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Effect of reference state on exergy efficiencies of one- and two-stage crude oil distillation plants

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Abstract

In this paper we deal with the effects of varying reference temperature on the exergy efficiencies of one- and two-stage crude oil distillation units. Such units essentially consist of the crude oil heating furnace, the distillation column and a network of heat exchangers. Since the exergy efficiency is a key parameter to see how well the system is performing, we undertake a study on the influence of the reference temperature on such efficiencies. In this regard, a commercial software package, SimSci/PRO II program is used for the calculations. The results show that increasing reference temperature decreases the exergy efficiency in both one- and two-stage crude oil distillation systems and also increases the difference between the exergy efficiencies of both systems. Therefore, the exergy losses increase in the crude oil distillation systems.

Keywords: Thermodynamics; Exergy efficiency; Reference state; Crude oil distillation plant

1. Introduction

Crude oil has low value in its original state and has no practical value. Even after separation of gas, water, H_2S and other components, crude oil is still a mixture of thousands of hydrocarbons ranging from very light to very heavy components. Therefore, refinery plants are used to produce the desired final useful products, e.g., liquefied petroleum gas (LPG), kerosene, diesel, gasoline, jet fuels, asphalt, etc. from the crude oil which goes through successive chemical and physical processes. The crude oil distillation is the first step which is purely physical to separate the crude oil into different fractions depending on the difference of boiling temperatures. In most distillation plants, the crude oil is processed into two towers. The first is the atmospheric tower where light hydrocarbons are separated, and the second is the vacuum tower where heavier hydrocarbons are separated. The products of the crude oil distillation plant can be either final products or feedstock to other plants for further processing. Fig. 1(a) and (b) show schematic diagrams of a one-stage and a two-stage crude oil distillation plants. Details of these plants are given in the simulation section of Ref. [1].

The crude oil distillation plant has many components of interest to be analyzed thermodynamically from both energy and exergy point of views. Such components are the crude oil heat furnace, the distillation towers and the heat exchangers network. The main aim of such an analysis is to make the system more efficient in a way to maximize the yield of the desired products. In this regard, exergy analysis appears to be (i) an effective method using the conservation of mass and conservation of energy principles together with the second law of thermodynamics for the design and analysis of energy systems, (ii) a suitable technique for furthering the goal of more efficient energy-resource use and for determining the locations, types, and true magnitudes of wastes and losses, and (iii) an efficient technique revealing whether or not and by how much it is possible to design more efficient energy systems by reducing the inefficiencies in the systems. Due to such advantages exergy analysis has

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Nomenclature

C_p	specific heat	$\mathrm{kJ\cdot kg^{-1}\cdot K^{-1}}$
E	total energy	kJ
$\bar{h}$	specific molal enthalpy	$\mathrm{kJ\cdot kmol^{-1}}$
$\bar{h}^\circ$	specific molal enthalpy evaluated at the restricted dead state	$\mathrm{kJ\cdot kmol^{-1}}$
$\dot{I}$	irreversibility or exergy losses	MW
$\dot{m}$	mass flow rate	$\mathrm{kg\cdot s^{-1}}$
$\dot{N}$	molal flow rate	$\mathrm{kmol\cdot s^{-1}}$
P	pressure	kPa
$\dot{Q}$	heat transfer rate	MW
S	total entropy	$\mathrm{MW\cdot K^{-1}}$
$\bar{s}$	specific molal entropy	$\mathrm{kJ\cdot kmol^{-1}\cdot K^{-1}}$
$\bar{s}^\circ$	specific molal entropy evaluated at the restricted dead state	$\mathrm{kJ\cdot kmol^{-1}\cdot K^{-1}}$
T	temperature	K
t	time	s
V	volume	$\mathrm{m^3}$
$\dot{W}$	work	MW
Ξ	exergy	kJ
$\dot{\Xi}$	exergy rate	MW
ε	specific exergy	$\mathrm{kJ\cdot kg^{-1}}$
μ	chemical potential	$\mathrm{kJ\cdot kg^{-1}}$
Ψ	exergy efficiency	

Subscripts

ch	chemical
cv	control volume
E1	crude heating furnace 1
E2	crude heating furnace 2
e	exit
i	inlet
ph	physical
T1	distillation unit 1
T2	distillation unit 2
0	ambient (dead state) properties
1–10	state points

Superscript

rev	reversible process

received great attention by many researchers for various applications.

As summarized in Al-Muslim et al. [1], limited studies have been undertaken by various researchers, e.g., [2–6] to conduct energy and exergy analyses of single- and multi-stage oil distillation plants and their components. In a more recent study, Al-Muslim et al. [1] have conducted an energy and exergy analysis to determine location, type and true magnitude of exergy losses in a one-stage and a two-stage crude oil distillation unit composed of a heating furnace and atmospheric distillation column and to study their energy and exergy efficiencies. In this present study, the authors go one step ahead to study the effect of reference temperature (varying from 15 to 40 °C) on the exergy efficiencies and exergy losses in one- and two-stage crude oil distillation plants and further investigate how exergy efficiency and exergy losses vary with the reference temperature. In this respect, SimSci/PRO II program [7] is employed to do the parametric study.

