Korean J. Chem. Eng., **31**(7), 1110-1114 (2014)
DOI: 10.1007/s11814-014-0105-4
pISSN: 0256-1115
eISSN: 1975-7220

RAPID COMMUNICATION

Does lower energy usage mean lower carbon dioxide emissions? - A new perspective on the distillation process

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(*Received 2 February 2014 • accepted 8 April 2014*)

Abstract−Although fossil fuels play an important role as the primary energy source that currently cannot be replaced easily with other energy sources, their depletion and environmental impact are becoming major concerns. Improvements in energy efficiency are believed to solve both problems simultaneously. We examined the relationships between the improvement in energy efficiency, energy usage and CO_2 emissions in industry, especially in the distillation process. The energy efficiency improvement of dimethyl ether (DME) purification performed with dividing-wall column distillation (DWC) and acetic acid recovery performed with mechanical vapor recompression (MVR) were evaluated by recalculating the amount of fuel burnt and its CO_2 emission. The results showed that the paradigm of lower energy being directly proportional to lower CO_2 emissions is not entirely correct. To avoid this confusion, a tool for examining the uncommon behavior of various systems was developed.

Keywords: Energy Efficiency Improvement, CO_2 Emissions, Distillation, Fossil Fuel, Industry

INTRODUCTION

The world consumption of fossil energy has been increasing annually. The estimated time for the depletion of oil, gas, and coal is approximately 35, 37, and 107 years, respectively [1]. In addition to its depletion, the increasing fossil fuel use promotes another problem related to the environment. Currently, the impacts of fossil fuel use on the environment, such as pollution, global warming, and climate change, are becoming a primary concern. The Kyoto Protocol was declared to provide binding commitments for countries to limit their fossil fuel use. This limitation creates a huge challenge for the development of alternative fuels and energy systems [2].

Improvement in energy efficiency is an important part in energy systems research. In industry, energy efficiency improvement means greater profit because it reduces the operating costs. The major concern for energy efficiency improvement is the distillation process because of being energy-intensive. Distillation processes use 40% of energy in a chemical plant [3]. Several configurations and techniques have been proposed to reduce energy usage in distillation, such as DWC [4-10], vapor compression (VC) [11,12], MVR [13, 14], compression-resorption heat pump (CRHP) [15], and thermoacoustics heat pump (TAHP) [16]. Related to the Kyoto Protocol, the present study examined the relationships among the improvement in process efficiency, energy use, and CO_2 emissions in the industry, particularly in the distillation process.

CARBON DIOXIDE EMISSION CALCULATIONS FOR DISTILLATION SYSTEMS

We considered CO_2 generation from a steam reboiler and electric equipment. Two systems were examined: one using only a reboiler as a power source and the other using both a reboiler and a compressor as a combined power source. The steam reboiler consumes fuel and is used to provide heat, steam, and power to the process. This unit becomes one of the most important elements in energy savings oriented projects and for reducing the environmental impact of emissions [17]. Electric equipment, especially compressors, are used to upgrade low quality energy in the condenser (sensible heat) to drive the energy to the column reboiler [18]. Here, the compressor acts as a heat pump that moves the heat energy from the top column to the reboiler.

The CO_2 emission effect of the steam reboiler was calculated by using the model developed by Gadalla et al. [17]. Fuel is combusted when mixed with air (oxygen), producing CO_2 and water according to the following stoichiometric reaction:

$$C_xH_y + \left(x + \frac{y}{4}\right)O_2 \rightarrow xCO_2 + \frac{y}{2}H_2O \quad (1)$$

Excess air is used to provide sufficient oxygen for burning all fuels. CO_2 emissions $[CO_2]_{emiss}$ (kg/s) of combustion in a steam reboiler

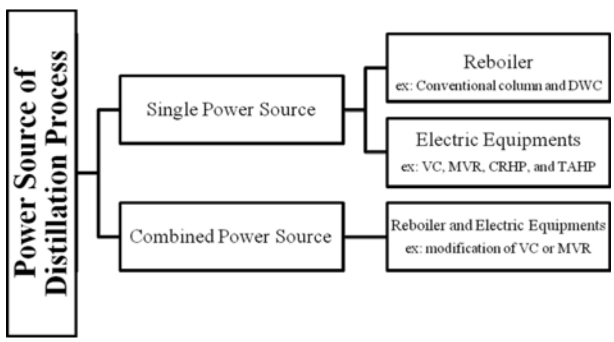

Fig. 1. Scheme of power source of distillation process.

