CONTROL LOOP CONFIGURATION AND ECO-EFFICIENCY

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Abstract

Since the eco-efficiencies of all industrial processes/plants have become more and more important, engineers need to find a way to integrate control loop configuration and measurements of eco-efficiency. A new measure of eco-efficiency for control loop configuration was developed, the exergy efficiency factor. The exergy 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) and the exergy efficiency factor will help guide the process designer to reach the optimal control design with low operating cost. The proposed method is validated by dynamic simulation.

Keywords

Control loop configuration, Eco-efficiency, Dynamic exergy efficiency.

Introduction

Control loop configuration or control pair selection focuses on selecting the best control scheme for pairing manipulated and controlled variables. Several common techniques: Relative gain array (RGA), Niederlinski index (NI), Singular value decomposition (SVD) and Decoupling have been developed for control loop configuration (Seborg et al. 1989; Svrcek et al. 2006). Based on these common techniques, many researchers have developed more comprehensive techniques for assigning control loops on more complex processes. These techniques provide a reliable support for industry to guarantee the quality of products.

Now days, in the wake of the energy crisis and global warming control loop configuration can not only focus on control loop analysis techniques alone such as control loop stability analysis and consideration of the quality of the controller variable, but must also include energy cost and environment impact. A new tool must be developed to integrate above two aspects for process control and economics/sustainability. In most control loops, exergy can play an important role in this new tool since it can be used for determining the exergetic efficiency and sustainability of a process (Dincer 2002). For example, environmental impacts can be minimized by reducing exergy losses and by efficient use of exergy (Rosen and Dincer 1997; Rosen and Dincer 1999).

The use of thermodynamic properties like exergy has potential to be used for the development of process control structures. Luyben et al. (1998) added an appendix in his book which acts as a basic framework for the development of a dynamic exergy balance for process control evaluation. The Relative Exergy Array (REA) was developed based on analyzing the exergy for the control configuration within the process design (Montelongo-Luna et al. 2009; 2011). Some research has also been done on process control effects on entropy production (Alonso et al. 2002; Ydstie 2002; Martin et al. 2005).

The REA is the extension of the RGA into the exergy domain. The REA is defined by placing the exergy

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thermodynamic property in the place of gain in the RGA analysis. The REA may provide a deeper insight into process control structure interactions and measurement of exergetic efficiency and can be used for quick comparison between several process/control structure candidates. REA calculation using a commercial simulator (VMGSim) has been developed (Munir et al. 2010; Munir et al. 2011).The effect of recycle on the REA analysis was studied by Munir et al.(2011) . If RGA and REA conflict then final selection should be based on RGA.

The REA evaluates the eco-efficiency only within the scope of the control loops studied; it cannot provide the eco-efficiency of the whole unit or plant. In this paper, we will extend the eco-efficiency of the control loop configuration into the whole unit/process or even plant. A new measure of eco-efficiency, exergy efficiency factor, is proposed.

This manuscript is organized as follows. After this general introduction, the concept of eco-efficiency is introduced, the relevant exergy definitions are discussed and the exergy efficiency factor is proposed. Then, the proposed method is implemented for two simulation examples. Finally, the results are discussed and conclusions are made in the summary.

Eco-efficiency

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." This concept describes a vision for the production of economically valuable goods and services while reducing the ecological impacts of production. In other words eco-efficiency means producing more with less.

When applying the concept of eco-efficiency to control loop configuration, we need to develop a method which can help engineers select the manipulated variables which achieve the best products with the lowest energy cost.

In every chemical process there are some materials coming in or going out. Similarly, every process needs some energy to perform its work and/or the process rejects energy to the surroundings. So the material and energy balances of the process are generally used to evaluate the efficiency of the process at the process design stage. For energy balance calculations chemical engineers mostly only focus on the 1st Law of Thermodynamics (Himmelblau and Riggs 2004). However this approach may not fully reflect realistic energy efficiency. The 2nd Law of the thermodynamics must be included to provide a more realistic understanding of energy usage and wastage (Denbigh 1956).

