Simulation and Techno-Economic Analysis of the Integration of a Combined Heat and Power System in a Flare Gas Recovery Unit – Case Study: Tabriz Oil Refining Company (Northwest Iran)

Farrokhi, Mahmoud**; Neyestani, Fatemeh; Kazemi-Beydokhti, Amin; Heydarzadeh Darzi, Hamid
Department of Chemical Engineering, School of Petroleum and Petrochemical Engineering,
Hakim Sabzevari University, Sabzevar, I.R. IRAN

ABSTRACT: *Combined Heat and Power (CHP) systems can reduce energy waste in various industries including oil, gas, and petrochemical plants. In this research, the feasibility of the establishment of a CHP system in A Flare Gas Recovery (FGR) unit is studied. The integration of CHP system in FGR unit is investigated from the economic, technical, and environmental viewpoints. The FGR unit of Tabriz Oil Refining Company which is located in northwest Iran is considered as a case study. No such an integration has been investigated previously. The simulation of the proposed system is performed using ASPEN-HYSYS software. Rankine cycle is considered for the combined production of heat and power and water is utilized as the Rankine cycle working fluid. The fuel needed by the CHP system is supplied from the FGR unit. In order to more utilization of the fuel energy, the thermal energy of furnace flue gases is recovered through a regenerator heat exchanger. The simulation results showed that the proposed system can generate about 4 MW of electrical power and 16 MW of thermal power corresponding to 15.42% and 77.63% electrical and thermal efficiencies, respectively. Moreover, 4,532 kg/h of hot steam with a temperature of 381.4 ˚C is produced by utilizing the furnace flue gases' thermal energy. The results of this study showed a promising performance for the integration of a CHP system in FGR unit of Tabriz Oil Refining Company. The present study may be a step forward towards the efficient use of energy sources. Future works in this field can be done with a view to the practical integration of CHP systems in FGR units.*

KEYWORDS: *Combined heat and power; Rankin cycle; Flare gas recovery; ASPEN-HYSYS; Technoeconomic analysis.*

INTRODUCTION

Industrial processes are among the energy-intensive activities. Therefore, energy saving and its effective utilization will have significant effects on the progress and development of any country. Combined heat and power systems, as an efficient method to reduce energy consumption, are currently on the agenda of many

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**To whom correspondence should be addressed.*
\+ *E-mail:* m.farrokhi@hsu.ac.ir

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developed countries and a significant portion of the electrical and thermal energy required in these countries is produced using this method [1, 2]. Electricity and heat are two basic needs in any country or industry. In most countries, huge power plants have been built to supply electricity, and most large industries, such as refineries and petrochemicals, have independent units within their complex to provide these services [3].

Recently, more attention has been paid to CHP systems due to their higher energy efficiency. These units are supplied with energy sources such as fossil, biomass, solar, and geothermal, among which the use of fossil fuels has been more common despite environmental problems [4, 5].

There are various researches in the field of simultaneous production of heat and power from a single energy source in the literature. For example, *Lee et al*. [6] modeled and simulated a CHP system using a 1 MW solar power plant in Beijing. The results showed that using the renewable solar energy as fuel for the CHP unit and using the absorption heat pump, 6,214 kWh of electricity and 14,502 MJ of thermal energy can be obtained daily. The efficiency of the proposed system is 15.96%, which is 4.55% higher than that of the current solar power plant. Additionally, 914 MJ/day of thermal energy was recovered using the absorption heat pump in the considered system. In another study, *Kazemi et al*. [7] proposed a hybrid system for combined production of heat and electricity from solar energy. The hybrid system comprised of a solar air collector, solar chimney, thermoelectric generators, and wind turbine. The air passed through the solar chimney was utilized to produce electricity through a wind turbine during the night-time. The solar energy was also used for heat generation and running the wind turbine for power generation during the daytime. They performed economic and environmental analysis on their proposed system and concluded that the payback period is less than 1.5 years and system is capable in CO_2 emission reduction of 5,111 kg/yr.

Mahian et al. [8] performed exergy analysis for different CHP systems with different power sources in the gas turbine, reciprocating engine, Rankine cycle, fuel cells, Organic Rankine Cycle (ORC), and hybrid energy systems. They stated that the use of renewable energy sources in ORC and hybrid systems could be a very influential research topic. Their results showed that further studies could be conducted on fuel cells, internal combustion engines, and the use of nanofluids in ORC systems in order to improve the efficiency of CHP systems. Simulation and experimental investigation of the efficiency improvement of a CHP system through utilizing carbon nanotube as an additive to the water to make a nanofluid performed by *Kazemi-Beydokhti et al*. [9]. They utilized different nanofluids in their experimental CHP system and concluded that the modified carbon nanotube had an improving effect on the heat recovery in the CHP system compared with some other fluids. *Eyerer et al*. [10] examined the potential of using geothermal energy for CHP systems in Germany. The results showed that the proposed system can provide 1.51% of the electricity consumption and 1.48% of the thermal energy required for ambient heating and domestic hot water. They also showed that Germany could use renewable and clean geothermal energy instead of fossil fuels in the future to meet its electricity and heating needs.

In order to more efficient utilization of energy in the CHP units, the heat of combustion gases is generally used for more thermal efficiency in various industries, especially in chemical companies [11, 12]. In fact, by consuming one fuel source, electricity and thermal energy can be produced in these units simultaneously. Recently, some studies have been conducted on the reduction of fuel and energy consumption and efficiency enhancement of CHP units. *Kazemi-Beydokhti* and *Zeinali Heris* [13] investigated the thermal optimization of CHP systems using nanofluids. Their results showed that higher thermal efficiency and acceptable economic benefits can be achieved using nanofluids as working fluid and biogas as fuel in these units. In another study, *Ortega et al.* [14] investigated the use of recovered gases in the FGR unit as fuel for CHP systems. They argued that the solution could not only prevent the loss of valuable hydrocarbons in the flaring process but also prevent global warming and the release of greenhouse gases into the environment.

Semmari et al. [15] investigated the simultaneous production of electricity and heat by an ORC utilizing toluene as the working fluid. The energy source was the recovered heat from flare gas. In this study, they investigated the thermodynamic performance of the system in terms of energy and exergy. They also performed a sensitivity analysis to identify the most important parameters affecting system performance. Sensitivity analysis was performed on evaporation temperature, flare gas temperature, working fluid superheat temperature, and turbine efficiency. The results showed that with a constant temperature for the inlet flare gas, the total exergy destruction is reduced and as a result, the thermodynamic performance of the system and the turbine power output are improved. The sensitivity analysis on the inlet flare gas temperature showed that with the increasing temperature of the hot source, an exergy destruction occurs in the evaporator and the entire system. Superheating temperature sensitivity analysis showed that superheating of toluene should be minimized because it belongs to the dry fluids' category. Superheating reduces the thermal performance of the system and causes significant exergy degradation, especially in the condenser. Also, increasing the turbine efficiency leads to improving the thermodynamic performance of the system both from the total exergy destruction and turbine power output viewpoints.

