Exergy Analysis of Distillation Column Using Concept of Driving Forces

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In this paper, a new method for exergy analysis of distillation column is presented. It is based on the principle that there are exergy losses wherever driving forces exist. An approach has been developed for investigation the effects of various parameters on exergy losses. For verification of results, some experiments were performed using a pilot plant. The thermodynamic simulation of this pilot plant has been performed using a simulator. A thermodynamic model has been used to calculate the exergy losses of each stage in this simulation. The experimental and model results were observed to be accurate and in good agreement. The results showed that the use of the model results in more accurate analysis than the prevalent streamwise method exergy analysis in distillation column does. Both calculations and experiments showed that heat transfer in reboiler and condenser, and mass transfer are the two most significant sources of exergy losses.

Introduction

The limitations of non-renewable fossil energy sources on one hand and potential environmental consequences of using them (greenhouse effects) on the other have resulted in serious industrial management challenges. This necessitates serious considerations for economy in general and industry in particular. Distillation is used for about 95% of all fluid separations in the chemical industry, and around 3% of the total energy consumed in the world is used in distillation units (Engelien *et al.*, 2003). For these reasons, attempts are being made to establish systematic techniques for improving the efficiency of the distillation process. Almost 70 years ago, the heat-integration concept was first introduced to improve energy efficiency. So far, various heat-integrated distillation schemes have been proposed. Brugma (1937) first proposed distillation using a thermally coupled distillation column. This energy-efficient separation operation was reintroduced by Wright (1949) and latter analyzed by Petlyuk *et al.* (1965). Freshwater (1951, 1961) was the first researcher who explored a novel distillation technique that is based on the heat transfer from the rectifying to stripping section in a single unit. Flower and Jackson (1964) analyzed this approach by performing different numerical experiments based on the second law of thermodynamics. Among the various energy-efficient distillation systems, the first one was the heat-pump-assisted distillation column that was proposed by Null (1976), King (1980), and Smith (1995). The heat-integrated distillation column (HIDiC)

technique was first introduced for gas separation processes by Haselden (1958). Mah *et al.* (1977), and Fitzmorris and Mah (1980) evaluated the operation of the HIDiC under the name of secondary reflux and vaporization (SRV), where only a part of the rectifying and stripping sections was integrated for heat transfer. They formulated a steady-state equilibrium-stage SRV model for the first time on the basis of the Wang and Henke (1966) tridiagonal matrix method incorporating the trim-reboiler, trim-condenser, and compressor in the column structure. Next, Shimizu and Mah (1983), and Shimizu *et al.* (1985) extended the internal heat integration to the whole rectifying and stripping sections. Nakaiwa *et al.* (1986), Takamatsu *et al.* (1988), and Lueprasitsakul *et al.* (1990a, 1990b) thoroughly evaluated the benefits of the HIDiC over a conventional distillation system. Then, Takamatsu *et al.* (1996, 1997) and Huang *et al.* (1996) proposed a unique HIDiC structure that has neither a trim-reboiler nor a trim-condenser; this structure is usually referred to as the ideal heat-integrated distillation column (i-HIDiC). Recently, it was shown (Fukushima *et al.,* 2006) that the i-HIDiC operation is more energy efficient than the operation of the general HIDiC that includes both the reboiler and condenser along with the internal heat-integration arrangement. However, when the feed rate is increased above the design value, the i-HIDiC is not economical. In recent years, several groups have been actively involved in research on the design (e.g., Kjelstrup *et al.*, 1995; Aguirre *et al.* 1997; Huang *et al.*, 2007), analysis (e.g., Rivera *et al.*, 1999; Iwakabe *et al.*, 2004) and operations (e.g., Rivera-Ortega *et al.*, 1999; Liu and Qian, 2000; Iwakabe *et al.*, 2004; Huang *et al.*, 2007) of energy-efficient distillation columns. Since 1990, several heat-integrated distillation structures have been patented (Aso *et al.*, 1998, 2002, 2007; Takamatsu

et al., 1999; Graauw *et al.*, 2003, 2004, 2005).

Most of the mentioned studies were based on the first law of thermodynamics and heat energy balance around the distillation process. However, energy balance can provide useful information about the state of the system; in particular, it provides information about the losses from the plant body and about incomplete combustion. However, it does not display any difference between the types of energy and does not consider the losses due to the deterioration of energy quality. By combining the first and second laws of thermodynamics, designers and engineers establish exergy analysis, which is a powerful and efficient tool.

By definition, exergy is referred to as the maximum shaft or electrical work done in a reversible process when the system reaches the environment conditions. Exergy analysis makes it possible to develop methods for thermodynamic development (Szargut *et al.*, 1988). Bosnjakovic (1963) was one of the first to apply exergy analysis to processes in order to overcome irreversibility. Kotas (1995) studied the exergy balance and irreversibility sources in distillation columns. Zemp *et al.* (1997) investigated the profile of driving forces and determined the exergy loss profile of the distillation columns. Sauar *et al.* (2001) studied and compared the efficiency of binary distillation columns in two ideal thermodynamic cases. Maia and Zemp (2000) carried out the thermodynamic analysis of distillation columns to determine the best feed condition. Yunus (2002) studied the distillation columns for the distillation of salt water to determine the minimum work for these columns. Koeijer and Rivero (2003) studied the entropy generation and exergy losses in experimental distillation columns. Tijani *et al.* (2007) conducted a thermoeconomic study to compute the highest economical efficiency of distillation columns. They determined the exergy and entropy balance for distillation columns and investigated the thermodynamic efficiency of distillation columns by considering thermodynamic and economic factors. Araujo *et al.* (2007) performed exergy and economic analysis for industrial distillation columns. They studied the effect of the temperature difference in a reboiler, on various parameters. Dincer and Rosen (2007) analyzed a distillation column for petroleum refinement. Anozie *et al.* (2009) studied the effects of key process parameters on the stage-exergy rate diagrams in binary distillation columns.

