Energy Conversion and Management 71 (2013) 51–61

Contents lists available at SciVerse ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Energy, exergy, environmental and economic analysis of industrial fired heaters based on heat recovery and preheating techniques

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ARTICLE INFO

Article history:
Received 11 September 2012
Accepted 10 March 2013
Available online 11 April 2013

Keywords:
4E analysis
Fired heater
Sensitivity analysis

ABSTRACT

Fired heaters are ubiquitous in both the petroleum and petrochemical industries, due to it being vital in their day to day operations. They form major components in petroleum refineries, petrochemical facilities, and processing units. This study was commissioned in order to analyze the economic benefits of incorporating both heat recovery and air preheating methods into the existing fired heater units. Four fired heater units were analyzed from the energy and environmental point of views. Moreover, the second law efficiency and the rate of irreversibility were also analyzed via the exergy analysis. Both analyses was indicative of the fact that the heat recovery process enhances both the first and second law efficiencies while simultaneously assisting in the production of high and low pressure water steam. The implementation and usage of the process improves the thermal and exergy efficiencies from 63.4% to 71.7% and 49.4%, to 54.8%, respectively. Additionally, the heat recovery and air preheating methods leads to a substantial reduction in fuel consumption, in the realm of up to 7.4%, while also simultaneously decreasing heat loss and the irreversibility of the unit. Nevertheless, the results of the economic analysis posits that although utilizing an air preheater unit enhances the thermal performance of the system, due to the air preheater's capital and maintenance costs, incorporating an air preheater unit to an existing fired heater is not economically justifiable. Furthermore, the results of the sensitivity analysis and payback period showed that the economic results are highly susceptible to the interest rate, and the payback period for the most economical case is 2.6 years.

1. Introduction

Energy, once a luxury afforded to a precious few, has become a commodity that the modern world cannot survive without. Without a doubt, it forms the lifeline of industries that provides us with basic needs such as transportation, electricity and agriculture [1–3]. The industrial energy consumption is expected to grow up to 303.9×10^{15} (kJ) in 2035 [4]. These figures are staggering, but also serve to underline the fact of how energy seamlessly permeated our daily lives.

The cost associated with industrial output is heavily manipulated by its industrial energy consumption and fuel mixtures [5–7]. The analysis of energy use performance and the efficiencies of the industrial sector have been carried out using different methods in many countries [8,9]. Currently, researchers are devising methods to reduce the overall energy consumption in this particular sector [10,11]. Additionally, the utilization of surplus energy improves the industrial thermal efficiency and reduces the amount of emission [12–15].

Crude oil heating during the petroleum refining process in the petrochemical industry utilizes direct-fired heaters. It provides the required heat essential to processes such as cracking metallurgical furnaces, and is made up of many different sizes and wattages, ranging from 0.15 MW in package generation gas heaters, to 300 MW for steam hydrocarbon reformer heaters. The net thermal efficiency (NTE) and the stack gas temperature varies, from 60% for a vertical–cylindrical configuration, to about 80% NTE, and 650 °C for this type of fired heaters, equipped with a convection section [16].

Literature is littered with an abundance of optimal design methods for fired heaters. Bahadori and Vuthaluru introduced a correlation with the specific purpose of designing radiant and convection coils for industrial fired heaters [16]. Meanwhile, in order to optimize their design, Mussati et al. used a mixed integer nonlinear programming method, and compared it with three other similar cases [17].

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http://dx.doi.org/10.1016/j.enconman.2013.03.008

Nomenclature

A.P.H	air preheater
CC	capital costs (US$)
CPW	compound present worth factor
EC	energy consumption (GJ/year)
EF	emission factor (kg/GJ)
EM	emission production (kg/year)
EMP	emission penalty (US$/year)
EP	CO_2 emission penalty (US$/kg)
FC	fuel costs (US$/year)
h	enthalpy (kJ/kg)
HD	hydrocarbon
HHV	higher heating value (kJ/kg)
HS	high pressure steam
i	year
LS	low pressure steam
MC	maintenance costs
PP	payback period
PWF	present worth factor
r	interest rate
s	entropy (kJ/kg K)
T_0	environment temperature (K)
ψ	exergy flow (kJ/kg)
$\dot{I}$	irreversibility rate (kJ/s)
$\dot{m}$	mass flow rate (kg/s)
n	life span (year)
γ	fuel exergy grade function
η	efficiency
Δ	difference

Subscripts

a	air
ad	adiabatic
f	fuel
fl	flue gas
HD	hydrocarbon
HS	high pressure steam
j	emission type (e. g. CO, CO_2, etc.)
LS	low pressure steam
NG	natural gas
St	stack

The first law of thermodynamics has been widely used for energy utilization analysis; however, it is limited in a sense that it is incapable of quantitatively determining the quality of energy. The second law of thermodynamics supplants this limitation, where it introduces the exergy analysis that quantifies the potential useful work for a given amount of energy. It is essential that both the quantity and quality of the energy used for gaining the effective usage of energy be taken into consideration [18,19]. Expressing the true efficiency makes the exergy a powerful tool in sectoral energy analysis and engineering design [20]. This concept has stimulated great interest, and for the past three decades, it has been applied to various economic sectors, such as industrial and thermal processing to determine the inherent energy and financial savings. Exergy analysis for the assessment of energy utilization was first applied in the USA by Reistad [21], with the details discussed in their groundbreaking papers [22,23].

Additionally, comparisons between energy and exergy balance in certain thermodynamic processes such as power generation systems, heat pumps, boilers and combustion processes have been successfully carried out. The effect of different temperature on energy and exergy efficiencies of the combustion process has also been revised [24], and it was found that techniques that reduce exergy losses in the distillation towers are numerous; encompassing changing feed locations, adjusting reflux ratios and feed conditioning, or side re-boiling and condensing. The study on an atmospheric distillation column in Tabriz's refinery showed that changing the feed conditioning resulted in maximum exergy loss reduction and simultaneously reduces the furnace's fuel consumption [25]. Al-Muslim et al. investigated the effect of changing the reference state from 15 °C to 40 °C on the exergy efficiency of a distillation plant using the simsci/PROII software, and the results showed that as the reference temperature increases, the exergy efficiency decreases, confirming that the reference temperature affected the exergy efficiency at rates higher than irreversibility [26].

In the United States, the largest fired system energy consumer is the petroleum refining industry, which accounts for around one third of the total energy consumption, whilst the largest losses are also exhibited in the fired systems, which are employed by companies involved in the petroleum industry [27]. It can be surmised from this fact that the energy losses are significantly higher in the context of its application in developing nations.

The efficiency of the fired heaters can be increased by preheating the intake air using hot combustion gases [16,28]. Wang et al. measured the effect of irreversibility in a rotary air preheater on the efficiency of a thermal power plant, and their results showed that in the case of rotary air preheaters, the exergy analysis is capable of evaluating the effect of air leakage on energy efficiency [28].