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can be calculated by using the following equation:

$$[CO_2]_{emiss}=\left(\frac{Q_{fuel}}{NHV}\right)\left(\frac{C\%}{100}\right)\alpha \quad (2)$$

where Q_{fuel} denotes the energy from the burnt fuel, NHV stands for the net heating value of the fuel with carbon content of C%, and α (equal to 3.67) is the molar mass ratio of CO_2 and carbon. Natural gas was used as a fuel in this study with NHV of 48,900 kJ/kg and a carbon content of 0.41 kg/kg. The energy released from the burnt fuel is calculated as follows:

$$Q_{fuel}=\frac{Q_{proc}}{\lambda_{proc}}(h_{proc}-419)\frac{T_{FTB}-T_0}{T_{FTB}-T_{stack}} \quad (3)$$

where Q_{proc} is the heat duty needed by the system, λ_{proc} and h_{proc} (kJ/kg) are latent heat and enthalpy of the steam respectively. T_{FTB}, T_{stack}, and T_0 (°C) are the flame temperature of the boiler flue gases, stack temperature, and ambient temperature, respectively. Typical values of 1,800 °C, 160 °C, and 25 °C for T_{FTB}, T_{stack}, and T_0, respectively were adopted [17].

In the real world, electricity production fuel varies from natural gas, oil, and coal. The CO_2 emissions are higher using oil or coal to produce electricity, than that using natural gas. The CO_2 emissions of electric equipment were calculated from the data provided by the US Energy Information Administration [19]. The electric equipment energy was considered to have been supplied from a steam-electric generator fueled by natural gas, which is the cleanest fossil fuel. Natural gas was chosen to make a fair comparison with the steam reboiler, which previously also considered using natural gas as a fuel, and to show the impact of the cleanest fossil fuel in terms of CO_2 generation from electricity production.

CASE STUDIES

In this section, three processes using either single power source or combined power source are arbitrarily chosen to examine the relationships among the improvement in process efficiency, energy usage, and CO_2 emissions. These three processes are a DME purification process with DWC configuration and two acetic acid recovery processes with MVR configuration.

1. Dimethyl Ether Purification

The energy efficiency improvement of DME was performed by Minh et al. [6] using DWC. The study showed that the reboiler duty

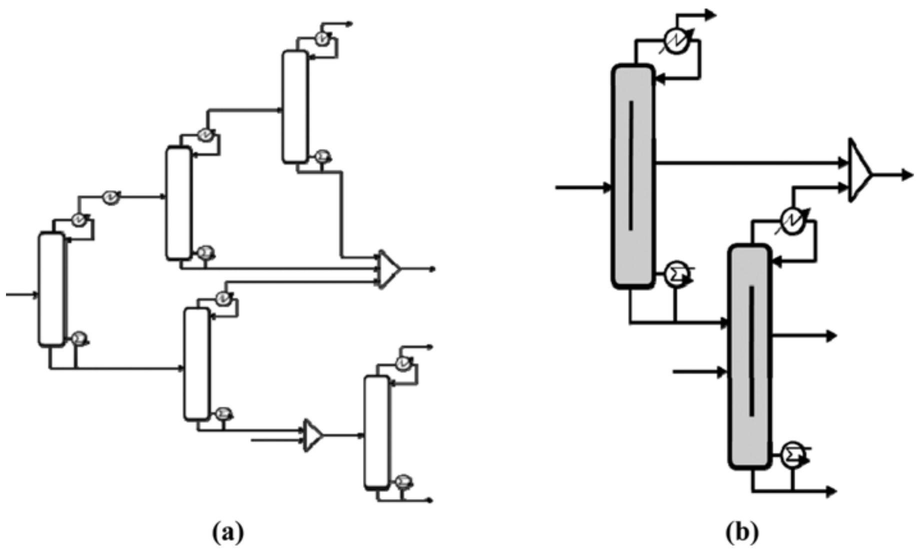

Fig. 2. DME purification process; base case (a) and energy improvement case (b).