2. Model simulation

In the simulation, SimSci/PROII software is employed for two cases, namely one-stage and two-stage distillation systems to study the effect of varying reference temperature on the exergy efficiencies of both distillation systems. The program has the flexibility to model refinery processes in detail. Its modeling capabilities address a wide range of applications from crude oil characterization and preheating to complex reaction and separation units.

Case 1: One-stage distillation unit

Fig. 1(a) shows a schematic of the one-stage distillation system and its components. The model consists of a crude heating furnace (E1) and an atmospheric distillation column (T1). In our model, we will assume a crude oil flow of 420 $\mathrm{kg\cdot s^{-1}}$. The crude oil is heated in this furnace by burning the fuel. The crude oil starts vaporizing as heat input increases. Typical outlet temperature values are 350 °C. The crude oil is directly supplied from storage tanks at atmospheric temperature 25 °C. We approximate the heating furnace by a heat exchanger whose cold side fluid is crude oil and hot side fluid is air, which enters at 1100 °C. The mass flow rate of air is determined by energy balance of the heat exchanger noting that rate of heat transfer to the crude oil is known and assuming that the air outlet temperature is 20–50 °C higher than the outlet temperature of the crude oil. Air is used because its properties are close to the properties of the exhaust of combustion gases. The 27-tray atmospheric distillation column operates at atmospheric pressure. The crude oil is introduced in tray number 23. The side-cut trays are number 27 for residue, number 17 for heavy gas oil, number 13 for light gas oil, number 8 for kerosene, number 4 for heavy naphtha and number 1 for overhead vapors. In the model, 10 state points are assumed for the heat exchanger and the distillation column. Important parameters for our study are composition of crude oil and temperature, pressure and flow rates as inputs. By defining those parameters, we can find enthalpy and entropy to carry out our thermodynamic analysis. Table 1 gives the composition and properties of the crude oil while Table 2 summarizes the parameters used to simulate this case.

