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Quick assessment of binary distillation efficiency using a heat engine perspective

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ABSTRACT

With emphasis on close boiling, (near-)ideal VLE mixtures, this paper links the efficiency of distillation to the binary feed composition and thermal properties of the compounds. The proposed approach, treating the process as a heat engine, allows to directly quantify distillation performance (in terms of energy intensity & efficiency) based on the components boiling points and feed composition. In addition, this approach reviews and formulates simple, approximate and essentially non-iterative calculation procedures to quickly estimate the energy efficiency of distillation. These estimations may be applied to identify opportunities to save significant amounts of energy.

The results show that the reboiler duty for low relative volatility is relatively independent of the heat of vaporization and feed composition, while being reciprocally proportional to the Carnot efficiency of the distillation column. The internal efficiency for distillation of mixtures with low relative volatility has a maximum of about 70% for a symmetrical feed (equimolar ratio) and decreases to zero for unsymmetrical feed compositions approaching infinite dilution. With increasing relative volatility, the maximum efficiency is preserved, but the locus shifts towards lower light component fractions. At very high relative volatility, the internal efficiency increases with decreasing concentration of light component, as typical for evaporators.

1. Introduction

Distillation is historically the most extensively studied, well-known and analyzed separation unit operation. In spite of its benefits and wide-spread use, distillation is by its nature an energy inefficient process and thus it remains a significant contributor to the total use of energy resources worldwide, claiming about 95% of the total energy used in separations and roughly 3% of the total energy used in USA [9].

Proper understanding of distillation processes is clearly needed to elaborate on its efficiency. The energy intensity of processes is coupled with the origin of the energy, and transformation of the used energy to perform the desired separation task, i.e. objective evaluation of the efficiency of such processes. Understanding the energy intensity and efficiency of distillations by simple calculations is of practical importance. One interpretation of efficiency refers to the possible separation efficiency (i.e. product purities) relative to the number of theoretical (equilibrium) stages. Another interpretation refers to the thermodynamic efficiency (i.e. energy usage) that indicates possible reduction of energy use in separations. Numerous papers deal with the energy intensity and efficiency of distillation based on approaches using second thermodynamic law analysis, such as exergy analysis [8,17,31,32], entropy production analysis [10,16] and related pinch-analysis using equilibrium temperature-enthalpy profiles of distillation columns [5,12]. Table 1 summarizes the most encountered definitions of thermodynamic efficiency for distillation [14].

Ideally, a reasonably accurate estimation of the efficiency can be made on the basis of simple calculations. Some well-known rules of thumb for process feasibility based on properties of the separated compounds have been proposed [7]. These rules of thumb lack quantification of the estimated performance efficiency, and mostly present only boundaries of feasible or infeasible regions of individual process parameters, disregarding any interactions between those. In this work, a quantitative efficiency analysis based on exergy analysis is described.

Exergy analysis based and entropy production based analysis

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Table 1
Definitions of thermodynamic efficiencies for uncoupled and coupled processes.

Efficiency type	Uncoupled process	Coupling efficiency (coupled process)	Overall efficiency (coupled process)
Entropy (S)	–	$\eta_S = \frac{S_{SEP}}{S_H}$	$\eta_S^O = \frac{S_{SEP}}{S_H + S_L}$
Exergy (B)	$\nu_B = \frac{\sum B_{out}}{\sum B_{in}}$	$\eta_B = \frac{B_{SEP}}{B_H}$	$\eta_B^O = \frac{B_{SEP}}{B_H + B_L}$
Energy (E)	$\nu_E = \frac{\sum E_{out}}{\sum E_{in}}$	$\eta_E = \frac{\eta_S \eta_C}{\frac{T_1}{T_2} + \eta_S \eta_C}$	$\eta_E^O = \frac{\eta_S^O \eta_C^O}{\frac{T_1^O}{T_2^O} + \eta_S^O \eta_C^O}$

and optimization methods for distillations were reviewed over a decade ago [11]. The concept of the zero entropy production column was introduced as a theoretical machine with a thermodynamic efficiency equal to unity [13]. The effect of the thermal state of the feed was also studied [2,4]. Various strategies to improve the low thermodynamic efficiency of distillation of binary mixtures were proposed, such as introduction of various heat-pumping technologies [28,29], a diabatic distillation column with side reboilers and condensers [1,3] or advanced internal heat integrated distillation systems [20,24].

