The importance of heat integration in distillation columns engineering essay

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The combination of high crude oil prices due to increasing energy demand and concern about pollution has led researchers to exploring the possibilities of more energy efficient and environmentally friendly process technologies. The importance of distillation as a separation technique has made making it more energy efficient a high priority. Consequently, many heat integrated design schemes have been produced through the decades that it has been investigated and many of these techniques are outlined in this report along with some current commercial schemes. However, this technology has not been fully commercialised and this is mainly due to the high initial investment costs and the complexities of the equipment design, control schemes and operation. There is also a lack of real experimental data that is needed in order to verify the many theoretical predictions that claim that large energy saving are possible. Several areas have been identified as in need of further research in the future to hopefully allow this technology to become an industrial standard and not just a theory.

Introduction

1. 1 The Importance of Heat Integration in Distillation Columns

The combined threat of increasing energy demands and costs, global warming and the increased dependence upon oil imported from politically unstable parts of the world have resulted in an interest in enhancing the thermodynamic efficiency of current industrial processes. Increasing energy efficiency in chemical processes not only provides economic benefits but also it leads to reduce the emissions resulting from the process operation. Distillation is perhaps the most important and widely used separation technique in the world today as it is used for about 95% of all fluid separation in the chemical industry. In the US, about 10% of the industrial energy consumption accounts for distillation while it accounts for an estimated 3% of the world energy consumption. More than 70% of the operation costs are caused by the energy expenses (Nakaiwa et al. 2003.) It is a fact that the energy consumption in distillation and CO2 gases produced in the atmosphere are strongly related as the higher the energy demands are the larger the CO2 emissions to the atmosphere are. This is due to the energy being mostly generated through the combustion of fossil fuel. Despite its apparent importance the overall thermodynamic efficiency of a conventional distillation is only around 5-20% (Jana, 2009). Clearly, improving on this value is imperative and a top priority objective. In order to achieve this, the concept of heat integration was introduced almost 70 years ago (Jana, 2009.) The basic idea of heat integration is that the hot process streams are heat exchanged with cold process streams which results in a more economic use of resources. Consequently a whole range of heat integrated distillation schemes have been proposed.

In a conventional distillation column (Figure 1) with a feed, a top product and a bottom product, heat is added at the bottom of the stripping section. In distillation, heat is used as the separating agent. The heat is conventionally supplied at the bottom reboiler in order to evaporate a liquid mixture but is lost when liquefying the overhead vapour at the reflux condenser. The temperature of this heat corresponds to the highest temperature point in the distillation column. The temperature of the heat rejected at the top of the rectifying section corresponds to the lowest temperature point in the distillation column. Thus, distillation involves the loss of heat from a higher temperature level to a lower temperature level in order to perform the work of separation. The efficiency of distillation is reduced if the heat rejected in the rectifying section of the distillation column is not reutilized (Smith, 2005.) This is the principle from which heat integration of distillation is mainly based.

Full-size image (28 K)

Figure - A schematic representation of a conventional distillation column (Kiran, 2012)

1. 2 - Benefits and Drawbacks of Heat Integration

The possible benefits of heat integration tend to be potential energy savings due to greater efficiency and also less waste. Unfortunately due to a number of issues the technology has yet to be commercialised. Installation of any type of heat integration will entail a higher capital investment than that of any standard distillation column due to the increased complexity of the design. Also, the amount by which the efficiency is improved by is not always substantial in certain cases and therefore it must be considered whether the perceived benefits from the greater efficiency outweigh those of the added costs. The increased complexity can also increase the difficulty of designing, operating and controlling the system. There has also been a lack of experimental data for large scale examples to verify theoretical predictions. A successful heat integrated column design would show positive energy savings at reasonable economic figures that can be effectively operated and controlled.

2. Energy-efficient distillation techniques

This section discusses some of the many heat integrated techniques that have so far been proposed with the purpose of improving the energy efficiency of separation processes.

