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# Energy efficient distillation

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ABSTRACT

Distillation is responsible for a significant amount of the energy consumption of the world's process industry and also in the natural gas processing. There is a significant energy saving potential that can be obtained by applying new energy saving distillation technology that has appeared in the last two decades. The fully thermally coupled dividing wall columns have the attractive feature of both savings in energy consumption and reduction of investment cost. In this paper we give an overview of some energy saving distillation arrangements and show how the Vmin-diagram can be used to assess separations and calculate energy requirements and provide a basis for detailed design. Reduced CO2 emission is an additional benefit that actually comes for free by the reduction of energy consumption.



## 1. Introduction

New distillation arrangements, like the dividing wall columns (DWC) (Kaibel, 1987), internally heat integrated columns (HIDiC) (Nakaiwa et al., 2003), heat integrated double and multi-effect columns show that there is a potential for significant reduction of energy consumption in distillation.

The separation of a feed mixture into a set of product streams is a basic task in natural gas processing. The objective is to obtain products that are sufficiently pure for further usage and conversion, and to carry out this separation with a minimum cost and energy consumption. Distillation is the most widely used industrial separation technology and distillation units consume a significant part of the total heating energy in the world's process industry. Distillation has been in use for a very long time and is often regarded as mature technology. However, demands to reduce capital costs, energy consumption and operation and maintenance costs, has lead to rethinking how the separation should be carried out. As CO2 emissions are directly related to the energy consumption, more energy efficient distillation also contribute directly to reduction in CO2 emissions. In addition, more energy efficient configurations that reduce the internal vapour and liquid flow rates give more compact units with a smaller diameter and thus reduce the capital cost (Agrawal, 2001).

The dividing wall column is an implementation of the fully thermally coupled Petlyuk column arrangement (Petlyuk et al., 1965) in a single shell. All these new arrangements aim at making the column operate closer to the ideal reversible system by reducing the thermodynamic losses. However, whereas the HIDiC approach with internal heat exchange between sections focuses on increasing the efficiency of a single binary distillation column, the Petlyuk (fully thermally coupled) arrangements and multi-effect columns are used for multicomponent separations.

We will illustrate some energy saving distillation arrangements and present how minimum energy requirements and detailed internal flow distribution can be calculated for fully thermally coupled arrangements. The solution is amazingly simple, as the minimum energy for a complex integrated extended Petlyuk arrangement is given by the most difficult of the product splits if that split is performed in a single two-product column.

In addition, external heat integration with other units in a plant is an option to save energy and reduce thermodynamic losses. A particular plant may have available heat sources and heat consumers at various temperature levels that may be utilised in conjunction with distillation units (Smith, 2005). However, this paper focuses on the energy efficiency within the distillation arrangements, and on multicomponent separation.

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The number of installed Dividing Wall Columns has passed one hundred (2009) and covers a range of different applications and sizes. A comprehensive overview of applications and engineering development is given by Dejanovic et. al. (Dejanović et al., 2010). Most of these are three-product columns but also some four-product columns have now been built: The largest at present has a diameter of 4 m (Olujic et al., 2009). A very attractive feature of the DWC is that in addition to save energy, it also saves capital cost and installation space. There are also revamp examples (Kolbe and Wenzel, 2004) resulting in both higher purity, higher throughput and less energy consumption compared to the original conventional arrangement. Many of the installed DWCs are in the chemical industry where energy usage is not a main concern, so the main reason for using Petlyuk columns is to simplify the design and save capital costs (Kaibel et al., 2004; Parkinson, 2007).

In this paper, we want to emphasize the potential energy savings (Halvorsen, 2001; Halvorsen and Skogestad, 2003a), where one main concern is good operation and control (Wolff and Skogestad, 1995; Halvorsen and Skogestad, 1999a). The typical potential energy savings for a three-product Petlyuk arrangement are in the range 20–30% (Triantafyllou and Smith, 1992). However, more complex fully thermally coupled arrangements have even larger potential, and an analysis of typical petroleum crude distillation towers shows a potential reduced vapour flow of 48% for a light crude by applying fully thermally coupled sections (Shah and Agrawal, 2009).

