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TECHNICAL AND ECONOMIC ANALYSIS OF RETROFITTING CONCENTRATED SOLAR COLLECTOR TO GENERATE THE THERMAL ENERGY REQUIRED FOR THE CRUDE OIL PRODUCTS DISTILLATION PROCESS

Saif W. Mohammed Ali [1,*], Hussam H. Jabbar [2] ,and Abbas K. Al-Shaibani [3]

[1] University of Kufa, Faculty of Engineering, Department of Mechanical Engineering, Najaf, Iraq, Email: saifw.alturaihi@uokufa.edu.iq

[2] Department of Cooling and Air Conditioning Engineering, Imam Ja'afer Al-Sadiq University, Baghdad, Iraq

[3] Central Refineries Company, Al-Najaf Oil Refinery, Najaf, Iraq

[*] Corresponding Authors

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ABSTRACT

Recently, most oil companies are working to reduce the cost and carbon emissions accompanied crude oil distillation process by developing suitable sustainable technologies. The present work studies the viability of retrofitting concentrated solar collector (CSC) represented by parabolic trough collector (PTC) through the crude oil distillation process in three stages; crude oil preheating in a furnace, live steam injection, and the reboiler heater. The whole oil distillation unit and the PTC unit are modeled and solved using an American software called COCO V 3.6.0.13 and SAM 2022.11.21 (System Advisor Model). Three different working fluids are investigated through the study: therminol VP-1, hitech solar salt, and pressurized water at different mass flow rates. Additionally, the proposed system was analyzed economically using levelized cost of energy (LCOE) method. The required land area for the solar unit is analyzed through the study too. It was found that hitec solar salt requires higher input flow rate than the other heat transfer fluids (HTF) where the maximum flow rate reaches about (75 kg/s) while the minimum flow rate was found for pressurized water as the flow rate value reaches about (25.7 kg/s). It was found also that the maximum required thermal energy is the energy exhausted in the furnace for crude oil preheating process, and the minimum value is the energy required for steam generation. The economic feasibility study shows that retrofitting such a solar units would be more beneficial in the years period between 2022-2050 as the LCOE of flue gas

(0.0363 $/kWh) is higher than the LCOE of PTC (0.01604 $/kWh) leading to an overall cost saving reaches about 14523013 $ after year of 2021. The land area analysis shows that the required area is increasing linearly in a rate of (0.62 kW/m2). The validation with recorded data from literature shows a good agreement in compare with the current work.

KEYWORDS

Crude oil distillation process, Solar thermal energy for distillation, Parabolic trough collector, Economic feasibility.

1. INTRODUCTION

In the shadow of increasing global warming, the recent regulations to reduce carbon emissions and energy dissipation require technological solutions to reduce the greenhouse gas emissions and energy use in crude oil refineries. It was reported that the energy used through the oil distillation process consumes about 7-15% from the crude oil processed through the refinery before 1995 (Szklo A., and Schaeffer R., 2007) while this ratio was reduced to 9-10% in 2001 in the US (Worrell et al., 2004 and Nakamura D., 2003). Number of recent reports show that this percent was reduced to 1-2% (Chen L., 2008 and Liu J., 2012). However, the amounts of the energy used, and carbon emitted are still needed to be reduced more to meet the policy makers regulations. Energy is executed mostly through three stages from the crude oil distillation process; crude oil preheating stage, generating live steam to be injected in the tower, and in the reboiler heater. The most viable solutions to reduce the energy exhausted through these operations are using concentrated solar collector (CSC) technologies. Specifically, in Iraq, it was found that the annual received solar radiation is about 4000 hours where the daily incident radiation reaches about (4.5 – 5.5 kWh/m^2) (Amori K. E. and Sari R. R., 2020). Parabolic trough collector (PTC) has taken the attention of researchers and manufacturers recently for their lower operation and maintenance cost (Jassim N. A., and Al-Chlaihawi, K. K., 2017) and for their lower thermal energy requirements (Sanda A. et al., 2019) in compare with other solar energy resources. Therefore, the present study focuses on retrofitting concentrated solar collector units for crude oil preheating, steam generating, and reboiler heater instead of using flue gas or heat exchanger units in the above-mentioned operations. In addition, retrofitting such techniques in the crude oil distillation process has further benefits represented by reducing the carbon emissions which affect global warming. Thus, adopting such solutions would be efficient in term of technical, economical, and environmental impact. In term of concentrated solar collector, there are number of researches focus of developing such sustainable tools to generate the required heating flow that is used on other processes like crude oil distillation. A mathematical model was developed by (Hamood H. S. et al., 2015) to analyze the performance of a flat solar collector under Mosul city's weather conditions using different inlet conditions, different working fluids, and different absorbing materials utilizing EES (Engineering Equation Solver). It was found that Copper and Aluminum give better performance than Carbon Steel when water is used as a working fluid instead of using Propylene Glycol solution. Another experimental study was investigated by (Abbood M. H. et al., 2018) testing three different configurations of solar parabolic trough collector (PTC) under Najaf climatic conditions. It was found that maximum collector efficiency is achieved at higher flow rate for evacuated and nonevacuated glass receiver. However, there are few numbers of works from literature investigate such alternative solutions in the crude oil distillation process. (Alnifro M. et al., 2017) investigated the technical and economic feasibility of integrating several renewable energy resources (PV solar, CSP solar, and wind turbine) into an oil refinery unit process in the Middle East region. ASPEN HYSIS software was used to perform the simulation while Levelized Cost of Energy (LCOE) method was used to perform the economic feasibility study. It was found the payback period of using solar CSP is 10 years with 411 GWh annual capacity while the payback period was 7-6 years for the solar PV and wind energy. A study was developed by (Taqvi S. et al., 2021) using Multi-Energy Hub approach to investigate integrating wind and solar energy resources into a refinery processes. Carbon emission and cost were the criterion for comparison. It was found that using such technologies lead to reduction in carbon emissions reaches about 9.8 ktonnes with an additional annual cost of 88000 $ while using thermal storage unit leads to an additional reduction of about 1.94 ktonnes of emission with an additional annual cost of about 275000 $. (Li C. et al., 2024) developed a new term called by “Solar Oil Refinery” by integrating solar energy system to crack the residual oil products. They found that using such analysis enhances the oil conversion rate significantly specially at higher temperature values leading to reduction in the fossil fuel consumption in petroleum industry. (Khan et N. A. et al., 2023) investigated the retrofitting of hybrid solar-heating system with using thermal energy storage in the crude oil refinery processes. The study was performed using TRNSYS software. It was found that the proposed hybrid system with about 26.99% of yearly solar fraction saves about 21046 $ for annual heat supply equals to 116944 MWh, and it reduces the carbon footprint by about 34.045 ton/CO_{2eqv}. (Altayib K., and Dincer I., 2019) studied the effect of integrating solar-based system to crude oil refinery to be used in the crude oil preheating processing. Solar energy obtained from parabolic trough collector (PTC) would share about 10% of the total required heat used in the crude oil preheating process while the remaining energy gained from the solar collector would be used to generate power in a solar power system. Thermal energy storage (TES) was integrated into the system, and energetic and exergetic analysis was performed to the overall system through the study. Integrating concentrated solar collector (CSC) represented by parabolic trough collector (PTC) with a furnace in the Parsian Gas Refinery was modeled by (Shahdost B. M. et al., 2019) using TRNSYS. The optimum energy share by the solar-based system reaches about 23.8%. It was found that at its optimum energy share, using PTC unit would reduce the fuel consumption by about 1996000 m^3/year and the carbon emission by about 3557.7 tonCO_2/year. Economically, it was found that using such a solar-based system would be more convenient especially with increasing the price of fossil fuel nowadays.