Thermodynamic laws (1st and 2nd) may give an idea about process efficiency, energy loss, work done, required work and entropy production. For energy efficiency of a process, inputs, outputs and losses are defined in terms of energy (Smith and Ness. 2005).The combination of the 1st and 2nd laws of thermodynamics gives rise to the concept of exergy which is the basic measure of eco-efficiency. Exergy is the maximum possible amount of work which can be drawn from a material stream when it interacts only with the environment as it comes from its initial state to the final dead state (Denbigh 1956; Kotas 1985).

Exergy

A general thermodynamic process is shown in Figure 1. The process has many arbitrary material streams coming from and going out of the process boundary. The process has its own temperature (T), pressure (P) and composition (Z). The process is also heated from different heating sources at different temperatures T_i delivering different amounts of heat q_i. The process produces some shaft work (W) and delivers it to the environment with fixed values of temperature, pressure and composition (T_0, P_0 and Z_0).

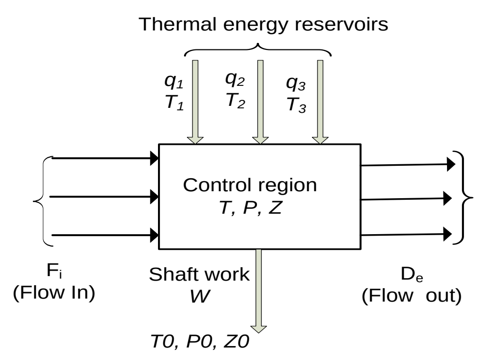

Figure 1: A general thermodynamic process

The change in internal energy (ΔU) of the general thermodynamic system shown in Figure 1 is due to the addition of energy inputs (q_i) and work done (W). According to the 1st Law of Thermodynamics, internal energy change (ΔU) can be expressed as,

$$\Delta U = -q_0 + \sum_i q_i - P_0 \Delta V + W \quad (1)$$

where q_0= heat provided to the system, $\sum_i q_i$ = all other heat effects, $-P_0\Delta V$ = work done in displacing the atmosphere at constant pressure, and W = all other work terms.

According to the 2nd law of thermodynamics, the total entropy created, σ, can be expressed as,

$$\Delta S + \Delta S_0 + \sum_i \Delta S_i = \sigma \geq 0 \quad (2)$$

where S = Entropy, ΔS_0 = Change in entropy outside the process and ΔS_i = Change in entropy inside the process.

The heating medium is a heat reservoir at a constant temperature and its change in entropy is ΔS_0.

$$\Delta S_0 = Q_0 / T_0 \tag{3}$$

From Equations (1), (2) and (3), we can obtain the following thermodynamic expression for the process in Figure 1,

$$W + \sum_i \left(q_i + T_0 \Delta S_i \right) = T_0 \sigma + \Delta U + P_0 \Delta V - T_0 \Delta S \tag{4}$$

where $W + \sum_i \left(q_i + T_0 \Delta S_i \right)$ denotes the total work performed on the process and $T_0 \sigma$ denotes the energy loss due to irreversibility.

Exergy is the maximum possible amount of work which can be drawn from a material stream when it interacts only with the environment and it comes from its initial state to the final dead state (Denbigh 1956; Kotas 1985). At the dead state the material stream is in thermal, mechanical and chemical equilibrium with the environment. Since exergy accounts for the quality of energy, thus 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 calculation of the physical exergy change of the thermodynamic process in Figure 1 can be obtained from Equation (4) as,

$$\Delta B_{phys} = \Delta U + P_0 \Delta V - T_0 \Delta S \tag{5}$$

Because the thermodynamic process composition *Z* and the environmental composition *Z0* in Figure 1 are designed for different work potentials, the total exergy of the material stream will also change. The total exergy, including the three components: physical exergy, chemical exergy and exergy due to mixing, is defined as (Hinderink et al. 1996),

$$B_{total} = B_{phys} + B_{chem} + \Delta_{mix} B \tag{6}$$

The detailed definitions of chemical exergy, B_{chem}, and exergy change due to mixing, $\Delta_{mix} B$, are provided in (Hinderink et al. 1996). Based on an understanding of the total exergy of each material stream in and out of the thermodynamic process, it is possible that engineers can build an eco-efficient process which is ecological and economical.