Fired heaters are industrially ubiquitous, and use a significant amount of energy. Its alteration, improvement and degradation will invariably affect energy savings and environmental pollution. The Kyoto protocol, introduced by the United Nations Framework Conversion on Climate Change (UNFCCC), prescribes the binding of greenhouse gas emission target to about 5% below their pre-1990 level [29].

Thermal systems are conventionally assessed from an economic perspective. A system might be thermodynamically and technically appropriate, but it might fail to adhere to the criteria governed by economic concerns. In this regard, Varghese has studied the effect of area energy targeting on the economic viability of industrial fired heaters [30].

The present work analyzes the incorporation of heat recovery and air preheating equipment to the existing industrial fired heater units from an economical perspective. Four industrial fired heater systems were modeled and analyzed from energy and environmental standpoints. The Net Present Value (NPV) of each system are compared in order to determine the most economic fire heater. It should be pointed out that the economic analysis is indirectly affected by the results of environmental and energy analysis. Furthermore, the second law efficiency and the rate of irreversibility were studied via the exergy analysis for each particular case. This paper contributes to the body of knowledge in the following way:

- Four industrial fired heaters were modeled and analyzed from an energy, exergy, economic, and environmental (4E) standpoint.
- The effects of energy recovery and air preheating on the system(s) were analyzed.

- The effect of thermal efficiency, CO_2 emission penalty, and all of the capital and current cost (direct and indirect costs) were integrated into the economic analysis.
- The performance of the most thermal efficient system was compared to a conventional fired heater system.
- The paper provides a guideline to policy makers in petroleum and petrochemical organizations that are willing to improve their existing fired heater systems, in light of its economic benefits. Moreover, this study can also serve as a guide to policy makers in nations that are currently mulling over the construction of new refineries.

2. Methodology

2.1. Energy saving potential

Industrial scale processes utilizes many methods such as cogeneration, power recovery and waste heat recovery to reduce the overall energy consumption [31]. Similarly, fired heaters in modern refineries use the stack's heat recovery and burner's air preheating to minimize the overall energy consumption. However, conducting an economic analysis is considered a prerequisite in the decision-making process with regards to equipping an existing fire heater system with the energy recovery and air preheating methods.

2.1.1. Stacks heat recovery

A large proportion of input energy is dissipated via its motion through the stacks at high temperatures. In order to reduce the impact of this phenomenon, the utility sections require the installation of an auxiliary steam water stream, where it will utilize this high temperature flue gas in producing high and low pressure steam. These are then used to preheat the desalted hydrocarbon supplied to the fired heaters, for purposes such as air-conditioning during winters, electricity generation, turbine pumps operations for transferring petroleum products, adjust processes conditions in atmospheric and vacuum towers, and also for industrial heat exchangers cleanups.

2.1.2. Air preheating

The air entering the burners can be preheated using high-energy flue gas, and as the enthalpy of the entering air directly affects the flame temperature and the enthalpy of combustion, a higher temperature of the intake air is capable of reducing the industrial fuel consumption.

2.2. Model description

As described in Section 2.1.1, high and low pressure steam lines are widely used in petroleum industries, and a high amount of energy is consumed to produce these utility water streams by the industrial boilers. This study recommends and analyzes the incorporating heat recovery and air preheating techniques that improves the thermal performance of the existing industrial fired heaters.

The schematic diagrams of the basic case (case 1), and the three recommended cases (2–4) are illustrated in Fig. 1. Case 1 shows a fired heater that is unequipped with any waste energy recovery system, representing a baseline case or an existing situation. Case 2 showcases a recommendation that mounts a high-pressure steam line in the convection coil zone for heat recovery purposes. Meanwhile, case 3 recommends adding a low-pressure steam line to the setup from case 2, consisting of a fired heater with high-pressure and low-pressure steam lines in the convection coil zone. This represents the second recommendation for waste recovery purposes from the system. Finally, the addition of an air preheater to the setup in case 3 forms the basis for case 4, which differs substantially from the intake and stack properties of case 3.

It was assumed that in all of the cases, the company's demand for hydrocarbon and water steam is similar to the studied case (same mass flow rates and inlet/outlet conditions). Obviously, in cases 1 and 2, respectively, the needed high and low pressure steam, and low pressure steam in the company should be produced by industrial boilers. Natural gas is used as a conventional fuel to supply the high and low-pressure steam lines, thus, any of the aforementioned cases (2–4) can be used as an option for the augmentation of the thermal performance. The energy, exergy, economic and environmental analysis (4E) of each case is conducted in this study; and the most beneficial case was selected, taking into account the thermal performance and environmental results.

2.3. Combustion

Although the highest adiabatic flame temperature takes place with a stoichiometrically balanced air:fuel ratio, an amount of excess air is widely used in the industries in order to ensure a 100% fuel combustion. In this case, methane, as fuel, reacts with the 30% excess air in order to undergo complete combustion. The intake air and combustion products are assumed to be ideal gases, and the following chemical reaction occurs in the burners:

$$CH_4 + 2.6(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 9.8N_2 + 0.6O_2 \tag{1}$$

2.4. Energy analysis

An almost perfectly insulated fired heater results in a near zero heat dissipation to its surroundings. It is a steady-state process, with the kinetic and potential energies of the fluid streams neglected. It is also worth noting that there is no work involvement in all of the cases.

First law analysis of case 1

$$(\dot{m}_a h_a)_{case1} + (\dot{m}_f h_f)_{case1} + \dot{m}_{HD}\Delta h_{HD} = (\dot{m}_{st} h_{st})_{case1} \tag{2}$$

First law analysis of case 2

$$(\dot{m}_a h_a)_{case2} + (\dot{m}_f h_f)_{case2} + \dot{m}_{HD}\Delta h_{HD} + \dot{m}_{HS}\Delta h_{HS} = (\dot{m}_{st} h_{st})_{case2} \tag{3}$$

First law analysis of case 3

$$(\dot{m}_a h_a)_{case3} + (\dot{m}_f h_f)_{case3} + \dot{m}_{HD}\Delta h_{HD} + \dot{m}_{HS}\Delta h_{HS} + \dot{m}_{LS}\Delta h_{LS} = (\dot{m}_{st} h_{st})_{case3} \tag{4}$$

Obviously, because of the utilization of an air preheater unit in case 4, the intake and stack properties in cases 3 and 4 differs. Thus, the first law analysis of case 4 will be:

$$(\dot{m}_a h_a)_{case4} + (\dot{m}_f h_f)_{case4} + \dot{m}_{HD}\Delta h_{HD} + \dot{m}_{HS}\Delta h_{HS} + \dot{m}_{LS}\Delta h_{LS} = (\dot{m}_{st} h_{st})_{case4} \tag{5}$$

The right hand side term in first law analysis of each case equals to the heat loss by stack. The formulas were written using the definition of the first law efficiency by Cengel and Michel [18].