2. 1 - Pseudo-Petlyuk column

The thermally coupled distillation scheme was first patented by Brugma in 1937. The process is used for separating a ternary feed and consists of a conventional prefractionator and side stream tower. Both of these parts are equipped with a reboiler and a condenser. The unit is divided vertically by a wall through a set of trays in order to keep the feed stream and side product separated. It was Wolff and Skogestad (1995)who referred to this set up as a pseudo-petluk column. However, their research led to some concerns about serious issues during operation for high purity separations which would limit the effective use of this system in many cases (Wolff, 1995.)

2. 2 - The Divided-Wall Column

The elimination of the prefractionator unit from the pseudo-Petlyk column leads to a configuration known as the divided-wall column (DWC) (Robin Smith et al, 1992.) It is displayed in figure 2. It is achieved by introducing a vertical partition into a distillation column to arrange a prefractionator and a main column inside a single shell. The advantage of this partitioned column is that a ternary mixture can be distilled into pure product streams with only one distillation structure, one condenser and one reboiler. Naturally the cost of the separation is reduced along with the number of equipment units which leads to a reduced initial investment cost.

Subsequently, further research has been undertaken with for example Agrawal (2001) discussing for multicomponent mixture separation the various types of partitioned columns and their advantages and disadvantages. However, as a result of the lack of experience in design and control, the dividing wall columns were yet to be extensively used in industry. This is changing though and there has been a rapid growth in the number of units in use. In 2004 there were 40 units used worldwide (Adrian et al, 2004)

Full-size image (11 K)

Figure - A schematic representation of a Petlyuk distillation column (also known as divided-wall column) (Jana, 2009).

2. 3. Petlyuk column

Petlyuk et al (1965) presented a detailed theoretical study on a divided-wall column called the Petlyuk column. This reduced Petlyuk structure involves low initial investment and consumes less energy which reduces the operating costs. However, upon comparison with a conventional distillation unit the Petlyuk column has many more degrees of freedom in both design and operation which can cause difficulty when designing the column and creating a control system.

As displayed in figure 3, the two-column Petlyk configuration will commonly consist of a prefractionator connected to a distillation shell equipped with only one condenser and reboiler (Jana, 2009.). The thermal coupling in a Petyluk scheme has lead to large energy savings. Unfortunately, little progress has been made with regard to improving operation and control of the structure which hinders its usability.

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Full-size image (20 K)

Figure - A schematic representation of a two-column Petlyuk structure. (Jana, 2009)

2. 4 - Multi-Effect Column

The basic idea of this method for separating multicomponent mixtures is to use the overhead vapour of the one column as the heat source in the reboiler for the next column. The columns may be heat integrated in the direction of the mass flow which is forward integration or back integration can be used with is in the opposite direction. A sample column that represents a multi-effect column with a prefractionator for a ternary mixture separation is displayed in figure 4.

Full-size image (19 K)

Figure - A schematic representation of a multi-effect system for ternary (A-C) feed mixture (Jana, 2009)

This integrated arrangement has been proved to provide considerable energy savings (Cheng et al, 1985.) However, the issue preventing commercialisation of the process is the operation difficulties owed to the nonlinear, multivariable and interactive nature of the process (Han et al, 1996.) More research must be undertaken to try and find appropriate solutions before there can be a more extensive use for this system and to make use of the energy saving potential.

2. 5 - Heat Pump-assisted Distillation Column

The heat pump is mainly used as a way for increasing the thermal economy of a single distillation column. The heat pump-assisted distillation column or vapour recompression column (VRC) was implemented as an energy-efficient process for the chemical industries after an oil crisis in 1973 (Jana, 2009.) In the system the overhead vapour is pressurised by a compressor to the point where it can be condensed at an increased temperature which will supply the heat required in the reboiler. A schematic representation of this can be seen in figure 5.

Full-size image (14 K)

Figure - A schematic representation of a heat pump-assisted distillation column (Jana, 2009)

There are potentially large energy savings to be made, mainly for fractionating close boiling mixtures. This is due to the small temperature difference between the top and bottom of the column which will result in small compression ratios and consequently small compressor duties being required (De Rijke, 2007.) For a conventional distillation column attempting to fractionate the same close boiling mixture there will be a higher reflux ratio and thus larger reboiler duties would be required. The drawback for this technique is the high capital costs. Reducing the cost of running the heat pump-assisted distillation column would certainly increase its cost effectiveness and make it more viable as an option.