The present study investigates integration of CSC represented by PTC into three stages of the crude oil distillation process; crude oil preheating process instead of using furnace, generating live steam to be injected at the bottom of distillation tower, and supplying thermal energy to the reboiler heater. A selected crude oil refinery unit in Manchester UK is tested using an American dynamic flow sheet software called by COCO V 3.6.0.13 for modeling all stages of the oil distillation units beside using SAM software (System Advisor Modeling) V 2022.11.21. The field input values are selected for validation purposes according to (Chen L., 2008 and Liu J., 2012) while the new proposed system is investigated under Najaf Climatic conditions. Three different heat transfer fluids are studied with different mass flow rates: - pressurized water, therminol VP-1, and hitech solar salt. The annual averaged thermal energy required for the stages is determined through the day hours along with analyzing the required area for different generated thermal energy. In addition, an economic analysis is established through the study using levelized cost of energy method (LCOE) to evaluate the feasibility of the proposed technique. To assure the viability of the current work, the presented data are validated with reported data from literature.

2. CRUDE OIL DISTILLATION UNIT.

Fig.1 is a conventional schematic diagram that shows consequent stages of crude oil distillation process. In the real crude oil refinery unit, crude oil is preheated primarily to specific temperature to enter a desalter to remove salts and other unwanted particles. Then, it would be preheated through heat exchangers using the products of the distillation tower itself to around 120 ^oC, and then it enters the main furnace to raise its temperature to around 340 ^oC to pervaporate lighter components from crude oil. The produced oil from the abovementioned process enters two stages of distillation columns: atmospheric distillation columns and vacuum distillation column. The object of the current study focuses on the first stage of distillation, which involves the atmospheric distillation column. In the atmospheric distillation column, the distillation of products would be based on boiling temperature range for each product. In the first stage of distillation, residue is produced from the bottom of the column that is reheated again to a temperature range equal to 400 ^oC (Chen L., 2008) to be utilized in the vacuum distillation process. There are number of side-withdrawal strippers in the other stages of distillation process to distillate the light products from the heavy products. Firstly, heavy gas oil (HGO) is produced from the bottom while light gas oil (LGO) is distillated to enter new stage. Next, light Naphtha (LN) with off-Gas and light hydrocarbons is stripped while the heavy naphtha (HN) is produced from the bottom of the side stripper. Live steam is injected to the first and second stages of the distillation process for further light components stripping. While reboiler heater would be used in the final stages to produce the (LN) and Off-Gas products. In the present proposed study, concentrated solar collector (CSC) would be retrofitted to generate the heat required for crude oil preheating processing, steam generating, and reboiler heater.