In most of the chemical industry processes, including oil and gas refining, a pressure control system is used and a flare tower is placed at the end of this system. In case of unexpected and high-pressure flow inside these units and for protecting equipment and pipelines, some of the existing gas is discharged to the pressure control system using control valves and burned in the burners [16]. Therefore, the existence of flaring systems is essential in these industries. Despite eliminating the risk of pressure vessels exploding in oil and gas industries and maintaining employee safety, these systems are not harmless. This is because flare burners emit various pollutants into the atmosphere and cause environmental problems such as air pollution, acid rain, noise pollution, unpleasant odors, and eventually diseases in humans and living organisms [17, 18]. Hence, its environmental effects must be reduced. Additionally, it's possible to create added value from flare gases due to the presence of hydrocarbon compounds such as methane, ethane, and propane, as well as hydrogen in these gases [19]. Gathering and recovering of these gases are among the activities performed in this field in the industries which have considerable amount of flare gas [20, 21]. In fact, they can be sold as a product or burned as fuel in some units in these industries. Another solution is to establish a CHP system to utilize these gases as fuel and provide all or part of the electricity and heat needs of these industries [22].

Some investigations have recently been performed on FGR and CHP systems in Iran. For instance, in a case study in southern Iran, *Mousavi et al*. [23] assessed the technical, economic, and environmental aspects of FGR systems using HYSYS, Thermoflow, and ASPEN software. They considered three scenarios for flare gas recovery with the objective of energy consumption reduction and control of environmental pollution. The first scenario was the compression of flare gas and injection into oil wells to enhance oil recovery. The second scenario was electricity generation and surplus gas injection into oil wells and the third one was power generation using a CHP system and an internal combustion engine. The results showed that the first scenario with an internal investment rate of 171% and a payback period of 1.02 years is the best method. In another study, the feasibility of using a CHP system in a car-manufacturing factory in the northeast of Iran was investigated by *Deymi-Dashtebayaz* and *Kazemiani-Najafabadi* [24]. They proposed the use of a gas engine for electricity generation and recovery of its exhaust waste to supply the heating demands of the car factory. Two different investment scenarios were proposed. The electricity sales to the grid and in-site consumption of generated heat were the preferred scenarios. Integration of a hot oil system and a CHP generator through the combination of pinch technology and mathematical programming was studied by *Shahidian Akbar et al*. [25]. The integrated system included a gas turbine as the top cycle a hot oil system and an ORC as the bottoming cycle. The proposed integrated design provided 30% increase in income compared to the conventional design.

Due to the destruction of the environment by industrial processes in the past years, attention to the environment along with economic and technical issues such as energy and exergy efficiency, has recently attracted the attention of many researchers [26, 27]. In this regard, *Sarkari et al.* [28] conducted a case study on the recycling of regeneration gas from a mercaptan removal unit through flash gas compression in order to flare gas reduction. The flow rate of flaring gas was 13,000 Nm^3/h. Experimental investigations as well as dynamic simulation were performed to prevent this amount of flaring. A new configuration was proposed and tested to achieve this goal. The proposed configuration was capable of reducing 75% of flare gas, and decrease 75% of CO_2, and CH_4 emissions. Furthermore, process simulation was recently used for hazard identification of integration of flare gas with cogeneration system by *Sarkar et al*. [29]. The effect of flare gas quality and conditions under abnormal situation were studied. The results showed the nominal effect of flare gas temperature on the process. In addition, it was found that flare gas composition could affect the heat transfer behavior of fired gas boiler. Tube rupture, firebox instability, steam explosion, and flame impingement were among the hazards identified which must be prevented.

The main objective of the present work is performing a case study on the feasibility of integration of a simultaneous electricity and heat production system in the flare gas recovery unit of Tabriz Oil Refining Company (northwest Iran). The study focused on the effects of the proposed system from the technical, economical, and environmental aspects. No such an integration has been performed previously in the FGR unit under consideration. The fuel needed in CHP system is supplied from the FGR unit. A Rankine cycle utilizing water as the working fluid is considered for the combined production of heat and power. The working fluid undergoes evaporation, expansion, condensation, and compression processes sequentially. Mechanical and thermal energy are produced in the expansion and condensation processes, respectively. To more utilization of the fuel energy and increase the efficiency of the process, the thermal energy of combustion hot gases exhausted from the furnace, which have a significant temperature and flow rate, are also used to generate a superheated vapor. The results of this case study are presented in this paper. The next section of this paper describes the details of proposed process for simultaneous heat and power production using the fuel supplied from the FGR unit as well as its simulation. Furthermore, the simulation assumptions are introduced. Thereafter, the simulation results are presented and discussed. Finally, the conclusion section summarizes the paper, highlights and concludes the main results and findings, and recommends the next step for this study.

THEORETICAL SECTION

The products of the FGR unit of Tabriz Oil Refining Company are liquid and gaseous hydrocarbon streams. The liquid product (line 113 in Fig. 1) is sent to Isomax unit to produce gasoline, and the gaseous product (line 115) is burned in a furnace and its generated heat is used in the factory. Fig. 1 shows a simple view of the FGR unit of Tabriz Oil Refining Company.

This study investigates the feasibility of using the gaseous product of the FGR unit (line 115) to generate thermal energy and electricity. Fig. 2 represents an overview of the proposed process for the simultaneous production of electricity and heat using the gaseous fuel supplied by the FGR unit.

The process of simultaneous production of heat and electricity is simulated with the aid of ASPEN-HYSYS software using the Peng-Robinson equation of state. The Peng-Robinson equation of state is generally the recommended thermodynamic model for oil, gas, and petrochemical applications. This model supports the greatest variety of systems and the widest range of operating conditions (temperatures greater than – 271 ˚C, and pressers lower than 100,000 kPa). The main assumptions made throughout the simulation are introduced below.

Steady-state conditions were assumed and pure water was used as the Rankine cycle working fluid and cooling agent of the Rankine cycle condenser. Besides, the pressure drop across the shell and tube of the heat exchangers was assumed to be 0.1 kPa. Negligible pressure drop and heat loss were assumed throughout the piping. The furnace efficiency was assumed to be 75% and 20% of excess air was supplied to the furnace. In addition, the efficiency of the turbine and pump was kept constant at 75% and negligible heat loss in heat exchangers was also assumed. The condenser minimum temperature approach of 5 ˚C was assumed.

It is noted that in process simulation, the temperature and pressure of the working fluid at the furnace inlet, the corresponding temperature at the outlet of the furnace, the outlet pressure of the turbine, and the outlet temperature of the condenser were adopted according to the information received from the utility unit of Tabriz Oil Refining Company. Furthermore, the properties (temperature, pressure, flow rate, and composition) of the furnace fuel were exactly the specifications of the gaseous product of the FGR unit.

Fig. 3 illustrates the partial flow diagram of the simultaneous production of electricity and heat using the FGR unit gaseous product as fuel. As can be seen from Figs. 2, and 3, the proposed system for combined generation of heat and power has a closed cycle in which water was used as the working fluid. Temperature and pressure of water at stream 101 were 60.44 ˚C and 4,200 kPa,

