other things. Eldean & Soliman (2017), in their research, investigated the use of waste heat from the refinery to produce power and fresh water. They used the ORC cycle and hybrid MSF and MED for a desalination plant [1] . Yu et al. (2016) used a systematic method; they analyzed the use of the organic Rankine cycle in the network of heat exchangers for a refinery. They examined different options in several scenarios. The WHCC waste heat composite curve was used for this purpose. Also, in their work, the working fluid of water was used as a medium for heat transfer to maintain the necessary safety [2]. Jung et al. (2014) used an organic Rankine cycle in the flow of kerosene in the vacuum distillation tower as a heat source, and they produced power. The investment return of this project is 6.8 years [3]. Lu et al. (2023), in their research, used a hydrogen production reformer that has corrosive gases in the waste, and they recovered heat up to 30 degrees Celsius using a suitable alloy [4]. Nazerifard et al. (2022) used ORC and Post-combustion capture in the Tabriz refinery furnace for carbon capture and power generation [5]. Ghavami et al. (2023) introduced a new multigeneration system consisting of Power heating and cooling and water from the waste heat of gas refineries. The payback period of the multigeneration is lower

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than 5 years [6]. Varga & Csaba (2018) used ORC with pure and mixed working fluids for heat recovery in the refinery [7]. Wang et al. (2022) used a new design of a heat exchanger network for plate exchanger in the crude oil distillation system [8]. Picón-Núñez & Rumbo-Arias (2021) improved the method for welded plate heat exchanger technology for the revamping project. Their case study was a crude preheat train with 12 heat exchangers [9]. Jirandeh et al. (2021) introduced a new model for a network of heat exchangers by Plate- fine. They use 10 different geometrical parameters for decision-making [10]. Vathi & Chaudhuri (1997) modelled and simulated the commercial catalytic reformer [11]. Arani et al. (2010) developed a model for the dynamic simulation of a catalytic reforming unit [12]. Duchêne et al. (2020) optimized light naphtha isomerization and catalytic reforming by two steps of optimization [13]. Jiang et al. (2022) used real-time optimization (RTO) and a sequential quadratic programming (SQP) algorithm for optimization of profits [14]. Babaqi et al. (2020) use the PSO for the maximization of reformate production and reduction of energy consumption by mathematical modeling and simulation [15]. Auta et al. (2012) used pinch technology to improve the energy recovery [16]. Pinch technology was used by Babaqi et al. (2017) for utilizing the energy consumption in the Continuous Catalytic Regeneration Reformer Process (CCRRP), and energy reduction was 32 % [17]. The objectives of this study are to demonstrate the economic and financial viability of the targeted installation via the following steps:

o Defining the basis for replacement of Shell & Tube heat exchanger with PACKINOX type and also installation of flue gas heat recovery steam generation, Identifying the different scenarios based on hot end approach of PACKINOX heat exchanger, PACKINOX and HRSG configuration study in CRU Layout, and Development of an economic analysis to evaluate the different PACKINOX/HRSG installation scenarios, a recommendation for the most economic option to be installed. The process scheme scoped in the project is provided below for CRU.

The following steps are considered in this manuscript: Conceptual calculation basis for the HRSG and PHE, Amount of flue gas raised in the common stack of the fired heaters, Amount of fired heaters' duty reduction, New fuel gas/fuel oil consumption for the fired heaters, Amount of steam raised in HRSG and BFW consumption, and Cost analysis of the scenario.

2. Process description of CRU

This unit consists of two distinct parts: the Naphtha Refining Unit and the Platformer Unit. The task of the naphtha refining unit is to provide suitable feed for the platform unit. In this unit, metal poisons and impurities in the incoming naphtha are removed to provide a suitable feed for the platformer unit. This operation is performed in the unifier reactor and its vicinity, near the catalyst. The unifier unit includes a furnace, reactor, deaerator tower, compressor, and other accessories. In the existing process, a tube shell heat exchanger is used, and the heat produced in the process is given to the atmosphere. Therefore, we will improve the process by using the recycling approach and a new heat exchanger that is accepted in the world. Figure 1 shows a schematic of a real catalytic converter unit and its furnaces and reactors.