First law efficiency of case 1

$$\eta = \frac{\dot{m}_{HD}\Delta h_{HD}}{(\dot{m}_a h_a)_{case1} + (\dot{m}_f h_f)_{case1}} \tag{6}$$

First law efficiency of case 2

$$\eta = \frac{\dot{m}_{HD}\Delta h_{HD} + \dot{m}_{HS}\Delta h_{HS}}{(\dot{m}_a h_a)_{case2} + (\dot{m}_f h_f)_{case2}} \tag{7}$$

First law efficiency of case 3

$$\eta = \frac{\dot{m}_{HD}\Delta h_{HD} + \dot{m}_{HS}\Delta h_{HS} + \dot{m}_{LS}\Delta h_{LS}}{(\dot{m}_a h_a)_{case3} + (\dot{m}_f h_f)_{case3}} \tag{8}$$

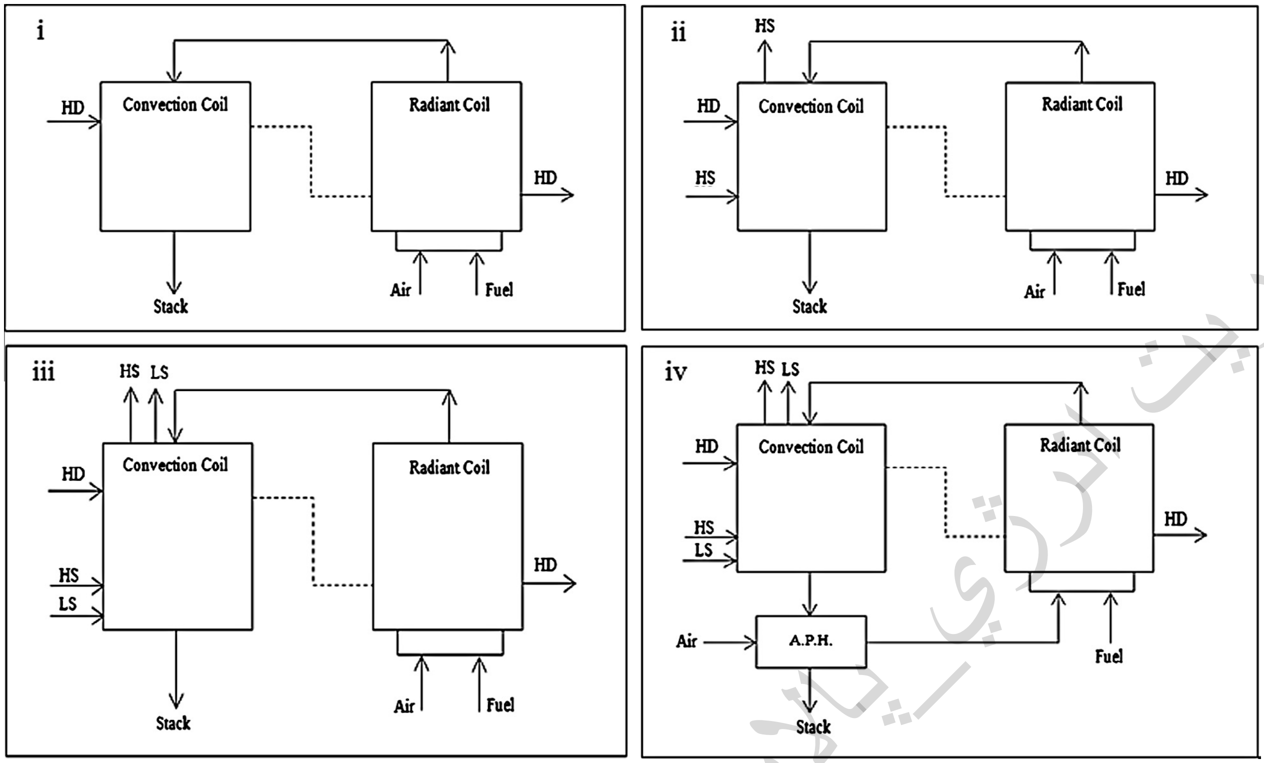

Fig. 1. Schematic diagrams of case 1 (i), case 2 (ii), case 3 (iii), and case 4 (iv).

First law efficiency of case 4

$$\eta = \frac{\dot{m}_{HD}\Delta h_{HD} + \dot{m}_{HS}\Delta h_{HS} + \dot{m}_{LS}\Delta h_{LS}}{(\dot{m}_a h_a)_{case4} + (\dot{m}_f h_f)_{case4}} \tag{9}$$

2.5. Exergy analysis

2.5.1. Chemical exergy

The specific exergy of the hydrocarbon fuels is equal to their chemical exergy, especially when the hydrocarbon is in a similar state to its surroundings [32,33]. The chemical exergy and heating value of the hydrocarbon fuels are proportionally correlated to the fuel exergy grade function, which is assumed to be 0.99 for methane [19,32]:

$$\psi_f = \gamma \times \mathrm{HHV}_f \tag{10}$$

2.5.2. The reference environment

Based on the climate of Abadan, and with some modifications, this analysis uses $T_0 = 25\,°C$ and $P_0 = 100$ kPa as the surrounding temperature and pressure for the reference state, respectively. Water vapor, with saturated air and the following condensed phases at the reference environment are taken as the chemical composition: water (H_2O), limestone ($CaCO_3$) and gypsum ($CaSO_4$) [19,32]. As the intake air in all cases are similar to its environment, its exergy is assumed to be zero.

Second law analysis of case 1

$$(\dot{m}_f\psi_f)_{case1} + \dot{m}_{HD}\Delta\psi_{HD} - (\dot{m}_{st}\psi_{st})_{case1} = \dot{I} \tag{11}$$

$$(\dot{m}_f(\gamma \times \mathrm{HHV}_f))_{case1} + \dot{m}_{HD}(\Delta h_{HD} - T_0\Delta S_{HD}) - (\dot{m}_{st}(h - T_0 S_{st}))_{case1} = \dot{I} \tag{12}$$

Second law analysis of case 2

$$(\dot{m}_f\psi_f)_{case2} + \dot{m}_{HD}\Delta\psi_{HD} + \dot{m}_{HS}\Delta\psi_{HS} - (\dot{m}_{st}\psi_{st})_{case2} = \dot{I} \tag{13}$$

$$(\dot{m}_f(\gamma \times \mathrm{HHV}_f))_{case2} + \dot{m}_{HD}(\Delta h_{HD} - T_0\Delta S_{HD}) + \dot{m}_{HS}(\Delta h_{HS} - T_0\Delta S_{HS}) - (\dot{m}_{st}(h - T_0 S_{st}))_{case2} = \dot{I} \tag{14}$$

Second law analysis of case 3

$$(\dot{m}_f\psi_f)_{case3} + \dot{m}_{HD}\Delta\psi_{HD} + \dot{m}_{HS}\Delta\psi_{HS} + \dot{m}_{LS}\Delta\psi_{LS} - (\dot{m}_{st}\psi_{st})_{case3} = \dot{I} \tag{15}$$

$$(\dot{m}_f(\gamma \times \mathrm{HHV}_f))_{case3} + \dot{m}_{HD}(\Delta h_{HD} - T_0\Delta S_{HD}) + \dot{m}_{HS}(\Delta h_{HS} - T_0\Delta S_{HS}) + \dot{m}_{LS}(\Delta h_{LS} - T_0\Delta S_{LS}) - (\dot{m}_{st}(h - T_0 S_{st}))_{case3} = \dot{I} \tag{16}$$