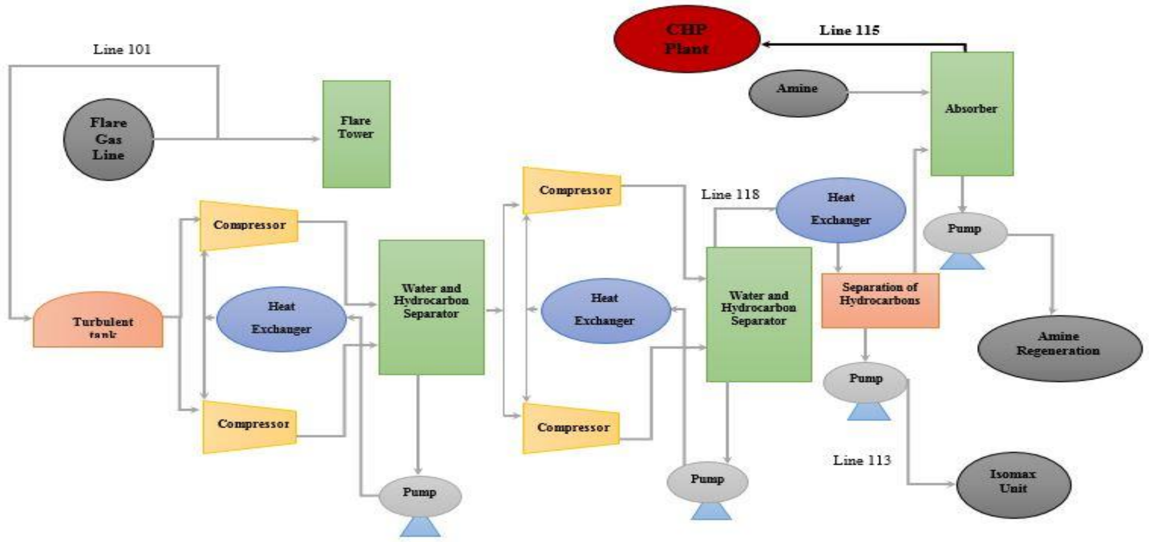


Fig. 1: Simple view of the FGR unit of Tabriz Oil Refining Company

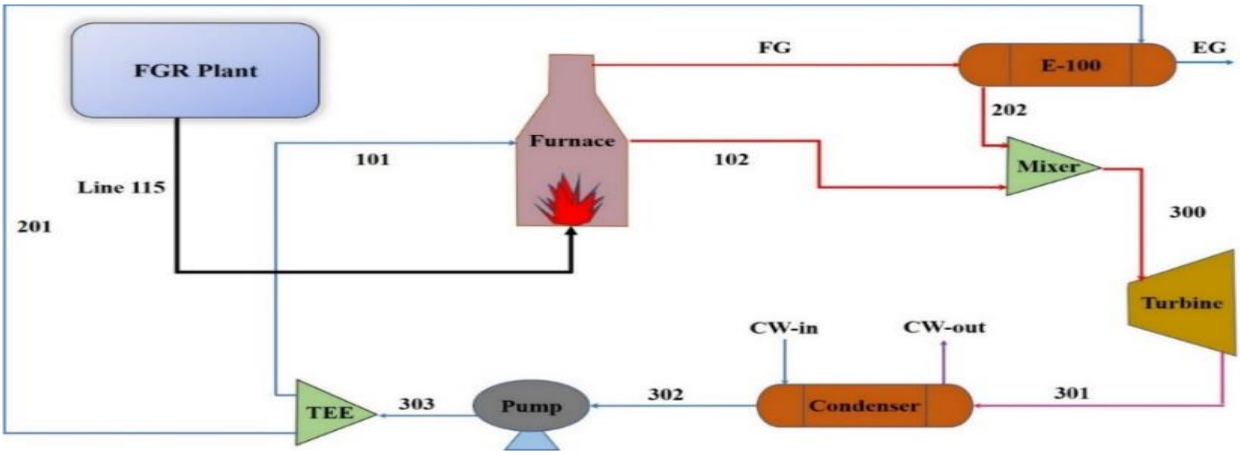


Fig. 2: Overview of the CHP process using fuel supplied by the FGR unit

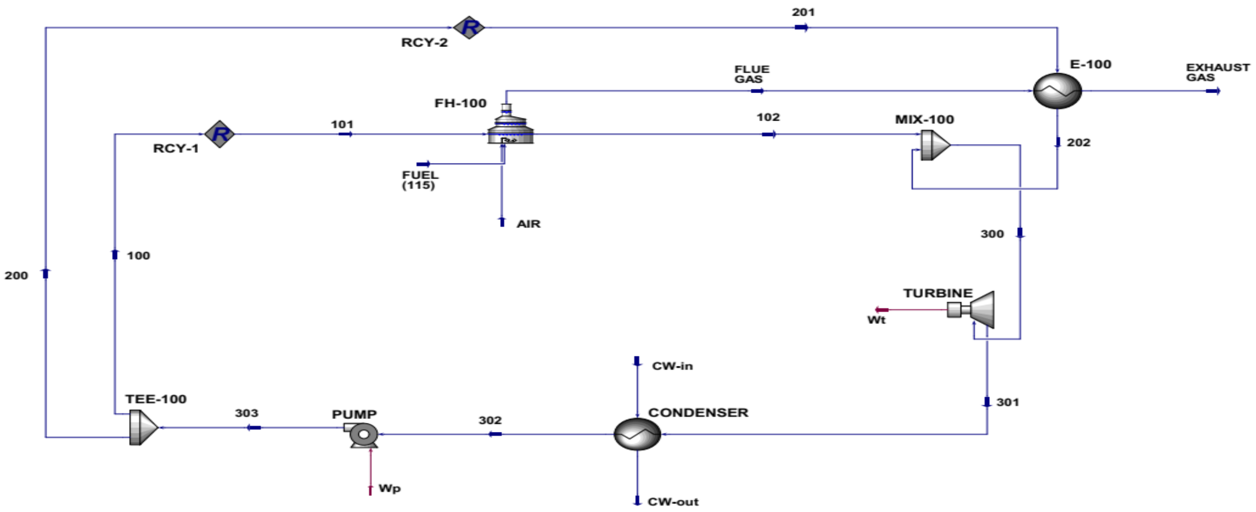


Fig. 3: Partial flow diagram of the simulated CHP system

respectively. Then, water was entered to the FH-100 furnace with a mass flowrate of 20,330 kg/h and heated up to a temperature of 395 ˚C. The furnace fuel was supplied from the FGR unit through line 115 with the specifications given in Tables 1 and 2. As exclaimed earlier, line 115 was sweetened gas in the FGR unit of Tabriz Oil Refining Company, which has been used as fuel in the CHP system. The required air for the furnace was provided by a stream named "AIR", which was considered with an excess air content of 20%. The temperature and pressure of the combustion gases released through the FLUE GAS stream were 411.5 ˚C and 202.3 kPa, respectively. The steam coming out of the furnace (line 102) at 395 °C was combined with the steam in line 202, at a temperature of 381.4 °C in the MIX-100 mixer. The steam in line 202 was generated in the shell and tube heat exchanger E-100 by recovery the heat of the hot flue gases from the combustion in the furnace. In this heat exchanger, the temperature of the working fluid was increased from 60.44 °C to 381.4 °C. The hot gases leaving the furnace were finally discharged to atmosphere through the EXHAUST GAS stream at 65.44 °C, from which a significant amount of heat has been recovered. The steam coming out of the MIX-100 mixer with a mass flowrate of 24,862 kg/h was entered the turbine through line 300 and produced 4,439 kW of mechanical power. The generated mechanical power could then be converted to electricity with high efficiency through an electric generator. The pressure and temperature at the turbine outlet (line 301) was reached to 50 kPa and 81.35 ˚C. The vapor quality at the turbine outlet was about 96%. Subsequently, the temperature of working fluid passed the condenser was reached to 60 ˚C through heat transferring to the cold water. In the condenser, pure water flowing in the shell side of the heat exchanger was acted as a cooling agent. Its temperature and pressure at the inlet were 25 ˚C and 300 kPa, respectively. After receiving heat from the working fluid, the temperature of water was reached to 76.35 ˚C, which can be considered as an appropriate temperature for heating purposes. Then, using a pump, the pressure of the working fluid leaving the condenser was increased to 4,200 kPa. To complete the CHP process cycle, the working fluid in line 303 was divided into two streams of 100 and 200 through the TEE-100 splitter. In this flow divider device, the flowrate of stream 100 was adjusted so that the fuel consumption of the furnace was obtained according to the available data (flowrate of line 115).