The common method of exergy analysis for distillation column is the streamwise method in which the exergy of the input and that of outputs are considered. The first step in correctly is to determine the main sources of exergy losses. The originality of the present study is its novel approach to distillation-column exergy analysis. The philosophy underlying such an approach is based on the principle that wherever there are driving forces, there are exergy losses, and the total exergy losses in the system would be equal to the sum of the exergy losses due to these driving forces. In the present research, the energy–exergy relationship and design have been considered to take into account the effects of various parameters, such as design and operational parameters, on the exergy losses in a distillation column. Another differ-

ence between this and previous studies is that exergy losses caused by different kinds of irreversibilities such as mass and heat transfer, occurring in the distillation columns can be computed separately. Thus, the sources of irreversibility can be compared.

1. Exergy Analysis for Distillation Columns

The common method used to analyze distillation columns involves applying the exergy balance around the column and computing the exergy losses from the exergy difference, i.e., the difference between the input and output exergies (Kotas, 1995). Consider the system shown in **Figure 1**.
There are three streams and three heat loads that cross the system boundary. Then,

$$
\begin{aligned}
EL_{\text{total}} &= -\Delta EX_{\text{total}} = -(\Delta EX_{\text{streams}} + \Delta EX_{\text{Heat loads}}) \\
&= (EX_{\text{F}} - EX_{\text{D}} - EX_{\text{B}}) \\
&\quad + (EX_{Q_{\text{B}}} - EX_{Q_{\text{C}}} - EX_{Q_{\text{loss}}})
\end{aligned}
\tag{1}
$$

Another method that appears to be effective in understanding the concepts and in facilitating appropriate interpretations, involves identifying the source of irreversibility, calculating the exergy losses (or exergy difference) of each one, and then computing the total losses of the column by adding all the calculated losses. The main sources of irreversibility in a distillation column are mass transfer between phases, heat transfer in reboiler, heat transfer in condenser, heat transfer between the flows inside the column, heat losses through the external surface of the column, friction of fluids, and conduction heat transfer along the column. Exergy differences evaluation due to these sources is described in the following sections. In this study, the following assumptions were made:

1 — The system was considered to be a steady-state, steady-flow (SSSF) system.
2 — All calculations were performed by assuming the pressure to be equal to atmospheric pressure.
3 — Changes in kinetic and potential energy were neglected.
4 — Exergy losses due to fluids' flow friction and heat transfer along the column were neglected.
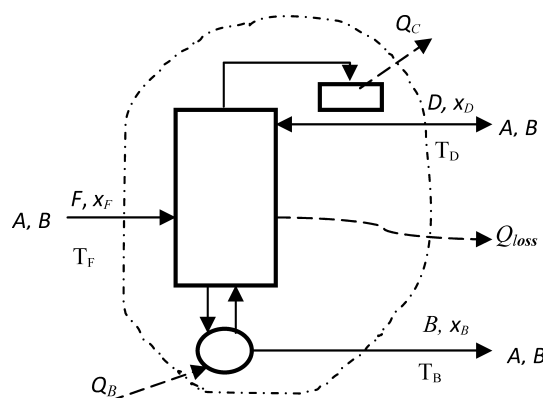5 — Feed and products were in liquid phase.

Fig. 1 Distillation system

1.1 Exergy difference caused by mass transfer

Sato (2004) shows that the mixing exergy due to the change in the concentration of substances can be calculated by Eq. (2):

$$\Delta EX_{\Delta C} = RT_0 \sum_i n_i \ln\left(\frac{n_i}{\sum_i n_i}\right) \tag{2}$$

Consider a distillation-column feed stream (F) with two components (A and B), and let there be two products (D and B). The exergy difference due to the change in concentration (mass transfer) is the difference between the mixing exergy of the feed and that of the products. From the Eq. (2), the following can be proved:

$$\Delta EX_{\Delta C} = RT_0 \ln\left(\frac{x_{AF}^{n_{AF}} x_{BF}^{n_{BF}}}{x_{AD}^{n_{AD}} \cdot x_{BD}^{n_{BD}} \cdot x_{AB}^{n_{AB}} \cdot x_{BB}^{n_{BB}}}\right) \tag{3}$$

1.2 Condenser exergy difference

In a condenser, heat transfer occurs because of a temperature gradient. This gradient leads to irreversibility and therefore exergy difference. The exergy difference caused by heat transfer in the condenser can be computed using Eq. (4).

$$\Delta EX_{\text{cond}} = Q_C\left(1 - \frac{T_0}{\overline{T}_C}\right) \tag{4}$$

Where, Q_C is the rate of heat transfer inside the condenser.