2. 6 - Heat integrated distillation column

Using heat pump technology it is possible for separate rectifying columns and stripping columns to be heat integrated internally. This structure is a heat integrated distillation column (HIDiC.) Originally only part of the stripping and rectifying sections were integrated under the name of the SRV scheme but later column design has incorporated heat integration between the whole rectifying and stripping sections (Jana, 2009.) Figure 6 displays a typical partial energy integrated distillation scheme.

Full-size image (26 K)

Figure - A schematic representation of a partial HIDiC scheme (Jana, 2009))

In this configuration the stripping column operates at pressure lower than the rectifying column. A compressor and throttling valve are installed in order to adjust the pressures. The pressure differential means there will be a corresponding difference in operating temperature which allows energy to be transferred between the two columns through heat exchangers. Reflux flow for the rectifying section and vapour flow for the stripping section is generated from the heat exchanged between the rectifying hot vapour and the stripping cold liquids. This allows the reboiler heat load to be substantially reduced. Less energy is consumed the more heat that is exchanged and through appropriate process design it can be possible for reflux and/or reboil free operations to be performed.

It has been shown that the HIDiC, compared to the VRC, can lead to energy savings of about 50% (Sun et al, 2003.) However, the structure has a very complex design and requires large capital investment (Jana, 2009.)

Meanwhile it has also been found find that there are many binary feed separations where HIDiC is actually less energy efficient than simple heat pump schemes using only one or two heat transfer locations. Furthermore, it was shown that the energy efficiency of HIDiC cannot be solely decided based on the feed composition or product purities as many calculations are based. A better performance indicator is the temperature profile along the height of the rectifying section relative to the corresponding temperature profile in the stripping section (Herron , 2011)

Research is ongoing, focussing on the dynamics and the thermodynamic efficiency aspects while extensive research was undertaken by Suphanit (2011) focussing on optimal heat distribution depending on the column arrangement and number of heat exchangers.

Suphanit also produced a couple of potential schemes display in figure 7.

Full-size image (41 K)

Figure - Fig. 2. Internally heat-integrated distillation column (HIDiC) (a) and HIDiC constructed in a concentric column (b) (Suphanit, 2011)

The development of HIDiC has now reached the pilot plant stage in some countries such as Japan and the Netherlands. Despite this, further research, both in terms of design and hardware development issues, is still needed before this application can be fully established and accepted in commercial use while further detailed study on the economic evaluation of this column structure is needed in order to ensure its advantage over more conventional schemes (Suphanit, 2011.)

2. 7 - Heat Integrated Batch Distillation Column

Batch distillation is generally known to be a less energy efficient option than its continuous counterpart. However, the batch distillation is extensively used in pharmaceutical, fine and specialty chemicals industry due to its greater flexibility where the demand and lifetime of the products can be uncertain and may vary significantly with time. Jana (2009) proposed a novel heat integrated batch distillation column (HIBDC.) The proposal was based on a binary batch distillation example that separates an equimolar ethanol/water mixture.

In comparison with the conventional batch process, the HIBDC also includes a compressor. The produced vapour in this concentric reboiler is firstly compressed and is then introduced at the bottom of the rectifier. This results in a pressure difference between the rectifier and reboiler. Consequently, energy is exchanged from the rectifier to the reboiler through the internal wall and brings the downward liquid flow for the former and upward vapour flow for the latter. This reduces the reboiler and condenser heat loads. However, an additional compressor duty is involved in the thermally coupled column.

Full-size image (28 K)

Figure - Schematic of a heat integrated batch distillation column (HIBDC) [D = distillate rate (kmol/h), L1 = flow rate of liquid leaving 1st tray (kmol/h), nt = top tray, Qc = condenser duty (kW), Qn = rate of internal heat transfer from nth tray (kW), R = ref reflux rate (kmol/h), VB = vapor boil-up rate (kmol/h)] (Jana, 2009)

From the investigation it was observed that the HIBDC system appears overwhelmingly superior to its conventional stand alone column providing a significant savings in energy as well as cost. The potential energy integration leads to achieving about 56. 10% energy savings and 40. 53% savings in total annual cost. However, a single example comparing different configurations does not indicate that the proposed method would perform equally successfully for all mixtures. Therefore it was proposed that further investigation would take place in the future to come to a full conclusion as to the future promise of this technique.