Second law analysis of case 4

$$(\dot{m}_f\psi_f)_{case4} + \dot{m}_{HD}\Delta\psi_{HD} + \dot{m}_{HS}\Delta\psi_{HS} + \dot{m}_{LS}\Delta\psi_{LS} - (\dot{m}_{st}\psi_{st})_{case4} = \dot{I} \tag{17}$$

$$(\dot{m}_f(\gamma \times \mathrm{HHV}_f))_{case4} + \dot{m}_{HD}(\Delta h_{HD} - T_0\Delta S_{HD}) + \dot{m}_{HS}(\Delta h_{HS} - T_0\Delta S_{HS}) + \dot{m}_{LS}(\Delta h_{LS} - T_0\Delta S_{LS}) - (\dot{m}_{st}(h - T_0 S_{st}))_{case4} = \dot{I} \tag{18}$$

The formulas obey the definition of second law efficiency, where the exergy recovered is higher than the exergy supplied [18].

Second law efficiency of case 1

$$\eta = \frac{\dot{m}_{HD}\Delta\psi_{HD}}{(\dot{m}_f \times \gamma \times \mathrm{HHV}_f)_{case1}} \tag{19}$$

Second law efficiency of case 2

$$\eta = \frac{\dot{m}_{HD}\Delta\psi_{HD} + \dot{m}_{HS}\Delta\psi_{HS}}{(\dot{m}_f \times \gamma \times \mathrm{HHV}_f)_{case2}} \tag{20}$$

Second law efficiency of case 3

$$\eta = \frac{\dot{m}_{HD}\Delta\psi_{HD} + \dot{m}_{HS}\Delta\psi_{HS} + \dot{m}_{LS}\Delta\psi_{LS}}{(\dot{m}_f \times \gamma \times \mathrm{HHV}_f)_{case3}} \tag{21}$$

Second law efficiency of case 4

$$\eta = \frac{\dot{m}_{HD}\Delta\psi_{HD} + \dot{m}_{HS}\Delta\psi_{HS} + \dot{m}_{LS}\Delta\psi_{LS}}{(\dot{m}_f \times \gamma \times \mathrm{HHV}_f)_{case4}} \tag{22}$$

2.6. Efficiency of air preheater unit

The unit is divided into multiple parts that define its respective function and features. The hotter part of the unit is taken as a heat exchanger, while the colder part acts as an absorber that absorbs fresh atmospheric air via a suction fan. The combustion product(s) of this process lies in between these two parts. Neglecting the energy input to the suction fans, the first law of efficiency is defined as the change of energy in the atmospheric airflow, over the change for the combustion products:

$$\eta_{\mathrm{A.P.H}} = \frac{\dot{m}_a \Delta h_a}{(\dot{m}_a + \dot{m}_f) \times (h_{fl} - h_{st})} \tag{23}$$

The flue gas refers to the combustion products that leaves the convection coil, and enters the air of the preheater unit.

2.7. Entropy of stack

The enthalpy of the stack gases in each case is obtained from dividing the heat loss by the summation of air, with the fuel mass flow rates. The stack temperature can be calculated in an iterative solution using the enthalpy of combustion products and Eq. (1). Stack's temperature, and the molar contribution of CO_2, H_2O, N_2 and O_2 in the combustion products can lead to the solving of the entropy of stacks.

2.8. Economic analysis

In this section, the economic analysis of equipping an existing fired heater unit with heat recovery and air-preheating techniques is expressed. It takes into account the total CO_2 emission penalty and energy consumption of both fired heater and industrial boilers to the level of satisfaction of the companies' demand.

2.8.1. Net Present Value (NPV)

As previously mentioned, case 1 forms the basis of this study (studied case). The three other cases (2–4) are recommended in order to decrease the annual energy consumptions, emission production and annual energy costs. The utility water is produced in the refinery companies in order to generate electricity, operate turbine pumps to transfer petroleum products, and adjust processes conditions in atmospheric and vacuum towers. It was assumed that the high and low-pressure steams are required in all of the cases. Obviously, the utility steam water should be produced by an external source (i.e. industrial boilers) if this surplus amount of energy is not recovered from the system. This means that in case 1, if high and low pressure steam lines are required without using the recovered energy from the system, it will inevitably require an increased amount of total energy. The low and high-pressure steams are provided in the refinery via industrial boilers. Therefore, all of the required energy for sustaining a low or high pressure steam lines in different cases is calculated and considered as energy costs in the course of the life span. It is worth mentioning that the maintenance costs for the A.P.H are considered in case 4.

The NPV is used as the economic method to compare the cases. Its calculations are widely used in business and economics to compare cash flows at different times, with this approach utilized here. The NPV can be written as follows for the designated cases:

$$\mathrm{NPV} = \mathrm{CC} + \mathrm{CPW} \times (\mathrm{FC} + \mathrm{EMP}^{\mathrm{CO_2}} + \mathrm{MC}_{case4}) \tag{24}$$

where CC is the capital cost to equip the studied case (case 1) with high pressure steam line for case 2, high and low pressure steam lines for case 3, and high and low pressure steam lines and A.P.H for case 4, while FC is the fuel cost per year for each case (i.e. fired heater's fuel cost in addition to the boilers' fuel cost in cases 1 and 2 to produce high and low pressure steam). In other words, the current costs for case 1 are the fuel consumption associated with heating the hydrocarbon line in the fired heater, and the energy consumption by boilers to produce high and low pressure steam, taking into consideration the typical thermal efficiency of industrial boilers. In case 2, as the high-pressure steam is produced by the fired heater surplus energy, the current costs are the cost of the fired heater's fuel consumption and energy consumption by boilers to produce low-pressure steam. The current costs for both cases 3 and 4 are the fired heaters fuel consumption, and the A.P.H maintenance costs for case 4. The cost of CO_2 penalty for all the four cases is also taken into account as a part of the current costs in each year.

