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Eco-efficiency and control loop configuration for recycle systems

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Abstract−To integrate measurements of eco-efficiency with control loop configuration has become an important topic since all industrial processes/plants are requested to increase their eco-efficiency. The exergy eco-efficiency factor, a new measure of eco-efficiency for control loop configuration, has been developed recently [1]. The exergy eco-efficiency factor is based on the thermodynamic concept of exergy, which can be used to analyze a process in terms of its efficiency. The combination of the relative gain array (RGA), NI, CN, dynamic RGA, and the exergy eco-efficiency factor will help guide the process designer to find the optimal control design with low operating cost/eco-efficiency. In this paper, we validate the proposed exergy eco-efficiency factor for processes with recycles which are very common industrially.

Key words: Eco-efficiency, Control Loop Configuration, Recycle

INTRODUCTION

After designing a continuous process at steady state for given operating conditions, control system structure selection/control pair selection is an important part of process control. As decentralized control systems are common in the process industry due to their simplicity, control structure selection mostly focuses on selecting the best decentralized control scheme for pairing manipulated (MV) and controlled variables (CV). For selecting the best control configuration there are many mathematical formulations and systematic strategies, such as the relative gain array (RGA), the Niederlinski index (NI), singular value decomposition (SVD), the condition number (CN) and Morari's resiliency index (MRI) [2,3]. During the last decade, several attempts have been made to apply these common techniques to more complex processes. For example, the development of a controllability index for heat exchange networks [4], mathematical formulations of the decomposed relative interaction array, the dynamic relative gain array, the effective relative gain array, ERGA [5-7] and comprehensive criteria for performance assessment of plant-wide control systems [8,9].

In the present era, increasing energy demands and energy costs are exacerbating the energy crisis. As a poorly structured control algorithm can lose a lot of energy from the plant, a control loop configuration should not only focus on control loop stability and quality of control, but should also include energy cost/energy usage and environmental impacts. Control quality and energy cost/energy usage/environmental impacts can be amalgamated by using the potentialof thermodynamic properties like exergy. The concept of exergy indicates what is wasted in terms of energy or the eco-efficiency of the process/plant. More details on exergy are given by Szargut et al. [10]. Exergy analysis of a process/plant is used to locate its inefficient parts, which improves energy usage and decreases energy cost [10-13]. Exergy also plays an important role for sustainability and minimizing environmental impacts by efficient use of exergy [14-19].

In recent decades, the utilization of exergy has spread to the process control spectrum: for example, a basic framework for the development of a dynamic exergy balance for process control evaluation [20], development of the relative exergy array (REA) based on analyzing the exergy interactions for the control configuration [21-23] and development of the exergy eco-efficiency factor (EEF) a new measure of eco-efficiency [24]. For REA calculation a simple algorithm/software package using VMGSim, a commercial simulator, has been developed [21,25]. The effect of recycle on the REA analysis was also studied by Munir et al. [26].

The REA is simple, easy to use and based on steady state exergy information, but it evaluates the eco-efficiency only within the scope of the control loops studied; it cannot provide the eco-efficiency of the whole unit/plant. A new measure of eco-efficiency, EEF, was developed to join together eco-efficiency and control loop configuration [24]. To make eco-efficiency a useful indicator, it must be coupled with other indicators/tools like control quality. In this paper, we will continue investigating the EEF for the whole unit/process or plant which includes recycle loops. Measurements of eco-efficiency from EEF can be used to guide process designersor control engineers to achieve more eco-efficient control configurations.

For a multi-input-multi-output (MIMO) process, a definite amount of exergy is used due to certain change in a CV by using an MV. The EEF is designed to measure the amount of exergy used for different control pairing combinations. Out of different possible control pairing combinations, the control pair which fulfils its control target by utilizing the least exergy will be the most eco-efficient control pairing. Integration of control system structure analysis techniques such as RGA, NI and SVD with an eco-efficiency measure, EEF helps engineers to select the best control configuration for both controllability and eco-efficiency. EEF is used during early process design stages to check the effect of control configuration on eco-efficiency of a process. Its main purpose is to minimize the num-

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ber of potential control configuration candidates for detailed analysis, e.g., dynamic simulation, ISE criterion.

It is a common practice to recycle material and energy streams in the chemical process industry to reuse material and energy and improve the material usage and energy efficiency. However, recycling of material and energy from an individual unit like a distillation column can change the controllability and eco-efficiency of that unit significantly [27]. The EEF can be used to select the most eco-efficient control configuration for a process with recycle. The results for EEF are validated by dynamic simulation.

This work is a continuation of our previous work [1], and is based on the effect of recycle loopson EEF results. In this work, the intention is to show the further investigation of the EEF for the whole plant, which also includes recycles. It is necessary to study the effect of recycle loops on the EEF results as recycle loops are common in the process industry and consideration of recycle loops can have a significant effect on EEF results. The EEF value decreases due to recycle/reuse of material and energy.

As the EEF values of a unit/plant are affected by the consideration of recycle loops, in this work the EEF also is employed to provide the exergy difference between the process with and without recycle.

This manuscript is organized as follows. After this general introduction, control loop configuration methods based on controllability and eco-efficiency are explained, then the concept of eco-efficiency is introduced, the EEF is definedand its validation is explained. Then, the proposed method is implemented for a simulation example. Finally, the results are discussed and conclusions are made in the summary.

CONTROL LOOP CONFIGURATION

We used three basic techniques of control structure selection: RGA, NI and SVD to select the control pairs. The selected control pairs based on the results of these three techniques are further considered to ascertain the most eco-efficient control pairs by using the EEF. The EEF can also be integrated with any other comprehensive/advanced control loop configuration technique or set of techniques, such as MRI, dynamic RGA, and ERGA.

1. Methods Based on Controllability

RGA, which started in the 1960s after the work of Bristol [28], is a popular tool to check the controllability of a process or for the selection of control loop pairings. Since then, an extensive amount of research has been done: for example, the selection of the best control configuration for a distillation column [29], the dynamic RGA [6,30], the effective relative gain array (ERGA) [7] and the normalized RGA (NRGA) [31].

The Niederlinski Index (NI) is used for testing the stability of RGA selected control loop pairing [32]. Its use is more applicable for lower order systems (2×2). For higher order systems it can only inform about the instability of the loop. The NI has also been used as an interaction measure itself as well asa stability criterion [33].

Singular value decomposition (SVD) is a useful tool to check the sensitivity of the control loop interaction to small errors in process gains. SVD also informs the decoupling of the control loops. It may not be possible to decouple control loop interactions in the presence of a singular set of steady state gain matrix equations. In this case of singular steady state gain matrix equations, the problem is ill conditioned and control loop interactions may not be possible to decouple [3,34-36].