Table 1: Compounds in line 115 and outlet stream from furnace chimney

Composition (mole %)	Stream	
	115 [30]	FLUE GAS
Methane	20.88	0.00
Ethane	7.20	0.00
Propane	11.41	0.00
i-Butane	4.79	0.00
n-Butane	7.45	0.00
i-Pentane	3.53	0.00
n-Pentane	2.33	0.00
n-Hexane	2.81	0.00
Oxygen	0.00	3.24
H_2O	0.80	14.37
Hydrogen	35.77	0.00
CO	0.11	0.00
Nitrogen	2.92	73.34
CO_2	0.00	9.05
H_2S	0.00	0.00

Table 2: Operating conditions of the CHP process streams*

Stream	Vapor Fraction	Temperature (˚C)	Pressure (bar)	Mass Flow (kg/h)
100	0	60.44	42	20,330
101	0	60.44	42	20,330
102	1	395	42	20,330
200	0	60.44	42	4,532
201	0	60.44	42	4,532
202	1	381.4	41.999	4,532
300	1	392.5	42	24,862
301	0.9579	81.35	0.5	24,862
302	0	60	0.499	24,862
303	0	60.44	42	24,862
FUEL (115)	0.9874	35.03	6.642	1,585
AIR	1	25	2.023	29,635
FLUE GAS	1	411.5	2.023	31,220
EXHAUST GAS	0.9819	65.44	2.022	31,220
CW-in	0	25	3	259,600
CW-out	0	76.35	2.999	259,600

* The streams' numbers and names are based on Figs. 2 and 3.

RESULTS AND DISCUSSION

Electricity and heat generation

Petroleum and gas refining as well as petrochemical industries require a lot of energy (heating, cooling, and electricity).

Table 3: Heating value and mass flow rate of line 115 components

Component	Methane	Ethane	Propane	i-Butane	n-Butane	i-Pentane	n-Pentane	n-Hexane	Hydrogen
Heating value (MJ/kg)	50.168	47.63	46.47	45.74	45.86	45.36	45.47	45.22	120.95
Mass flow (kg/h)	204.01	131.89	306.64	169.55	263.80	155.25	102.19	147.52	43.92

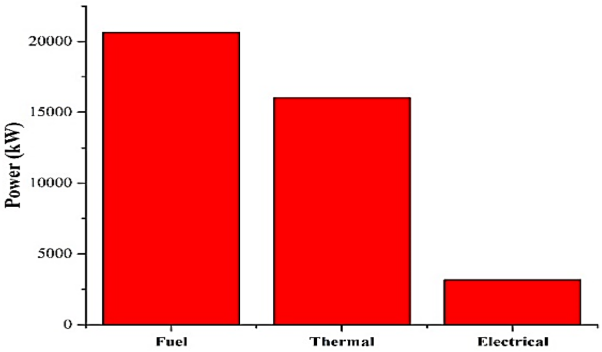


Fig. 4: Fuel total heating value, thermal and net electrical power produced by the CHP system

These industries meet their energy requirements by an in-site energy unit at a high cost. In CHP systems thermal energy and electricity is generated simultaneously by utilizing a single energy source. In the integrated CHP system in the FGR unit, 16,019 kW of thermal energy is generated by the condenser. This amount of energy is used to heat 259,600 kg/h of water up to a temperature of 76.35 ˚C. This heated water can be used for space heating, preheating the material streams and so on. In addition, for more utilization of the fuel supplied by the FGR unit (line 115), the furnace exhaust hot gases were kept in contact with the working fluid in E-100 heat exchanger. This can prevent the heat pollution caused by the release of these hot gases to the atmosphere. Consequently, 4,532 kg/h of steam at a temperature of 381.4 ˚C and pressure of 42 bar is generated. The steam generated by this heat exchanger is added to the steam produced by furnace and fed to the turbine for mechanical power production. Table 3 shows the heating value and mass flow rate of the main constituents of line 115.

According to the mass flow rate of each of the components in line 115 and their heating value, the total heating value of line 115 can be calculated from Equation (1).

$$(HV)_{115} = \sum_i \dot{m}_i (HV)_i \tag{1}$$

In which, $(HV)_{115}$ is the total heating value of line 115, $\dot{m}_i$ is the mass flow rate of each component in this line, and $(HV)_i$ is the heating value of each component. According to Equation (1) and the information in Table (3), the total heating value of line 115 is 74,290 MJ/h which is equal to 20,636 kW. The thermal efficiency of the CHP system can be calculated by Equation (2).

$$\eta_{heating} = \frac{\dot{Q}_{gained}}{\dot{Q}_{fuel}} \tag{2}$$

In Equation (2), $\eta_{heating}$ is the thermal efficiency of the cogeneration system, $\dot{Q}_{gained}$ is the amount of thermal energy obtained in the condenser of the CHP system, and $\dot{Q}_{fuel}$ is the amount of heat generated from the combustion of the fuel. According to the data obtained from the simulation, the thermal efficiency of the system is 77.63%. Correspondingly, the electrical efficiency of the CHP system ($\eta_{electrical}$) can be calculated from Equation (3), in which the net generated electric power ($\dot{P}_{electrical}$) is divided by the heat generated from fuel combustion ($\dot{Q}_{fuel}$).

$$\eta_{electrical} = \frac{\dot{P}_{electrical}}{\dot{Q}_{fuel}} \tag{3}$$

The amount of electrical power produced by the CHP system was obtained as 3,995 kW by considering the 90% efficiency of converting the mechanical power produced by the turbine into electrical power through an electric generator. It should be noted that 43.3 kW of electrical power is consumed by the pump and 769.7 kW is required to supply atmospheric air to the furnace. Therefore, the net electricity produced by the system is 3,182 kW, from which the electrical efficiency of the CHP system will be 15.42%. Fig. 4, shows the total heating value of the fuel, thermal and net electrical power produced by the cogeneration system.

Fig. 5, shows the comparison of the proposed cogeneration unit with the conventional generation of heat and power. As can be seen from this Figure, the cogeneration unit is more efficient than conventional generation. In the proposed CHP system 16,019 kW of thermal energy and 3,182 kW of electricity were generated through consumption of 20,636 kW of energy corresponding to an energy conversion efficiency of 93%. Producing the same amount of electricity in a typical power plant with an efficiency of 35% requires 9,091 kW of energy. Besides,

Table 4: Required information for economic analysis

Generated heat by the system	Net power generated by the system	Fuel total heating value	Base price of electricity [31]	Base price of natural gas (methane) [31]
16,019 kW	3,182 kW	20,636 kW	0.078 $/kWh	2.5 $/Million Btu

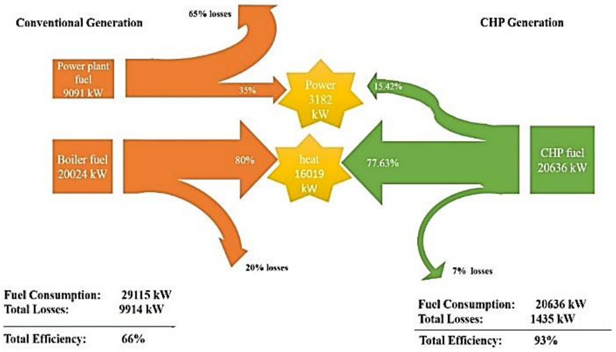


Fig. 5: Comparison of simultaneous and conventional generation of electricity and heat

production of the same amount of thermal energy in a boiler with an efficiency of 80% requires 20,024 kW of energy. Therefore, the overall efficiency of independent production of electricity and heat will be 66%.