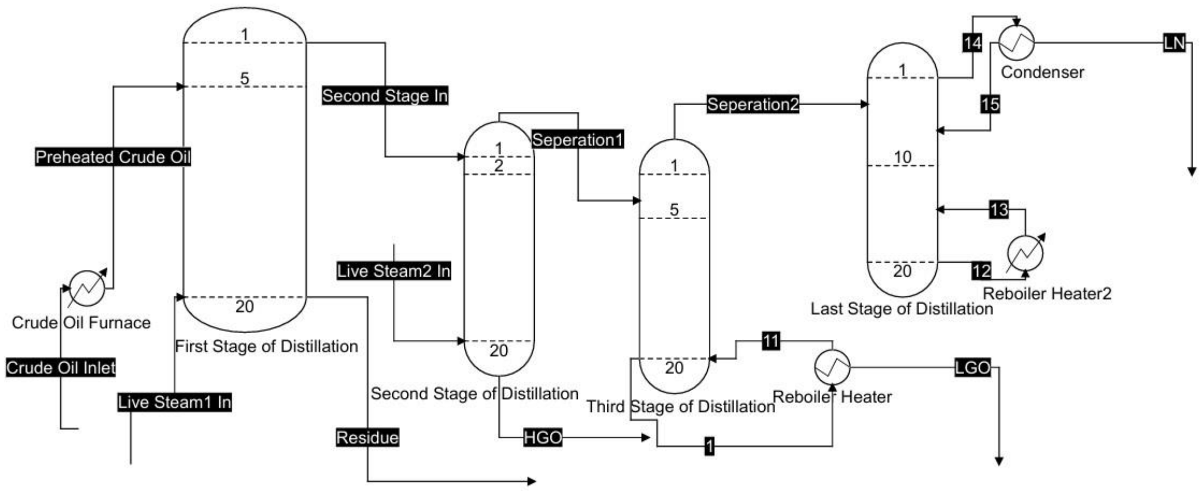


Fig. 1. Schematic configuration shows the stages of crude oil distillation

3. MATHEMATICAL MODELING OF THE SOLAR ENERGY UNIT

The most used governing equations in the current study are the equations utilized within the solar collector system. As solar thermal energy is the produced energy from the PTC unit, and used in the crude oil distillation processing, the formulated model can be estimated as below according to (Saif W. Mohammed Ali et al., 2020):

$$q_{solar}^{thermal.enrg} = \dot{m}_{fluid} \times (h_{out} - h_{in}) \quad (1)$$

$$q_{solar}^{thermal.enrg} = q_{rec} - q_{losses} \quad (2)$$

$$q_{losses} = F \times A_c \quad (3)$$

$\dot{m}_{fluid}$, $h_{out}.and\ h_{in}$ are the mass flow rate of the working fluid, the inlet, and the outlet enthalpy. q_{rec} is the heat transferred to the collector receiver while F is the losses factor which is assumed to be equal to (0.008 W/m2) (Saif W. Mohammed Ali et al., 2020).

$$q_{rec} = Q_{solr} \times \eta_{opt} \times \eta_{END} \times \eta_{CLN} \times IAM(\theta) \quad (4)$$

$$Q_{solr} = DNI \times A_c \quad (5)$$

where $\eta_{opt}.\eta_{CLN}.and\ IAM(\theta)$ are the optical efficiency, cleanliness efficiency, and incident angle modifier, respectively. DNI is the direct normal irradiation while η_{END} is the end loss efficiency which can be determined as:

$$\eta_{END} = 1 - \frac{F_l}{M_l}\tan(\theta_L) \quad (6)$$

Where F_l, M_l, and θ are the collector focal length, collector module length, and the longitudinal angle, respectively.

$$\theta_L = sin^{-1}(\cos(\gamma)\,.\cos(\alpha)) \quad (7)$$

γ, and α are the azimuth angle and elevation angle, respectively.

On the other hand, mass and heat balances are applied on the units of the distillation processing where the total mass enters the distillation unit is equal to the summation of the top and bottom products. In addition, the overall energy enters the distillation tower is equal to the overall energy produced from the tower. The distillation model used in the current work can be simplified as was shown by (Saif W. Mohammed Ali, 2019):

The component mass balance is written as:

$$V_{j+1}y_{i.j+1} + L_{j-1}x_{i.j-1} + F_j z_i - \left(1 + r_j^v\right)V_j y_{i.j} - \left(1 + r_j^L\right)L_j x_{i.j} = 0 \quad (8)$$

While the component energy balance is written as:

$$V_{j+1}H_{j+1}^v + L_{j-1}H_{j-1}^L + F_j H_j^F - \left(1 + r_j^v\right)V_j H_j^V - \left(1 + r_j^L\right)L_j H_j^L - Q_j = 0 \quad (9)$$

Where:

$$r_j^v = \frac{U_j}{V_j} \text{ and } r_j^L = \frac{W_j}{L_j}$$

As j represents stage number inside the distillation unit, x_i is the product composition at the rate i of phase L while y_i is the product composition at the rate i of phase V. F represent the new added stream to stage j while U_j and W_j are the exit streams. z_i is the product composition at the rate i of stream F. H is the enthalpy of each phase while Q_j represents the heat added to the distillation unit while by steam injection or reboiler heater.

4. VALIDATION OF THE PRESENT MODEL

Table 1. demonstrates comparisons between the data obtained from the distillation process modeled in the current work and data reported by (Chen L., 2008 and Liu J., 2012) for validation purposes.

As it is shown in the table, the data obtained from the current work is almost placed within the same range of the data gotten by (Chen L., 2008 and Liu J., 2012). However, the only significant gap found is a gap in the temperature of LGO and HGO where the errors reach about 35% and 10% for the LGO and HGO, respectively, while the error in the other data does not pass 6%. This gap can be returned to the methodology used for distillation calculations in both models. In the model solved by (Chen L., 2008 and Liu J., 2012), the true boiling temperature and density for each component were the base used for solving the model while in the current work-study, the real chemical structures for the real chemical compositions of crude oil were considered through modeling the distillation process. Overall, as most of the data obtained from the current work are valid in comparison with the data collected by (Chen L., 2008 and Liu J., 2012), the validation of the current model is placed within an acceptable range.