This paper analyzes distillation of near-ideal binary systems from a heat engine perspective (considering distillation as a process creating separation work) and investigates the influence of the feed composition and thermal properties of separated compounds on the internal efficiency of the heat engine. Limits of the heat engine analogy arising from additional thermal effects are defined using rigorous exergy analysis of a distillation process. This original approach allows a simple and direct quantification of distillation performance (energy intensity and efficiency) based on boiling points of the separated compounds and the feed composition. Although the efficiency formulas can be also derived from rigorous exergy balance approach [2], and numerical results obtained using pinch-analysis of equilibrium column temperature-enthalpy profiles [4], the approach proposed in this paper is more instructive and natural due to its clear analogy to Carnot's heat engine – especially if the reader is not an expert in exergy analysis and optimization approaches of distillation systems.

The transformation of heat in separation work in a distillation process is decomposed in partial contributions arising from the basic properties and composition of the separated mixture. Such an analysis reveals the challenge associated with distillation of particular binary mixtures and addresses the appropriate modifications of distillation technology, or selection of an alternative separation technique. This paper also provides some practical recommendations to improve the energy efficiency of distillation.

2. Results and discussion

Mixing of compounds is a spontaneous irreversible process that occurs with generation of entropy of mixing. Separation of a mixture is basically a reversed mixing process, thus non-spontaneous. As such, it needs delivery of work from outside to be driven [26]. This work can be done by:

- Addition of higher potential heat (e.g. desorption), with possible withdrawal of lower potential heat (e.g. distillation, evaporation)
- Shaft work using pumping or compression (e.g. membrane processes)
- Transport induced by external force-field (e.g. electrodialysis)

Besides external addition of work, separation operations can utilize the physical potential of the stream to be separated as well (i.e. the mixture to be separated has higher enthalpy, e.g. by elevated pressure, temperature or being saturated vapor instead of boiling liquid in case of distillation feed). Distinguishing between external work delivery and the physical potential of stream as sources of work is often just a matter of definition of boundaries. For example, physical potential of the stream can be achieved at the expense of external utility (e.g. mechanical energy of reverse osmosis inlet stream due to its pressure acquired by shaft work of a pump, or vaporization of a distillation feed prior to its injection to the column).

Understanding of separation processes as heat engines is advantageous to define the objective efficiency of such processes [2,9,14]. This definition reflects the fact that external work delivered combined with the work potential of the streams can be fully transferred into separation work only if such process works in a reversible mode, which is of course only a theoretical concept. Real irreversible separation processes always use more of the work potential than theoretically needed, and part of it is destroyed, which is reflected in the generation of entropy due to mass and heat-transfer phenomena. Fig. 1 provides a qualitative overview of the utilization of work potential for separation work and entropy production in distillation processes. The process efficiency can be defined as ratio of separation work produced over the work delivered & physical work potential used.

2.1. Separation work

The energy intensity of distillation is commonly expressed as heat duty of the reboiler, normalized on the feed or one of the products of importance (e.g. MJ/kg product). Although, such an expression is relevant regarding the expectably proportional consumption of utilities, it does not provide sufficient information on any objective assessment of:

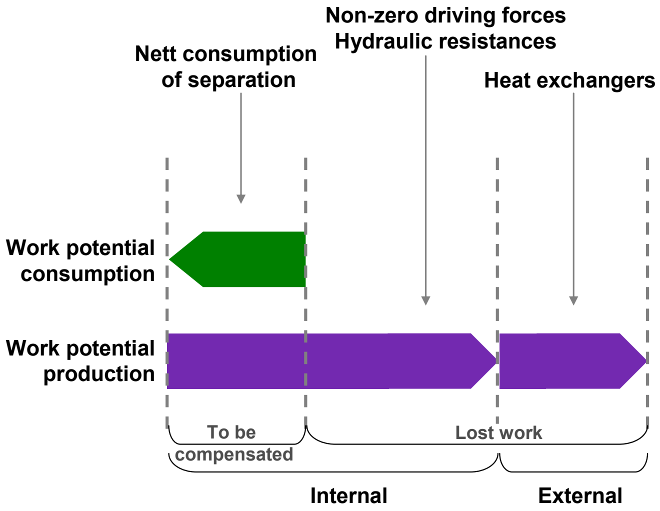

Fig. 1. Utilization of delivered work potential in distillation processes for separation and adjacent losses.