Present Worth Factor (PWF) is the value by which the future cash flow is collected in order to obtain the current present value of the project. The PWF is used to determine the feasibility of the energy efficiency method implementation investment for a given rate of interest. PWF in year i is defined as,

$$\mathrm{PWF} = \frac{1}{(1+r)^i} \tag{25}$$

Summing this over a project life of n years yields the compound present worth factor,

$$\mathrm{CPW} = \sum_{1}^{n} \frac{1}{(1+r)^i} = \frac{(1+r)^n - 1}{r(1+r)^n} \tag{26}$$

The CO_2 penalty can be calculated by the following formula:

$$\mathrm{EMP}^{\mathrm{CO_2}} = (\mathrm{EC}_{\text{Fired Heater}} + \mathrm{EC}_{\text{Boiler}}) \times \mathrm{EF}_{\mathrm{CO_2}} \times \mathrm{EP}_{\mathrm{CO_2}} \tag{27}$$

It needs to be pointed out that as the required streams for a refinery company are assumed to be the same for all cases (i.e. necessity to have high and low pressure steam streams and hydrocarbon line with the same input/output temperatures and mass flow rates), energy analysis indirectly affects the economic analysis. For example, in case 3, although the fuel consumption is similar to cases 1 and 2, as the high and low pressure steam streams are supplied by case 3, the company benefiting from this system is exempted from payment for the fuel consumption by the boilers to produce high and low pressure steam streams. Applying the same line of logic, the CO_2 production penalty for case 3 is significantly lower than this value for case 1, because although the fuel consumption in both cases are considered to be similar, the companies' demand for high and low pressure steam will inevitably lead to the use of industrial boilers in case 1, which increases the consumption of fossil fuels. In summary, the results of energy and environmental analysis are inseparable from the economic analysis.

2.8.2. Payback period

Payback period is defined as the time taken to gain a financial return that is on par with the original investment costs, and is a simple method of evaluating the viability and feasibility of the investment. The payback method uses the ratio of capital cost over annual earning as an approach to monitor the project. The payback period is determined using the following model:

$$\mathrm{PP}_{case2,3,4} = \frac{\mathrm{CC}_{case2,3,4}}{(\mathrm{FC}_{case1} - \mathrm{FC}_{cases2,3,4})} \tag{28}$$

2.8.3. Sensitivity analysis

Sensitivity analysis is an investigation into how the projected performance varies with changes in key assumptions on which the projections are based. It also enables the examination of how the uncertainty, for example in international prices, can alter the outcome of the project. Important variables are interest rate, initial cost to equip the fired heater with the high and low pressure steam lines and air preheater unit, unit energy cost, and CO_2 penalty.

2.9. Emission analysis

Since the carbon emission penalty directly affects the economic calculations, the determination of the amount of CO_2 emission in different cases could be one of the most important steps in developing effectual policies that will eventually solve various problems associated with fired heaters. The estimation of the produced emission determined using emission factors is not necessarily the best option, but forms the only feasible option due to the lack of any continuous emission or frequent stack measurements [34]. Thus, in order to determine the potential environmental impacts of these cases, the CO_2 emission factor of natural gas is taken as 53.9 (kg CO_2/GJ NG) [35]. The amount of the produced CO_2 in each case can be calculated as follows:

$$EM^{CO_2} = (EC_{\text{Fired Heater}} + EC_{\text{Boiler}}) \times EF_{CO_2} \tag{29}$$

2.10. Fuel consumption

The fired heater's fuel consumption in cases 2 and 3 is assumed to be similar to case 1 (studied case), and equal to 1.9 (kg/s), whereas the boilers' fuel consumption to supply the high and low pressure steam is fundamentally different for cases 1 and 2, and were calculated based on the typical thermal efficiency of industrial boilers. The mass flow rate of fuel in case 4 was evaluated to be 1.76 (kg/s), considering the chemical reaction (Eq. (1)), 30% of excess air, energy analysis of case 4 (Eq. (5)) and efficiency of the A.P.H unit (Eq. (23)).

3. Study case and input data

The fired heater of a distillation unit in the Abadan refinery is utilized for the purpose of this study. The Abadan Oil Refinery Company (AORC) is located in Abadan, near the coast of the Persian Gulf. Its nominal capacity is 350,000 barrel per day (BPD), and it uses extra heavy crude oil from Ahwaz Asmari, and heavy exporting crude oil from the central zone and Darkhuoin as its feedstock. The physical/chemical properties of the Iranian crude oil is shown in Table 1 [36].

After preheating and desalting, the crude oil is delivered to the fired heater section, where the fired heaters increases the temperature of the liquid phase of the crude oil from 280 °C, to a mixed phase of liquid/gas, at about 370 °C. The two-phase crude oil is delivered to an atmospheric distillation tower for it to be separated to lighter components.

Table 2
Properties of intake air and entering fuel.

Properties	Fuel in	Intake air
Temperature (K)	298	298
Mass flow rate, $\dot{m}$ (kg/s)	1.9	42.4
Enthalpy, h (kJ/kg)	50,050	298.2

The mass flow rates, temperature and enthalpy of air and fuel related to cases one, two and three are tabulated in Table 2. An increase in the heat transfer area leads to a corresponding increase of both the thermal efficiency of heat exchangers and its capital costs. The conventional materials that are being used to manufacture the air preheaters, which functions under 400 °C, are stainless steel and certain nickel-and iron-based alloys that raises the thermal efficiency of the air preheaters to up to 90%, due in part to their high thermal conductivity. Furthermore, the strength and stability of such materials at this operating temperature and their corrosion resistance is quite high [37]. Assuming a thermal efficiency of 90% for the air preheater unit, and 290 °C for the temperature of preheated air that is leaving the air preheater and entering the burners, and 587 °C for the temperature of the flow gas, which enters the air preheater, the mass flow rate of fuel and air in case 4 was determined to be 1.76 (kg/s) and 39.25 (kg/s), respectively [36,38].

Table 3 shows the properties of the entering hydrocarbon, high and low pressure steam lines, and the output desired for each stream in the company. Additionally, the table shows the difference between enthalpy and entropy in the input and output streams [18].

The economic data collection forms an essential part of this study. The input data were collected from various technical sources, such as the refinery's experts, researchers, and seasoned practitioners in this field, technical notes and research papers, as well as the latest market prices. The data that were used in the economic analysis are tabulated in Table 4.

4. Results and discussion

4.1. Thermal performance

The calculation results of substituting input and survey data into the first and second law equations are tabulated in Table 5. It shows the thermodynamic efficiencies, heat loss and irreversibility of each case, and the results are depicted in Figs. 2 and 3.

Fig. 2 shows the first and second law efficiency values for each case. As discerned from the figure, the first and second law efficiencies increased due to heat recovery and air preheating. Due to the high rate of exergy destruction in every case, the second law efficiency is inevitably lower than its first law counterpart. Potentially, the first and second law efficiencies are capable of increasing from 63.4% and 49.4% in case 1, to 71.7% and 54.8% in case 4, respectively.

Fig. 3 shows the heat loss and irreversibility for each case. The heat loss decreased from 39440.88 kW in case 1, to 28202.65 kW in case 4, indicating irreversibility decrease for both cases. The

Table 1
Supplied crude oil to Abadan Oil Refining Company (AORC).

	Sulfur (wt.%)	Viscosity at 100 °C	Carbon residue of residuum (wt.%)	Gasoline and Naphta (%)	Kerosin distilate (%)	Gasoil (%)	Lubricity (%)	Residuum (%)
Agha Jari	1.43	46	9.1	28.8	10.2	14.6	15.2	28.9
Central area	1.2	40	11.2	32.2	10.8	14.8	16.8	21.5
Gachsaran	1.66	55	15	27.2	8.3	13	15.2	32.1

Table 3
Properties of hydrocarbon, high pressure steam and low pressure steam.