Takamatsu et al. (1998) also performed a comparative study between the heat integrated batch distillation and the conventional batch distillation that proved the superiority of the heat integrated scheme over its conventional counterpart in terms of energy efficiency. However, no more development has been found with regard to energy-efficient batch distillation.

2. 8 - Intensified Heat Integrated Ternary Distillation Column

Kiran et al. (2012) extensively investigated a novel intensified heat integrated ternary distillation column (int-HITDiC.) Their objective was to show that the int-HITDiC was superior in terms of energy consumption and economics than its general form, namely the HITDiC and the conventional standalone column. It was also investigated that the traditional HITDiC scheme shows a reasonable energy household and better economic figures than the conventional standalone column.

The int-HITDiC is a hybrid scheme which gets the advantage of both the HIDiC and VRC strategies. It was found that this kind of heat integration could help to improve the process design not only in terms of thermodynamic efficiency but also in terms of capital investment. The intensified scheme can be classified into two different structure based on the number of compressors: the single compressor int-HITDiC and the double compressor int-HITDiC. From experimentation it was found that the double compressor system provided the best performance in terms of cost and energy consumption where it produced a maximum energy saving of 59. 15%. Another attraction of the proposed double compressor int-HITDiC was its least payback time of excess capital which was 3. 44 years.

The performance of this proposed thermal integration techniques was measured using a ternary distillation system. A more general conclusion regarding energy and economic viewpoints could be found by extending its application to other example processes and checking for a consistent performance. An issue that should be mentioned regarding intensification is that although economic benefit is usually achieved the operability of the column tends to be reduced. Also, if the HIDiC is sensitive to disturbances then potentially the economic, safety and environmental performance may be unfavourably affected (Kiran et al, 2012.)

2. 9 - Internally Heat-Integrated Reactive Distillation Processes

Internally heat-integrated distillation and reactive distillation are two promising technologies that can potentially result in considerable economical benefits. Jiao et al. (2012) conducted a study regarding internally heat-integrated reactive distillation; a technology which combines internally heat-integrated distillation and reactive distillation and is employed in order to further enhance the advantages of both technologies.

The study tested three ideal quaternary systems, that reactive distillation processes with internal heat integration have been designed to use, to find which had the best potential for decreasing the total annual cost. These systems are types IP and IIP with stoichiometric design and also type IR which has excess design. In the case of type IP which has the reaction zone located in the centre of the reactive distillation column (RDC,) M-HIRDC will provide the highest economical benefit for the endothermic and exothermic reactions, chemical equilibrium constants and various relative volatilities. Here the reaction rate in the reactive trays in the high pressure section increases while in the reactive trays located in the pressure section the reaction rate will decrease. It is desirable to use HIRDC.

The reaction zone is located at the bottom of the RDC when using type IIP . Here the process with M-HIRDC will have better economical design than that of a conventional reaction distillation process in the case of both exothermic and endothermic reactions. The M-HIRDC's reactive trays are mostly positioned in the low-pressure section. Due to low pressure and temperature values the reaction rate is also smaller. It can be concluded that there are only minimal benefits to using HIRDC.

The final system, type IR, has its reaction zone placed at the top of the RDC. This process shows the smallest total annual cost for the endothermic and exothermic reactions. The reactive trays are situated in the HP section and due to the increased temperature and pressure values the reaction rate is also increased. Thus, HIRDC is again a desirable operation. In conclusion, when the reaction zone is situated at the top of the column the lowest total annual cost will be found for the RDC.

2. 10 - Externally Heat-Integrated Double Distillation Column

Liu et al. (2011) investigated the potential of externally heat-integrated double distillation columns (EHIDDiC.) In terms of the separation of an ideal binary mixture of hypothetical components A and B, the synthesis and design of the EHIDDiC were studied with the assumption of a constant pressure elevation between the low-pressure (LP) to the high-pressure (HP) distillation columns that are involved.