## 2. Background theory

### 2.1. Entropy and minimum energy

There is “no free lunch” with regards to separation. Thermodynamic work has to be provided to facilitate the increase in the entropy of mixing the streams ($\Delta S$). Distillation is a thermal separation process, where separation work is supplied by adding heat ($Q$) at high temperature $T_H$ in the reboiler and removing about the same amount of heat ($Q$) at low temperature $T_C$ in the condenser. The theoretical minimum heat supply for a reversible process operating under these conditions is given by:

$$Q_{\min} = \frac{\Delta S T_C}{1 - \frac{T_C}{T_H}} \tag{1}$$

Here, the entropy change for ideal mixing of pure components is given by:

$$\Delta S = -R \sum x_i \ln(x_i) \tag{2}$$

Here $x$ denotes the molar fraction of component $i$ and $R$ is the universal gas constant.

The energy usage $Q$ in conventional distillation arrangements is typically more than 50% higher than $Q_{\min}$ due to inevitable entropy losses, in particular due to remixing within column sections and interconnections and temperature differences in heat exchangers (reboiler and condenser).

Ideally, we want both a low energy consumption $Q$ (ref. 1st law of thermodynamics) and a high thermodynamic efficiency $Q_{\min}/Q$ corresponding to a small entropy loss (2nd law). In practise, this is in a way translated to a balance of capital cost (CAPEX) an operating cost (OPEX) as thermodynamic ideal configurations tend to require larger columns and heat exchanger areas.

Observe that $Q_{\min}$ is not fixed, but depends heavily on the temperature span, $T_H$-$T_C$. Thus, if we change the process to work across a larger span and we observe that the required heat flow $Q$ is reduced (improved 1st law efficiency), then the thermodynamic efficiency may not be improved after all because $Q_{\min}$ has also decreased (so 2nd law efficiency may not improve). Thus, we have to check the entropy production against the ideal reversible process at the actual temperature spans. However, to turn the case around, if we have available heat at a certain temperature, e.g. from a reactor, and have cooling available at another low temperature, then we should design the distillation arrangement to utilize the given temperature span.

### 2.2. Reversible distillation

It is possible to device a theoretical, reversible distillation column. Grunberg (1956), Petlyuk et al. (1964) and Fonyo (1974) give a basic description of both a binary column in Fig. 1 and a multicomponent arrangements. To get the minimum energy for distillation, we assume an infinite number of stages.

The key to the binary reversible column is to supply heat along the stripping section and to remove heat along the rectifying section in order to obtain the local operating line parallel to the equilibrium curve. An interesting observation is that the required vapour flow across the feed stage will have to be exactly the same as for ordinary columns (Halvorsen, 2001). A reversible multicomponent arrangement can be made by fully thermally coupled reversible sub-columns as shown in Fig. 2 for a ternary feed. Fully thermally coupled arrangements are described closer in section 3.2.

In multicomponent distillation, Petlyuk (F.B.a.P. Petlyuk and Slavinskii, 1965) and Fonyó (Fonyo, 1974) list two main properties that limit the possibilities for reversible operation:

1. Only one component can be removed in each end of a 2-product column. This is due to the fact that a pinch zone is needed across the feed stage, and this is only possible for so-called Class 1 separations. If we relate this to the Vmin-diagram (see below), reversible operation is only possible at

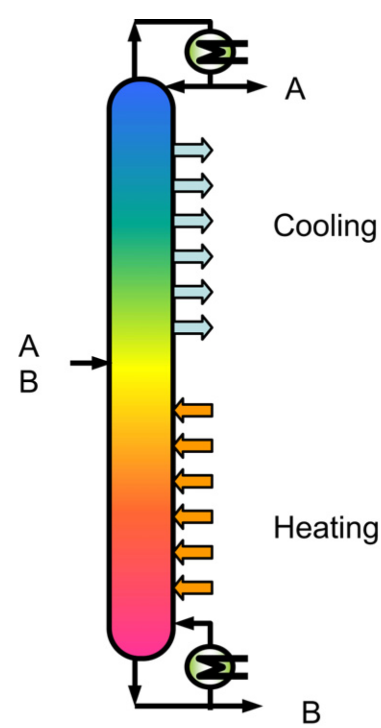


**Fig. 1.** A reversible binary distillation column has heat supply along the stripping section and cooling along the rectifying section.