Properties	HD			HS			LS		
	HD_{in}		HD_{out}	HS_{in}		HS_{out}	LS_{in}		LS_{out}
Temperature (°C)	281		370	323		387	165		356
Pressure (kPa)	1510		390	2300		2260	700		650
Mass flow rate $\dot{m}$ (kg/s)		176			7.5			5.3	
Enthalpy, Δh (kJ/kg)		388.0			146.3			415.7	
Entropy, Δs (kJ/kg K)		0.32			0.24			0.82	

Table 4
Summary of economic data and indicators.

Item	Data
Interest rate	15%
Life span	20 years
Unit energy cost [12]	0.07 US$/m^3
Initial cost of adding low pressure steam line	1,000,000 US$
Initial cost of adding high pressure steam line	1,500,000 US$
Capital cost of A.P.H	7,000,000 US$
Thermal efficiency of typical industrial boiler [19]	72.46%
Maintenance cost of A.P.H	200,000 US $/year
CO_2 penalty (EP) [39]	0.09 US$/kg

Table 5
Heat loss, irreversibility and thermodynamic efficiencies in different cases.

	Case 1	Case 2	Case 3	Case 4
Heat loss (kJ/s)	39440.88	38343.78	36140.57	28202.65
Irreversibility (kJ/s)	119738.87	119361.23	119119.62	109889.85
First law efficiency (%)	63.4	64.4	66.4	71.7
Second law efficiency (%)	49.4	49.9	50.7	54.8

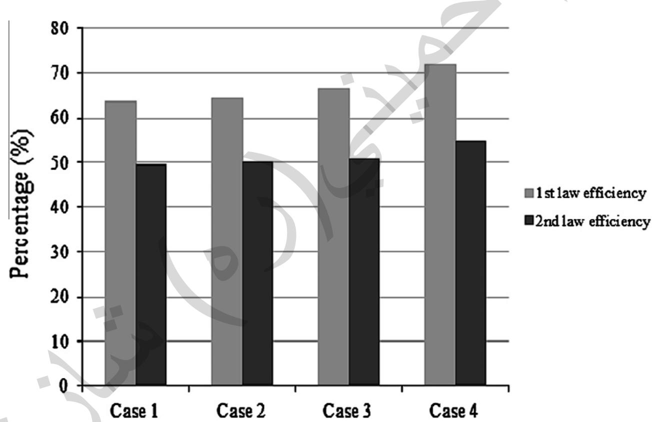

Fig. 2. First and second law efficiency for different cases.

overall exergy destruction was calculated to be 119738.87 kW in case 1, and 109889.85 kW in case 4. Neglecting the overhaul periods, the fired heaters are continuously working during their life cycle, and it is concluded that each decremented heat loss significantly reduce the energy consumption of the unit and consequently, its associated cost. The effect of using an air preheater unit to arrest the heat loss and irreversibility is illustrated in Fig. 3. As

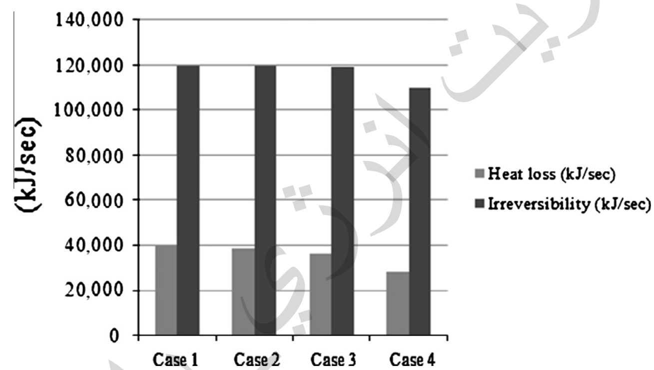

Fig. 3. Heat loss and irreversibility in each case.

the stack gases are hot, the irreversibility is higher than the heat loss in all of the cases.

Moreover, Fig. 4 illustrates the effect of the gradual change in the efficiency of a fired heater. As can be seen, the effect of heat recovery for case 1 to case 2, and for case 2 to case 3 on the first and second law efficiencies are 1%, 0.5% and 2%, 0.9%, respectively, and the effect of air preheating for case 3 to case 4 was raised to 5.3% and 4%, respectively. This proves that the effect of mounting an air preheat unit in order to enhance thermodynamic efficiencies supersedes the heat recovery for the fired heater.

Table 6 shows the temperature, enthalpy and entropy of the stacks in each case. The entropy values of this table were used in the second law analysis, due to heat recovery in cases 2 and 3. Owing to the simultaneous heat recovery and air preheating in case 4, the overall enthalpy of the stack is decreased. Additionally, the heat loss in case 4 are much lower than the other cases, and the stack temperature in this case is also comparatively lower.

To compare the studied case (case 1) with the most efficient fired heater (case 4) from an energy and exergy perspective, the Sankey diagram was used. Figs. 5 and 6 show the energy flow diagram or Sankey diagram for case 1 and case 4, respectively. Fig. 5 shows the energy entering the system via the fuel, air and the hydrocarbon line, and exiting by its stacks and the same hydrocarbon line. For case 4, Fig. 6 shows the energy entering the system via the fuel, air, hydrocarbon line, and high and low pressure steam utility lines, and exiting by its stack, hydrocarbon and the steam lines. Comparing Figs. 5 and 6, the input energy in case 4, through the fuel (88.08 MW), is lower for case 1 (95.1 MW), and due to the higher efficiency in case 4, the heat loss in this case is lower than the one shown in case 1.

Figs. 7 and 8 show the exergy flow diagram (schematic diagram) for cases 1 and 4. This diagram shows the consumption of exergy in various components, or the degradation of the available energy through the system. The difference between the exergy in and out of the hydrocarbon line is 51.5 MW. Comparing Fig. 7 with Fig. 8, the exergy loss by stack would be reduced from 66.8 MW in case 1, to 66.1 MW in case 4.

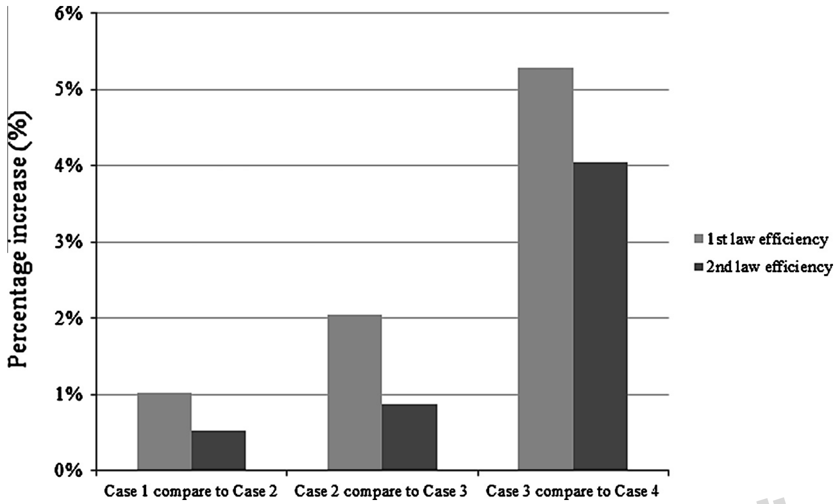

Fig. 4. Heat loss and irreversibility when comparing cases.