It was found employing between one and three external heat exchangers results in a reasonable design option for the EHIDDiC. When a number of external heat exchangers greater than three were employed the process configuration has to be carefully determined as the increase in number of stages externally heat-integrated may not actually be beneficial to the system performance. This is due to the strong mass and heat couple between the LP and HP distillation columns that are involved and reflects the unique feature of the EHIDDiC.

To reduce capital investment, the total external heat exchange areas should be installed through as small a number of heat exchangers as possible. The extreme situation would be the employment of a single external heat exchanger which would need knowledge in arranging the total heat heat transfer areas between the HP and LP distillation columns involved. These findings are of great significance both to process synthesis and design. A novel decentralised control scheme was also proposed for use for EHIDDiC operation. (Liu et al, 2011.)

Huang et al. (2011) investigated three different configurations for externally heat-integrated double distillation column's performances for separating a binary mixture of ethylene and ethane. The configurations were a symmetrical EHIDDiC (S-EHIDDiC), an asymmetrical EHIDDiC (A-EHIDDiC), and a simplified asymmetrical EHIDDiC (SA-EHIDDiC), which were compared with respect to aspects related to process design and controllability. It was found that the A-EHIDDiC and SA-EHIDDiC were both superior to the S-EHIDDiC in terms of thermodynamic efficiency as well as in terms of process dynamics and controllability. Upon comparing the A -EHIDDiC and SA-EHIDDiC, the latter showed similar behaviour with the former in terms of process design and controllability. These results demonstrated that the asymmetrical configuration should generally be favoured over the symmetrical one for the development of the EHIDDiC (Huang et al, 2011.)

2. 11 - The structured heat integrated distillation column

Krikken et al's (2012) recent investigation into a structured heat integrated distillation column showed that a plate-packing configuration using structured packing gave a superior performance in comparison with the HIDIC based on the plate-fin heat exchanger. Further experimentation showed that the mass transfer and heat transfer efficiency increased significantly with increasing throughput. However, this was accompanied by an increasing pressure drop per stage. By simulating an industrial scale plate-packing unit it was found that an even better performance is possible through increasing the volumetric thermal load by further optimisation of the internals.

The principle of a S-HIDiC is shown in figure 9. Here the rectifier and the stripper are alternatively stacked in a " sandwich" of layers which creates a high surface area for the heat and mass transfer while maintaining a high voidage.

Full-size image (36 K)

Figure - Flow scheme of an S-HIDiC.(Krikken et al, 2012)

Internals are used inside the layers to optimize the HIDIC performance. In the plate-packing HIDiC, which was developed and tested in this study, both heat and mass transfer are in balance at an acceptable pressure drop. This result of this is a column design providing substantial cost and energy savings.

It could be possible to optimise the column configuration even further by decreasing the number of heat integrated stages and by increasing the volumetric thermal load but research is ongoing with regard to this. It is also important to note that the results obtained were purely based on one experience with conventional packed columns so further optimisation of the performance through adjustment of the internals is required. It was also noted that in order to achieve this development of design models would be useful (Krikken et al, 2012.)

2. 12 - Other Noteworthy Techniques

Other techniques worth mentioning but are not explored in detail here are the inter-coupled column, concentric HIDiC, the fractionating heat-exchanger (all outlined by Jana, 2009,) control systems for heat integrated distillation systems with a multicomponent stream (Amidpour et al. 2012) and membrane distillation system using heat exchanger networks (Lu et al. 2012.)

3 - Industrial Applications

3. 1 - Using i-HIDiC to Separate a Close-boiling Mixture

It has already been proven that HIDiC can be superior in terms of energy savings when compared to other thermally coupled and conventional distillation columns. In an attempt to broaden the application of the ideal integration concept the economical and operational feasibility of the i-HIDiC scheme has been explored for the use in separating components of a close-boiling multicomponent mixture. It was found to be possible to employ two ideal HIDiCs to separate a hypothetical close boiling ternary mixture and two options of a direct and indirect sequence have been considered just as with its conventional equivalent.