2. Methods Based on Eco-efficiency

Eco-efficiency is analogous to the notion that increasing industrial and economic developments should be correlated with lowering of environmental impacts and optimized use of resources. Eco-efficiency analysis of a process harmonizes its economy and ecology. The purpose of eco-efficiency analysis is to use as small amount of material/energy as possible with reduced wastes and emissions.

According to the World Business Council for Sustainable Development (WBCSD) definition, eco-efficiency is achieved through the delivery of "competitively priced goods and services that satisfy human needs and bring quality of life while progressively reducing environmental impacts of goods and resource intensity throughout the entire life-cycle to a level at least in line with the Earth's estimated carrying capacity." In brief, eco-efficiency means producing more with less.

For control engineers to design/select control loop configurations, they need to convert the concept of eco-efficiency into a tool or method which can help them select the manipulated variables that achieve the best products with the lowest energy cost. Exergy is a suitable concept to evaluate the eco-efficiency of a controlled process. Exergy, the basic measure of eco-efficiency, is defined by combination of the 1^{st} and 2^{nd} laws of thermodynamics. The maximum possible amount of work which can be drawn from a material stream/process when it interacts only with the reference environment as it comes from its initial state to the final dead state is known as the exergy of that material stream/process [37,38].

The energy efficiency of a process is calculated by the 1^{st} law of thermodynamics. In such a case, the inputs, outputs and losses are defined in terms of energy. Although it is not the true efficiency of the process, it can still give some idea about the efficiency of the process [39,40]. The exergetic efficiency of a process is a true efficiency based on the exergy balance. It uses the concept of quality of energy or available energy. Exergetic efficiency is defined as the ratio of the exergy going out to the exergy going into a process [10].

Control scheme selection/controllability must also include energy usage and ecological impact to integrate the control scheme selection and eco-efficiency of the process. The integration of control scheme selection/controllability and eco-efficiency is necessary due to increases in energy demand/cost and government regulation regarding ecological impacts. Thermodynamic properties such as exergy can be used to integrate the control scheme selection and eco-efficiency of the process because the exergy destruction rate is linked with the dynamic state of the process, and controllability is an issue of process dynamics.

2-1. Exergy

Since exergy accounts for the quality of energy, it can be used as a measure to evaluate the eco-efficiency for a process design. A process is called eco-efficient if it uses a relatively small amount of energy or destruction of exergy is low. The total exergy, which consists of three components (physical exergy, chemical exergy and exergy due to mixing), is defined as [41].

$$B_{total}=B_{phys}+B_{chem}+\Delta_{mix}B \tag{1}$$

where, B_{total}=Total exergy, B_{phys}=Physical exergy, B_{chem}=Chemical exergy and $\Delta_{mix}B$=Exergy change due to mixing.

The physical exergy of a material stream/process is the amount of exergy due to the thermo-mechanical difference between pure components at process conditions and pure components at reference conditions. The chemical exergy of a stream/process is the amount of exergy due to the process components' chemical potential difference at the process and reference conditions. The exergy change upon mixing is due to the mixing of pure components at process conditions to form the actual composition of the material stream. The total exergy calculation in Eq. (1) is relatively simple and only needs easily obtainable thermodynamic data. Detailed definitions and explanations of physical exergy, B_{phys}, chemical exergy, B_{chem}, and exergy change due to mixing, $\Delta_{mix}B$, are provided in [41].

For exergy calculations in this work, an integrated visual basic (VB) program and graphical user interface (GUI) was developed [21,25]. The exergy calculation has also been automated by using process simulators. For example an open source simulator (Sim42) and a commercial simulator (Aspen HYSYS) have been used for automation of exergy calculation [11].

2-2. Exergy Eco-efficiency Factor (EEF)

EEF is a new tool for analyzing the eco-efficiency of a process. It is based on an understanding of the total exergy of each material stream in and out of the thermodynamic process. EEF helps engineers to build an eco-efficient process which is ecologically friendly and economical [1]. In the above section, we discussed that exergy can be used to measure the energy changes of one process/unit/plant.

The exergetic efficiency of a process is equivalent to eco-efficiency. For a general process as shown in Fig. 1, exergetic efficiency is defined as the ratio of the exergy going out, to the exergy coming in [42], namely,

$$\eta = B_{out}/B_{in} \tag{2}$$

where η=exergetic efficiency, B_{out}=total exergy going out of a process and B_{in}=total exergy coming in to a process.

The exergetic efficiency for the whole process is shown in Eq. (2) however, it does not provide any information about how the control loop configuration affects this exergetic efficiency. The EEF was developed to estimatethe effect of control loop configuration on exergetic efficiency [24]. The EEF connects control loop configuration to the eco-efficiency. The EEF for a control pair (u_j, y_i), is defined as,

$$\tau_{ij} = (\Delta B_{out} - \Delta B_{in})\frac{\Delta u_j}{\Delta y_i} \tag{3}$$

where Δu_j denotes a step change of the MV, (u_j), Δy_i denotes a response in the CV, (y_i), caused by a step change of the MV, (u_j), and ΔB_{out} and ΔB_{in} represent the exergy differences caused by the MV step change for exergy out and exergy in, respectively. The units of EEF would be kW in this paper after dividing Δu_j and Δy_i by their spans (transmitter and valve spans).

For example, for a 2×2 system, if τ_{21} is less than τ_{22}, it means that for the same amount of CV change, Δy_2, using MV u_1, will cause less exergy loss/change than using MV u_2. A larger value of EEF is due to a larger value of the term in parentheses in Eq. (3), which accounts for total exergy destroyed in a process for a given step change of the MV. The final interpretation is that the control pairing (u_1, y_2) is more eco-efficient than the pairing (u_2, y_2).

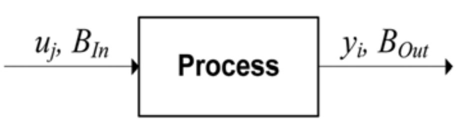

Fig. 1. Exergy flows for a general process.

Techniques such as RGA, NI and SVD are used to determine control loop configurations. Several candidate control configurations can usually be implemented. EEF can be used to select the best control loop configuration among the candidates in the sense of eco-efficiency.

In plant-wide layouts the presence of recycle can also have a significant effect on the control configuration selection of a unit/process [27]. The final selection of a control configuration should be based on the plant-wide layout. After selection of a control configuration, the proposed method of EEFis applied and validated by dynamic simulation. The use of EEF is illustrated by a process simulation case study.

As the recycling of material and energy streams in a chemical process improves energy efficiency, it also has an impact on the EEF. The EEF decreases for a unit when it is considered with recycle and vice versa. Recycle of material and energy reuses energy, which decreases the destruction of exergy. In the EEF Eq. (3), the term in brackets accounts for the exergy destruction. If exergy destruction is small then this term in brackets will be small, which means the EEF is small. A smaller value of EEF for units with recycles means a more eco-efficient process.