Table 6
Stack properties in different cases.

Stack properties	Stack case 1	Stack case 2	Stack case 3	Stack case 4
Temperature (°C)	522	517	497	327
Enthalpy, h (kJ/kg)	890.8	884.6	860.3	658.3
Entropy, s (kJ/kg K)	8.05	8.04	8.01	7.72

4.2. Economic analysis

The economic analysis was carried out using the method described in Section 2.8. The effect of capital costs, energy costs, thermal performance and emission are taken into account in the NPV calculations. The NPV for the four industrial fired heaters were cal-

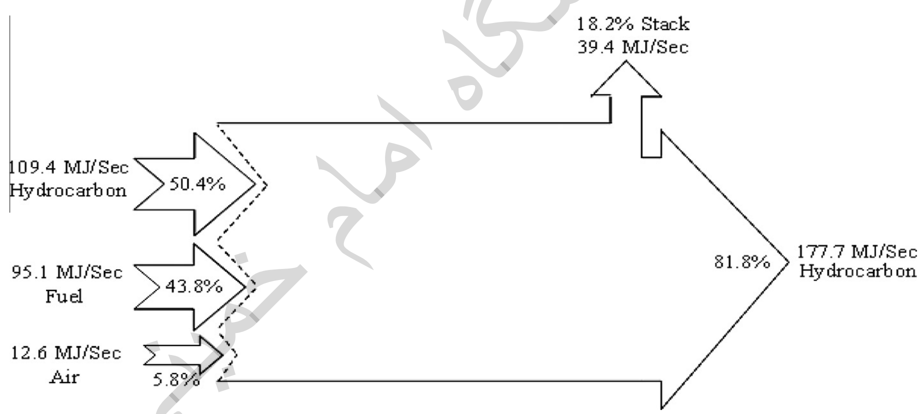

Fig. 5. The Sankey diagram for case 1.

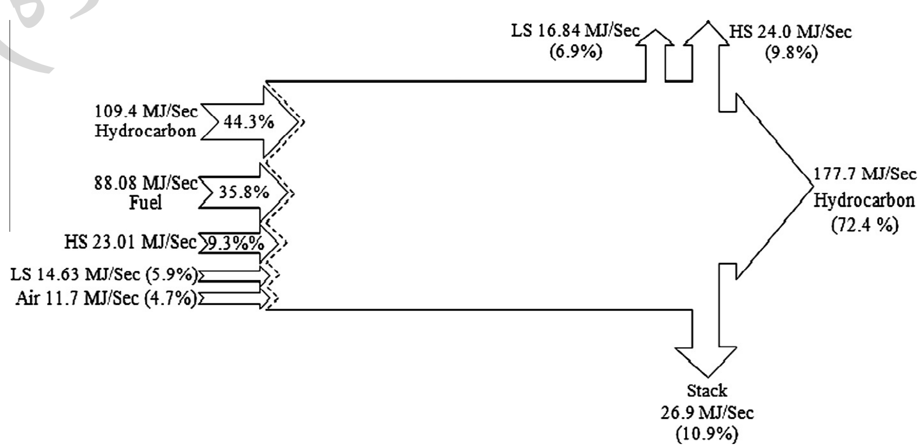

Fig. 6. The Sankey diagram for case 4.

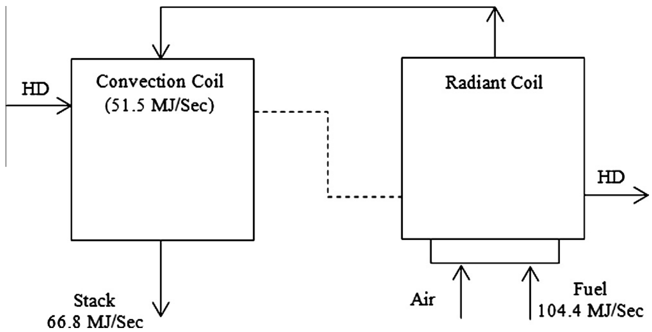

Fig. 7. The schematic diagram for case 1.

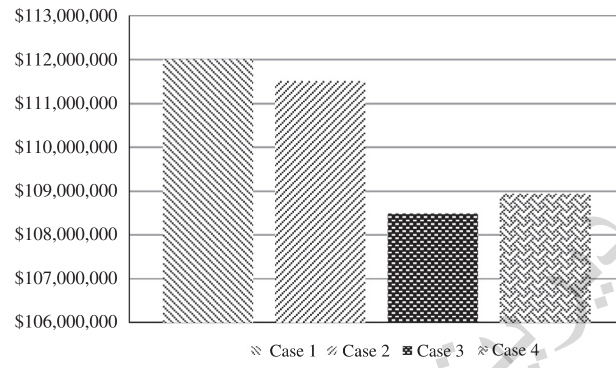

Fig. 9. NPV results in US$.

culated based on the data in Table 4, and illustrated in Fig. 9. It should be emphasized that the company's demand to have 176 (kg/s) hydrocarbon in 370 C, 7.5 (kg/s) high pressure steam in 387 C and 5.3 (kg/s) low pressure steam in 356 C was assumed to be the same in all of the cases. In cases 3 and 4, high and low pressures steam are channeled from the recovered energy of the system, while in case 1 and 2, respectively, the high and low pressure steam lines and low pressure steam line are separately supplied by the industrial boilers. According to the results, as the NPV for case 3 is 108.5 million US$ and lower than the other cases, this particular setting is recommended for refinery companies willing to improve their respective systems. However, the NPV for cases 3 and 4 are analogous to each other, and the difference between the NPVs (US$ 442,221) is associated with the capital and maintenance costs of the proposed air preheater.

The payback period for cases 3 and 4 were found to be 2.6 and 4.7 years, respectively. Being less than one third of the 20-year project life, this result indicates that the projects are economically feasible.

Figs. 10 and 11 present the results of the sensitivity analysis for five input variables. The legend on the left of the figure provides the variation in the sensitivity variable from favorable, to planned, to unfavorable. The figures show that the variation in the interest rate and the cost of CO_2 penalty, respectively, represent the dominant impact on the NPV for both cases. The variation in the cost of incorporating the fired heater with high and low pressure steam lines has the lowest effect on the results of the NPV. As can be gleamed from Fig. 11, the variation in the capital cost of an air preheater unit did not significantly contribute to the NPV calculation results, and therefore, until this cost is in the domain of 1.5–2.5 million dollar, the decision maker can order an air preheater that has the higher thermal performance, longer life span, and lower maintenance cost.