It has been previously found that it possible to achieve 30% to 50% energy savings for the separation of two close-boiling mixtures using a HIDiC (Iwakabe et al, 2006.) However it was then found that the ideal HIDiC system is even more thermodynamically efficient than a conventional distillation system (Huang et al, 2007.) Huang et al. (2007) found a process that was conducted with minimization of the total annual cost in mind. They analysed the closed-loop controllability for the ternary mixture separation using the i-HIDiC and the intensified i-HIDiC. Upon comparison it was shown that the intensified i-HIDiC showed worse closed loop control performance with large overshoots and a longer settling out time due to the positive feedback mechanism that is involved within the intensified structure.

3. 2 - Heat-integrated Extractive Distillation

It is not possible to separate a binary mixture which has a very low value of relative volatility as the two components will evaporate at almost the same temperature and at a similar rate. For such cases extractive distillation can be utilised where a third components called solvent (which is a high boiling and relatively non-volatile component) is added in order to alter the relative volatility of the original feed components.

It has previously been investigated as to the effectiveness and operation feasibility of several energy-integrated extractive distillation technologies including the divided-wall column, Petlyuk column and heat-integrated extractive distillation scheme (Abushwireb et al, 2007.) The work included a comparison between energy-integrated extractive distillation columns and conventional extractive distillation technique based on the recovery of aromatics from pyrolysis gasoline using a solvent called N-methylpyrolidone.

The optimum design was found through using a minimal total annual cost as the objective function. The conclusion of the study was that the designed extractive distillation schemes should meet all expectations in terms of energy consumption and purity of cuts. It was shown that the heat-integrated extractive distillation configuration is the preferred option ahead of the Petlyuk column, divided-wall column and conventional column.

3. 3 - Separating Close-boiling Mixtures using Heat Integrated Pressure-swing Distillation

Three commonly used techniques for fractionating a binary close-boiling mixture are azeotropic distillation, extractive distillation and pressure swing distillation (PSD.) The first two techniques require a third component called a solvent that enhances the relative volatility of the components that are to be separated. This can lead to certain drawbacks such as the solvent never being completely removed thus adding impurity to the products, the cost of solvent recovery, the loss of solvent and potential environmental concerns (Treybal, 1980.)

These potential issues with using a solvent have allowed the PSD approach to emerge as an attractive alternative option. An important prerequisite for the use of a PSD column is that the azeotrope separate has to be pressure sensitive. Here you have a low pressure (LP) distillation column and high pressure (HP) distillation column that are combined to avoid the azeotropic point. The inclusion of the HP and LP columns in the PSD configuration allows for the possibility of heat integration to be explored. Two appropriate types of energy integration for PSD processes were shown by K. Huang et al. (2008.) The first is the condenser/reboiler type heat integration where the condenser of the HP distillation column is integrated with the reboiler of the LP distillation process. The other option is the stripping/rectifying section type heat integration where the stripping section of the LP distillation unit is coupled with the HP distillation unit's rectifying section. It was found that for separating close-boiling mixtures the best option is the latter while for other types of mixtures the reverse is actually true. However it was clear that both types of heat integrated PSD column have potential for large energy savings when separating close-boiling mixtures.

Yu et al. (2012) also developed a new method for separating methyal/methanol using PSD. There it was found that the fully heat-integrated pressure swing distillation process had lower costs due its energy saving capabilities.

3. 4 - Heat integrated Cryogenic Distillation

Cryogenic distillation columns will generally operate at extremely low temperatures. An example of this the process of separating air into its basic components where the process will run at about 100K (Mandler, JA. et al. 1989.) This temperature is low enough that oxygen and nitrogen will be in their liquid state and can consequently be separated in the column.

The cryogenic separation unit has a highly costly installation arranged with the condenser if the overhead vapour is meant to covert to liquid phase as the overhead vapour is enriched with more volatile component which has a very low boiling point. The heat integration principle can be used by coupling the reboiler and condenser in the cryogenic distillation unit in order to reduce this high energy cost. The energy that is expelled in the condenser can then be utilised in the reboiler.

A heat integrated cryogenic distillation column (HICDiC) that is constructed with two smaller c