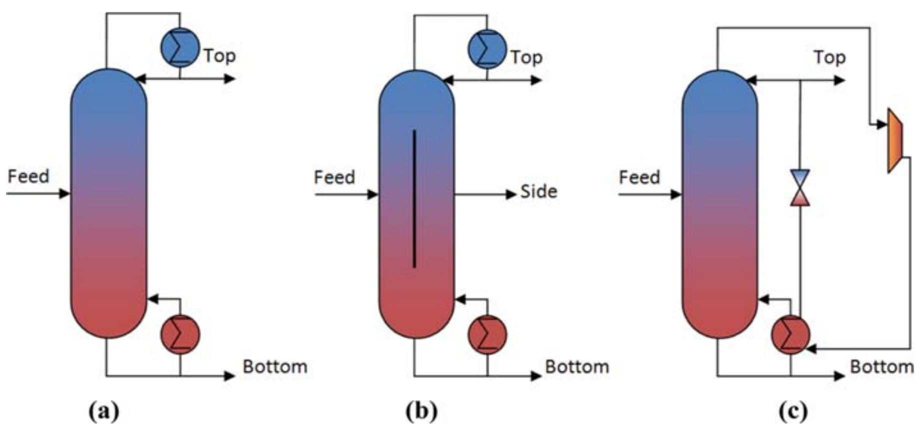

Fig. 3. Basic configuration of conventional distillation (a), DWC (b), and MVR (c).

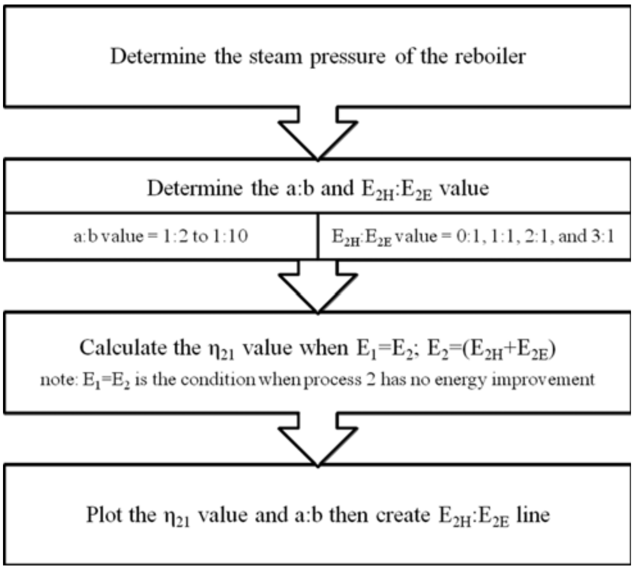

Fig. 4. Calculation step of tool for examining the uncommon system behavior.

of the conventional column sequence (base case) was 84.31 MW and the reboiler duty of DWC was 66.96 MW, which means that operating DME purification using DWC can save 17.43 MW or 20.57% less than the conventional distillation columns.

2. Acetic Acid Recovery with MTBE as Entrainer

Kürüm and Fonyo [20] examined the improvement in the energy efficiency of acetic acid recovery using MVR-based configuration. The aim of the study was to recover acetic acid with low boiling solvents and produce a glacial product of minimum 99.9% of the acid mass. The result was 37.70% energy savings using methyl tertiary-butyl ether (MTBE) as the entrainer compared to the conventional column (base case).

3. Acetic Acid Recovery with Ethyl Acetate as Entrainer

Same as the above case study, Kürüm and Fonyo [20] examined the improvement in the energy efficiency of acetic acid recovery using MVR based configuration but with different entrainer [20]. The result is 65.84% energy savings using ethyl acetate as the entrainer compared to the conventional column (base case).