Fig. 1. Schematic of CRU Plant in Tehran Refinery

Figure 2 also shows a schematic example of the arrangement of the various components. Naphtha is first introduced and preheated by a heat exchanger. The furnace and reactor are then in series in three stages. At the exit of the third reactor, the product in the heat exchanger preheats the feed. As mentioned in the introduction, the exchanger will be changed, and the gases from the furnace combustion are also collected and recovered.

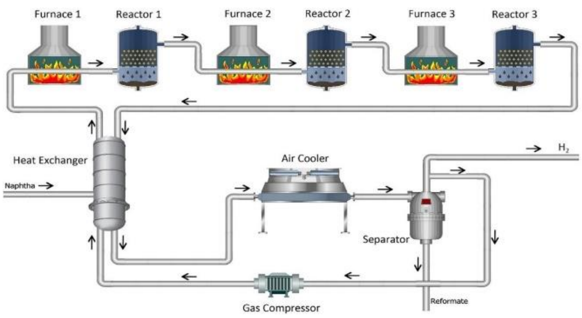

Fig. 2. Schematic Illustration of a Catalytic Reforming Unit

3. Technical Study

3.1. Simulation for Base Case Generation

The effluent stream from the feed/effluent exchanger to the air cooler was composed of true and pseudo components. The pseudo-component properties are defined in Table 1:

Table 1. Pseudo Component Properties

Name	NBP[C]	MW	Liq Density [kg/m3]	Tc [C]	Pc [bar_g]	Vc [m3/kgmole]	Acentricity
Hypo70*	65	84.7	689	233.3	30.25	0.3588	0.2684
Hypo80*	75	92	709.4	247.6	30.45	0.3659	0.2737
Hypo90*	85	97.3	720.6	260.5	30.04	0.3778	0.2902
Hypo100*	95	103	731	272.8	29.48	0.3913	0.3072
Hypo120*	115	114	749.8	296.2	28.07	0.4238	0.3364
Hypo130*	125	119	758.4	307.7	27.29	0.442	0.3521
Hypo140*	135	125	766.3	319	26.49	0.4614	0.3662
Hypo150*	145	131	773.8	330.3	25.7	0.4807	0.3881
Hypo170*	165	143	787.4	352.4	24.14	0.5249	0.4136
Hypo190*	185	156	799.6	373.9	22.64	0.5704	0.4513
Hypo210*	205	170	810.6	394.6	21.2	0.6205	0.4823

Table 2. Stream Composition

Name	Mole Fractions
Hydrogen	0.6721
Methane	0.0776
Ethane	0.0719
Propane	0.0454
i-Butane	0.0114
i-Butene	0.0001
n-Butane	0.0161
i-Pentane	0.0083
1-Pentene	0.0002
n-Pentane	0.0063
Hypo70*	0.0123
Hypo80*	0.0003
Hypo90*	0.0036
Hypo100*	0.0129
Hypo120*	0.0163
Hypo130*	0.0039
Hypo140*	0.0266
Hypo150*	0.001
Hypo170*	0.0119
Hypo190*	0.0017
Hypo210*	0.0001

Before modeling the optimization scenarios, some pre-cases are examined to set the base case (simulation model of the existing condition) for CRU. In order to provide a representative and consistent set of data that could be used for designing two identical heat exchangers, both units have been modeled using the Petro-Sim reactor model and operating data of each unit. After comparing operating conditions and product specification with model output, required data such as heating curve and physical properties generated from the model are provided for these systems.

By comparing model output data with operating conditions and test run data, the model is good enough to use for generating heating curves and physical properties for designing the plate-type heat exchanger and HRSG. The characteristics of the flue gas from the furnace are also presented in Table 3. The liquid fuel is also considered to contain a maximum S content of 3.5% by weight. Fuel gas: A maximum of 100 ppm H2S is considered.

The composition of this effluent stream in two cases (i.e., with existing shell and tube and after PACKINOX installation) is assumed unchanged, and the composition is as follows (Table 2):

Table 3. Flue Gas Composition

%wt. wet	value
N2	72.52
O2	5.05
H2O	7.85
CO2	14.38
SO2*	0.19

3.2. Simulation by Hysys

The schematic below shows the simulation result for the improvement scenarios (Figure 3):