Environmental aspects

Industries such as petrochemicals and petroleum and gas refineries are highly harmful to the environment due to their flaring operations. In flaring process, greenhouse gases such as CO_2 and H_2S are released to the atmosphere. In addition, gas flaring in these industries causes heat pollution and as a result change the climatic patterns. This issue is currently receiving a great deal of attention from international environmental organizations. As previously mentioned, in the simulated CHP system, a significant portion of the heat carried by the hot flue gases absorbed by the working fluid, and therefore the flue gases are discharged to the atmosphere with a lower temperature. During this process, the temperature of the flue gases is reduced from 411.5 ˚C to 65.44 ˚C. This consequently prevents the heat release of 3,962 kW to the environment. The quantitative value of this heat can be calculated from Equation (4).

$$\dot{Q} = \dot{m}C_p\Delta \tag{4}$$

Where, $\dot{Q}$ is the amount of heat recovered from the hot flue gas leaving the furnace in kJ/h, $\dot{m}$ is the mass flow rate of flue gas in kg/h, C_p is the specific heat of flue gas in kJ/(kg·˚C) and ΔT is the difference in flue gas temperature at the inlet and outlet of regenerator heat exchanger (E-100) in ˚C.

Economic aspects

In this section, the establishment of a CHP system in the FGR unit of Tabriz Oil Refining Company is investigated from the economic viewpoint. It is noted that in this analysis, the initial investment costs for the design and construction of the proposed system are not considered and only the annual profit from the process is calculated based on the revenues and related costs. In the CHP system, the revenues come from electricity and heat generation. On the other hand, the process is associated with costs that include the cost of fuel combusted in the furnace, the injection of air into the furnace by the blower and the compression and circulation of the working fluid by the pump. The information required to perform economic analysis is summarized in Table 4.

The base price of natural gas can be determined in terms of $/kg using the heating value of methane along with Equation (5).

$$NG\ Price\ = 2.5\frac{\$}{10^6 Btu} \times \frac{Btu}{252\ cal} \times \frac{cal}{4.184\ J} \times \frac{50{,}168{,}000\ J}{1\ kg} = 0.12\frac{\$}{kg} \tag{5}$$

Methane must be burned at a rate of 0.41 kg/s to produce 20,636 kW of thermal energy (this amount of energy is released through combusting the fuel of line 115). This is obtained by dividing the fuel total heating value by the methane heating value. Taking into account 335 working days in a year, the cost of fuel consumed in the furnace is estimated at 1,424,045 $/yr. The income from the heat

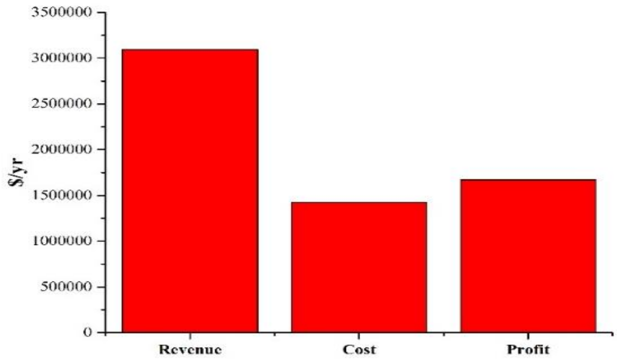


Fig 6. Revenue, costs and profit of the proposed CHP system

produced by the system can similarly be calculated. The amount of this annual income is 1,099,364 $. Equation (6) shows how to calculate the revenue from the electricity generated by the system.

$$Electricity\ Revenue = 0.078\frac{\$}{kWh}\times\frac{kWh}{3{,}600\ kJ}\times\frac{3{,}182\ kJ}{s}\times\frac{(335\times24\times3{,}600)\ s}{yr} = 1{,}995{,}496\frac{\$}{yr} \quad (6)$$

Finally, the amount of profit from the process can be calculated according to the estimated revenues and costs of the cogeneration unit. The calculated profit was 1,670,815 $/yr which was obtained by deduction of total expenses from the total income. The result of the economic calculations of the process is shown in Fig. 6.

Analysis of the CHP system on the temperature-entropy and temperature-heat flow diagrams

Temperature-entropy (T-s) diagram is a thermodynamic diagram usually used to analyze thermodynamic cycles and visualize the temperature and specific entropy changes during a process. Once a T-s diagram has been prepared, various deductions can be made from it. For example, the heat added to or removed from the working fluid as well as the work done by or on the system can be visualized on this diagram. For ideal processes (i.e. reversible), the area under the T-s curve of the process equals the heat added to or removed from the system during that process. In addition, the surface area enclosed between different points of the cycle represents the net mechanical work produced by the system.

Fig. 7, illustrates the process of simultaneous generation of electricity and heat on a T-s diagram. Yellow line in this diagram represents the pathway that the working fluid undergoes in the CHP system. The working fluid first enters the furnace (through line 101) with a temperature of 60.33 ºC and a specific entropy of 3.462 kJ/(kg·K). Consequently, its temperature and entropy increased at a constant pressure of 4200 kPa. The working fluid experiences different thermodynamic states in the furnace. First, it changes from the subcooled liquid to the saturated liquid state with a temperature of 254.3 ºC and specific entropy of and 5.529 kJ/(kg·K), (point 1). It is then subjected to a phase change (evaporation) process at constant temperature and pressure, and its specific entropy increases to 8.868 kJ/(kg·K), (point 2). Following the heating process of the working fluid in the furnace, the saturated steam is heated to 392.5 °C at a constant pressure and becomes superheated steam with a specific entropy of 9.407 kJ/(kg·K), (line 300). Thereafter, the working fluid expands in the turbine and its pressure and temperature are reduced from 4200 kPa to 50 kPa and 392.5 ºC to 81.35 ºC and mechanical power is produced. The working fluid at the turbine exhaust is a mixture of saturated vapor and liquid. During the expansion process, the specific entropy of the working fluid increases to 10.01 kJ/(kg·K). The working fluid is then enters the condenser and firstly turns into saturated liquid in constant temperature and pressure and then changes to subcooled liquid with a temperature of 60 ºC and a specific entropy of 3.46 kJ/(kg·K). Subsequently, the working fluid is fed to the furnace by a pump to complete the cycle. During this process, temperature and entropy changes are not significant, but the pressure increases from 49.9 kPa to 4200 kPa. Due to the proximity of the constant pressure lines in the subcooled liquid region on temperature-entropy diagram, the points 302, 303 and 101 are located very close to each other on this diagram.