RESULTS AND DISCUSSION

In the case of DME purification and acetic acid recovery, the CO_2 emissions can be calculated, as listed in Table 2. The results of DME separation revealed 17.34 MW energy savings, indicating a 2634.08 kg/h decreased in CO_2 emissions. For acetic acid recovery with ethyl acetate as the entrainer, the result revealed 914.45 kW energy savings, showing 74.79 kg/h decreased in CO_2 emissions. For acetic acid recovery with MTBE as the entrainer, the result was against the common belief, showing 209.45 kW energy savings, but a 25.17 kg/h increase in CO_2 emissions. This uncommon result was attributed to CO_2 emission generation by the use of different power sources, heat from the reboiler and electricity from power generation, in which the electric equipment requirement of energy at the same amount with the energy produced from the reboiler causes an increase in CO_2 emissions.

According to the CO_2 calculations for DME purification and acetic acid recovery, the paradigm of lower energy being directly proportional to lower CO_2 emissions is not entirely correct. This type of uncommon system can be found, e.g., a heat pump system that produces more CO_2 and improvement in energy savings such as the second case study. These uncommon systems normally have several energy sources, such as a steam reboiler and steam-electric generator. To avoid this problem, an efficient way for examining the uncommon system behavior was developed based on Eqs. (4)-(10).

$$\eta_{21}=\frac{E_1/\left(\frac{1}{\lambda_{proc}}(h_{proc}-419)\frac{T_{FTB}-T_0}{T_{FTB}-T_{stack}}\right)-\left(E_{2H}/\left(\frac{1}{\lambda_{proc}}(h_{proc}-419)\frac{T_{FTB}-T_0}{T_{FTB}-T_{stack}}\right)+E_{2E}\right)}{E_1/\left(\frac{1}{\lambda_{proc}}(h_{proc}-419)\frac{T_{FTB}-T_0}{T_{FTB}-T_{stack}}\right)} \quad (4)$$

$$\eta_{21}\geq 0 \quad (5)$$

$$1\geq\frac{\left(E_{2H}/\left(\frac{1}{\lambda_{proc}}(h_{proc}-419)\frac{T_{FTB}-T_0}{T_{FTB}-T_{stack}}\right)+E_{2E}\right)}{E_1/\left(\frac{1}{\lambda_{proc}}(h_{proc}-419)\frac{T_{FTB}-T_0}{T_{FTB}-T_{stack}}\right)} \quad (6)$$

where η_{21} is the energy improvement in process 2 over process 1 (base process). Eqs. (5) and (6) show that process 2 has lower energy use than process 1. Eqs. (5) and (6) are the first criteria that must be fulfilled by the system. If these equations are not fulfilled then the system will produce higher CO_2 levels compared to process 1 (base case). If these equations are fulfilled, then Eqs. (9) and (10), which represent the CO_2 emissions and act as the second criterion, can be used. Eqs. (9) and (10) determine whether a system is a common system or not. If the constraint in this criterion is fulfilled, then the system is certainly a common system and vice versa.

Table 1. CO_2 production per kWh by steam-electric generator

Fuel	Lbs of CO_2 per Million Btu	Heat rate (10^6 Btu per kWh)	Lbs CO_2 per kWh
Coal			
Bituminous	205.300	0.010128	2.03
Sub-bituminous	212.700	0.010128	2.10
Lignite	215.400	0.010128	2.13
Natural gas	117.080	0.010414	1.12
Distillate oil (No. 2)	161.386	0.010414	1.55
Residual oil (No. 6)	173.906	0.010414	1.67

Table 2. Comparison of energy usage, CO_2 emissions, and energy efficiency improvement of DME purification and acetic acid recovery