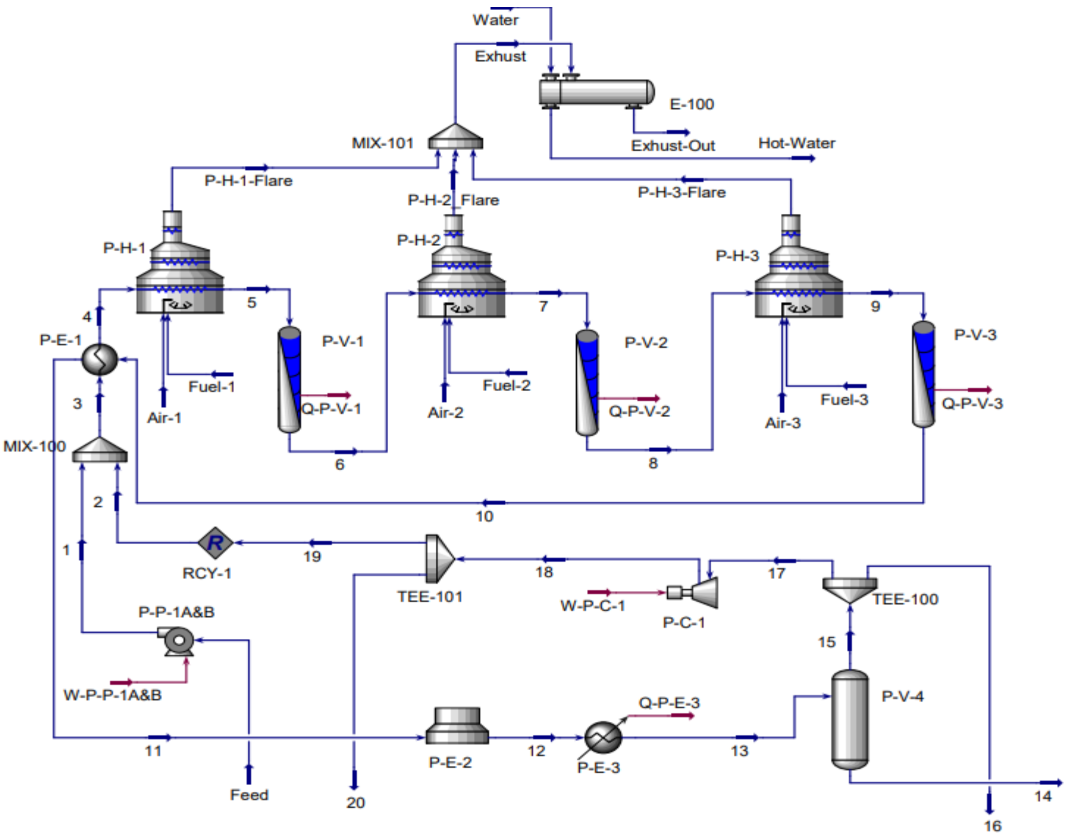

Fig. 3. Simulation Schematic by HYSYS Software

4. Results and Discussion

Three scenarios were chosen for this project based on Alfa Laval PACKINOX options. The characteristics of each scenario are shown in Table 4.

Table 4. Operation Scenarios Definition for CRU Unit

Scenarios	Definition	Hot End Temperature Approach (HEA)
Scenario 1	Existing Condition	90 °C
Scenario 2-1	PACKINOX + HRSG	50 °C
Scenario 2-2	PACKINOX + HRSG	40 °C
Scenario 2-3	PACKINOX + HRSG	30 °C

4.1. Process Specifications of Main Equipment

The following scenarios are defined for a feasibility study. The process conditions of each scenario are summarized in the tables below.

The new process conditions of the plate heat exchanger, fired heater, and air cooler will be as in Table 5.

The inlet temperature of the air cooler will be decreased since the outlet temperature remains in the existing conditions. Also, the heater efficiency is based on Table 6.

Table 5. Process Condition of New Heat Exchanger and Fire Heater

Scenario	HEA 50 °C (Scenario 2-1)	HEA 40 °C (Scenario 2-2)	HEA 30 °C (Scenario 2-3)
Feed Side Temperature, °C (Inlet / Outlet)	81 / 444	81 / 454	81 / 464
Effluent Side Temperature, °C (Inlet / Outlet)	494 / 116	494 / 108	494 / 100
Duty heat exchanger, Gcal/hr	42.6	43.9	45
Duty of Heater, Gcal/hr	7.3	6.1	4.9
Fluid Temperature air cooler, °C	116 / 60	108 / 60	100 / 60
Duty air cooler, Gcal/hr	7.6	6.4	5.2

Table 6. Heater Efficiency

Heater tag number	H-251
Absorbed duty, MM Btu/hr	22.6
Heat release, MM Btu/hr	36.7
Efficiency, %	61%

4.2. Utility Summary

Table 7 shows the margin of consumption and production for both CRU, showing the difference between future and current conditions.