1.3 Reboiler exergy difference

As in the case of the condenser, the exergy difference in the reboiler can be obtained using Eq. (5):

$$\Delta EX_{\text{reb}} = Q_B\left(1 - \frac{T_0}{T_B}\right) \tag{5}$$

Where, Q_B is the rate of heat transfer in the reboiler.

1.4 Exergy difference due to heat transfer caused by flows

Complex flows exit inside the column, and they transfer heat and mass simultaneously. Computing the rate of heat transfer by the flows inside the column is complicated due to the complexity of the process and the simultaneity of vaporization and condensation inside the column. As the exergy is a state function, the exergy difference due to mass and heat transfer can be calculated separately. Mass transfer and the
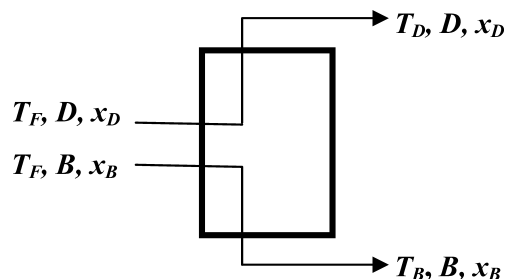
computation of exergy difference caused by it are discussed in Section 1.1. To avoid complexity, a hypothetical model as shown in **Figure 2** is considered.

According to the fifth approximation, it is assumed that the feed and products are in one phase (liquid phase). In addition, since exergy is a state function, no problems are encountered in computing exergy difference. Therefore, it can be expressed as follows:

$$\Delta EX_{\Delta T} = EL_{\Delta TB} + EL_{\Delta TD} \tag{6}$$

$$\begin{cases} \Delta EX_{\Delta TB} = \Delta H_{\text{F-B}}\left(1 - \frac{T_0}{\overline{T}_{\text{F,B}}}\right) \\ \Delta EX_{\Delta TD} = \Delta H_{\text{F-D}}\left(1 - \frac{T_0}{\overline{T}_{\text{F,D}}}\right) \end{cases} \tag{7}$$

Log. mean temperature can be calculated using Eq. (8):

$$\overline{T} = \frac{T - T_F}{\ln\left(\dfrac{T}{T_F}\right)} \tag{8}$$

$\Delta H_{\text{F-B}}$ and $\Delta H_{\text{F-D}}$ are the enthalpy differences between the feed and the products B and D, and it can be calculated using Eqs. (9) and (10):

$$\Delta H_{\text{F-D}} = H_D - H_{FD} = D\left(\sum_{i=1}^{n}(x_{iD}\hat{h}_{iD} - x_{iF}\hat{h}_{iF})\right) \tag{9}$$

$$\Delta H_{\text{F-B}} = H_B - H_{FB} = B\left(\sum_{i=1}^{n}(x_{iB}\hat{h}_{iB} - x_{iF}\hat{h}_{iF})\right) \tag{10}$$

1.5 Exergy difference caused by heat losses

The difference between the temperature of the surface of the column and that of the environment causes undesirable heat transfer between them. This loss can be reduced by insulating the surface. The rate of heat transfer from the surface of the column can be computed by dividing the temperature gradient between the inside and outside of the column by the total heat resistance. **Figure 3** schematically shows the heat losses from the column surface.

According to the basic relation of heat transfer,

$$q_{\text{loss}} = \frac{\Delta T_{\text{overall}}}{\sum R_{\text{th}}} \tag{11}$$

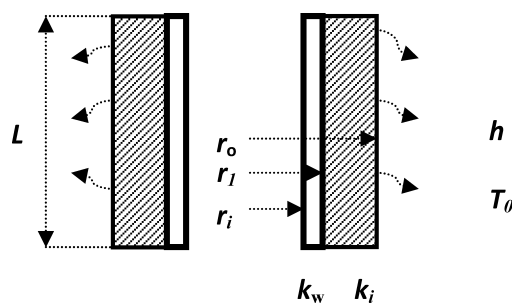By substituting the equivalent heat transfer resistance, it can be written as

Fig. 2 Model for calculation of heat-transfer-induced exergy difference in distillation column

Fig. 3 Heat losses from the column

$$q_{\text{loss}} = \cfrac{T_i - T_0}{\cfrac{\ln\left(\dfrac{r_1}{r_i}\right)}{2k_{\text{w}}\Pi L} + \cfrac{\ln\left(\dfrac{r_0}{r_1}\right)}{2k_{\text{iso}}\Pi L} + \cfrac{1}{2h\Pi L}} \qquad (12)$$

From the rate of heat transfer from the body of the column, the exergy difference can be determined:

$$\Delta EX_{Q_{\text{loss}}} = Q_{\text{loss}}\left(1 - \frac{T_0}{T}\right) \qquad (13)$$

In Eq. (13), "T" is the temperature of each ideal stage, and it must be computed by determining the temperature of each tray. In other words, Q_{loss} for an ideal stage is computed, and then   for the losses from the surface of each tray is determined:

$$\Delta EX_{Q_{\text{loss}}} = \sum_{i=1}^{n} \Delta ex_{Q_{\text{loss}}} \qquad (14)$$