2-3. Validation of EEF

Dynamic simulation is used to validate the EEF results, which are based on steady state information. During the dynamic response of a process, several exergy calculations at different conditions are performed to approximate the dynamic change of exergy with time, as explained below.

The latest simulators still do not have the ability to directly calculate and display the total exergy of a material stream at every point versus time automatically. These simulators can only calculate steady state total exergy of a material stream via a customized calculation/external programme routine at given process conditions.

To approximate the dynamic change of exergy/dynamic exergy analysis, different points are selected during the process dynamic response due to step input disturbances. Selection of calculation points to reduce the computation depends on the process response. When the outputs changes are dramatic, the sampling interval is short; otherwise the sampling interval is large. Exergy values are then calculated at those selected points during the dynamic process response. The procedure developed by Munir et al. [1] is used for the calculation of exergy values at those selected points. Then the dynamic exergy response is approximated by joining those exergy points.

The selection of calculation points depends on the dynamic response of the process. To get the maximum information in regard to dynamic response, if the variation in the process conditions with time is large, then the time interval between the selected points is decreased. With less variation in the process conditions, the time interval between the selected points is increased.

2-4. Plant-wide EEF

As the final selection of a control configuration should be based

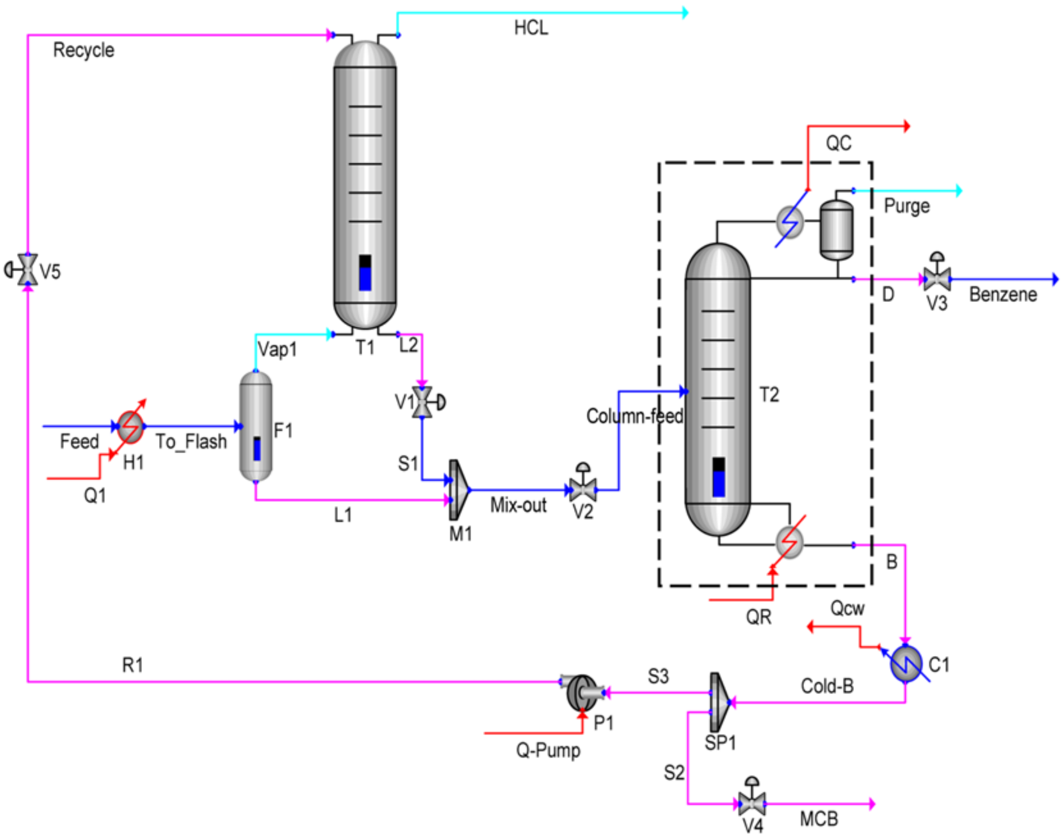

Fig. 2. MCB separation process schematic.

on plant-wide layout considerations, this paper is an exploration of the EEF for the whole process/plant which includes recycle loops, to select the best plant-wide control loop configuration in the sense of eco-efficiency among the good performing control configuration candidates obtained from controllability analysis. This work is performed with the aid of a case study (an MCB plant).

CASE STUDY - MCB SEPARATION

A monochlorobenzene (MCB) separation process is selected for this case study. It consists of three main units: a flash vessel (F1), an absorption column (T1) and a distillation column (T2) as shown in Fig. 2. The detailed information of the feed conditions and column specification can be found in [43]. VMGSim with the NRTL activity thermodynamic model is used for simulation of the MCB separation process.

The feed of this process consists of a mixture of monochlorobenzene (MCB), benzene and HCl. The vapor stream coming out of the flash tank is fed into the absorber where it is contacted with recycled MCB. Most of the HCl product comes out of the absorber as vapor. The liquid product (L2) coming out of the absorber is mixed with liquid product (L1) from the flash vessel (F1) in a mixer (M1). The mixture coming out of the mixer (M1) is then fed into the distillation column (T2). In this column a fixed amount (1% of inlet feed to the plant) is purged from the process to avoid HCl build-up in the system. The distillate product (D) contains most of the benzene, and the bottom product (B) contains most of the MCB. Some fraction of bottom product stream is recycled back into the absorber.

Although these techniques' "classical" controllability techniques, e.g., RGA, DRGA, NI and CN, provide reliable support for industry to guarantee the quality of products, there is less consideration of the energy cost among these techniques. We consider this via the EEF in this paper/study. We study four aspects in this case study: 1) An isolated distillation column, 2) a distillation column with recycle, 3) the whole plant with a distillation column but without recycle, and 4) the whole plant with a distillation column and recycle.

1. An Isolated MCB Distillation Column

As the first step of the case study, the distillation column in an MCB plant is considered in isolation without any recycle, as shown by the dashed boundary in Fig. 2. The results for controllability for different control loop configurations are shown in Table 1. From Table 1, the RGA results show that the leading diagonal elements of the LB (L (reflux rate) are used to control the composition of

Table 1. RGA, DRGA, NI and CN Results for the MCB distillation column alone (T2)

Configurations	RGA	DRGA	NI	CN
LV	$\begin{bmatrix} 0.11 & 0.89 \\ 0.89 & 0.11 \end{bmatrix}$	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$	−213.9	1.18
LB	$\begin{bmatrix} 0.97 & 0.03 \\ 0.03 & 0.97 \end{bmatrix}$	$\begin{bmatrix} 1.24 & -0.24 \\ -0.24 & 1.24 \end{bmatrix}$	1.02	71
DV	$\begin{bmatrix} 0.84 & 0.16 \\ 0.16 & 0.84 \end{bmatrix}$	$\begin{bmatrix} 0.86 & 0.14 \\ 0.14 & 0.86 \end{bmatrix}$	1.19	264

top product (x_D) B (bottom productrate) is used to control the composition of bottom product (x_B)) DV (D (distillate rate) is used to control the composition of top product (x_D), and V (boil-up rate) is used to control the composition of bottom product (x_B)) control configurations are positive and close to 1. The RGA results are validated with the dynamic relative gain array (DRGA), which confirms that leading diagonal elements of the LB and DV control configurations are positive and close to 1.