The total exergy calculation in Equation (6) is relatively simple and only needs easily obtainable thermodynamic data. This calculation requires data such as the Gibbs energy formation for the calculation of standard chemical exergies. The Gibbs energy formation data can be obtained from different sources like thermodynamic databanks or process simulators but special attention must be paid to the consistency of this data.

However, even in the presence of many commercial chemical process simulators, exergy calculation is not easy or straight forward in practice. The automation of exergy calculation was done by using a commercial simulator (Aspen HYSYS) and an open source (Sim42) (Montelongo-Luna et al. 2007). An integrated Visual Basic (VB) program and Graphical User Interface (GUI) was recently developed for exergy calculation (Munir et al. 2010).

Eco-efficiency factor of the Manipulated Variable

In the above section, we introduced the idea that exergy can be used to measure the energy changes of one process/unit/plant. Exergetic efficiency was defined as the ratio of the exergy going out to the exergy going into a process as shown in Equation (7) (Sazargut et al. 1988).

$$\eta = B_{out} / B_{in} \tag{7}$$

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

The ratio can be used to measure the exergy efficiency of a process which is equivalent to eco-efficiency. A general process for exergetic efficiency calculation is shown in ***Figure 2***. This general process is a portion of the control loop between the manipulated and the control variable.

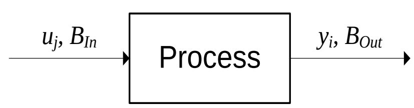

Figure 2: A general process

Equation (7) includes the exergy efficiency for the whole process; however it does not provide any information about how the control loop configuration affects this exergy efficiency. In this paper we propose a new measure, eco-efficiency factor, which connects the control loop configuration to the eco-efficiency. The exergy efficiency factor for a control pair (u_j, y_i), is defined as,

$$\tau_{ij} = (\Delta B_{out} - \Delta B_{in}) \frac{\Delta u_j}{\Delta y_i} \tag{8}$$

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. For example, 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 than using *MV*, u_2. The final interpretation is that control pair (u_1, y_2) is more eco-efficient than pair (u_2, y_2). Usually control loop configuration is determined by techniques such as RGA and NI. The result is often that several candidate control loop configurations can be used. Our new eco-efficient factor can be used to select the best control loop configuration among the candidates in the sense of eco-efficiency.

Validation of Eco-efficiency factor

Dynamic simulation is the best way to validate the proposed eco-efficiency factor. By recording the exergy consumptions of several control configurations, we can identify the most eco-efficient control configuration and compare the dynamic result to the result from the eco-efficiency factor.

Dynamic exergy versus time can be approximated by several exergy calculations at different conditions during the dynamic response of a process. The exergy values of the process dynamic response at different time intervals are calculated. As chemical simulators still do not have the ability to directly calculate and display the total exergy of a material stream, these simulators cannot calculate exergy at every point versus time automatically. Simulators such as HYSYS and VMGSim can only calculate steady state exergy values at given process conditions. For dynamic exergy versus time, different points are selected during the process dynamic response due to step input disturbances. The selection of calculation points depend on the process response. Then the exergy values are calculated on those selected points during the dynamic process response. Exergy values at different points are calculated with the procedure developed in Munir et al. (2010). Then those exergy points are used to approximate the dynamic exergy response versus time.

Case Study

For this case study, a distillation column with dual composition control is selected. A schematic of this distillation column is shown in Figure 3.

VMGSim with the NRTL activity thermodynamic model is used for this simulation. Table 1 summarizes the feed conditions and the distillation column specifications.