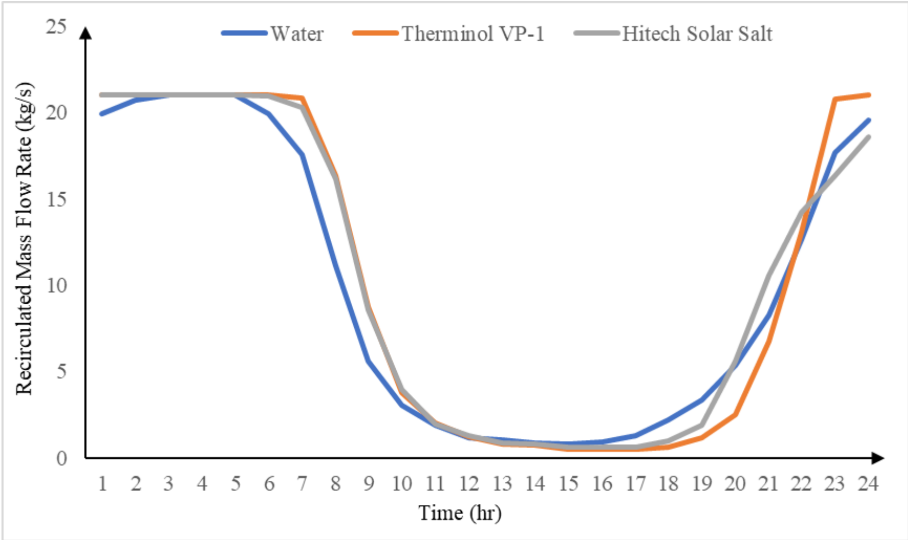
Table 1. Comparison between data from current study and literature for validation.

Data Reported by (Chen L., 2008 and Liu J., 2012)	Data calculated through the current study
Feed Preheat temperature (372.3 ^{o}C)	Feed Preheat temperature (372.3 ^{o}C)
Vaporization Mechanism (Steam and Reboiler)	Vaporization Mechanism (Steam and Reboiler)
Steam Mass Flow Rate (0.691 kg/s)	Steam Mass Flow Rate (0.69 kg/s)
Reboiler Duty (8.466 MW)	Reboiler Duty (8.5424594 MW)
Residue Mass flow rate (15.544651 kg/s)	Residue Mass flow rate (15.555165 kg/s)
Residue Temperature (320.51 ^{o}C)	Residue Temperature (348.42753 ^{o}C)
HGO Mass flow rate (7.9129517 kg/s)	HGO Mass flow rate (7.9171659 kg/s)
HGO Temperature (236.71 ^{o}C)	HGO Temperature (263.51257 ^{o}C)
LGO Mass Flow Rate (13.6 kg/s)	LGO Mass Flow Rate (13.600899 kg/s)
LGO Temperature (176.5 ^{o}C)	LGO Temperature (114.12884 ^{o}C)
HN Mass Flow Rate (10.35 kg/s)	HN Mass Flow Rate (10.3503 kg/s)
HN Temperature (110.21 ^{o}C)	HN Temperature (103.72864 ^{o}C)
Furnace Duty To Preheat the Crude Oil (76.37 MW)	Furnace Duty To Preheat the Crude Oil (72.27 MW)
Feed Crude Oil Pressure (2.5 bar)	Feed Crude Oil Pressure (2.5 bar)
Feed steam Pressure (4.5 bar)	Feed steam Pressure (4.5 bar)

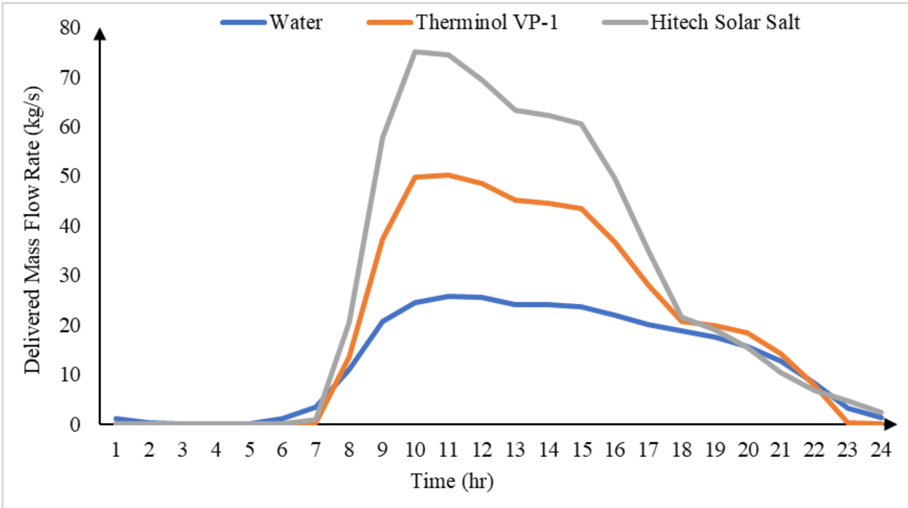
5. RESULTS AND DISCUSSION

Fig. 2 shows the annual averaged daily mass flow rate of the CSC field for three different working fluids; pressurized water, therminol VP-1 oil, and Hitec solar salt through day hours. Fig. 2(a) represents the recirculated mass flow rate. While the delivered mass flow rate is represented by Fig. 2(b).

As the total mass flow rate used in the PTC unit is equal to summation of the recirculated and delivered mass flow rates, it can be noticed that the recirculated mass flow rate starts decreasing from its maximum value at the morning till reaching its minimum value after evening. Then, it increases again to reach its maximum value. On the other hand, the delivered mass flow rate starts with its minimum values at the morning and then it starts increasing to reach its maximum values after evening to start decreasing again in an opposite trend to the behavior of the recirculated mass flow rate. This behavior is consistent with the behavior of pressurized water in Fig. 3(a) and Fig. 3(b). This trend is expected as the annual averaged solar irradiation behaves similarly as would be shown in Fig. 4.