The NI results of the LB and DV control configurations are positive and greater than 1, which is favorable. The CN of the LB control configuration is close to 50, so it indicates that LB is favorable. The CN of the DV control configuration is much greater than 50, but it may be still acceptable depending on how rigorously the heuristic of <50 is adhered to. The LV (L (reflux rate) is used to control the composition of top product (x_D) and V (boil-up rate) is used to control the composition of bottom product (x_B)), control configuration is not selected as its leading diagonal elements are significantly less than 1 which is not acceptable. Its off-diagonal elements are positive and close to 1, but the pairing of off-diagonal elements introduces a significant amount of dead time in the process. The DRGA also confirms that the off-diagonal elements of the LV control configuration are positive and close to 1. The NI result for the LV control configuration is negative, which means the system is unstable.

The results based on eco-efficiency analysis (EEF) for control loop configurations are shown in Table 2. From Table 2, the control pairing (V, x_B) will use the most exergy and be the least eco-efficient control pair, and the control pairing (D, x_D) is the most eco-efficient pairing. The sums of the EEFs for the LB and DV control configurations are 3.57×10^5 kW and 6.44×10^5 kW, respectively. So from Table 1 and Table 2, both LB and DV control configurations are controllable, but the process with the LB control configuration is more eco-efficient than the same process with the DV control configuration. The LB control configuration can save up to 44% more exergy compared to the DV control configuration as calculated from Table 2.

Table 2. EEFs for the MCB column alone

Control pairs	(L, x_D)	(D, x_D)	(V, x_B)	(B, x_B)
EEF (kW)	3.28 E5	691.05	6.44 E5	2.91 E4

For the validation of the EEFs shown in Table 2, dynamic simulation of the isolated distillation column is used. Figs. 3 and 4 show the total dynamic exergies in and out of the isolated distillation column for the two control configurations LB and DV, respectively. Figs. 3(a) and 3(b) show the dynamic exergies in and out of the column under LB control due to a step change in the set points of CVs x_D and x_B, respectively. Similarly, Figs. 4(a) and 4(b) show the dynamic exergies of the column under DV control.

The total exergies of isolated column for the entire 560 min time period of the test are listed in Table 3. The total destroyed exergy for the whole column is 1.12×10^7 kW under LB control. Compared to DV control, LB control can save up to 45% in exergy. This conclusion agrees with the result (save 44% in exergy) from the EEF analysis.

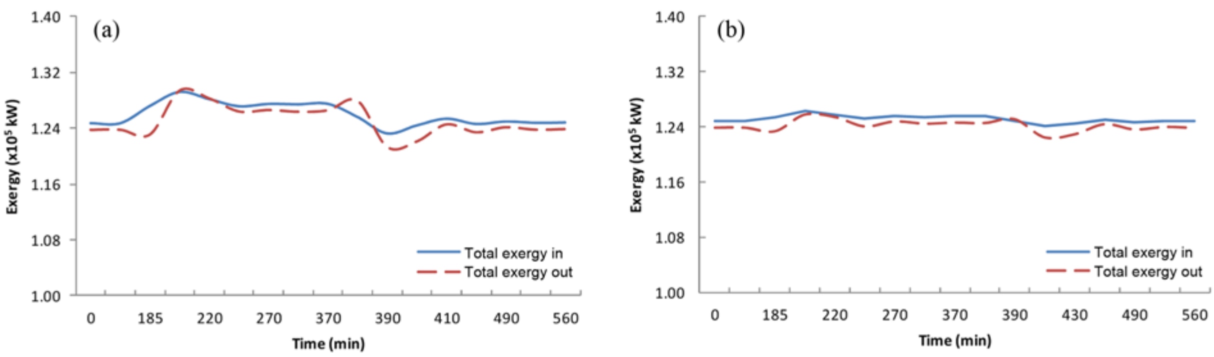

Fig. 3. Variation of exergy in and out of the isolated MCB column due to composition set point changes for the LB configuration (a) exergy variation due to step change in x_D, (b) exergy variation due to step change in x_B.

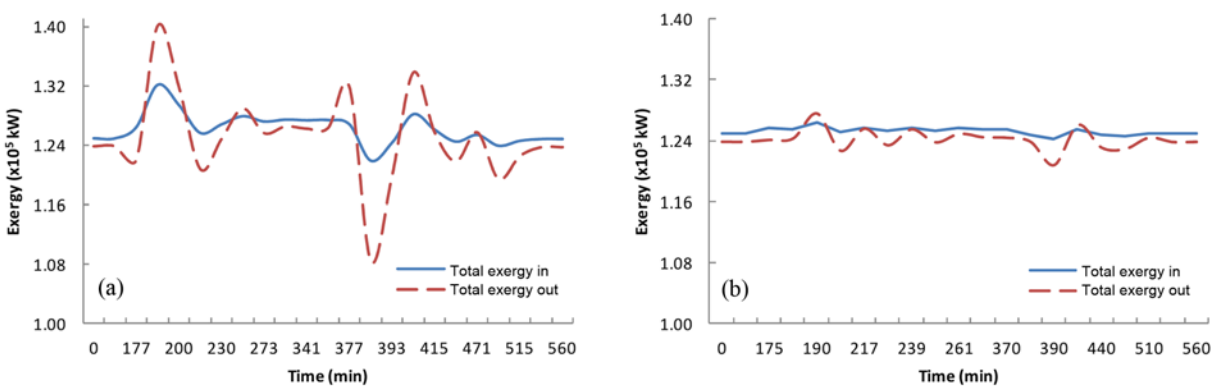

Fig. 4. Variation of exergy in and out of the isolated MCB column due to composition set point changes for the DV configuration (a) exergy variation due to step change in x_D, (b) exergy variation due to step change in x_B.