The Carnot cycle is also shown with green color in this diagram for comparison (points 1, 2, 3, and 4). In the Carnot cycle, all of the processes are reversible and there are two isothermal processes (evaporation and condensation) and two constant-entropy processes (compression in the pump and expansion in the turbine). The efficiency of the cycle in converting thermal energy into mechanical energy can be calculated through the area of the enclosed surface between the different lines of the cycle and the horizontal axis as explained through Equations (7) to (10).

$$Q_H = T_H(s_2 - s_1) = 1{,}725.65\ kJ/kg \quad (7)$$

$$Q_L = T_L(s_4 - s_3) = -1{,}159.92\ kJ/kg \tag{8}$$

$$W_{net} = |Q_H| - |Q_L| = 565.73\ kJ/kg \tag{9}$$

$$\eta_c = \frac{W_{net}}{Q_H} = 0.329 \tag{10}$$

In the above equations, T_H and Q_H are the temperature of the working fluid and the amount of heat received by it in the boiler, respectively. T_L and Q_L stand for the temperature of the working fluid and the heat rejected from it in the condenser, respectively. W_{net} is the net mechanical work produced by the cycle, η_c is the thermal efficiency of the Carnot cycle and s is the specific entropy of the working fluid at different points in the cycle. As can be observed, the thermal efficiency of the Carnot cycle at operating conditions similar to the proposed cogeneration system is 32.9 %. The efficiency of the CHP system in converting heat into work is about 17%. The difference between the Rankine and Carnot cycle efficiencies can be attributed to the irreversibility of the processes in the Rankine cycle.

Fig. 8, shows the temperature and the amount of heat exchanged in each equipment of the cogeneration unit. According to this Fig., the temperature of the working fluid passed through the turbine decreased from 392.5 ºC to 81.75 ºC because of its expansion and power generation. During this process, superheated steam converted into a two-phase mixture of saturated liquid and vapor with 96% quality by losing 1.59 × 10^7 kJ/h of heat. Then the working fluid passed through the condenser and is cooled by cooling water. In the condenser, the working fluid is first converted to the saturated liquid state (at constant temperature) by losing 5.534 × 10^7 kJ/h energy as latent heat. It then became subcooled liquid by losing 2.29 × 10^6 kJ/h energy as sensible heat and decreasing the temperature from 81.75 ºC to 60 ºC. The fracture observed in the temperature-heat flow diagram of the condenser is owing to the change in the type of heat transfer from the latent heat to the sensible heat. In addition, in order to more utilization of the fuel energy and subsequently increasing the system efficiency, the furnace's flue gas is kept in contact with the working fluid in E-100 heat exchanger. This led to reduce the flue gas temperature from 411.5 ºC to 65.44 ºC. In this process, the flue gas experiences two-step energy losses. Firstly, 1.23 × 10^7 kJ/h heating energy is taken from the flue gas as sensible heat which changes it to the saturated vapor state and then 9.295 × 10^5 kJ/h heating energy is rejected from it as latent heat which leads to producing some liquid in the stream (VF = 0.9819). It should be noticed that the liquid water formed in this process was due to the condensation of water vapor produced during the combustion process. Regarding the analysis of the behavior of the working fluid in the furnace, it can be said that firstly the temperature of the working fluid increases from 60.44 ºC to 254.3 ºC by receiving 1.88 × 10^7 kJ/h of heat from the combustion of fuel in the furnace and becomes a saturated liquid. It then receives 3.51 × 10^7 kJ/h more heating energy to make phase change at a constant temperature and change the working fluid state to the saturated vapor. Then, the remaining heating energy resulting from the fuel combustion, which is equal to 0.66 × 10^7 kJ/h, is received by the working fluid leading to an increase the temperature of the steam and converted it into a superheated state with a temperature of 395 ºC.

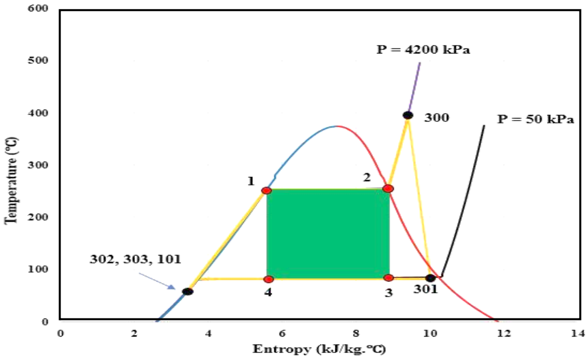


Fig. 7: Combined heat and power production process on temperature-entropy diagram

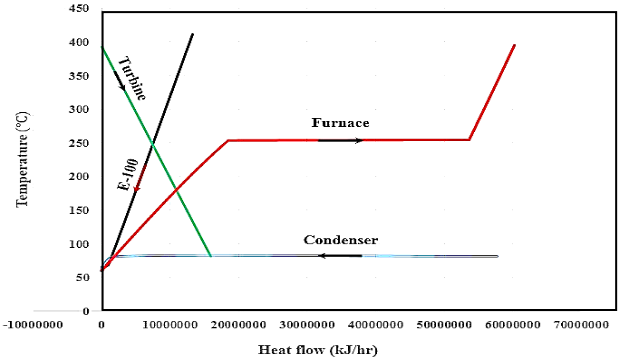
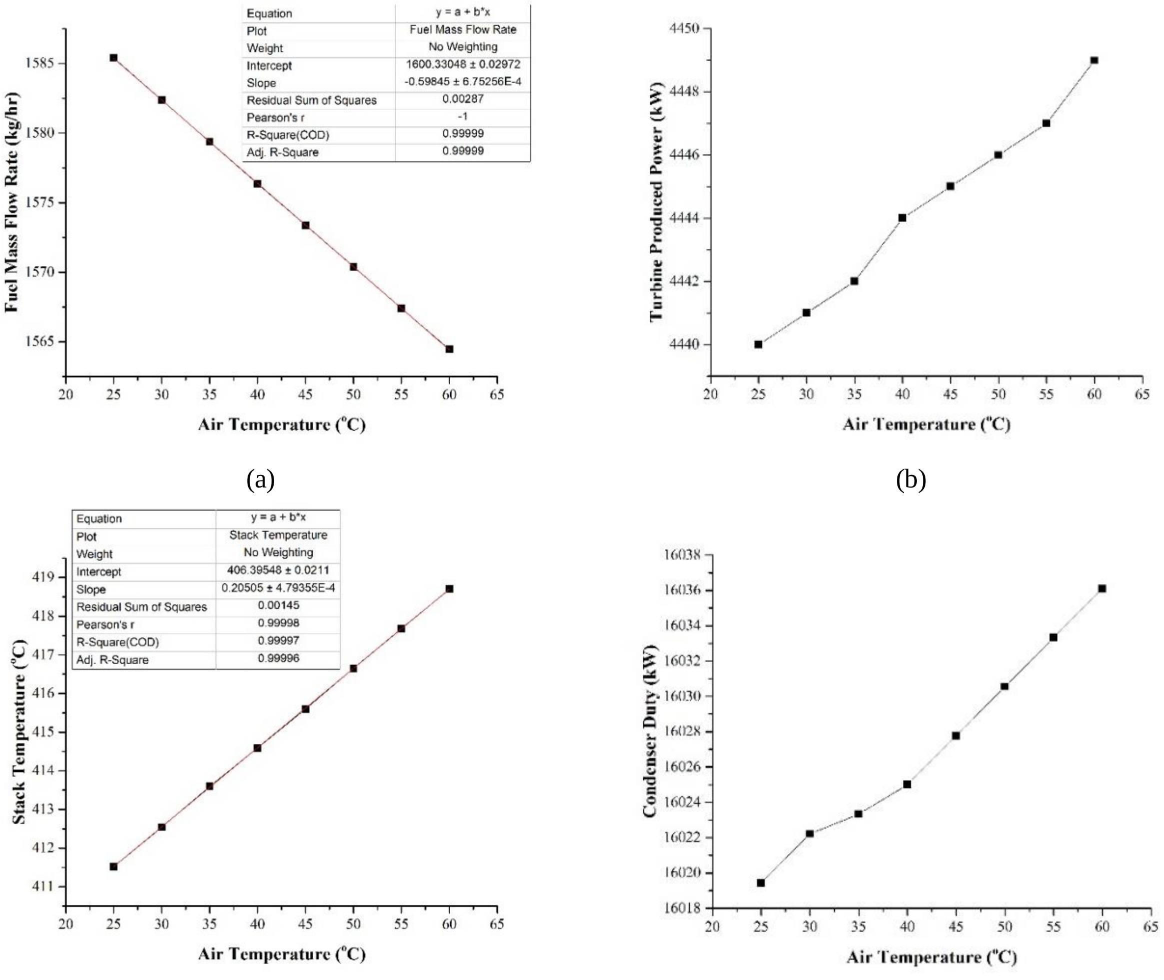