The temperature of each stage can be estimated from the composition by using equilibrium data, the Rault law, and the Antoin equation. Finally, the exergy difference from the whole column can be determined using the following equations:

$$\Delta EX_{\text{total}} = \Delta EX_{\Delta C} + \Delta EX_{\text{cond}} + \Delta EX_{\text{reb}} + \Delta EX_{\Delta TD} \\ + \Delta EX_{\Delta TB} + \Delta EX_{Q_{\text{loss}}} \qquad (15)$$

$$\Delta EX_{\text{total}} = T_0 \ln\left(\frac{x_{\text{AF}}^{n_{\text{AF}}} \, x_{\text{BF}}^{n_{\text{BF}}}}{x_{\text{AD}}^{n_{\text{AD}}} \cdot x_{\text{BD}}^{n_{\text{BD}}} \cdot x_{\text{AB}}^{n_{\text{AB}}} \cdot x_{\text{BB}}^{n_{\text{BB}}}}\right) + Q_{\text{C}}\left(1 - \frac{T_0}{T_{\text{C}}}\right) \\ + Q_{\text{B}}\left(1 - \frac{T_0}{T_{\text{B}}}\right) + \Delta H_{\text{F-D}}\left(1 - \frac{T_0}{T_{\text{lmF-D}}}\right) \\ + \Delta H_{\text{F-B}}\left(1 - \frac{T_0}{T_{\text{lmF-B}}}\right) + \sum_i q_i\left(1 - \frac{T_0}{T_i}\right) \qquad (16)$$

The main goal of exergy analysis is to find the parts of the process where there has been drastic deterioration in the energy quality. This will give a better insight to reduce the losses. By following conventional analysis approaches, the expected improvement in the quality is not achieved. Equation (16) calculates the exergy losses by taking into account the driving forces in all parts of the column. Therefore, it is a simple representation of the complex exergy losses calculation. Using Eq. (16), one can deal with the parameters affecting the exergy loss in distillation column.

The first term on the right side of Eq. (16) represents the exergy difference caused by mass transfer. Then, with an increase in the rate of separation, the value of this term will increase proportionally. The second and third terms on the right side represent the exergy differences caused by heat transfer inside the condenser and reboiler. As the rate of heat transfer and the temperatures of the condenser and reboiler increase, these differences will also increase. The fourth and fifth terms represent exergy differences caused by transfer of the heat of the flows inside the column. These differences increase in proportion to the increase in the rates of separation and mean temperature at the upper and lower parts of the column. The last term represents the exergy

difference from the surface of the column, and it increases with the difference between the temperature of the stages and that of the environment or with the rate of heat transfer from the column.

2. Numerical Model

A computer code for investigating the effects of various parameters on exergy differences has been developed in the MATLAB environment. The parameters in Eq. (16) are calculated by considering design and energy–exergy relationships. Input data are feed and distillate flow rate, feed and distilled concentration, temperature of the flows, reflux ratio, surface and (insulator) conductivity, thermodynamic properties of the substances, and ambient temperature. Having provided the aforementioned data to the model, the processing work to calculate the parameters start in a sequential order as follows:
- Calculation of bottom flow rate and concentration by mass balance.
- Density and enthalpy calculation for feed and products.
- Determination of average volatility factor in the column.
- Calculation of the number of ideal stages.
- Calculation of condenser load.
- Calculation of pressure drop.
- Calculation of liquid and vapor flow rate in the column.
- Column dimension estimation.
- Estimation of temperature of each stage.
- Estimation of heat losses from the column.
- Determination of reboiler load by energy balance.
- Estimation of enthalpy difference between feed and products. (Eqs. (9) and (10))
- Calculation of exergy differences by using Eq. (16).

Obviously, the principle aim of this simulation is not the design of the column but the calculation of the parameters needed for exergy evaluation.

3. Experiments for Simulation-Accuracy Evaluation

For simulation-accuracy evaluation, some experiments were performed. The sample was water–methanol mixture and the system was a pilot-plant distillation column of Delta Lab Co. (Model: MP1010SPN°11). Some parameters were fixed in this system, and thus, numerous experiments with various free degrees were had performed. **Figure 4** shows the applied system. The main parts of this pilot plant are shown in the **Figure 5**.

In order to shorten the time to reach the steady state, the tower was primarily employed as a batch system with total reflux. After vapours started rising to the condenser, the reflux valve and the feed pump were used. One hour after steady-state operation of the column started, sampling and data recording were carried out.

The main parameters and their effects on exergy losses were investigated. These parameters include reflux ratio, feed flow rate, feed temperature, feed concentration, and

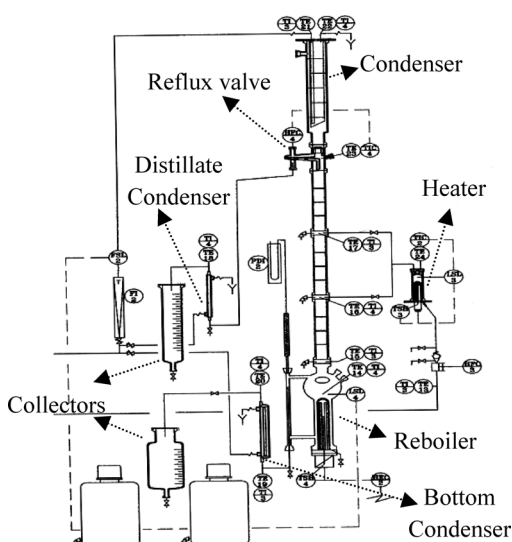**Fig. 4** Pilot-plant distillation column

Fig. 5 Main parts of pilot plant

reboiler heat load. In every experiment, each of the afore-mentioned parameters were varied against other constant factors. This made it possible to investigate the effect of each variable on exergy loss separately. The changes in each variable are shown in **Table 1**.