Table 3. Exergy used by the two control configurations LB and DV on the isolated MCB column

Exergy ($\times 10^7$ kW) \ Control configuration		LB	DV
Step change in x_D	Total exergy in	7.13	7.16
	Total exergy out	6.07	5.15
	Destroyed exergy	1.06	2.01
Step change in x_B	Total exergy in	7.03	7.03
	Total exergy out	6.97	6.98
	Destroyed exergy	0.06	0.05
	Total exergy destroyed	1.12	2.06

2. MCB Distillation Column with Recycle

In practice, control configurations are the same during start-up and steady state operational periods. Therefore, the chosen control configurations should work fine for both periods of operation, which is a consideration for the final selection of a control configuration. As the distillation column is ultimately connected to other units and recycles in a plantwide layout, therefore the final selection of a control configuration is based on RGA, DRGA, NI and CN for the column in plantwide layout. The results of studying an isolated distillation column are used only as a check that the selected control configuration based on plantwide layout can work fine during start-up period as well as during normal operational period of the plant which rules out the LV distillation column configuration.

In this part of the case study, a distillation column with a recycle in a plantwide layout is considered. There are three composition control loops. The composition of HCl (x_{HCl}) leaving in the vapor stream of the absorber is controlled by manipulating the cooler (C1) duty (Q_{cw}). The compositions at the top and bottom of the distillation column, x_D and x_B, are the other two controlled variables. For this three-point composition control of the MCB separation plant, three basic control configurations, LVQ_{cw}, LBQ_{cw} and DVQ_{cw}, are considered. For example, in the LVQ_{cw} control configuration, L (Reflux rate) is used to control the composition of the top product (x_D), boilup rate (V) is used to control the composition of the bottom product (x_B), and cooler duty (Q_{cw}) is used to control the composition of vapor stream leaving the absorber (x_{HCl}) [43]. The simulation results are in Table 4.

From Table 4, the RGA results show that the leading diagonal elements of the LVQ_{cw} and LBQ_{cw} control configurations are positive, although quite large for LVQ_{cw}. The RGA results of the DVQ_{cw} control configuration are far away from 1 except for one element. The dynamic relative gain array (DRGA) results are interesting, showing that the leading diagonal elements of the LVQ_{cw} control configuration are positive although quite large. The DRGA results for the LBQ_{cw} and DVQ_{cw} control configurations are also different from the results of the steady state RGA analysis. From Table 4, the DRGA results show that the leading diagonal elements of the DVQ_{cw} control configuration are positive and close to 1. The NI results of the LVQ_{cw} and DVQ_{cw} control configurations are positive, which is favorable. The CN of the LVQ_{cw} and DVQ_{cw} control configurations are less than 50, which indicates that the LVQ_{cw} and DVQ_{cw} control loops can be decoupled and are not sensitive to small errors in process gains. The LBQ_{cw} control configuration is not further selected as its DRGA leading diagonal elements are significantly away from 1, which is not acceptable, and the NI result for the LBQ_{cw} control configuration is negative, which indicates instability of the system. This is a different conclusion to the isolated distillation column case study.

Exergy analysis of the MCB separation plant shows that most of exergy of this plant is destroyed in the distillation column [44]. To minimize this exergy destruction in the column, a suitable control configuration is required.

Based on the analysis from RGA, DRGA, NI and CN, either of the LVQ_{cw} and DVQ_{cw} control configurations can be used to control this MCB separation plant, with pros and cons for both schemes. Through comparing the exergy destruction using the EEF, we can determine the best control configuration in the sense of eco-efficiency, which may help us choose between the two configurations. Here we are unlikely to choose LVQ_{cw} as the LV is uncontrollable, i.e., for a distillation column with no recycle. However, this is not necessarily always the case, so we will proceed with the analysis. The EEFs for the distillation column are calculated and are listed in Table 5. Exergy changes considered for this section are only included inside the distillation column inside the dashed boundary within the MCB separation plant schematic shown in Fig. 2. For comparing the exergy changes for the distillation column alone and with a recycle, we also re-list the EEF results from section 3.1 in the right column of Table 5.

Table 4. RGA, DRGA, NI and CN Results for the whole MCB plant

Configurations	RGA	DRGA	NI	CN
LVQ_{cw}	$\begin{bmatrix} 6.3 & -4.76 & -0.54 \\ -5.8 & 6.5 & 0.35 \\ 0.52 & -0.7 & 1.2 \end{bmatrix}$	$\begin{bmatrix} 3.8 & -2.8 & 0.02 \\ -1.4 & 2.6 & -0.23 \\ -1.4 & 1.2 & 1.2 \end{bmatrix}$	1.15	31.01
LBQ_{cw}	$\begin{bmatrix} 0.88 & 0.1 & 0.02 \\ 0.12 & 0.92 & -0.05 \\ 0 & -0.03 & 1.02 \end{bmatrix}$	$\begin{bmatrix} 0.84 & -1.6 & 1.76 \\ 0.18 & 0.37 & 0.43 \\ -0.03 & 2.2 & -1.19 \end{bmatrix}$	−1.0	16.07
DVQ_{cw}	$\begin{bmatrix} 0.52 & 0.49 & -0.01 \\ 0.39 & 0.51 & 0.1 \\ 0.1 & 0 & 0.91 \end{bmatrix}$	$\begin{bmatrix} 0.91 & 0.03 & 0.06 \\ 0.03 & 1.02 & -0.05 \\ 0.06 & -0.05 & 0.99 \end{bmatrix}$	0.97	23.62

Table 5. EEFs for the MCB column in the plant-wide layout

Control pairs	EEF (kW)	
	Without recycle ($\times 10^5$ kW)	With recycle ($\times 10^5$ kW)
(L, x_D)	3.0	0.032
(D, x_D)	0.00691	0.00652
(V, x_B)	6.0	1.2
(B, x_B)	0.029	0.022
(Q_{cw}, x_{HCl})	-	0.015

Table 6. PI controllers for the MCB distillation column

Control loops	LVQ_{cw} configuration		DV Q_{cw} configuration	
	K_c	T_i (min)	K_c	T_i (min)
Feed flow control	2.6	2	3	2
Overhead pressure control	3.3	0.6	3	0.5
Condenser level control	2	26	2	20
Reboiler level control	2	30	2	30
x_D Composition control	5	20	5	23
x_B Composition control	6.3	10	7	10

From Table 5, the control pairing (V, x_B) will use the most exergy and be the least eco-efficient control pair, and the control pairing (D, x_D) is the most eco-efficient pairing. The sums of the EEFs for the LVQ_{cw} and DVQ_{cw} control configurations are 1.77×10^5 kW and 1.44×10^5 kW, respectively. So both LVQ_{cw} and DVQ_{cw} control configurations are controllable, but the process with a DVQ_{cw} control configuration is more eco-efficient than the same process with an LVQ_{cw} control configuration. The DVQ_{cw} control configuration can save up to 19% of the exergy of the LVQ_{cw} control configuration. The exergy destruction involved in the control pairing (Q_{cw}, x_{HCl}) is the same for both configurations (LVQ_{cw} and DVQ_{cw}).

In the plant-wide layout, a bottoms product fraction is recycled back to the top of the absorber. Material and energy are reused due to the recycling of bottom product, which improves the exergy efficiency of the process. Improved exergy efficiency of the process decreases the amount of exergy destruction.