	Energy usage (kW)	Δ Energy usage (kW)	CO_2 emissions (kg/h)	CO_2 emissions (kg/h)	$Q_{proc1}/(Q_{proc2}+E_{2E})$ (%)
DME purification					
Base case	84.31×10^3		12805.11		
Energy improvement case	66.96×10^3	-17.32×10^3	10171.03	−2634.08	20.57
Acetic acid recovery with MTBE as entrainer					
Base case					
Reboiler	555.56		84.38		
Energy improvement case					
Reboiler	186.11	−209.45	109.55	+25.17	37.70
Compressor	160.0				
Acetic acid recovery with ethyl acetate as entrainer					
Base case					
Reboiler	1388.89		210.96		
Energy improvement case					
Reboiler	294.44	−914.45	136.17	−74.79	65.84
Compressor	180.0				

$$\Delta[CO_2]_{emiss}=E_1\cdot a-(E_{2H}\cdot a+E_{2E}\cdot b) \quad (7)$$

$$E_2=E_{2H}+E_{2E} \quad (8)$$

$$\Delta[CO_2]_{emiss}\geq 0 \quad (9)$$

$$E_1\cdot a\geq E_{2H}\cdot a+E_{2E}\cdot b \quad (10)$$

where E_1 and E_2 are the energy supply to processes 1 and 2, respectively; E_2 consists of E_{2H} and E_{2E} (kWh), which are the energy supply to process 2 for producing heat and electricity, respectively; a and b (kg CO_2/kWh) are the CO_2 generated by the heat and electricity source, respectively; a can be obtained from plant data and b can be obtained from Table 1. In this calculation, b always has a greater value than a because the electricity has lower efficiency. The inefficiency of electricity comes from the power generation efficiency, power loss in the transmission cables, and the electric equipment efficiency, which always produces higher CO_2 emissions. To avoid misusing the tool because of the differences in the process parameters, η_{21} should be added with β value. β value is a correction factor needed to manage slight differences because the calculation to make the tool is based on η_{21}, whereas it is common practice to use $Q_{proc1}/(Q_{proc2}+E_{2E})$. By specifying the ratio between E_{2H} and E_{2E} and also a and b, the boundary η_{21} value can be calculated, as shown in Table 3. A 20 bar gauge high pressure steam was used in this calculation.

The graph tool for examining the uncommon system behavior can also be obtained by plotting the η_{21} value on the graph as a function of a and b ratio, as shown in Fig. 5. The graph using the a and b ratio spans from 1 : 2 to 1 : 10. These ratios represent the CO_2 generation source ratio from the cleanest fuel, i.e., natural gas to the dirtiest fuel, i.e., coal.

The previous two case studies on the acetic acid recovery process were used as an example of using the graph. The x and y dots represent the acetic acid recovery using MTBE and ethyl acetate as entrainer, respectively. The E_{2H} and E_{2E} ratio for x and y was 1.64 : 1 and 1.16 : 1, respectively. The a and b ratio for both cases was 1 : 4.59. For safety and ease, 1 : 1 and 1 : 5 were used as the E_{2H} : E_{2E}

Table 3. Tool for examining the uncommon system behavior

a : b	E_{2H} : E_{2E} 0 : 1	1 : 1	2 : 1	3 : 1
1 : 2	$\eta_{21}\leq0.3144$	$\eta_{21}\leq0.1572$	$\eta_{21}\leq0.1048$	$\eta_{21}\leq0.0786$
1 : 3	$\eta_{21}\leq0.5429$	$\eta_{21}\leq0.2715$	$\eta_{21}\leq0.1810$	$\eta_{21}\leq0.1357$
1 : 4	$\eta_{21}\leq0.6572$	$\eta_{21}\leq0.3286$	$\eta_{21}\leq0.2191$	$\eta_{21}\leq0.1643$
1 : 5	$\eta_{21}\leq0.7258$	$\eta_{21}\leq0.3629$	$\eta_{21}\leq0.2419$	$\eta_{21}\leq0.1814$
1 : 6	$\eta_{21}\leq0.7715$	$\eta_{21}\leq0.3857$	$\eta_{21}\leq0.2572$	$\eta_{21}\leq0.1929$
1 : 7	$\eta_{21}\leq0.8041$	$\eta_{21}\leq0.4021$	$\eta_{21}\leq0.2680$	$\eta_{21}\leq0.2010$
1 : 8	$\eta_{21}\leq0.8286$	$\eta_{21}\leq0.4143$	$\eta_{21}\leq0.2762$	$\eta_{21}\leq0.2072$
1 : 9	$\eta_{21}\leq0.8476$	$\eta_{21}\leq0.4238$	$\eta_{21}\leq0.2825$	$\eta_{21}\leq0.2119$
1 : 10	$\eta_{21}\leq0.8629$	$\eta_{21}\leq0.4314$	$\eta_{21}\leq0.2897$	$\eta_{21}\leq0.2157$