Fig. 8: Temperature-heat flow diagram of the proposed CHP system

The temperature-heat flow diagram presented in Fig.8, confirms the expected physical phenomena occurred in each of the unit operations of the CHP system. It shows cooling, heating, subcooling, superheating, and phase



Equation	y = a + b*x
Plot	Fuel Mass Flow Rate
Weight	No Weighting
Intercept	1600.33048 ± 0.02972
Slope	-0.59845 ± 6.75256E-4
Residual Sum of Squares	0.00287
Pearson's r	-1
R-Square(COD)	0.99999
Adj. R-Square	0.99999

Equation	y = a + b*x
Plot	Stack Temperature
Weight	No Weighting
Intercept	406.39548 ± 0.0211
Slope	0.20505 ± 4.79355E-4
Residual Sum of Squares	0.00145
Pearson's r	0.99998
R-Square(COD)	0.99997
Adj. R-Square	0.99996

(a) (b)

(c) (d)

Fig. 9: The effect of the furnace's inlet air temperature on the fuel consumption (a), turbine power output (b), flue gas temperature (c), and condenser heat load (d)

changes (i.e. evaporation and condensation) in the process of simultaneous production of heat and power. In addition, this confirmation can be a support for the simulation results.

Effect of the furnace's inlet air temperature on the system performance

In the proposed CHP system in this study, a furnace has been used to heat the working fluid. The performance of the furnace can be enhanced by alteration of operating parameters such as the temperature of the fuel and injected air for combustion. Due to the hydrocarbon nature of the fuel and safety requirements, increasing the fuel temperature is not recommended. Therefore, increasing the air temperature can be a suitable option which has been chosen in many industrial processes. This is also an important research topic to minimize the emission of pollutants produced by the furnace and prevent environmental pollution [32]. The efficiency of the furnace can be enhanced by increasing the temperature of the supplied air to the furnace. This means that the working fluid needs less fuel to reach its desired temperature at the furnace outlet. On the other hand, increasing the supplied air temperature leads to an increase in furnace flue gas temperature. Therefore, more energy can be recovered from these gases and utilized in the simultaneous production of electricity and heat. Fig. 9, shows the effect of the furnace's inlet air temperature in the range of 25 to 60 ºC on the fuel consumption, turbine power production, flue gas temperature, and condenser heat load. It is obvious that increment of the air temperature increases the temperature of the flame. Therefore, the increase of the furnace's inlet air temperature is allowed to some extent considering the thermal resistance of the furnace pipes and the flue gas thermal energy recovery heat exchanger. As shown in Fig. 9, increasing the inlet air temperature supplied to the furnace increases the turbine power output, furnace flue gas temperature, and condenser heat load and reduces the furnace fuel consumption. A linearity can be seen in Figs 9(a) and 9(c). The fuel mass flow rate is reduced linearly by the increment of the inlet air temperature. In addition, the stack's temperature increases linearly by the increase of the furnace's inlet air temperature. The results of linear regression are presented in the Figure.

CONCLUSION

In this study, simulation of the combined heat and power production using the fuel supplied from the flare gas recovery unit of Tabriz Oil Refining Company was considered. A Rankine cycle utilizing water as the working fluid was used for simultaneous production of heat and power. In this cycle, the mechanical power was generated by turbine and thermal energy was produced by the condenser. This study investigated the feasibility of establishment of a CHP system in the FGR unit from the energy efficiency, environment and economic viewpoints. The results of this study showed that recovery of flaring gases and using them in CHP unit as fuel will have about 1.7 million dollars economic savings annually. Also, using the thermal energy of hot flue gases resulted from the combustion of fuel in the furnace to produce steam in a regenerator heat exchanger reduces the temperature of these gases from 411.5 ℃ to 65.44 ℃. At the same time, it prevents the release of 3,962 kW of thermal energy into the atmosphere. The amount of electricity and heat generated by the CHP system is about 4 MW and 16 MW, respectively, corresponding to an electrical efficiency of 15.42 % and a thermal efficiency of 77.63 %.

The results of this study showed a promising performance for the integration of a CHP system in FGR unit of Tabriz Oil Refining Company. The main finding of this research is that there are many environmental and economically benefits if it is possible to establish a combined heat and power production system in the flare gas recovery unit in industries which have a significant amount of flaring. The present study may be a step forward towards the efficient use of energy sources. Future works in this field can be done with a view to practical integration of CHP systems in FGR units.

Nomenclature

C_p	Specific heat of flue gas (kJ/(kg·˚C))
$(HV)_{115}$	Total heating value of line 115 (MJ/kg)
$(HV)_i$	Heating value of each component (MJ/kg)
$\dot{m}$	Mass flow rate of flue gas (kg/h)
$\dot{m}_i$	Mass flow rate of each component (kg/h)
$\dot{P}_{electrical}$	Net generated electric power (kW)
Q_H	Amount of heat received by the working fluid in the boiler (kJ/kg)
Q_L	Amount of heat rejected from the working fluid in the consenser (kJ/kg)
$\dot{Q}$	Amount of heat recovered from the hot flue gas leaving the furnace (kJ/h)
$\dot{Q}_{fuel}$	Amount of heat generated from the combustion of the fuel (kW)
$\dot{Q}_{gained}$	Amount of thermal energy obtained in the condenser of the CHP system (kW)
s	Specific entropy of the working fluid (kJ/(kg·K))
T_H	Working fluid temperature in the boiler (K)
T_L	Working fluid temperature in the condenser (K)
W_{net}	Net mechanical work produced by the cycle (kJ/kg)

Greec Letters

η_c	Thermal efficiency of the Carnot cycle
$\eta_{electrical}$	Electrical efficiency of the CHP system
$\eta_{heating}$	Thermal efficiency of the cogeneration system
ΔT	Temperature difference (˚C)

Abbreviations

CHP	Combined Heat and Power
FGR	Flare Gas Recovery
HV	Heating Value
NG	Natural Gas
ORC	Organic Rankine Cycle
VF	Vapor Fraction

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REFERENCES

[1] Wang J., You S., Zong Y., Traeholt C., Yang Dong Z., Zhou Y., Flexibility of Combined Heat and Power Plants: A Review of Technologies and Operation Strategies, *Applied Energy*, **252**: 113445 (2019).

[2] Majidi M., Mohammadi-Ivatloo B., Anvari-Moghaddam A., Optimal Robust Operation of Combined Heat and Power Systems with Demand Response Programs, *Applied Thermal Engineering*, **149**: 1359-1369 (2019).

[3] Nazari-Heris M., Mohammadi-Ivatloo B., Gharehpetian G.B., A Comprehensive Review of Heuristic Optimization Algorithms for Optimal Combined Heat and Power Dispatch from Economic and Environmental Perspectives, *Renewable and Sustainable Energy Reviews*, **81**: 2128-2143 (2018).