4.3. Emission analysis

The amount of CO_2 emission and the associated penalty for each case were calculated by the methods described in Sections 2.9 and 2.8.1, respectively, with the results tabulated in Table 7. The difference between each two columns shows the amount of the potential emission reduction, as per each case. Hence, it can be summarized that within a year, the possibility of the reduction emission is quite high via the energy recovery method, as well as the air preheating technique. As can be gleamed from the table, cases 1 and 4 are the worst and the best cases in terms of environmental concerns, respectively. Nevertheless, since the effect of the CO_2 penalty has been taken into account in the economic analysis, case 3 is still recommended for the petroleum companies that are willing to augment their respective fired heater systems. It can be interpreted that future infrastructures that are going to be established by the CO_2 penalty in case 3 are more useful than incorporating the baseline system with an A.P.H unit for the environment.

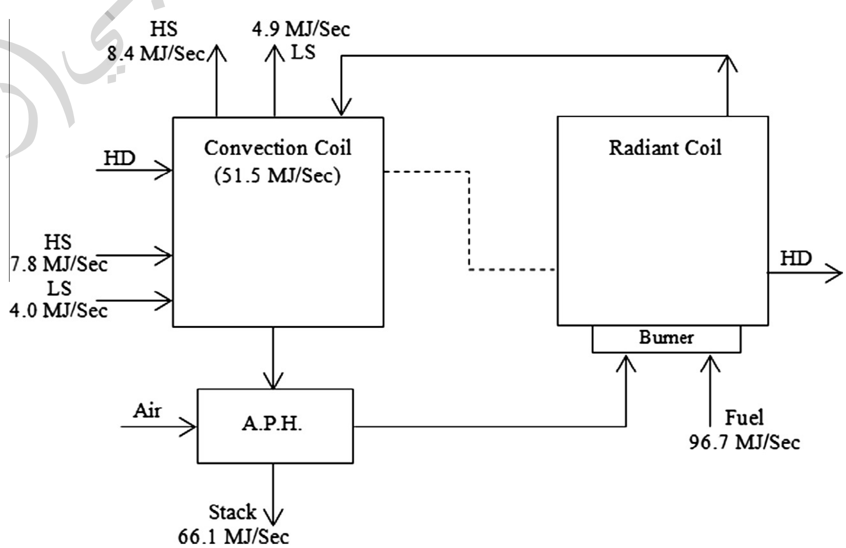

Fig. 8. The schematic diagram for case 4.

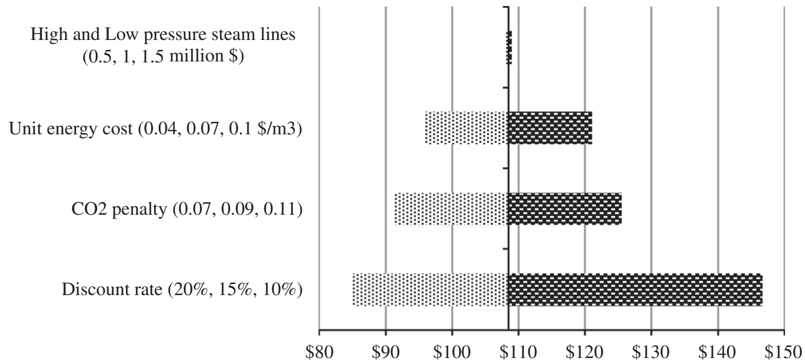

Fig. 10. Sensitivity analysis of NPV for case 3 ($ million).

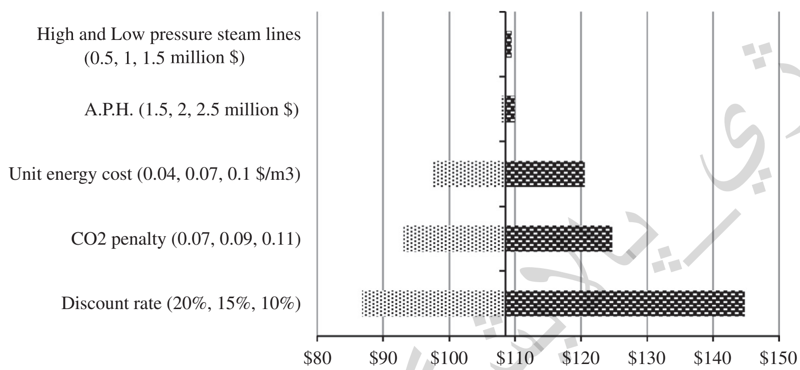

Fig. 11. Sensitivity analysis of NPV for case 4 ($ million).

Table 7
CO_2 emission per year for cases.

Case number	Case 1	Case 2	Case 3	Case 4
CO_2 (kg/year)	144,102,938	141,529,325	136,360,963	126,313,313
CO_2 penalty (US$/year)	12,969,264	12,737,639	12,272,487	11,368,198

5. Conclusions

This study investigated the economic feasibility of applying a heat recovery and air-preheating method(s) in existing fired-heater units. In this regard, three industrial fired heaters, equipped with high and low pressure steam streams, and the air preheater units were studied from the energy and environmental standpoints. Furthermore, in order to indicate the irreversibility rate of the systems, an exergy analysis was conducted as well.

The results showed that large amounts of energy input to the studied case is wasted via high temperature stacking. The utilization of this surplus energy can raise the overall efficiency of the unit. Heat recovery from the high quality energy wasted by stacking can increase the thermal and exergy efficiency of the system to 66.4% and 50.7%, respectively. Moreover, preheating of the intake air to the fired heater equipped with water steam lines can increase the efficiency of the first and second law to 71.7% and 54.7%, respectively. Additionally, the fuel consumption of the fired heater can be reduced to up to 7.4% in this case.

The Net Present Value (NPV) is selected for the purpose of economic analysis. Current costs were considered to be composed of direct (i.e. fuel costs and maintenance costs) and indirect costs, such as CO_2 penalty and the cost of production of high and low pressure steam in cases 1 and 2 with industrial boilers. The economical analysis showed that the most thermal efficient system (case 4) is not necessary the most economical system, and the initial cost to enhance the existing system with an air preheater unit will not be economically justifiable. Case 3 was recognized as the most economically favorable case, with an NPV of 108.5 million US$ during the project's lifetime. It is also worth pointing out that this value is quite close to the NPV of case 4, with 108.9 million US$. The results of sensitivity analysis for cases 3 and 4 proves that the NPV is highly susceptible to the interest rates and CO_2 penalty costs, and less sensitive with respect to high and low pressure steam lines and the capital cost of the air preheater unit.

Acknowledgements

The authors would like to acknowledge the Ministry of Higher Education of Malaysia and The University of Malaya, Kuala Lumpur, Malaysia for the financial support under UM.C/HIR/MOHE/ENG/21 (D000021-16001). Besides, grateful thanks for technical and economic consultation go to engineer Mehrdad Zarifi, Bandar Abbas Oil Refinery Company.

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