Table 7. Margin of Consumption & Production for CRU

PACKINOX TEMPERATURE APPROACH (HEA)	FUEL TYPE	FEEDSTOCK				PRODUCT
		Fuel	Electricity		BFW	Steam
			Air Cooler	ID Fan		
		(Ton/hr)	(KWh per year)	(KWh per year)	(Ton/hr)	(Ton/hr)
Scenario 2-1 (HEA=50 °C)	Fuel Gas (95%)	-0.79	-491260	1564120	16.49	16.17
	Fuel Oil (5%)	-0.05				
Scenario 2-2 (HEA=40 °C)	Fuel Gas (95%)	-0.99	-616170	1473716	15.54	15.23
	Fuel Oil (5%)	-0.06				
Scenario 2-3 (HEA=30 °C)	Fuel Gas (95%)	-1.19	-741937	1383312	14.59	14.30
	Fuel Oil (5%)	-0.07				

Minus: incremental of saving
Plus: incremental of consumption and production

4.3. Economic Study

The CAPEX developed for alternatives is based on input cost data from the major components, as well as in-house data. This is a conceptual study, and the estimates were used as the basis to develop the cost estimate with conceptual accuracy. The methodology associated with an AACE Class 4 estimation is appropriate for a conceptual study and for the identification of requirements necessary for the next phase of study. The estimation is based on the main process facility estimates from the vendors. Process packages have been scaled to capacity if required for each process case. The total installed cost of the HRSG and PACKINOX for three hot approach temperatures is provided in Tables 8 and 9.

The OPEX considers both variable costs and fixed costs. Variable costs consist of estimating for raw materials and utilities, while fixed costs consist of estimating for operations, maintenance, and insurance. The variable costs were developed using Cost input from the vendors for specialty chemicals and catalysts, considering dual fuel (fuel gas and fuel oil) and utility costs from data gathered.

The fixed costs were developed using: A staffing philosophy and labor rates based on in-house data, 50% of personnel costs as an estimate for direct overhead costs, 2% of TIC of the plant for maintenance costs (2% is a general factor used for maintenance), and 0.5% of total installed cost of the plant as an estimation for insurance costs.

Operating cost estimation for the existing and three considered scenarios for the CRU unit is provided in the tables below. The key assumptions for the project Economic Analysis are summarized in Table 10.

Table 8. Project CAPEX for HRSG and PACKINOX for Each Unit

COST	S2-1 (HAT=50 C)		S2-2 (HAT=40 C)		S2-3 (HAT=30 C)	
	HRSG	PACKINOX	HRSG	PACKINOX	HRSG	PACKINOX
Package Cost (USD	4,529,200	2,742,552	4,380,375	2,971,098	4,228,101	3,313,917
Installation Cost (USD	2,731,107	1,645,531	2,641,366	1,782,659	2,549,545	1,988,350
Package + Installation Cost, USD	7,260,308	4,388,083	7,021,742	4,753,757	6,777,646	5,302,267

Table 9. Total CAPEX for HRSG and PACKINOX for Different Scenarios

COST	S2-1 HAT=50 C	S2-2 HAT=40 C	S2-3 HAT=30 C
Total Installed Cost, USD (HRSG Package + PACKINOX)	11,648,391	11,775,499	12,079,913

Table 10. Project Economic Analysis Assumptions

Item	Assumed Value	Remarks
CAPEX spending profile	In 2 years, from 2018 to 2019	In-house data
Production Phase	20 years	
Plant Availability	98% or 358 days/year	In-house data
Valuation date	2023	
Discount Rate	5%	
Corporate income tax rate	22.5%	
Depreciation	10 years	Linear to scrap
Scrap Value	10%	
Escalation Rate	4%	
Annual maintenance cost	2% of Total Installed Cost	In-house data
Annual insurance & property tax cost	0.5% of Total Installed Cost	In-house data
Number of new operation staff	0	In-house data