[4] Arsalis A., A Comprehensive Review of Fuel Cell-Based Micro-Combined-Heat-and-Power Systems, *Renewable and Sustainable Energy Reviews*, **105**: 391-414 (2019).

[5] Budak Y., Devrim Y., Investigation of Micro-combined Heat and Power Application of PEM Fuel Cell Systems, *Energy Conversion and Management*, **160**: 486-494 (2018).

[6] Li X., Wang Z., Yang M., Yuan G., Modeling and Simulation of a Novel Combined Heat and Power System with Absorption Heat Pump Based on Solar Thermal Power Tower Plant, *Energy*, **186**: 115842 (2019).

[7] Kazemi K., Ebrahimi M., Lahonian M., Babamiri A., Micro-Scale Heat and Electricity Generation by a Hybrid Solar Collector-Chimney, Thermoelectric, and Wind Turbine, *Sustainable Energy Technologies and Assessments*, **53**: 102394 (2022).

[8] Mahian O., Mirzaie M.R., Kasaeian A., Mousavi S.H., Exergy Analysis in Combined Heat and Power Systems: A Review, *Energy Conversion and Management*, **226**: 113467 (2020).

[9] Kazemi-Beydokhti A., Farrokhi M., Menna E., Carbon Nanotube Nanofluid for the Efficiency Improvement in a CHP System: Simulation and Experimental Investigation, *Journal of Thermal Analysis and Calorimetry*, **140**: 489-499 (2020).

[10] Eyerer S., Schifflechner C., Hofbauer S., Bauer W., Wieland C., Spliethoff H., Combined Heat and Power from Hydrothermal Geothermal Resources in Germany: An Assessment of the Potential, *Renewable and Sustainable Energy Reviews*, **120**: 109661 (2020).

[11] Larionov V.M., Saifullin E.R., Konstantinov N.V., Nazarychev S.A., Malakhov A.O., Yunusova E.A., The influence of Hydrogen Concentration on the Flame Temperature of a Mixture of Methane-Hydrogen Fuel with Air, *Journal of Physics: Conference Series*, **1328**: 012048 (2019).

[12] Nwoye C.I S.O. Nwakpa, Nwosu I.E., Odo J.U., Chinwuko E.C., Idenyi N.E., Multi-Factorial Analysis of Atmospheric Noise Pollution level Based on Emitted Carbon and Heat Radiation During Gas Flaring, *Journal of Atmospheric Pollution*, **2(1)**: 22-29 (2014).

[13] Kazemi-Beydokhti A., Zeinali Heris S., Thermal Optimization of Combined Heat and Power (CHP) Systems Using Nanofluids, *Energy*, **44(1)**: 241-247 (2012).

[14] Tovar-Facio J., Eljack F., Ponce-Ortega J.M., El-Halwagi M.M., Optimal Design of Multiplant Cogeneration Systems with Uncertain Flaring and Venting, *ACS Sustainable Chemistry & Engineering*, **5**: 675-688 (2017).

[15] Semmari H., Filali A., Aberkane S., Feidt R., Feidt M., Flare Gas Waste Heat Recovery: Assessment of Organic Rankine Cycle for Electricity Production and Possible Coupling with Absorption Chiller, *Energies* **13(9)**: 2265 (2020).

[16] Kazi M-K., Eljack F., Amanullah M., AlNouss A., Kazantzi V., A process Design Approach to Manage the Uncertainty of Industrial Flaring During Abnormal Operations, *Computers & Chemical Engineering*, **117**: 191-208 (2018).

[17] Hajilary N., Rezakazemi M., Shahi A., CO_2 Emission Reduction by Zero Flaring Startup in Gas Refinery, *Materials Science for Energy Technologies*, **3**: 218-224 (2020).

[18] Soltanieh M., Zohrabian A., Gholipour M.J., Kalnay E., A Review of Global Gas Flaring and Venting and Impact on the Environment: Case Study of Iran, *International Journal of Greenhouse Gas Control*, **49**: 488-509 (2016).

[19] Umukoro G.E., Ismail O.S., Modelling Emissions from Natural Gas Flaring, *Journal of King Saud University - Engineering Sciences*, **29(2)**: 178-182 (2017).

[20] Yazdani E., Asadi J., Hosseinzadeh Dehaghani Y., Kazempoor P., Flare Gas Recovery by Liquid Ring Compressors-System Design and Simulation, *Journal of Natural Gas Science and Engineering*, **84**: 103627 (2020).

[21] Zolfaghari M., Pirouzfar V., Sakhaeinia H., Technical Characterization and Economic Evaluation of Recovery of Flare Gas in Various Gas-Processing Plants, *Energy*, **124**: 481-491 (2017)..

[22] Shayan M., Pirouzfar V., Sakhaeinia H., Technological and Economical Analysis of Flare Recovery Methods, and Comparison of Different Steam and Power Generation Systems, *Journal of Thermal Analysis and Calorimetry*, **139(4)**: 2399-2411 (2020).

[23] Mousavi S.M., Lari K., Salehi G., Torabi Azad M., Technical, Economic, and Environmental Assessment of Flare Gas Recovery System: a Case Study, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* (2020).

[24] Deymi-Dashtebayaz M., Kazemiani-Najafabadi P., The Feasibility of Using a Combined Heat and Power System in a Car Factory with Different Consumption and Investment Scenarios, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* (2020).

[25] Shahidian Akbar G., Salarian H., Ataei A., A Novel Approach to Integration of Hot Oil and combined Heat and Power Systems through Pinch Technology and Mathematical Programming, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* (2019).

[26] Norouzi N., Talebi S., Exergy, Economical and Environmental Analysis of a Natural Gas Direct Chemical Looping Carbon Capture and Formic Acid-Based Hydrogen Storage System, *Iran. J. Chem. Chem. Eng.(IJCCE)*, **41(4)**: 1435-1457 (2022).

[27] Khajehpour H., Norouzi N., Bashash Jafarabadi Z., Valizadeh G., Hemmati M.H., Energy, Exergy, and Exergoeconomic (3E) Analysis of Gas Liquefaction and Gas Associated Liquids Recovery Co-Process Based on the Mixed Fluid Cascade Refrigeration Systems, *Iran. J. Chem. Chem. Eng. (IJCCE)*, **41(4)**: 1391-1410 (2022).

[28] Sarkari M., Jamshidi B., Ahmadi Khoshooei M., Fazlollahi F., Flare Gas Reduction: A Case Study of Integrating Regeneration Gas in Flash Gas Compression Network, *Fuel*, **318**: 123661 (2022).

[29] Sarkar S., Quddus N., Mannan M.S., El-Halwagi M.M., Integrating Flare Gas with Cogeneration System: Hazard Identification Using Process Simulation, *Journal of Loss Prevention in the Process Industries*, **74**: 104635 (2022).

[30] Kazemi-Beydokhti A., Neyestani F., Farrokhi M., Simulation of Flare Gas Recovery Unit Using Liquid Ring and Centrifugal Compressors, *Nashrieh Shimi va Mohandesi Shimi Iran* (2021). [In Persian]

[31] Sabbagh O., Fanaei M.A., Arjomand A., Techno-Economic Evolution of an Existing Operational NGL Plant with Adding LNG Production Part, *Oil & Gas Science and Technology - Rev. IFP Energies Nouvelles*, **75(27)**: 20 (2020).

[32] Bhoi P.R., Channiwala S.A., Optimization of Producer Gas Fired Premixed Burner, *Renewable Energy*, **33(6)**: 1209-1219 (2008).