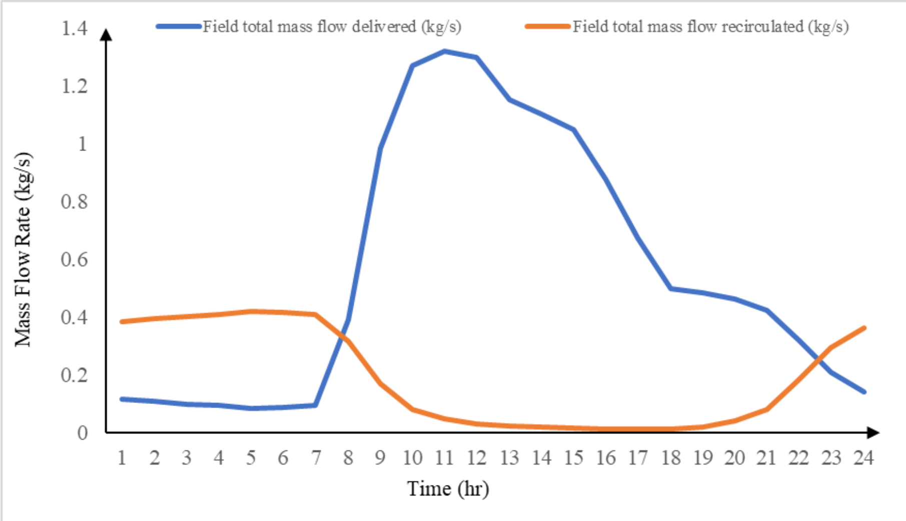
(a)



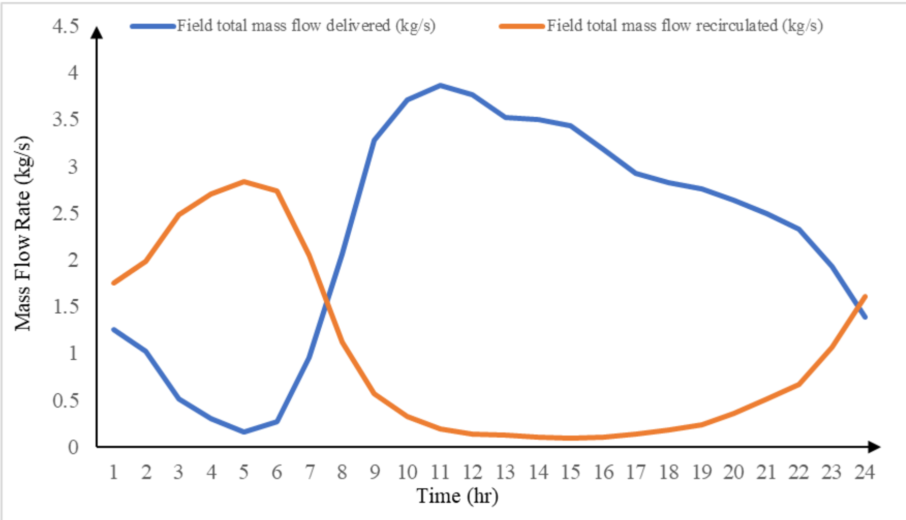
(b)

Fig. 2. Mass flow rate of different processing fluids in the concentrated solar through day hours for crude oil preheating process.
(a) recirculated mass flow rate, and (b) delivered collector mass flow rate.

An interesting finding is that the required field mass flow rate is the highest in case of using hitec solar salt as a working fluid where the maximum mass flow rate value approaches the threshold of 75.077 kg/s while less value would be for the case of using therminol VP-1 as the value reaches about 49.8553 kg/s, and the lowest value would be for the case of using pressurized water where the value reaches about 25.7256 kg/s. This comes from the fact that the design thermal energy is equal to the product of specific heat, mass flow rate, and temperatures. As the design temperature is constant, any increase or decrease in the specific heat of the working fluid corresponds to an opposite difference in the mass flow rate. Table 2. shows the density and specific heat values for the utilized working fluids.



(a)



(b)

Fig. 3. Recirculated and delivered mass flow rate of the pressurized water in the CSC: (a) for the first and second stages of distillation process, and (b) for the reboiler heater.

Table 2. Thermophysical properties of working fluids used in the current study.

Working Fluid Used	Therminol VP-1 Oil (Khan et N. A. et al., 2023)	Hitec Solar Salt (Bonk A., and Bauer T., 2021)	Pressurized Water (webbook.nist.gov US. Web)
Specific Heat (kJ/kg.^{o}k)	2.45793	1.59	4.2146
Density (kg/m^3)	764.293	1712.12	958.62

As being shown in Table 2. the lowest specific heat and the highest density would be for Hitec solar salt leading to maximizing the mass flow rate in the unit. On the other hand, the highest specific heat would be for the pressurized water leading to a lower value for mass flow rate in compare with therminol VP-1 and hitech solar salt. The results shown in Fig. (2-a, and b) are presented for the CSC proposed for the crude oil preheating processing where the required heat duty reaches about 72.27 MW.

Fig. 4 shows the distribution of annual averaged global solar irradiation (GHI W/m2) through day hours (24 hours a day) in addition to the distribution of ambient temperature. The data calculated was real field data recorded and obtained from NREL tool (nsrdb.nrel.gov US. Web) called by NSRDB for Al-Najaf, Iraq which is placed at Latitude 32.01, and longitude 44.24. As being shown in the figure, the radiation and temperature values increase exponentially from its minimum values at sun rise at the morning to reach its maximum values at 12:00 PM where the maximum averaged annual solar radiation approaches about (738.302 W/m2) while the maximum annual averaged temperature value approaches about (32.11 °C) at 2:00 PM, and then it starts to be decreasing exponentially to reach its minimum values at sun set.