The compositions at the top and bottom of the distillation column, x_D and x_B, are the controlled variables. For two-point composition control of this distillation column three basic control configurations: *DV, LV and LB* are the possible control candidates. For example, in the *LV* control configuration, *L (Reflux rate)* is used to control the composition of the top product, x_D and *V (Boil-up rate)* is used to control the composition of the bottom product, x_B (Svrcek et al. 2006).

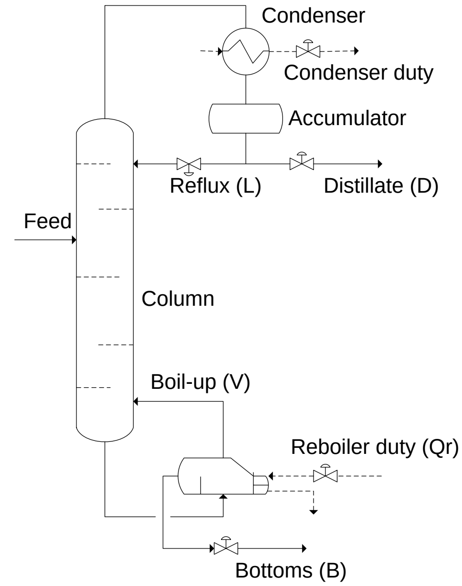

Figure 3: Distillation column schematic

Table 1: Feed and distillation column specifications

Feed		**Feed Composition**	
Flow *(kmole/hr)*	152	E- oxide *(Mole fraction)*	0.014
Tray specifications		Water *(Mole fraction)*	0.31
Diameter *(m)*	1.5	E-glycol *(Mole fraction)*	0.67
Weir height *(m)*	0.5	Pressure *(kPa)*	110
Weir length *(m)*	1.2	Temperature *(^oC)*	65
Column specifications			
Total number of stages		10	
Feed stage		5th	
Condenser type		Partial	
Column overhead pressure *(kPa)*		100	
Column reboiler pressure *(kPa)*		105	

Table 2: Control pairings for the three control configurations

Configuration	u_1	y_1	u_2	y_2
DV	*D*	x_d	*V*	x_b
LV	*L*	x_d	*V*	x_b
LB	*L*	x_d	*B*	x_b

The RGA values for the three basic control configurations calculated from the gain matrices are,

$$\Lambda_{LV} = \begin{bmatrix} 7.07 & -6.07 \\ -6.07 & 7.07 \end{bmatrix}$$

$$\Lambda_{DV} = \begin{bmatrix} -0.06 & 1.06 \\ 1.06 & -0.06 \end{bmatrix}$$

$$\Lambda_{LB} = \begin{bmatrix} 0.72 & 0.28 \\ 0.28 & 0.72 \end{bmatrix}$$

These RGA results show that the leading diagonal elements of the *LB* and *LV* control configurations are positive and can be further selected for evaluation of the exergy efficiency of the process. The *DV* control configuration is not further selected as its leading diagonal elements are significantly less than 1 and negative which are not favorable. Its off-diagonal elements are positive and close to 1, but the pairing of off-diagonal elements introduce a significant amount of dead time in the process which is not favorable.

After selecting the *LB* and *LV* control configurations, we will use the proposed eco-efficiency factor to evaluate the effect of each control pair on the overall exergetic efficiency of the process. The eco-efficiency factor of each pair of *MV* and *CV* is listed in Table 3. A control pair which gives lower exergy efficiency factor is favorable and vice versa.

Table 3: Eco-efficiency factor

Control Pairs	EEF (kW)
(L, x_D)	36.5E7
(V, x_B)	33.7E5
(B, x_B)	22.6E5

From Table 3, the control pair (L, x_D) will use the most exergy and be the least eco-efficient control pair, and the control pair (B, x_B) is the most eco-efficient pair. For controlling one *CV*, x_B, if we use *B* as the *MV*, it will save 33% exergy comparing to use *V* as the *MV*.

After building the dynamic model of this case study, we implemented the PI controllers for the two (*LB* and *LV*) control configurations with inventory controls. Ziegler Nichols open loop tuning method is used for this simulation, the PI controller parameters are listed in Table 4.