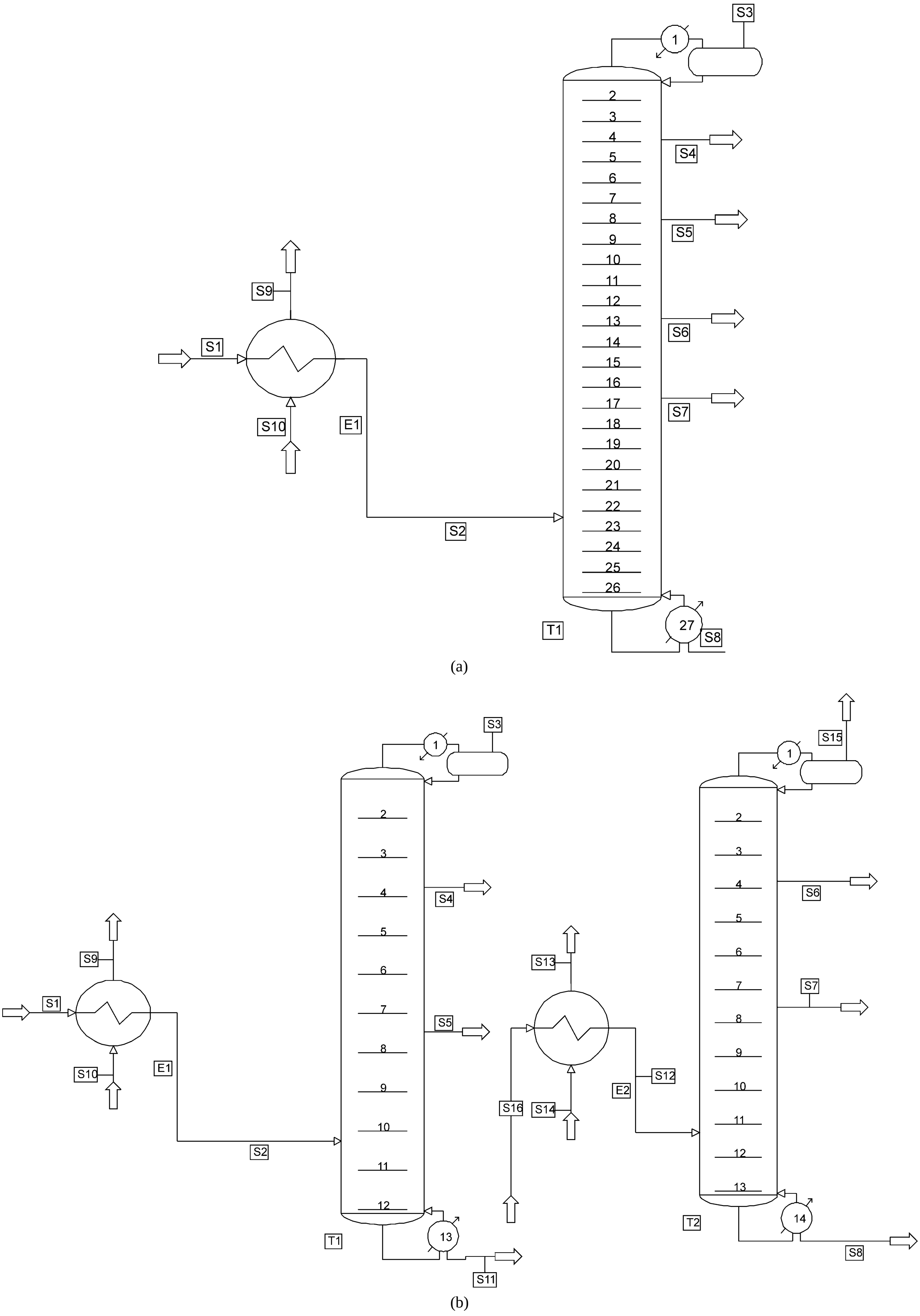

Fig. 1. (a) Schematic of single-stage distillation unit (case 1). (b) Schematic of two-stage distillation unit (case 2).

Table 1
Composition and properties of crude oil

No.	Substance	Weight %	Boiling temp. [°C]	Molecular weight [kg·kmol^{-1}]	Density [kg·m^{-3}]
1	LPG (Butane+)	2	40	52	500
2	Naphtas	20	190	114	750
3	Kerosene	20	220	170	800
4	Light gas oil	15	270	254	850
5	Heavy gas oil	23	320	310	900
6	Residue	20	360	426	950

Table 2
Parameter presentation for case 1

State	Substance	Phase	Temp. [°C]	Press. [kPa]	Flow [kg·s^{-1}]
1	Crude oil	Liquid	25	101	420
2	Crude oil	*	350	101	420
3	Butane+	Vapor/gas	130**	102**	8.4
4	Heavy naphtha	Liquid	190**	103**	84
5	Kerosene	Liquid	220**	104**	84
6	Light oil	Liquid	270**	106**	63
7	Heavy oil	Liquid	320**	108**	96.6
8	Residue	Liquid	350**	110**	84
9	Air	Gas	400**	101	*
10	Air	Gas	1100	101	*

* To be calculated by program.
** Initial guess. Exact values to be calculated by program.

Table 3
Parameter presentation for case 2

State	Substance	Phase	Temp. [°C]	Press. [kPa]	Flow [kg·s^{-1}]
1	Crude oil	Liquid	25	101	420
2	Crude oil	*	250	101	420
3	Butane+	Vapor/gas	130**	102**	8.4
4	Heavy naphtha	Liquid	190**	103**	84
5	Kerosene	Liquid	220**	104**	84
6	Light oil	Liquid	270**	102**	63
7	Heavy oil	Liquid	320**	104**	96.6
8	Residue	Liquid	350**	106**	84
9	Air	Gas	300**	101	*
10	Air	Gas	1100	101	*
11	Residue T1	Liquid	250	104**	*
12	Residue T1	*	350	104**	*
13	Air	Gas	400**	101	*
14	Air	Gas	1100	101	*

* To be calculated by program.
** Initial guess. Exact values to be calculated by program.

Case 2: Two-stage distillation unit

Fig. 1(b) shows a schematic of the two-stage distillation system and its components. The model consists of a crude heating furnace (E1), a first stage distillation column (T1), another crude heating furnace (E2) and a second stage distillation column (T2). As in Case 1, we assume a crude oil flow of 420 kg·s^{-1}. The outlet temperature values of E1 in this case are assumed to be 250 °C since we have only partial distillation at T1. Only vapor, heavy naphtha and kerosene are distilled in the first stage while the other components will leave from the bottom as residues. Therefore, less number of trays are needed here and assumed to be having 13 trays. The crude is introduced in tray number 12. The side cut trays are number 13 for residue, number 8 for kerosene, number 4 for heavy naphtha and number 1 for overhead vapors. The residue from T1 is charged into E2 at 250 °C. The outlet temperature is assumed to be 350 °C. Light gas oil and heavy gas oil will be distilled in the second stage column T2 leaving a residue at the bottom. Again, less number of trays are needed here and assumed to equal 14 trays. The re-heated residue is introduced in tray number 12. The side-cut trays are number 14 for residue, number 8 for heavy gas oil and number 4 for light gas oil. In this case, 14 state points are assumed for the two heat exchangers and the two distillation columns. Those parameters are presented in Table 3.

3. Exergy analysis

Exergy analysis is a methodology for the evaluation of the performance of devices and processes, and involves examining the exergy at different points in a series of energy conversion steps. With this information, efficiencies which are a measure of an approach to the ideal can be evaluated, and the process steps having the largest losses (i.e., the greatest margin for improvement) can be identified. Exergy is defined as the maximum work which could be produced by a stream or system in a specified environment, or with respect to a reference state. Although the basic concepts related to exergy analysis were formulated around the mid-to-late 1800 s, most developments in the area of practical application have occurred during the past few decades, e.g., [8–14]. At present, exergy analysis is gaining widespread acceptance in many areas of research. During the last decade, many researchers, e.g., [15–20] have recommended that exergy analysis be used to aid decision making regarding the allocation of resources (capital, research and development effort, optimization, life cycle analysis, materials, etc.) in place of or in addition to energy analysis.