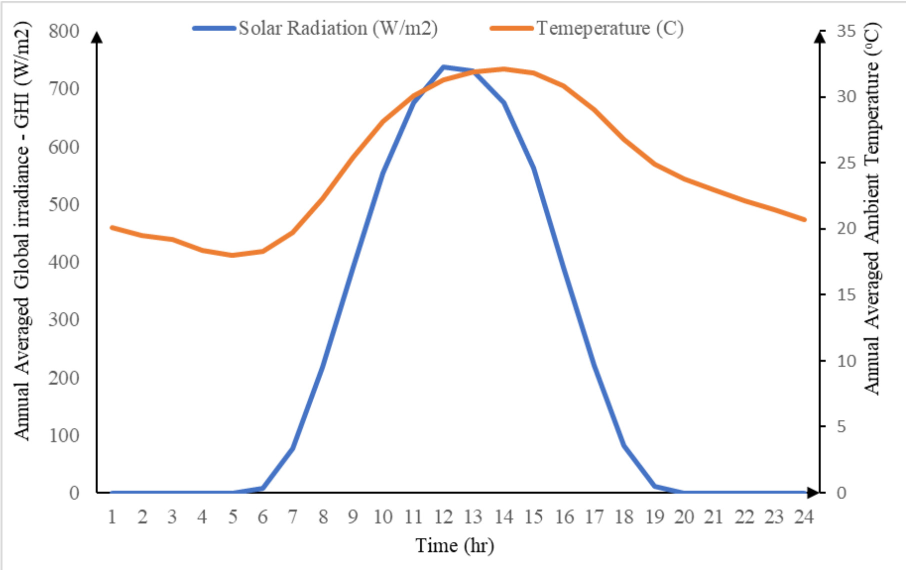


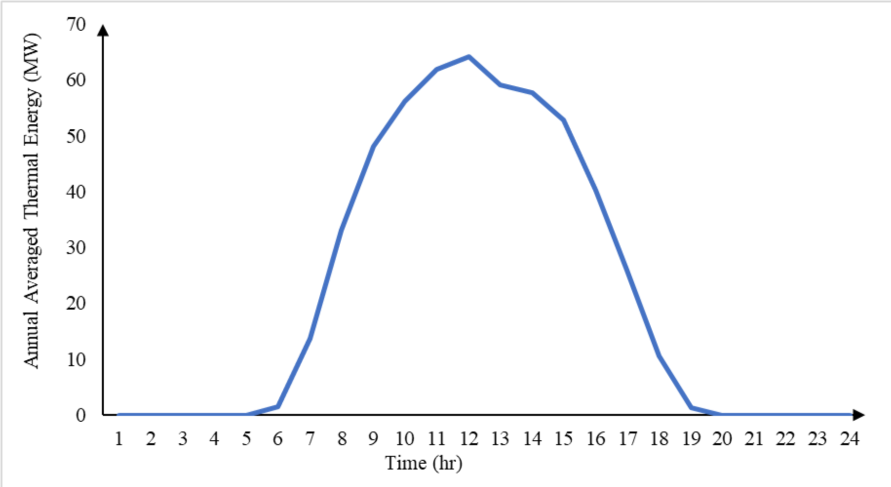
Fig. 4. Annual averaged daily global solar irradiation and ambient temperature (Najaf, Iraq, Latitude 32.01, Longitude 44.34).

Fig. 5(a), Fig. 5(b), and Fig. 5(c) illustrate the required thermal energy distribution to be used for; a) crude oil preheating process, b) generating the live steam required for the first and second stages of the distillation process, and c) generating the required thermal energy used in the reboiler heater respectively. The distribution of thermal energy is drawn over the day hours (24 hours a day). The behavior of the thermal energy required for the distillation process is very compatible to the behavior of GHI irradiation and ambient temperature through the day as has been shown in Fig. 4 as well as the field mass flow rates shown in Fig. 3. This behavior assures the functionality and dependency on these two parameters. As has been mentioned above, the value of thermal energy starts from its minimum values from sun rise to be increasing exponentially till approaching the maximum value at 12:00 PM, and then, it starts decreasing exponentially until reaching its minimum values at sun set. However, the maximum required thermal energy for the crude oil preheating processing is much higher than the energy required for steam generation and reboiler heater processing. As being shown in Fig.5 (a, b, and c), it was found that the maximum annual averaged thermal energy obtained from the PTC unit connected to the crude oil preheating system is about (64.1154 MWt) while the maximum averaged annual thermal energy obtained from the PTC unit connected to the reboiler heater is about (9.16 MWt). On the other hand, it was found that the lowest required thermal energy in distillation process would be for steam generation as the maximum averaged value of thermal energy required for steam generation reaches about (3.05 MWt).

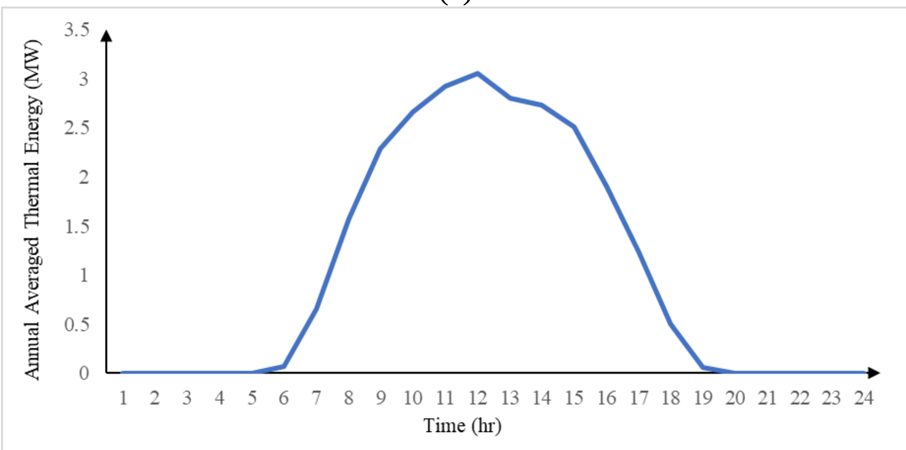
Fig. 6 (a) represents the levelized cost of energy (LCOE) for the base crude oil preheating case using flue gas, and for the retrofitted proposed case where PTC unit would be used for the crude oil preheating processing instead of using flue gas in a furnace. The LCOE represented by ($/kWh) is calculated as:

$$\mathrm{LCOE} = \frac{Total\ cost\ expended\ in\ the\ energy\ unit}{Total\ thermal\ energy\ generated\ by\ the\ unit}$$