The interval changes for each variable include five points. Each test was repeated three times to verify the reliability of the results. About 1.5–2 h were required in order to reach the S.S.S.F condition. Approximately 75 tests requiring about 300 h were performed. Data recording was started about an hour after the S.S.S.F condition was reached.

4. Pilot Plant Simulation

The Aspen plus simulator with a suitable thermodynamic model can calculate the molar enthalpies of the flows and the exergy losses at each stage in the distillation column. If the reboiler and condenser loads are given, the exergy losses

Table 1 Changes in each variable

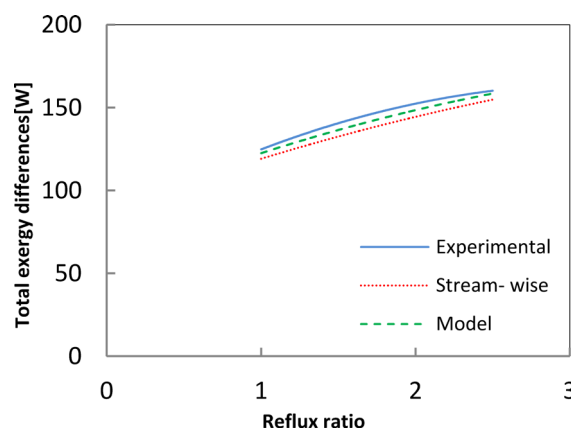| Variable	From	To
Reflux ratio	1	2.35
Feed flow rate [L/h]	1.5	3.33
Feed temperature [°C]	30	55
Feed concentration	0.05	0.20
Reboiler load [W]	600	1200

Fig. 6 Effect of reflux ratio on exergy differences in distillation column

in them can also be calculated.

The system was simulated using the abovementioned simulator that can plot CGCC graphs that can be used for the optimization of the distillation column. Wilson thermodynamic model has been used to calculate the exergy losses in each stage.

Exergy losses (or exergy differences) can be calculated by numerical and experimental methods. Comparative results from the abovementioned methods are shown in the next section.

5. Results and Discussion

By varying some parameters and maintaining others, the effects of these variations on exergy differences of the distillation process were observed. The main variables were reflux ratio, feed flow rate, feed temperature, feed concentration, and reboiler heat- transfer rate. These observation results were compared with calculation results obtained using the software. There was an acceptable correspondence in each case, and the results were more accurate than the results of the stream wise method. **Figures 6–10** show the experimental, the model and stream wise method's exergy-differences results. In each experiment, the controlled parameters were the same inputs to the model and the uncontrolled parameters were the parameters calculated by the model for exergy-difference calculation. After each experiment, these parameters were used for exergy difference calculation by the simulator. Figure 6 shows the rate of exergy differences vs. reflux ratio in the column.

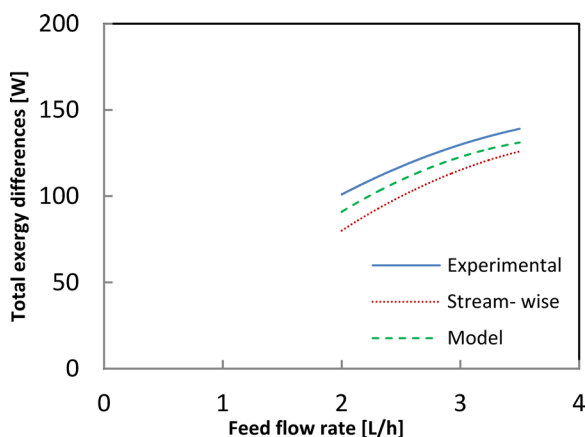According to Figure 6, the differences increase with a rise

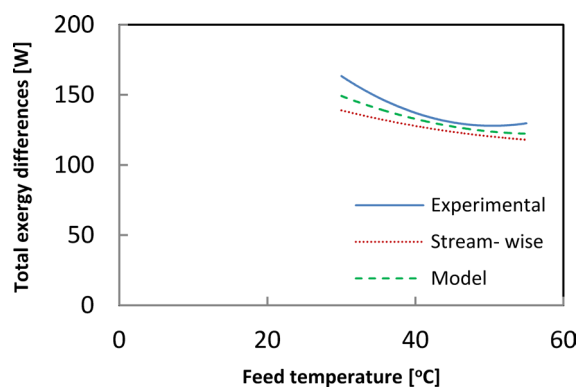**Fig. 7** Effect of feed flow rate on exergy differences in distillation column

Fig. 9 Effect of feed concentration on exergy differences in distillation column

Fig. 8 Effect of feed temperature on exergy differences in distillation column

Fig. 10 Effect of reboiler heat transfer rate on exergy differences

Fig. 11 Comparison of the effect of irreversibility sources in distillation column

in reflux ratio, and this can be expected because the reboiler and condenser duty increase. The variation in the exergy difference rate because of the feed flow rate can be seen in Figure 7.

It can be observed that the exergy differences increased with the feed flow rate rise. Figure 8 showed the exergy differences rate vs. the feed temperature.

As can be seen, the differences decrease with an increase in feed temperature. Figure 9 shows, the variation in the exergy differences with the feed concentration.

Exergy differences reduce with an increase in the feed concentration. The reason for this is a reduction in the mass- transfer driving forces in the column and normally a reduction in the number of stages. Figure 10 shows the effect of reboiler heat- transfer rate on exergy differences.