Exergy is a measure of the maximum capacity of a system to perform useful work as it proceeds to a specified final state in equilibrium with its surroundings. The available work that can be extracted from an energy source depends on the state of the source's surroundings. The greater the difference between the energy source and its surroundings, the greater is the capacity to extract work from the system [21].

Some energy and exergy values are dependent on the intensive properties of the dead state. Consequently the results of energy and exergy analyses generally are sensitive to variations in these properties. Before energy and exergy analyses can be applied with confidence to engineering systems, the significance of the sensitivities of energy- and exergy-analysis results to reasonable variations in dead-state properties must be assessed. Only very brief discussions of these sensitivities have been reported. For example, Wepfer and Gaggioli [22] have pointed out that exergy analyses of chemical plants are often relatively insensitive to variations in T_0 and P_0. Many have assumed that small and reasonable changes in reference-state properties have little effect on the performance of a given system. To the best of the authors' knowledge, the only study on the examination of reference state properties and their sensitivities has been undertaken by Rosen and Dincer [21]. The authors believe that one requirement for continued acceptance of exergy analysis is that the effects on the results of exergy analyses of variations in reference-state properties be fully examined and understood. In this regard, the research area of crude oil distillation needs an extensive research effort.

Recall that the exergy of a system is maximum amount of work that can be obtained from a system. In order to quantify the exergy of a system, we must specify both the system and the surroundings. The *exergy reference environment* is used to standardize the quantification of exergy. The exergy reference environment or simply the environment is assumed to be a large, simple compressible system. The temperature of the environment is assumed to be uniform at T_0, and the pressure is assumed to be uniform at P_0. Also, it is assumed that the intensive properties of the environment are not significantly changed by any process.

The reference state is normally selected to be as similar to the accessible natural environment as possible. Usually P_0 and T_0 are selected to be 101 kPa and 273.15 K, and the chemical composition is taken to be '1.0'. In this paper, we select the reference temperature ranging $288.15 \leqslant T_0 \leqslant 313.15$ K in order to reflect the practical conditions.

There are three governing equations that are normally used in energy-exergy analysis of open systems. These are conservation of mass equation, conservation of energy equation, and entropy generation equation [18–20]. We will use these equations to our steady-state steady-flow conditions for the case of negligible changes in kinetic and potential energy. For every individual component, the three conservation equations; are applied to calculate the heat added, the rate of exergy losses, and the exergy efficiencies. After simplifications, the mass, energy, and exergy balance equations, respectively, are

$$\sum_i \dot{m}_i = \sum_e \dot{m}_e \tag{1}$$

$$\sum_i \dot{E}_i + \dot{Q}_{\mathrm{cv}} = \sum_e \dot{E}_e + \dot{W}_{\mathrm{cv}} \tag{2}$$

$$\sum_i \dot{\Xi}_i + \sum_j (1 - T_0/T_j)\dot{Q}_{\mathrm{cv}} = \sum_e \dot{\Xi}_e + \dot{W}_{\mathrm{cv}} + \dot{I}_{\mathrm{cv}} \tag{3}$$

where the exergy losses from a control volume and total exergy is expressed, respectively, as

$$\begin{aligned}\dot{I}_{\mathrm{cv}} &= \dot{W}_{\mathrm{cv}}^{\mathrm{rev}} - \dot{W}_{\mathrm{cv}} \\ &= \sum_i \dot{\Xi}_i + \sum_j (1 - T_0/T_j)\dot{Q}_{\mathrm{cv}} - \sum_e \dot{\Xi}_e - \dot{W}_{\mathrm{cv}}\end{aligned} \tag{4}$$

$$\dot{\Xi} = \dot{N}\left[\left(\bar{h} - \bar{h}^*\right) - T_0\left(\bar{s} - \bar{s}^*\right) + \sum_i \left(\mu_i^* - \mu_{0,i}\right)x_i\right] \tag{5}$$

or the rate of total flow exergy is given by

$$\dot{\Xi} = \dot{\Xi}_{\mathrm{ph}} + \dot{\Xi}_{\mathrm{ch}} \tag{6}$$

where the rate of physical exergy, $\dot{\Xi}_{\mathrm{ph}} = \dot{N}e_{\mathrm{ph}} = \dot{N}[(\bar{h} - \bar{h}^*) - T_0(\bar{s} - \bar{s}^*)]$, while the rate of chemical exergy, $\dot{\Xi}_{\mathrm{ch}} = \dot{N}[\sum_i (\mu_i^* - \mu_{0,i})x_i]$, and the chemical potential, $\mu_{0,i} = h_{0,i} - T_0 s_{0,i}$. It is important to note that the word "total" reminds us that the flow stream is brought to thermal, mechanical, and chemical equilibrium with the environment. Introducing the exergy efficiency as

$$\Psi = \sum_e \dot{\Xi}_e \Big/ \sum_i \dot{\Xi}_i \tag{7}$$

Case 1: *Crude heating furnace (E1)*: The exergy losses in the heater can be found by exergy equation (3) and noting that no chemical exergy change will be noticed in the heater, in view of the fact that chemical composition of crude is expected to remain unaffected during this process. This gives

$$\dot{I}_{\mathrm{E1}} = \dot{m}_1(\varepsilon_1 - \varepsilon_2) + \dot{m}_9(\varepsilon_{10} - \varepsilon_9) \tag{8}$$