For the validation of EEFs, dynamic models for the MCB distillation column and MCB plant with recycle are built. We implemented PI controllers for the two (LVQ_{cw} and DVQ_{cw}) control configurations in the column in the plantwide layout along with inventory controls. In the plant wide layout, feed flow control, heater (H1) temperature control, flash tank (F1) level control and recycle stream flow controls are also implemented. Trial and error was used to determine acceptable tuning for this simulation and the PI controller parameters are listed in Table 6. Trial and error method to determine tuning parameters are explained in Svrcek et al. [3].

For each control configuration, the setpoints of CVs x_D and x_B are

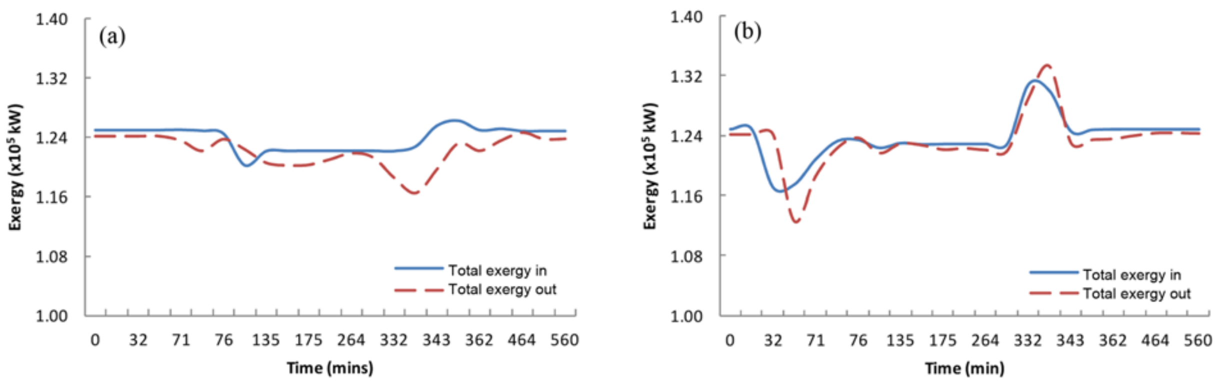

Fig. 5. Variation of exergy in and out due to composition set point changes for the LVQ_{cw} configuration (a) exergy variation due to step change in x_D, (b) exergy variation due to step change in x_B.

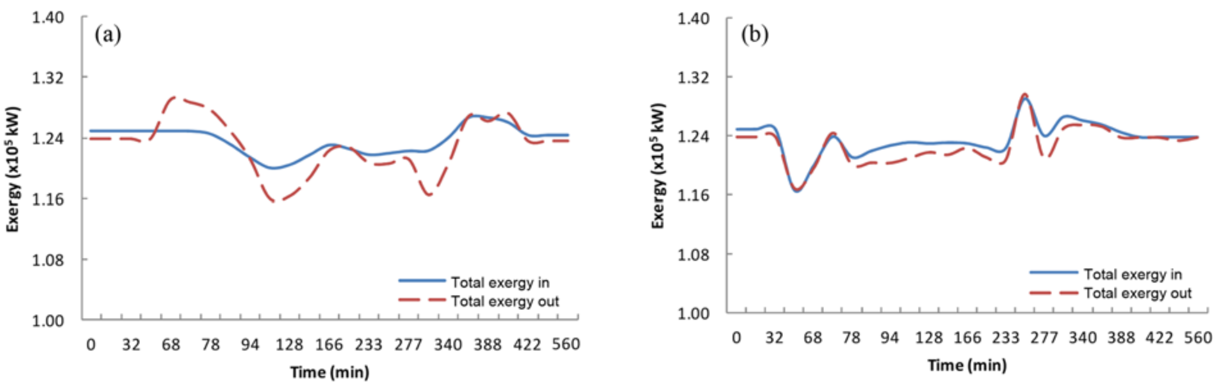

Fig. 6. Variation of exergy in and out due to composition set point changes for the DVQ_{cw} configuration (a) exergy variation due to step change in x_D, (b) exergy variation due to step change in x_B.

Table 7. Exergy used by the two control configurations LVQ_{cw} and DVQ_{cw} on the column within the MCB plant-wide layout

Exergy ($\times 10^7$ kW) \ Control configuration		LVQ_{cw}	DVQ_{cw}
Step change in x_D	Total exergy in	7.24	7.19
	Total exergy out	5.97	6.13
	Destroyed exergy	1.27	1.06
Step change in x_B	Total exergy in	10.3	10.42
	Total exergy out	5.3	6.76
	Destroyed exergy	5.0	3.66
	Total exergy destroyed	6.27	4.72

Table 8. EEFs for MCB plant with and without recycle

Control pairs	EEF (kW)	
	Without recycle	With recycle
(L, x_D)	115.2	94.3
(D, x_D)	5.87 E3	3.41
(V, x_B)	105.3	78.72
(B, x_B)	5.11 E3	1.08 E3
(Q_{cw}, x_{HCl})	-	1.28 E4

changed one by one and by the same amount (±5%). The dynamic exergies in and out of the process are approximated by the proposed method of Section 2.2.3. Figs. 5 and 6 show the total dynamic exergies in and out of the distillation column in the plantwide layout for the two control configurations LVQ_{cw} and DVQ_{cw}, respectively. Figs. 5(a) and 5(b) show the dynamic exergies in and out of the column under LVQ_{cw} control due to a step change in the set points of CVs x_D and x_B, respectively. Similarly, Figs. 6(a) and 6(b) show the dynamic exergies of the column under DVQ_{cw} control.

The total exergies for the entire 560 min time period of the test are listed in Table 7. From Table 7, the total destroyed exergy for the whole column is 4.72×10^7 kW under DVQ_{cw} control. Compared to LVQ_{cw} control, DVQ_{cw} control can save up to 24% in exergy. This conclusion agrees with the result (save 19% in exergy) from the EEF analysis.

From the results discussed above, in the plantwide layout the distillation column is more eco-efficient under DVQ_{cw} control, which contradicts the results from the eco-efficient control configuration LB control, for the same column in isolation. So the presence of recycle can have a significant impact on the control loop pair selection based on controllability and eco-efficiency. As the column has to be connected with other units of the plant in a plantwide layout, therefore the selection of controllable and eco-efficient control loop configuration should be based on plantwide layout.

Also from Table 5, significant EEF reduction is achieved by the control pair (V, x_B) from 6.44 ($\times10^5$ kW) to 1.22 ($\times10^5$ kW). The most eco-efficient control configuration for the process design including a recycle is DVQ_{cw} control where the total EEF will be 1.44 ($\times10^5$ kW). The most eco-efficient control configuration for the process design without a recycle is LB control. According to the analysis from Table 2, the total EEF is 3.57 ($\times10^5$ kW). From comparing the values of EEF, we may conclude that the process design with recycle may save up to 60% exergy. Thus, EEF can be used as an indicator to help evaluate different process designs.