It can be seen that the exergy differences increase with the rate of heat transfer in the reboiler. As can be observed from all of the figures, variations in some parameters can cause positive or negative effects on exergy differences. Moreover, the model results are more accurate than the results of the prevalent method is streamwise exergy analysis in distillation column. For reducing exergy differences the main sources of irreversibility need to be recognized and by employing some methods or innovations, their effects should
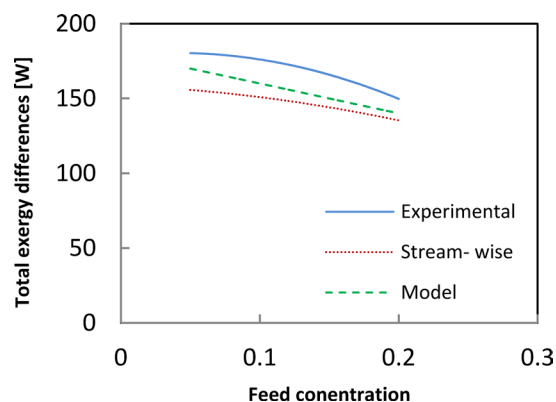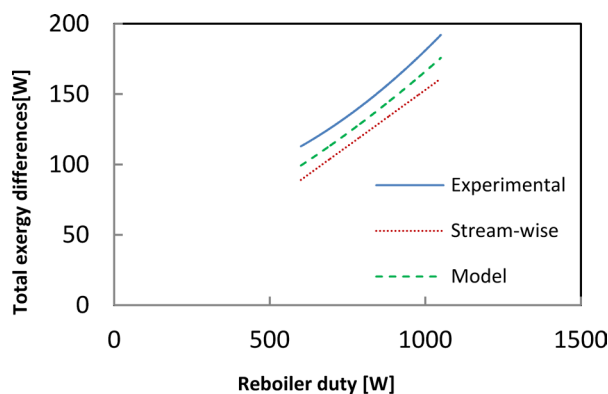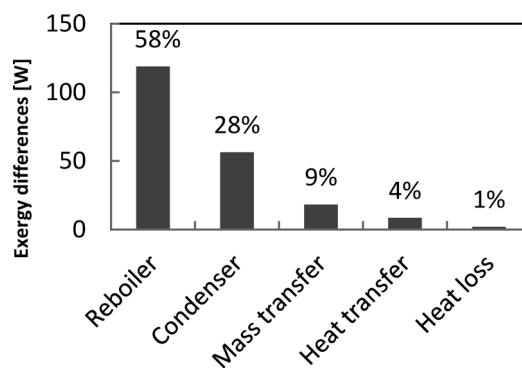
be reduced. The experiments and calculations showed that the heat transfer in both reboiler and condenser, and mass transfer along the column are respectively the first and second most significant sources of irreversibility. **Figure 11** shows the comparison of irreversibility sources for a specific case.

Irreversibilities can be reduced by a reduction in the driving forces. There are several methods for reducing driving forces, including feed preheating by the bottom product and secondary reflux (**Figures 12** and **13**, respectively).
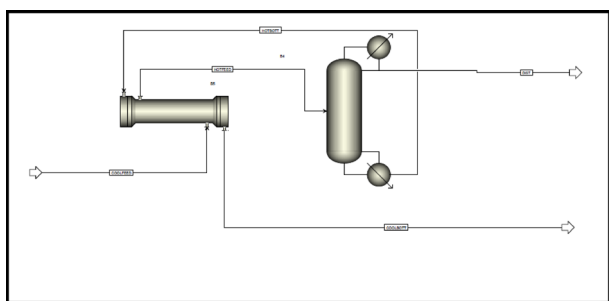
These two methods were combined and feed preheating
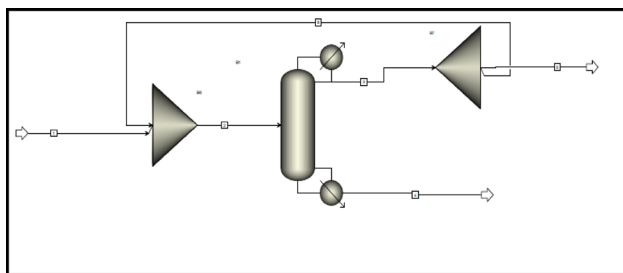
Fig. 12 Feed preheating by bottom product

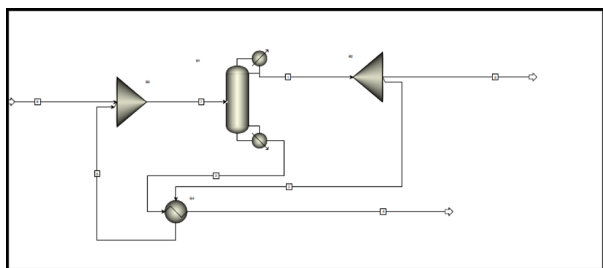**Fig. 13** Secondary reflux to the feed

Fig. 14 Simultaneous feed preheating and secondary reflux

Fig. 15 Effect of feed preheating on irreversibility sources (7.5% reduction in total exergy differences)

Fig. 16 Effect of secondary reflux on irreversibility factors (5% reduction in total exergy losses)

Fig. 17 Effect of the combined method on irreversibility factors (12% reduction in total exergy differences)

with secondary reflux were applied simultaneously (**Figure 14**).