However, the data demonstrated in the present study was cited from two resources; first, the LCOE for flue gas unit was obtained from the same reference used to validate the current model (Chen L., 2008 and Liu J., 2012). On the other hand, the LCOE for retrofitting the PTC unit was obtained from NREL tool called by “Annual Technology Baseline” ATB (atb.nrel.gov US. Web) which was calculated based on the methodology used in SAM (System Advisor Model) software. The data determined by ATB tool was illustrated over period of 30 years (from 2019 to 2050) while the LCOE of flue gas was calculated according to the model presented by (Chen L., 2008 and Liu J., 2012) which is considered as a constant over the mentioned period of time. However, both data was compared with data recorded by to assure the viability of the current economic analysis as being shown in Table 3. The Fig. 6(a) shows that the retrofitting of PTC in 2019 and 2021 was not feasible economically as the LCOE of using PTC are (0.0439 $/kWh) and (0.0419 $/kWh) for 2019 and 2020 years, respectively, where these values are higher than the value of flue gas which is equal to (0.0363 $/kWh). Then, the values would be more feasible from 2021 till 2050 where the values start as (0.0357 $/kWh) in 2022 till reaching its minimum threshold which is equal to (0.01601 $/kWh) in 2050. However, whether the retrofitting of PTC is feasible economically or not, using PTC for preheating process is still feasible environmentally as it considers as a renewable energy resource that emits no greenhouse gases like carbon dioxide emission. Fig. 6 (b) represents the expected annual cost saving in case of using PTC unit for crude oil preheating processing, live steam injection in the tower, reboiler heater, and total annual cost saving. The minus sign from 2019 to 2021 means that there is no saving but there is cost losing as the price of using flue gas is lower than the price of using PTC unit. Then, the price of using flue gas would be higher than the price of using PTC unit leading to annual saving reaches about 354788 $, 1497540 $, 12670684 $, and 14523013 $ for the steam generation in the tower, reboiler heater, crude oil preheating, and total annual saving, respectively.



(a)



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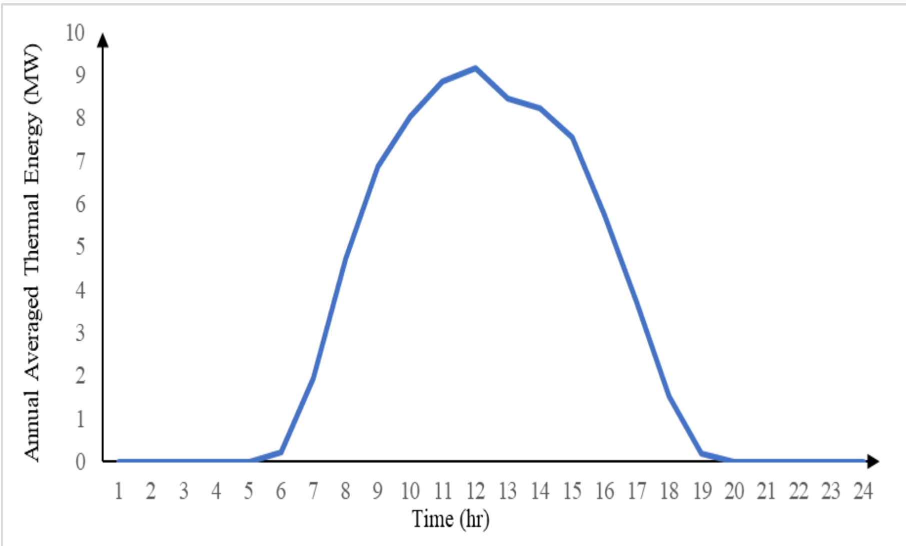
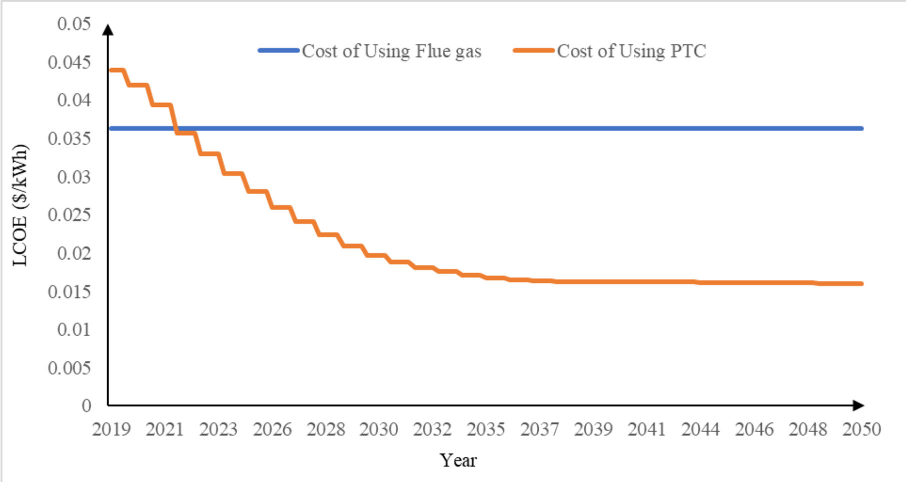
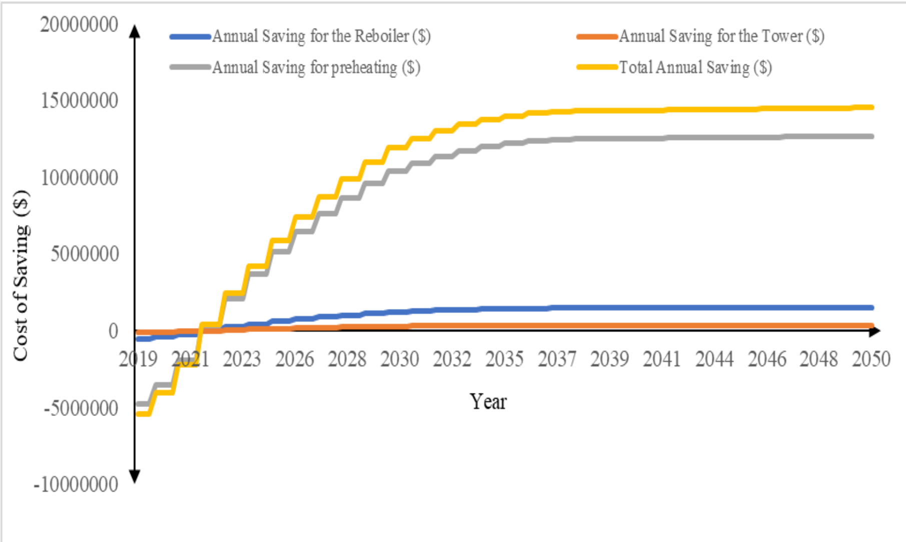