For each control configuration, the set points of *CVs* x_D and x_B are changed at the same time and by the same amount. The dynamic exergies in and out of this distillation column are approximated by the proposed method. Figure 4 and 5 show the dynamic exergies for the two control configurations *LV* and *LB* respectively. The total exergies for the 70 min time period are listed in Table 5.

Table 4: PI Controllers for dynamic simulation

Control loops	*LV* configuration		*LB* configuration	
	K_c	$T_i(min)$	K_c	$T_i(min)$
Feed flow control	*0.1*	*0.1*	*0.2*	*0.3*
Overhead pressure control	*2*	*20*	*2*	*20*
Condenser level control	*2*	*20*	*2*	*20*
Reboiler level control	*2*	*20*	*3*	*20*
x_D Composition control	*0.5*	*10*	*0.4*	*10*
x_B Composition control	*0.5*	*10*	*1*	*10*

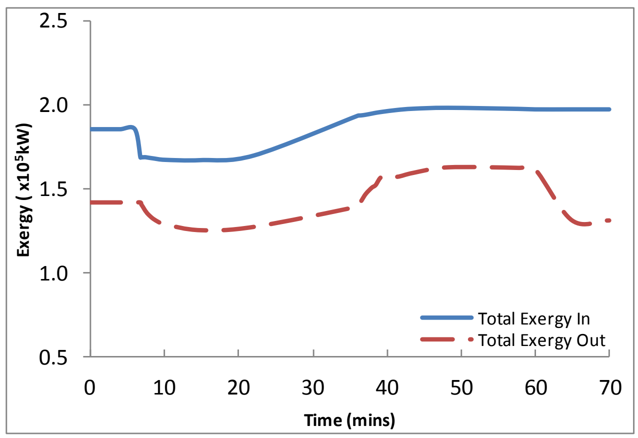

Figure 4: Variation of Exergy In and Exergy Out due to composition set point changes for the LV configuration

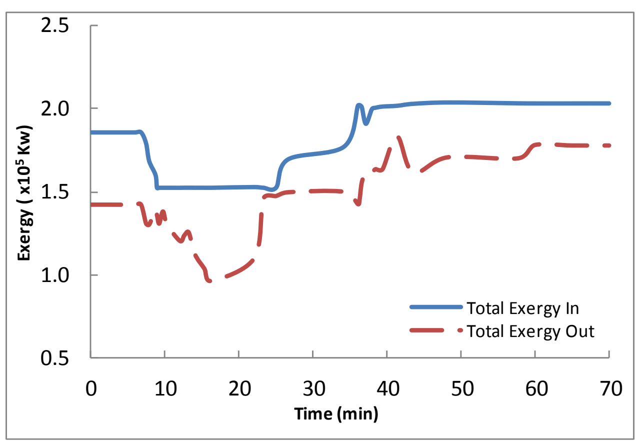

Figure 5: Variation of Exergy In and Exergy Out due to composition set point changes for the LB configuration

Table 5: Exergy used by two control configurations LV and LB

Control Configuration	*LV* ($\times 10^4$kW)	*LB* ($\times 10^4$kW)
Total Exergy in	23.9	22.9
Total Exergy out	18	19.3
Total destroyed Exergy	5.9	3.6

From Table 5, the total destroyed exergy for the whole operation is 3.6 $\times 10^4$ kW under the *LB* control configuration. Compared to the *LV* control configuration, *LB* control can save 38% exergy. This conclusion agrees with the result from the eco-efficiency factor. The percentages of the exergy saving from two methods are quite similar, which indicates that the EER can provide a reliable guide to selecting the more eco-efficient control configuration.

Conclusions

A new measure, eco-efficiency factor, for integrating the control loop configuration and eco-efficiency is proposed in this paper. The simulation result shows that the eco-efficiency factor can provide a qualitative and quantitative measure to guide control engineers to select the most eco-efficient control configuration.

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