Numerical calculation results show that the total reduction in the exergy differences is 7.5, 5, 12%, respectively using the mentioned methods three. The effects of these methods on the irreversibility factor are shown in **Figures 15–17**, respectively.

As can be seen, the percentage of exergy differences due to heat transfer in the distillation column reduced by feed preheating because the heat-transfer driving forces reduced. The total exergy differences were reduced by about 7.5% by employing this method.

The mass-transfer driving forces are reduced by the secondary reflux. Thus, the percentage of exergy differences due to mass transfer is significantly reduced. However, the exergy differences due to heat transfer increased because the temperature gradient increased in the column. However, the total exergy difference reduced by about 5% by using this method.

It can be observed that by simultaneously using feed preheating and secondary reflux, exergy differences caused by both mass and heat transfer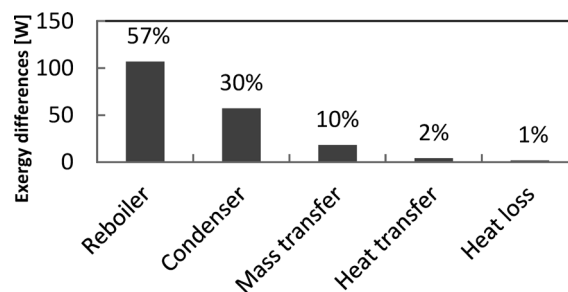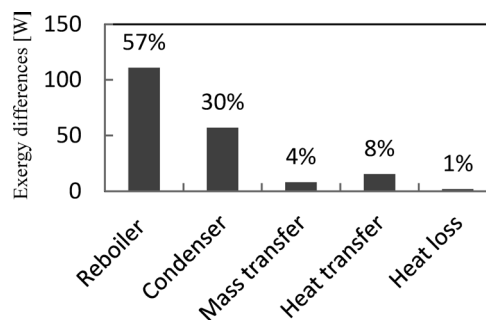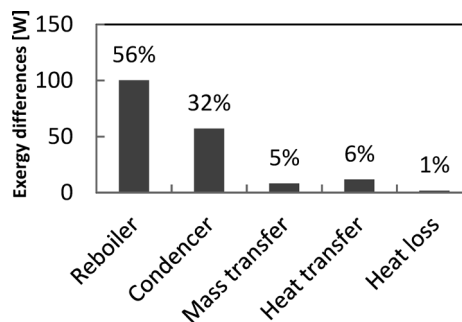 accounts for a considerably low percentage of the total exergy difference. These happened because the driving forces corresponding to these two phenomena decreased and the total exergy differences consequently reduced by about 12%.

Not only total exergy differences but also exergy losses in each tray improved by employing these methods. **Figures 18–21** show the exergy losses profile in ordinary state, feed preheating, secondary reflux to feed, and simultaneous feed preheating and secondary reflux, respectively. These figures are obtained using the Aspen plus simulator and the pilot-plant.

As can be observed from Figures 18–21, the total exergy losses decreased and the total exergy losses in the stages (the surface under the curves) also decreased by adopting the method of feed preheating and secondary reflux. The detailed calculation conditions for Figures 11 and 15–21 are
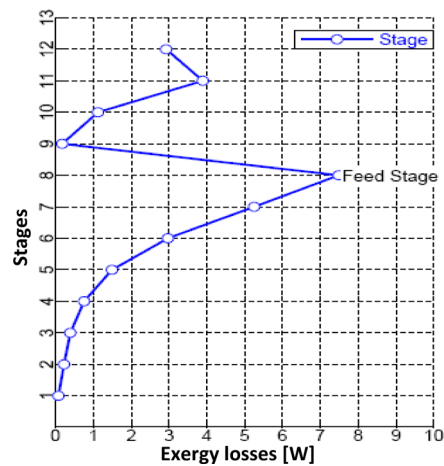
shown in the **Table 2**.
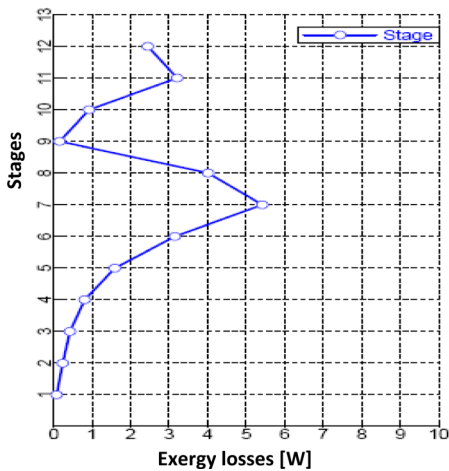

Fig. 18 Exergy losses of the stages (Ordinary state)