(c)

Fig. 5. Annual averaged thermal energy required for the whole crude oil distillation process; (a) for crude oil preheating, (b) live steam generating, and (c) Reboiler heater.



(a)



(b)

Fig. 6. (a) represents the levelized cost of energy (LCOE), and (b) The annual cost saving.

Table 3. Comparison between the cost reported in the current study and the cost reported by (Jalil R. R., and Mohammed H. J., 2022)

Cost of Flue gas (Current Study) (Chen L., 2008 and Liu J., 2012)	Cost of Flue gas (Jalil R. R., and Mohammed H. J., 2022)	Cost of Solar Energy (Current Study) (Averaged) (atb.nrel.gov US. Web)	Cost of Solar Energy (Jalil R. R., and Mohammed H. J., 2022)
0.0363 ($ /kWh)	0.038 ($ /kWh)	0.021 ($ /kWh)	0.0183 ($ /kWh)

One of the major problems stands in the way of investing in renewable energy units is the required area. Fig. 7 shows a sensitivity analysis for the required area for different design thermal energy. As being shown in the figure, the required area is increasing almost linearly with the corresponding design produced thermal energy. As the design produced thermal energy changes from (42 MW) to (84 MW), the corresponding required area changes from 68224 m^2 to 131200 m^2 where the ratio reaches about 0.62 kW per square meter (0.62 kW/m^2).

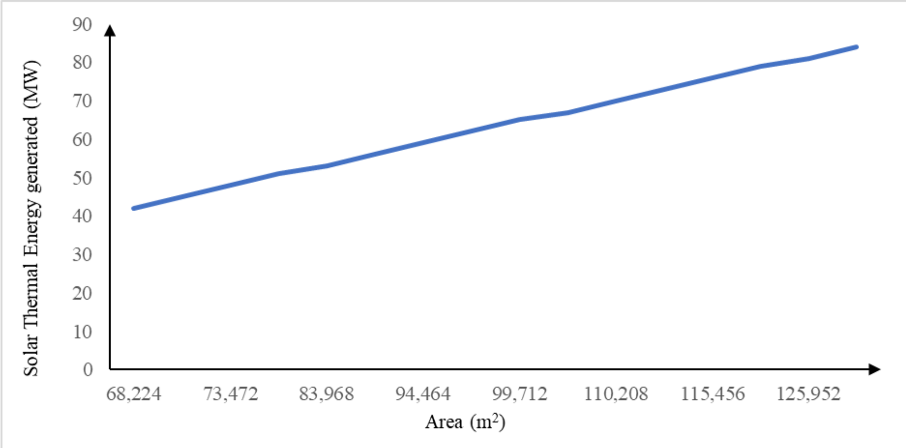


Fig. 7. The generated solar thermal energy from the PTC versus the required area.

6. CONCLUSION

Investigating the integration of CSC represented by PTC into three stages of crude oil distillation process has been studied in the current work and modeled using COCO V 3.6.0.13 and SAM V 2022.11.21. Different working fluids at different mass flow rates were tested. In addition, the proposed system was analyzed economically using LCOE method. Furthermore, the required thermal energy and land area was calculated. The conclusion remarks can be summarized below:

1- The required input mass flow rate in case of using hitec solar salt is the highest while lower value would be in case of using therminol -VP, and the lowest value would be in the case of using pressurized water. It was found that the values reach about 75 kg/s, 49.8 kg/s, and 25.7 kg/s for hitech solar salt, therminol VP-1, and pressurized water, respectively.

2- As the required thermal energy for the reboiler heater is lower than the required thermal energy to preheat the crude oil and higher than the energy required to generate the live steam, the mass flow rates would be the highest for crude oil preheating and lower for reboiler heater while the lowest would be for generating live steam to be injected into the distillation tower.

3- The economic analysis showed that retrofitting the proposed system would not be feasible between 2019 to 2021 as the LCOE of flue gas fuel is higher than the LCOE of the proposed system where the LCOE of flue gas is 0.0363 $/kWh while the LCOE of PTC is ranged from 0.04389 to 0.038 $/kWh. On the other hand, it was found that retrofitting such a system would be more feasible after 2021 as the LCOE of PTC is higher than the LCOE of flue gas where the LCOE of PTC reaches about 0.01604 $/kWh. The gap between both prices leads to an overall annual cost saving reaches about 14523013 $.

4- It was concluded that the required land area for the PTC unit increases linearly with the increase in the required generated thermal energy in a rate equal to (0.62 kW/m^2).

5- The validation with recorded data from literature shows that the average error doesn't pass 6% despite a significant error in the temperature of LGO and HGO comes from the methodology of calculating the products of the distillation between the current work and the literature.

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