On using Eq. (7), the exergy efficiency is written as

$$\Psi_{\mathrm{E1}} = \left(\sum_i \dot{\Xi}_i - \dot{I}_{\mathrm{E1}}\right) \Big/ \sum_i \dot{\Xi}_i \tag{9}$$

where exergy input for the crude heating furnace is

$$\sum_i \dot{\Xi}_i = \dot{m}_1\varepsilon_1 + \dot{m}_9\varepsilon_{10} \tag{10}$$

and the required hot air mass flow rate $\dot{m}_9$ is expressed in terms of crude flow rate and inlet and exit enthalpies of the heater,

$$\dot{m}_9 = \dot{m}_{10} = \dot{m}_1 \frac{(h_2 - h_1)}{(h_{10} - h_9)} \tag{11}$$

Case 1: *Atmospheric distillation unit (T1)*: The heat transfer rate from the distillation column is obtained by using Eq. (2). This gives

$$\dot{Q}_{\mathrm{T1}} = \sum_{\mathrm{exit}} \dot{m}_{\mathrm{exit}} h_{\mathrm{exit}} - \sum_{\mathrm{inlet}} \dot{m}_{\mathrm{inlet}} h_{\mathrm{inlet}} \tag{12}$$

where "exit" refer to states 3, 4, 5, 6, 7, and 8, while "in" to state 2 (refer to Fig. 1(a)) in the above equation as well as the equations given below. On using exergy Eqs. (3) and (6), we get physical and chemical exergy losses, respectively, as

$$\dot{I}_{\mathrm{T1,ph}} = \sum_{\mathrm{inlet}} \dot{m}_{\mathrm{inlet}}\varepsilon_{\mathrm{inlet,ph}} - \sum_{\mathrm{exit}} \dot{m}_{\mathrm{exit}}\varepsilon_{\mathrm{exit,ph}} + (1 - T_0/T)\dot{Q}_{\mathrm{T1}} \tag{13}$$

$$\dot{I}_{\mathrm{T1,ch}} = \sum_{\mathrm{inlet}} \dot{m}_{\mathrm{inlet}}\varepsilon_{\mathrm{inlet,ch}} - \sum_{\mathrm{exit}} \dot{m}_{\mathrm{exit}}\varepsilon_{\mathrm{exit,ch}} \tag{14}$$

and the total exergy loss is

$$\dot{I}_{\mathrm{T1}} = \dot{I}_{\mathrm{T1,ph}} + \dot{I}_{\mathrm{T1,ch}} \tag{15}$$

On using Eq. (7) we get the exergy efficiency as

$$\Psi_{\mathrm{T1}} = \left[\sum_i \dot{\Xi}_i + (1 - T_0/T)\dot{Q}_{\mathrm{T1}} - \dot{I}_{\mathrm{T1}}\right] \Big/ \sum_i \dot{\Xi}_i \tag{16}$$

Case 1: *Overall exergy efficiency*: Taking the whole unit as a control volume, we notice that heat transfer occurs at T1. Also, the overall exergy losses will be equal to the summation of the exergy losses of the individual components. This gives (refer to Eq. (7)) as

$$\Psi_{\mathrm{overall}} = \left[\sum_i \dot{\Xi}_i + (1 - T_0/T)\dot{Q}_{\mathrm{T1}} - \dot{I}_{\mathrm{overal}}\right] \Big/ \sum_i \dot{\Xi}_i \tag{17}$$

Noting that exergy input is at state 1 and 10, this gives

$$\sum_i \Xi_i = \dot{m}_1\varepsilon_1 + \dot{m}_{10}\varepsilon_{10} \tag{18}$$

$$\dot{I}_{\mathrm{overall}} = \dot{I}_{\mathrm{E1}} + \dot{I}_{\mathrm{T1}} \tag{19}$$

Case 2: *Crude heating furnace* 1 *(E1)*: The exergy losses in the heater can be found by Eq. (3) and noting that no chemical exergy change will be noticed in the heater, due to the fact that chemical composition of crude is expected to remain unaffected during this process. This gives

$$\dot{I}_{\mathrm{E1}} = \dot{m}_1(\varepsilon_1 - \varepsilon_2) + \dot{m}_9(\varepsilon_{10} - \varepsilon_9) \tag{20}$$

and exergy efficiency is given by

$$\Psi_{\mathrm{E1}} = \left(\sum_i \dot{\Xi}_i - \dot{I}_{\mathrm{E1}}\right) \Big/ \sum_i \dot{\Xi}_i \tag{21}$$

where the exergy input for the crude heating furnace is at states 1 and 10, given by

$$\sum_i \dot{\Xi}_i = \dot{m}_1\varepsilon_1 + \dot{m}_{10}\varepsilon_{10} \tag{22}$$

and the mass flow of the rate air is given by Eq. (11).