Fig. 20 Effect of secondary reflux on exergy losses of stages

Fig. 19 Effect of feed preheating on exergy losses of stages
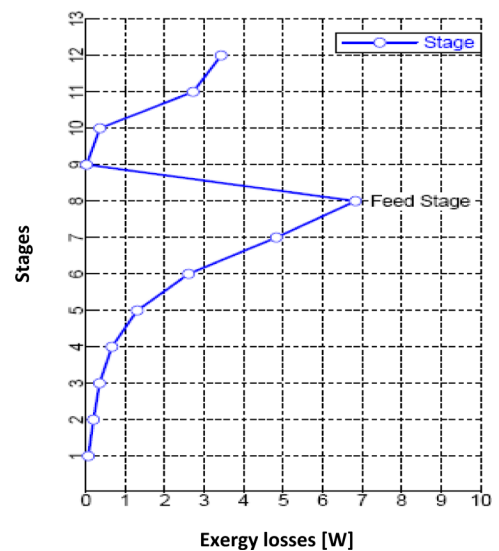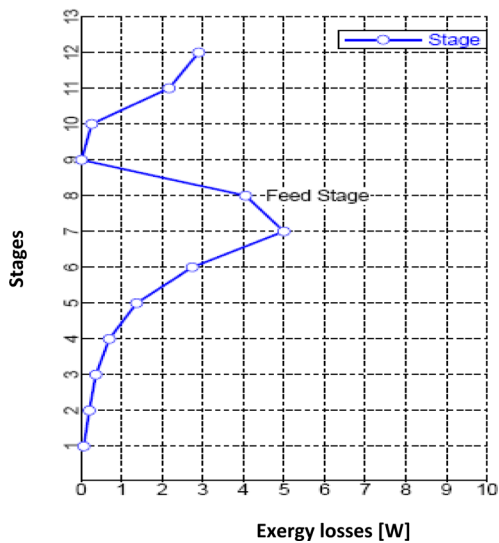
Fig. 21 Effect of feed preheating and secondary reflux on exergy losses of stages

Table 2 The detailed calculation conditions

Parameters	Ordinary state	Feed preheating	Secondary reflux	Combined method
T_F [°C]	50.5	70	50.5	70
Z_F [mole fraction]	0.1	0.1	0.1	0.1
F [mol/s]	0.0402	0.0402	0.0402	0.0402
T_D [°C]	64	64	64.63	64.63
X_D [mole fraction]	0.992	0.992	0.993	0.993
D [mol/s]	0.00276	0.00276	0.00276	0.00276
T_B [°C]	94.7	94.7	90.61	90.61
X_B [mole fraction]	0.0342	0.0342	0.0682	0.0682
B [mol/s]	0.0374	0.0374	0.0388	0.0388
Q_B [W]	626.66	564.28	614.9	555.76
Q_C [W]	486.92	487.087	486.58	486.69

Conclusion

The exergy-difference relation was developed for distillation columns on the basis of individual irreversibility factors. The main details about the new approach are as follows:

1. The new approach for exergy analysis of a distillation column in terms of driving forces gives a new simple equation for analyzing exergy in the distillation column. This will simplify the analysis.

2. In this new approach, the energy–exergy relationship and design are considered to take into account the effects of various parameters such as design and operational parameters on the exergy differences in a distillation column.

3. Using this new approach, the exergy differences caused by different kinds of irreversibilities such as mass and heat transfer in the distillation columns can be separately calculated. Thus, the sources of irreversibility will be identified.

On the basis of exergy–energy relationship, the distillation column was designed and simulated for exergy differences calculation. The simulation was evaluated by performing some experiments. The pilot plant was simulated using the Aspen plus simulator and the Wilson thermodynamic model. There was acceptable agreement between the model and experimented results. The accuracy of the analysis by using the model is more accurate than that using the prevalent method (streamwise) exergy analysis in distillation column. The observed results showed that the heat transfer in reboiler and condenser, and mass transfer along the column are the main causes for exergy differences. Obviously, irreversibilities can be reduced by reducing driving forces. Feed preheating by the bottom product and secondary reflux to the feed are effective methods for reducing exergy differences. These methods reduce some exergy differences and operating cost but result some increase in the capital cost or some decrease in the rate of productions. Consequently, a thorough analysis is needed to select an economically feasible method for each case of the distillation system. Several factors, particularly energy, and feed and product cost must be considered.

Nomenclature

B	=	bottom flow rate	[mol/s]
D	=	distillate flow rate	[mol/s]
EL	=	exergy losses	[W]
EX	=	exergy	[W]
el	=	exergy losses for each stage	[W]
F	=	feed flow rate	
H	=	enthalpy	[j]
h	=	convection heat transfer coefficient	[W/(m^2·K)]
$\hat{h}$	=	specific enthalpy	[j/mole]
i	=	iteration	
k	=	thermal conductivity	[W/(m·K)]
L	=	length	[m]
n	=	number of components	
Q	=	heat load	[W]
q	=	rate of heat transfer	[W]
R	=	ideal gas constant	[j/(mol·K)]
R	=	heat resistance	[K/W]
T	=	temperature	[K]
$\bar{T}$	=	Log mean temperature	
x	=	mole fraction	
z	=	mole fraction	

‹Subscripts›

0	=	reference state
B	=	bottom
B	=	boiler
C	=	condenser
Cond	=	condenser
D	=	distillate
F	=	feed
FB	=	part of feed that convert to bottom
F-B	=	thermodynamic difference between feed and bottom
FD	=	part of feed that convert to distillate
F-D	=	thermodynamic difference between feed and distillate
i	=	inlet
iso	=	isolate
iB	=	bottom components
iD	=	distillate components
iF	=	feed components
O	=	outlet
reb	=	reboiler
th	=	thermal
w	=	wall

ΔC	=	Concentration gradient
ΔT	=	Temperature difference
ΔTB	=	Bottom and feed temperature difference
ΔTD	=	Distillate and feed temperature difference

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