However, the exergy saving with a recycle may not be significant for the whole plantwide layout. In the next section, we will evaluate the exergy changes account for the whole plantwide layout.

3. MCB Plant with Distillation Column and without Recycle

Without consideration of the recycle, the control loop configuration selection (LB and DV) remains the same as that of an isolated column. To study the effect of exergy destruction under different, well-performing control configurations (LB and DV) on the whole MCB plant without a recycle, the effect on total exergy coming in and out of the plant due to step changes in composition controls (x_D and x_B) is studied. The EEFs in Eq. (3) for the MCB separation plant without recycle are listed in Table 8.

From Table 8, the control pairing (D, x_D) will use the most exergy and be the least eco-efficient control pair, and the control pairing (V, x_B) is the most eco-efficient pairing. The sums of the EEFs for the LB and DV control configurations are 5.22×10^5 kW and 5.98×10^5 kW, respectively. Both LB and DV control configurations are controllable, but the process with an LB control configuration is more eco-efficient than the same process with a DV control configuration. The LB control configuration can save up to 12% more exergy compared to the DV control configuration as calculated from Table 8.

For the validation of EEFs as shown in Table 8, dynamic simulation of the MCB plant without recycle is used. Figs. 7 and 8 show the total dynamic exergies in and out of the MCB plant without re-

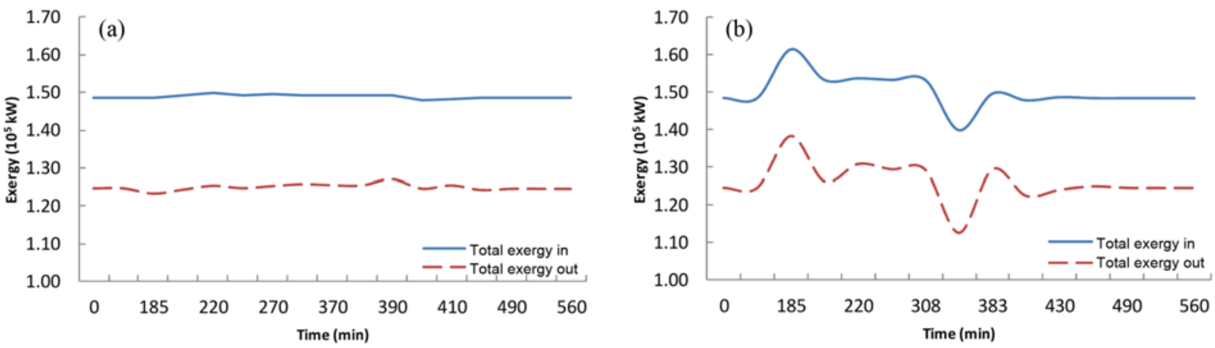

Fig. 7. Variation of exergy in and out of MCB plant without recycle due to composition set point changes for the LB configuration (a) exergy variation due to step change in x_D, (b) exergy variation due to step change in x_B.

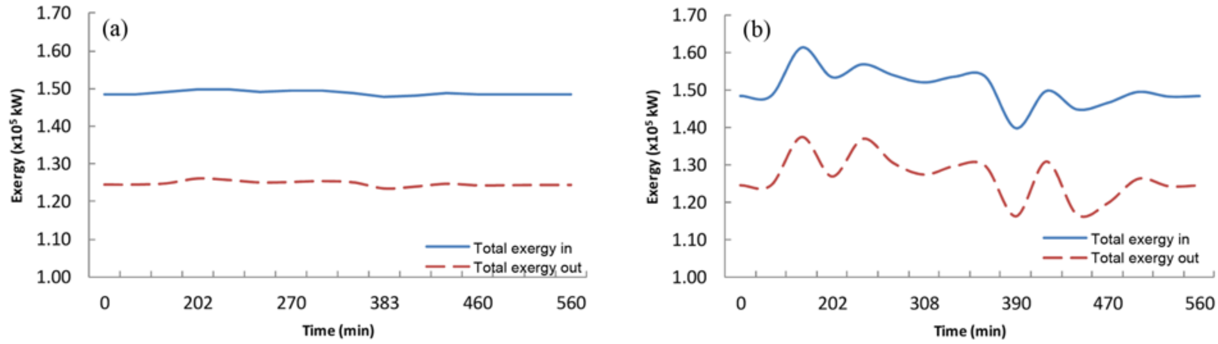

Fig. 8. Variation of exergy in and out of MCB plant without recycle due to composition set point changes for the DV configuration (a) exergy variation due to step change in x_D, (b) exergy variation due to step change in x_B.

cycle for the two control configurations LB and DV, respectively. Figs. 7(a) and 7(b) show the dynamic exergies in and out of the MCB plant without recycle under LB control due to a step change in the set points of CVs x_D and x_B, respectively. Similarly, Figs. 8(a) and 8(b) show the dynamic exergies of the MCB plant without recycle under DV control.

The total exergies of the MCB plant without recycle for the entire 560 min time period of the test are listed in Table 9. The total exergy destroyed for the whole MCB plant without recycle is 2.75×10^7 kW under LB control. Compared to DV control, LB control can save up to 3.1% in exergy.

4. MCB Plant with Distillation Column and Recycle

To study the effect of exergy destruction under different, well-performing control configurations (LVQ_{cw} and DVQ_{cw}) on the whole MCB plant, the effect on total exergy coming in and out of the plant

Table 9. Exergy used by control configurations LB and DV in MCB plant without recycle

Exergy ($\times10^7$ kW) \ Control configuration		LB	DV
Step change in x_D	Total exergy in	8.36	8.36
	Total exergy out	6.98	7.02
	Destroyed exergy	1.38	1.34
Step change in x_B	Total exergy in	8.59	8.67
	Total exergy out	7.22	7.19
	Destroyed exergy	1.37	1.48
	Total exergy destroyed	2.75	2.84

due to step changes in composition controls (x_D, x_B, and x_{HCl}) is studied. Similar to previously, LV is still uncontrollable alone but we will study LVQ_{cw} for completeness. The EEFs for the whole MCB plant are shown in Table 8. From Table 8, the control pairing (B, x_B) will use the most exergy and be the least eco-efficient control pair, and the control pairing (D, x_D) is the most eco-efficient pairing. The sums of the EEFs for the LVQ_{cw} and DVQ_{cw} control configurations are 1.297 ($\times10^4$ kW) and 1.28 ($\times10^4$ kW), respectively. Both LVQ_{cw} and DVQ_{cw} control configurations are controllable, but the process with a DVQ_{cw} control configuration is more eco-efficient than the same process with a LVQ_{cw} control configuration. The DVQ_{cw} control configuration can save up to 1.3% more exergy compared to the LVQ_{cw} control configuration as calculated from Table 8.