Case 2: *First stage distillation unit (T1)*: The heat transfer rate from the distillation column is obtained by using Eq. (2). This results in

$$\dot{Q}_{\mathrm{T1}} = \sum_{\mathrm{exit}} \dot{m}_{\mathrm{exit}} h_{\mathrm{exit}} - \sum_{\mathrm{inlet}} \dot{m}_{\mathrm{inlet}} h_{\mathrm{inlet}} \tag{23}$$

where “exit” refer to states 3, 4, 5, and 11, while “in” to state 2 (refer to Fig. 1(b)) in the above equation as well as the equations given below. On using exergy Eqs. (3) and (6), we get physical and chemical exergy losses, respectively, as

$$\dot{I}_{\mathrm{T1,ph}} = \sum_{\mathrm{inlet}} \dot{m}_{\mathrm{inlet}}\varepsilon_{\mathrm{inlet,ph}} - \sum_{\mathrm{exit}} \dot{m}_{\mathrm{exit}}\varepsilon_{\mathrm{exit,ph}} + (1 - T_0/T)\dot{Q}_{\mathrm{T1}} \tag{24}$$

$$\dot{I}_{\mathrm{T1,ch}} = \sum_{\mathrm{inlet}} \dot{m}_{\mathrm{inlet}}\varepsilon_{\mathrm{inlet,ch}} - \sum_{\mathrm{exit}} \dot{m}_{\mathrm{exit}}\varepsilon_{\mathrm{exit,ch}} \tag{25}$$

and the total exergy loss is given by

$$\dot{I}_{\mathrm{T1}} = \dot{I}_{\mathrm{T1,ph}} + \dot{I}_{\mathrm{T1,ch}} \tag{26}$$

while the exergy efficiency is obtained by Eq. (7) to give

$$\Psi_{\mathrm{T1}} = \left[\sum_i \dot{\Xi}_i + (1 - T_0/T)\dot{Q}_{\mathrm{T1}} - \dot{I}_{\mathrm{T1}}\right] \Big/ \sum_i \dot{\Xi}_i \tag{27}$$

Case 2: *Crude heating furnace* 2 *(E2)*: The exergy losses in the heater are obtained from Eq. (3) and noting that there is no chemical exergy change in the heater, as discussed earlier in the case of heating furnace 1. This gives the exergy efficiency as

$$\Psi_{\mathrm{E2}} = \left(\sum_i \dot{\Xi}_i - \dot{I}_{\mathrm{E2}}\right) \Big/ \sum_i \dot{\Xi}_i \tag{28}$$

where the exergy input for the crude heating furnace 2 (E2) and exergy losses for this furnace, respectively, are

$$\sum_i \dot{\Xi}_i = \dot{m}_{11}\varepsilon_{11} + \dot{m}_{14}h_{13} \tag{29}$$

$$\dot{I}_{\mathrm{E2}} = \dot{m}_{11}(\varepsilon_{11} - \varepsilon_{12}) + \dot{m}_{14}(\varepsilon_{14} - \varepsilon_{13}) \tag{30}$$

and the required mass flow rate of air for heating the crude in furnace 2 (E2) is given by

$$\dot{m}_{13} = \dot{m}_{14} = \dot{m}_1\frac{(h_{12} - h_{11})}{(h_{14} - h_{13})} \tag{31}$$

Case 2: *Second stage distillation unit (T2)*: On applying Eq. (2), the heat transfer rate from the distillation column is given by

$$\dot{Q}_{\mathrm{T2}} = \sum_{\mathrm{exit}} \dot{m}_{\mathrm{exit}} h_{\mathrm{exit}} - \sum_{\mathrm{inlet}} \dot{m}_{\mathrm{inlet}} h_{\mathrm{inlet}} \tag{32}$$

where “exit” refer to states 6, 7, and 8, while “in” to state 12 (refer to Fig. 1(b)) in the above equation as well as the equations given below. On using exergy Eqs. (3) and (6), we get physical and chemical exergy losses, respectively, as

$$\dot{I}_{\mathrm{T2,ph}} = \sum_{\mathrm{inlet}} \dot{m}_{\mathrm{inlet}}\varepsilon_{\mathrm{inlet,ph}} - \sum_{\mathrm{exit}} \dot{m}_{\mathrm{exit}}\varepsilon_{\mathrm{exit,ph}} + (1 - T_0/T)\dot{Q}_{\mathrm{T2}} \tag{33}$$

$$\dot{I}_{\mathrm{T2,ch}} = \sum_{\mathrm{inlet}} \dot{m}_{\mathrm{inlet}}\varepsilon_{\mathrm{inlet,ch}} - \sum_{\mathrm{exit}} \dot{m}_{\mathrm{exit}}\varepsilon_{\mathrm{exit,ch}} \tag{34}$$

and the total irreversible losses are given by

$$\dot{I}_{\mathrm{T2}} = \dot{I}_{\mathrm{T2,ph}} + \dot{I}_{\mathrm{T2,ch}} \tag{35}$$

while the exergy efficiency, similar to Eq. (27) is given by

$$\Psi_{T2} = \left[\sum_i \dot{\Xi}_i + (1 - T_0/T)\dot{Q}_{T2} - \dot{I}_{T2}\right] \Big/ \sum_i \dot{\Xi}_i \tag{36}$$