Contingency and owner costs are not included due to the high-level nature of the current analysis. The owner's cost of 10% and contingency of 20-30% is typically assumed in front-end studies for specific locations/projects. The pricing assumptions are based on feedback from the Tehran Oil Refinery. We have considered 2 scenarios for Fuel Oil and Fuel Gas prices: Based on Subsidy prices and based on International prices. It should be noted that the steam and power price in financial calculations is considered equal to the consumed fuel in the steam generation section and the power generation section. The following assumptions are considered in economic calculations:

- Fuel consumption (in the steam generation section) per one ton of steam is considered 73 kg;
- Fuel consumption (in the power generation section) per one megawatt of power is considered 400 kg;
- Power (saving or consumption) cost is considered equal to fuel cost, based on 60% Natural Gas and 40% Fuel Oil
- Produced steam price in HRSG is considered equal to fuel cost based on 60% Natural Gas and 40% Fuel Oil
- Fuel saving in fired heaters is considered based on 95% Natural Gas and 5% Fuel Oil

According to the client's request, the profit of steam generation (with HRSG) is calculated based on the fuel saving in the steam generation unit. This assumption is valid as long as the produced steam is more than the steam consumption of the refinery (Table 11).

Table 11. Pricing Inputs to the Economic Model Based on Subsidy Prices

Item	Unit	subsidy Price	International price
Fuel gas Price	USD/ton	51.78	161.31
Fuel oil Price	USD/ton	253	253
Power price*	USD/Kwh	0.053	0.079
Steam Price*	USD/ton	11.91	16.71
BFW Price	USD/m^3	2.21	2.21

* Based on fuel consumption price
Note: BFW is considered in steam price

4.4. Economical Result Analysis

Table 12 shows the comparison of NPV, IRR, and investment payback period, respectively, for CRUs and also considering both units together based on subsidy prices.

Table 12. Comparison of NPV, IRR for Different Scenarios (Based on Subsidy/ International Prices)

Scenarios	Scenario 2-1 HEA=50 °C	Scenario 2-2 HEA=40 °C	Scenario 2-3 HEA=30 °C
NPV [USD million]	10.9/30.1	11.5/32.9	11.8/35.4
IRR %	12.90/22.97	13.16/24.07	13.19/24.81
Payback Period (year)	7.22/4.21	7.11/4.01	7.09/3.88

Considering scenarios 2-3 (HEA=30 °C) as the selected case, shows that the project After-Tax IRR for CRU is 14.82% and 13.19%, respectively, which represents a reasonable Project viability. In addition, based on the discount rate of 5%, the project NPV for CRU is calculated as 14.7 and 11.8 million USD, respectively.

Table 12 depicts the comparison of NPV, IRR, and investment payback period, respectively, for both CRUs and also considering both units together based on international prices.

5. Conclusion

Outcomes from the simulation results indicate significant energy saving due to the installation of PACKINOX and HRSG in the Tehran refinery in the CRUs. Further to the energy saving and environmental improvement aspects, PACKINOX and HRSG system will have prominent benefits on the furnace's more reliable performance by reducing the flame intensity, risk of tube impingement, and improving the combustion pattern in the firebox, which in result increases the furnace's life and minimizes the maintenance cost of the refractories and burners at one most important refinery priority. Results from simulations in support of collecting data from the vendors have been based on developing a Feasibility Study to evaluate alternative options where the PACKINOX and HRSG system will appear at more economical performance by selecting vendor-recommended, 30 °C hot approach temperature for the PACKINOX and about 170 °C outlet flue temperature from the HRSG system. Considering the refinery demand for producing HP steam, an HRSG is selected as the most attractive option to enhance the recovered heat from the flue gases. An economic evaluation has been developed for CRU. In each case, IRR and payback years are calculated at different scenarios for approach temperatures of 30, 40, and 50 °C. In this study, the economic and financial parameters have been calculated in the worst conditions. Therefore, the economic results can be moderately improved upon considering the calculations based on normal conditions. At the end of this study, the impact of fuel gas/fuel oil ratio on IRR, NPV, and Payback, considering subsidy prices and also international prices, has been investigated. Summarizing the FS results for both cases (subsidy and international prices) indicates that PACKINOX and HRSG installation is feasible for the refinery. It is notable to mention that considering the intentional prices improves economic indexes (IRR, NPV, and payback period). To keep the results consistent, calculations have been made based on the utilities' prices at the site. Therefore, an incredible gross fuel price in the future will increase the calculated IRR. This FS is supposed to be updated along with the project progress upon receiving new information from the vendors.

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