These EEFs are validated by dynamic exergy plots after building a dynamic model of MCB plant. Figs. 9 and 10 show the total dynamic exergies in and out of the whole MCB plant with the distillation column in the plantwide layout having two alternativecontrol configurations LVQ_{cw} and DVQ_{cw}, respectively. Figs. 9(a), 9(b) and 9(c) show the dynamic exergies in and out of the MCB plant under LVQ_{cw} control due to a step change in the set points of CVs x_D, x_B, and x_{HCl}, respectively. Figs. 10(a), 10(b) and 10(c) show the dynamic exergies of the column under DVQ_{cw} control.

The total exergies of the MCB plant for the entire 560 min time period of the test are listed in Table 10. The exergy destroyed for the whole plant is 0.74×10^7 kW under the DVQ_{cw} control configuration. Compared to LVQ_{cw} control, DVQ_{cw} control can save up to 6% in exergy. Exergy destruction under both LVQ_{cw} and DVQ_{cw} control configurations due to step changes in x_B or x_{HCl} is similar. The

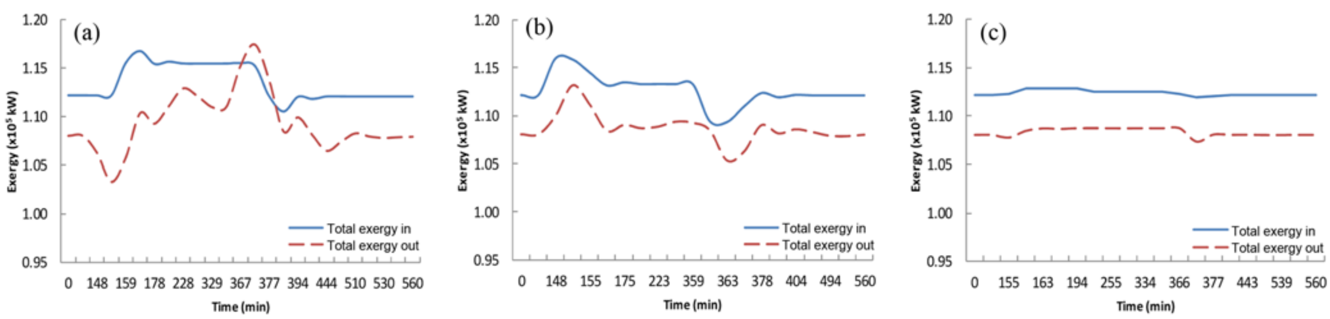

Fig. 9. Variation of exergy in and out of MCB plant due to composition set point changes for the LVQ_{cw} configuration (a) exergy variation due to step change in x_D, (b) exergy variation due to step change in x_B, (c) exergy variation due to step change in x_{HCl}.

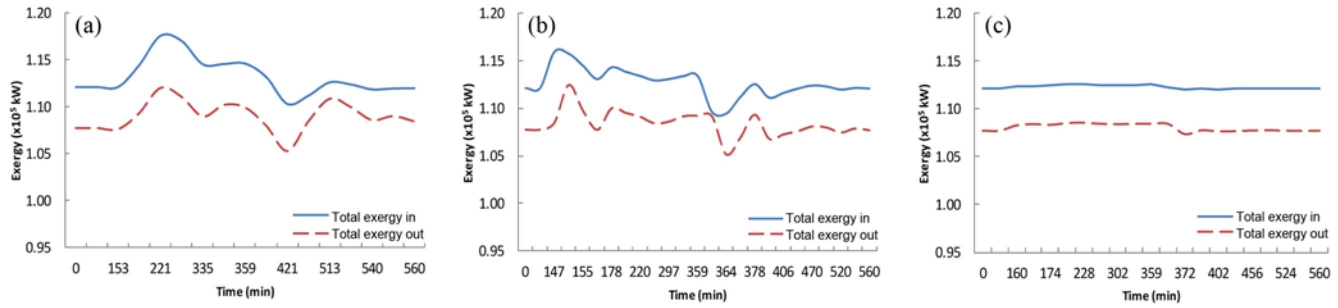

Fig. 10. Variation of exergy in and out of MCB plant due to composition set point changes for the DVQ$_{cw}$ configuration (a) exergy variation due to step change in x$_D$, (b) exergy variation due to step change in x$_B$, (c) exergy variation due to step change in x$_{HCl}$.

Table 10. Total Exergy used by the whole MCB plant with the two control configurations LVQ$_{cw}$ and DVQ$_{cw}$

Exergy ($\times 10^7$ kW)	Control configuration	LVQ$_{cw}$	DVQ$_{cw}$
Step change in x_D	Total exergy in	6.34	6.35
	Total exergy out	6.01	6.09
	Destroyed exergy	0.33	0.26
Step change in x_B	Total exergy in	6.30	6.30
	Total exergy out	6.07	6.05
	Destroyed exergy	0.23	0.24
Step change in x_{HCl}	Total exergy in	6.29	6.29
	Total exergy out	6.06	6.04
	Destroyed exergy	0.23	0.24
	Total exergy destroyed	0.79	0.74

major difference in exergy destruction between LVQ$_{cw}$ and DVQ$_{cw}$ control configurations is due to the step change in the top product composition control loop. So the selection of the manipulated variable for the top product composition control plays an important role in exergy destruction of the process during operation. It is not surprising that the exergy saved is much smaller for the whole plant than the individual distillation column (from 19% to 6%). The simple explanation is that the distillation column is only a portion of the whole plant.

We have used EEF to find that DVQ$_{cw}$ control is the most eco-efficient control configuration in the whole plantwide sense. Now we would like to know how much exergy we can save for the process design with a recycle.

Compared to the exergy consumption of 2.75 ($\times 10^7$ kW) using LB control for the whole process without a recycle in Table 9, the exergy consumption using DVQ$_{cw}$ control is 0.74 ($\times 10^7$ kW) in Table 10, so we may save 73% of the exergy. This value is very close to the 60% saving calculated in section 3.2.

CONCLUSIONS

The selection of a control configuration can change significantly depending on whether it is considered alone or within a plantwide layout. The selection of control configuration for a unit should be based on results from when that unit is considered within the plantwide layout, although it still needs to be controllable alone for start-up purposes, etc. EEF, a new measure, for integrating control loop configuration and eco-efficiency, is described in this paper in detail. For plants with recycles the EEF decreases due to recycle of material and energy since recycling of material and energy decreases the exergy destruction within a process. The case study results show that the EEFcan provide a qualitative and quantitative measure to guide engineers to select the most eco-efficient control configuration. For the MCB plant, LB is the most eco-efficient control configuration without recycle and DVQ$_{cw}$ control is the most eco-efficient control configuration in the whole plantwide sense with recycle.

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