Case 2: *Overall exergy efficiency*: Taking the whole unit as a control volume, we notice that heat transfer occurs at T1 and T2; and the fact that the overall exergy losses will be equal to the summation of the exergy losses of the individual components. This gives (refer to Eq. (7)) as

$$\Psi_{\text{overall}} = \left[\sum_i \dot{\Xi}_i + (1 - T_0/T)\dot{Q}_{T1} + (1 - T_0/T)\dot{Q}_{T2} - \dot{I}_{\text{overall}}\right] \Big/ \sum_i \dot{\Xi}_i \tag{37}$$

Noting that exergy input is at states 1, 10, 11, and 14, we get the exergy input and overall exergy losses as

$$\sum_i \Xi_i = \dot{m}_1\varepsilon_1 + \dot{m}_{10}\varepsilon_{10} + \dot{m}_{11}\varepsilon_{11} + \dot{m}_{14}\varepsilon_{14} \tag{38}$$

$$\dot{I}_{\text{overall}} = \dot{I}_{E1} + \dot{I}_{E2} + \dot{I}_{T1} + \dot{I}_{T2} \tag{39}$$

where the exergy losses for the components E1, T1, E2, and T2 are given, respectively, by Eqs. (20), (26), (30), and (35).

4. Results and discussion

The results of simulation and analysis of a single-stage distillation unit as case 1 and a two-stage distillation unit as case 2 are studied at a standard reference temperature of 25 °C (298.15 K) and with varying the reference temperature from 15 °C (288.15 K) to 40 °C (313.15 K).

By applying the methodology presented in the analysis section, we can find the exergy efficiencies and irreversibility rates for the individual components and the entire system. The calculations for exergy are made twice: (i) with neglecting the chemical exergy term and (ii) with the chemical exergy loss inherent to the separation process. This is done to see how much the contribution of chemical exergy loss to the total exergy loss is.

The results of simulation and analysis of single-stage distillation unit (Case I) are presented in Table 4a. For this case, 419.5 MW of crude furnace heat duty is needed to accomplish the distillation process. Very high irreversibilities occur at the heat exchanger with a value of 291.8 MW in addition to a low exergy efficiency of 0.503. Such a high loss, 68% of the total unit irreversible losses, is due to the high temperature difference across the furnace. As for the distillation column, the total irreversible loss is 137.2 MW, 21% of which are contributed to chemical exergy losses associated with separation process. The exergy efficiency of the distillation column is 0.461. The overall irreversible losses are 429.0 MW and the overall exergy efficiency is 0.140. It is worth noting that the overall exergy efficiency is not the multiplication of the individual components efficiencies which is equal to 0.231 in this case.

Table 4a
Results of single-stage at a reference temperature of 25 °C

ITEM	EXCHANGER (E1)	DISTILLATION (T1)	OVERALL (O)
Q (MW)	0	−194.3	−194.3
Heat Duty (MW)	419.5	N/A	419.5
I (MW)	291.8	137.2	429.0
Ψ	0.503	0.461	0.140

Table 4b
Results of two-stage at a reference temperature of 25 °C

ITEM	(E1)	(T1)	(E2)	(T2)	(O)
Q (MW)	0	−82.2	0	−50.8	−133.0
Heat Duty (MW)	276.6	N/A	103.7	N/A	380.3
I (MW)	71.5	88.2	48.0	33.4	241.1
Ψ	0.746	0.533	0.786	0.698	0.315

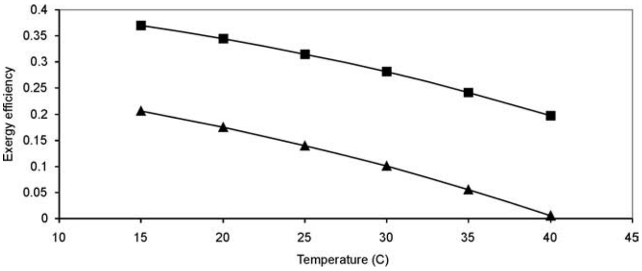

Fig. 2. Exergy efficiency vs. reference temperature (▲ single-stage, ■ two-stage).

The results of Case II for two-stage distillation unit are presented in Table 4b. For this case, 380.3 MW of crude furnaces heat duty is needed to accomplish the distillation process. Again, high irreversible losses occur at the heat exchangers with a value of 71.5 MW and 48.0 MW summing up to 119.5 MW, i.e. 50% of the total irreversible losses. The exergy efficiencies of the heat exchangers are 0.746 and 0.786. The distillation column irreversible losses are 88.2 MW and 33.4 MW summing up to 121.6 MW, of which the chemical exergy losses are 45% in the first stage and 33% in the second stage. The exergy efficiencies are 0.533 and 0.698, respectively. Finally, we find that the overall irreversibility losses are 241.1 MW and the overall exergy efficiency is 0.315.