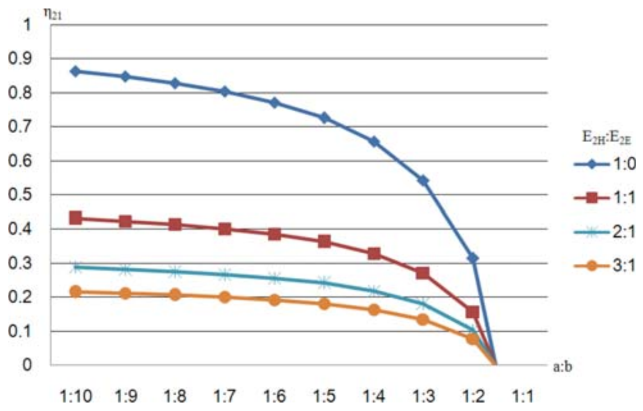

Fig. 5. Graphical tools for examining the uncommon system behavior.

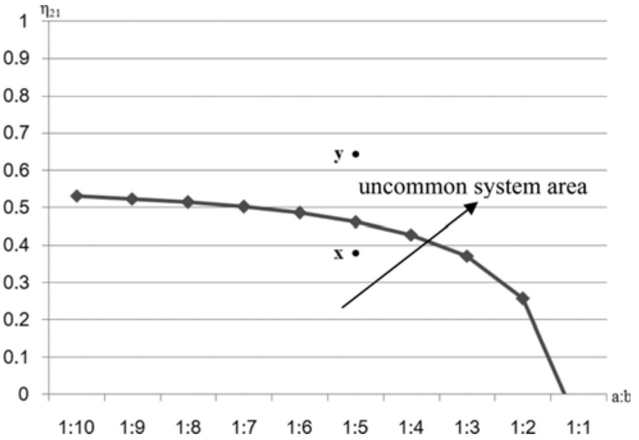

Fig. 6. Parameters of the case study in graph tool; MTBE case (x) and ethyl acetate case (y).

value and a : b value, respectively. In this example, the β value was specified as 0.1. The area below the 1 : 1 $E_{2H}:E_{2E}$ value is the area in which the system has a potential to be an uncommon system. Therefore, the acetic acid recovery using MTBE as entrainer is a system with a potential to have uncommon system behavior, as shown in Fig. 6. Further calculations (Table 2) showed that acetic acid recovery using MTBE is an uncommon system.

CONCLUSIONS

Many people believe the paradigm that lower energy use is directly proportional to lower CO_2 emissions. This study proves that this paradigm is not entirely correct. Several uncommon systems can be found, e.g., a heat pump system that produces more CO_2 with an improvement in energy savings. This highlights the need to carefully choose and use a heat pump system for the separation process when the reduction of CO_2 emissions is one of main concerns in process modification. To avoid the problem, an efficient tool for examining the uncommon system behavior was developed. This tool provides valuable guidelines as a first step to identify the potential of uncommon systems. The tool features several key criteria for estimating the existence of uncommon systemsw: a : b (ratio of CO_2 generated by heat to electricity), $E_{2H}:E_{2E}$ (ratio of energy supply to process with combined power source for producing heat to electricity) and η_{21}.

ACKNOWLEDGEMENTS

This work was supported by the Development of 300 MW class Korean IGCC demonstration plant technology of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and Doosan Heavy Industries and Construction grant funded by the Korea government Ministry of Knowledge Economy (2011951010001A).

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