We now go one step ahead to investigate the effect of varying the reference temperature from 15 °C (288.15 K) to 40 °C (313.15 K) on the exergy efficiency of the system.

Fig. 2 shows exergy efficiency versus reference temperature for both single- and two-stage distillation units. At 25 °C, exergy efficiency is 14% for single-stage and 32% for two-stage distillation units. It is noticed that as the reference temperature increases, the exergy efficiencies decreases significantly for both the systems. For a single-stage unit, it is even approaching zero at 40 °C reference temperature. It can be explained from the fact that exergy efficiency decreases when the reference temperature approaches the prod-

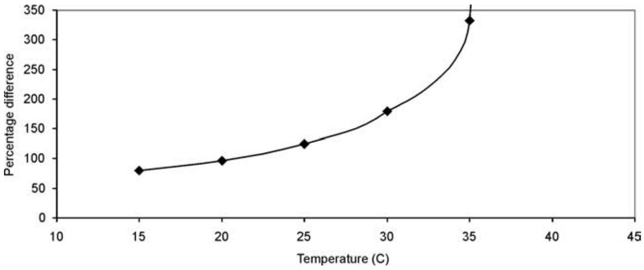

Fig. 3. Percentage difference in efficiency vs. reference temperature.

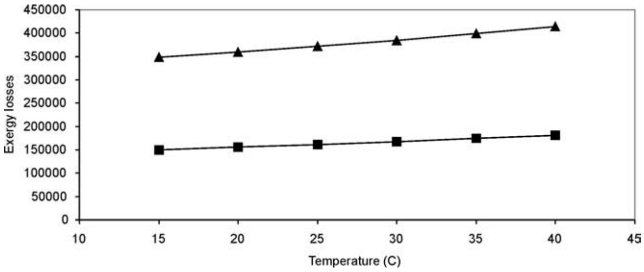

Fig. 4. Exergy losses vs. reference temperature (▲ single-stage, ■ two-stage).

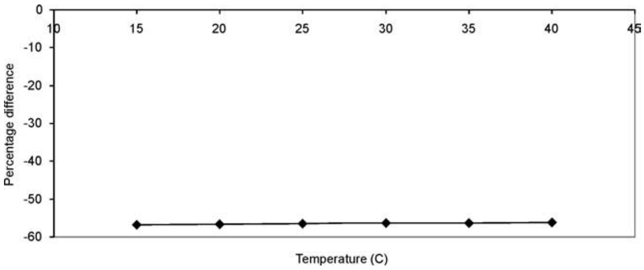

Fig. 5. Percentage increase in exergy losses vs. reference temperature.

ucts stream temperature, which in our present analysis is considered to be 60 °C. This figure clearly reflects that increasing the reference temperature implies that the exergy output is much lower and vice versa.

Fig. 3 illustrates the percentage difference between single- and two-stage distillation units with respect to the reference temperature changes. It is seen that the percentage difference increases exponentially and even approaches a very large number beyond 40 °C because of the low exergy efficiency of single-stage at that temperatures. A significant increase in exergy efficiencies of the two-stage unit at higher reference temperatures with respect to a single stage unit further emphasizes the advantages of two-stage distillation especially for hot climates like in Saudi Arabia.

There is a slight increase in exergy losses for both single- and two-stage distillation units with increase in reference temperature, as is shown in Fig. 4. We notice from this figure that the losses are almost linear, and the difference more-or-less remains constant with respect to the reference temperatures. However, taking a further look into Fig. 5 which shows a constant percentage difference in exergy losses between the two cases, it is reasonable to say that the main effect of changing the reference temperature is on the exergy efficiency rather than the exergy losses. It should be emphasized that exergy efficiency is basically controlled by the exergy input in the distillation units.

5. Conclusions

In this paper, we have studied the effect of varying reference temperature on the exergy efficiencies of and exergy losses in the one-stage and two-stage crude oil distillation plants. It has been demonstrated that exergy values are dependent on the intensive properties of the reference state and the main results of exergy analyses are usually significantly sensitive to the variations in the reference temperature. For realistic reference-state properties, efficiencies which are a rational measure of an approach to an ideal and the major causes of process inefficiencies are only determined consistently with exergy analysis. In the simulations, a commercial software package, SimSci/PRO II program is used for the calculations. The results show that increasing reference temperature decreases the exergy efficiency in both one- and two-stage crude oil distillation systems and also increases the difference between the exergy efficiencies of both systems. Thus, the exergy losses increase in the crude oil distillation systems.

In addition, further studies are suggested to account for the effect on the percentage yield of products between the two cases as well as economical impact of building and maintaining two smaller heat exchangers instead of one large heat exchanger and two smaller distillation columns instead of one large distillation column. This is currently under investigation. It is also important to recognize that the significance of exergy analysis can further be enhanced if linked with an appropriate operating and maintenance cost of distillation unit under exergoeconomic optimization scheme of the system.

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