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Design of Heat-Integrated Columns: Industrial Practice

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Heat integration of distillation columns offers a significant potential to reduce energy costs and carbon footprint in process plants. The conceptual design for heat integration is straightforward: candidate columns may be identified simply by evaluation of the vapor pressure curves of their top and bottoms products. Once the energy and cost savings potential is estimated, the easy part is over and the real fun for the designers begins. Successful implementation of heat integration will have a strong impact on the whole plant setup intensifying interactions between equipment design, plant layout, instrumentation, process control, and safety concept. In order to master this increased project complexity, the design team needs to begin to tackle these questions in early project stages and find sustainable solutions in the pre-basic engineering phase already.

The paper outlines a useful methodology for the successful design of heat-integrated column systems. The guidelines provided help the practitioner to anticipate typical problems and pitfalls and to find practical solutions resulting in in cost-effective, reliable designs near the energy optimum. The methodology has been successfully applied in industrial practice and is demonstrated using a recent project as an example.

1. Introduction

Distillation is the workhorse in industrial fluid separations and can be expected to remain so for the foreseeable future. Major advantages are its versatility, its ability to produce pure products in single steps, the availability of proven design software with appropriate models for vapor-liquid equilibrium (VLE) and hydraulics as well as internals manufacturers supporting the user with their experience and reliable hydraulic calculations. Major drawback of distillation is its energy demand, causing a sizeable part of the operational cost of process plants.

Separation systems are typically designed around reactors of given performance to recycle unconverted raw materials and separate unwanted by-products. In order to reduce the energy demand of distillation systems, a first step should address conversion and selectivity of reactors, to decrease the effort for by-product removal. Once these options to simplify the separation task are exploited, energy-saving distillation sequences and heat integration offer significant potentials to reduce energy costs (Jobson, 2014).

1.1 Energy saving in distillation sequences

Besides optimization techniques, there are several heuristic rules, guiding the designer in the search for good separation sequences, e.g. removing the lowest boiling component first or leaving the most difficult separation for the last step (King, 1971), keeping in mind system specific parameters like thermal stability, polymerization or foaming tendency. Each single column in this sequence should be optimized individually to find its best configuration like number of stages, feed location, pressure or preheating requirements. In this way, a separation system of simple columns is identified, which may serve as a fair basis for further optimization.

A first step to reduce energy cost is to look for chances to remove separation steps, e.g. by introduction of side-streams or side columns. A systematic way to identify locations of side reboilers or condensers saving utility cost is given by Smith et al. (2011). Next, opportunities for divided wall columns (Niggemann et al., 2010) should be investigated. For hybrid systems involving pervaporation, see Kreis and Górak (2006). In close-boiling systems of considerable energy demand, mechanical (or thermal) vapor recompression (VRC) may be economical despite large additional investment (see Ulyev et al. 2016, Liew and Walmsley 2016).

To enable heat integration, the operating pressures of selected columns are adapted to allow re-use of the condensation duty of a heat supplying column (HSC) to reboil a heat receiving column (HRC) in an integrating

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reboiler / condenser, see detailed studies by Luyben and co-workers (Cheng and Luyben, 1985). Heat integration is a standard in air separation (Moll, 2014). In forward and reverse integration, the direction of heat integration is co- or countercurrent to the main processing direction. Heat integration may also be applied to prefractionator systems (Jobson, 2014) and pressure dependent azeotropic separations (Repke et al. 2005).

Internally heat-integrated columns (HIDIC) are a combination of heat integration, vapor recompression and side heat exchangers, thus approaching the ideal reversible separation (Jobson, 2014). In a comparative optimization study, Harwardt and Marquardt (2013) conclude, that the VRC and HIDIC are more economical than conventional columns only for close boiling mixtures. In all cases investigated, VRC was more cost-efficient than HIDIC. Not surprisingly, the conventional column was best at higher relative volatility.

1.2 Pinch Point Analysis

As soon as a first conceptual design satisfying the principal requirements of target conversion, selectivity and product quality is found, it is time for a first Pinch Point Analysis. Hot and cold streams are aggregated into composite curves and the pinch point is identified by setting a minimum temperature difference for heat transfer. The composite curves show that the reboilers and condensers of individual columns are working across the pinch and are candidates for heat integration, if suitable changes in process parameters can be achieved (Dhole and Linnhoff, 1993). Therefore, it is useful to separate the columns from the background process and draw them as simple boxes in a temperature-duty diagram, Figure 1. In this diagram, the boxes representing columns C1 to C3 of the example process (section 3) can be moved by increasing their pressures so far, that their top temperatures are sufficient to reboil the HRC, saving both external heating and cooling duty (Kemp, 2007).

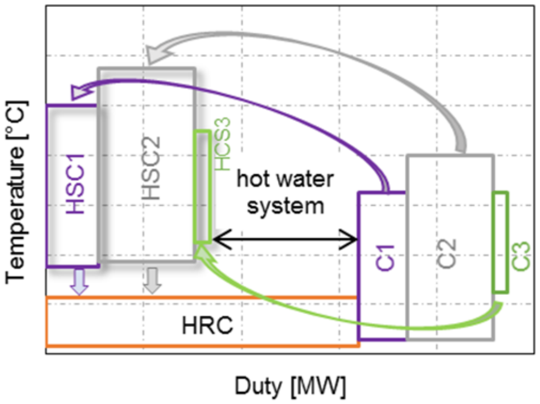


Figure 1: Adjusting pressures of columns C1 to C3 for heat integration in the example process.

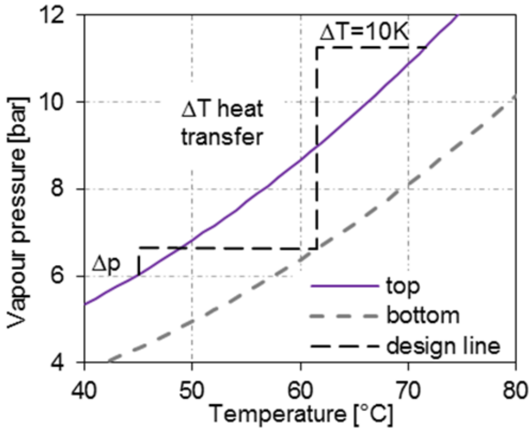


Figure 2: Selection of column pressures for integration in Butane systems.

2. Design of heat-integrated column systems

In industrial practice, investment or optimization projects are executed under the twofold pressures of limited cost and time. Starting out from a conceptual design fulfilling the most basic processing requirements, the project team is challenged to quickly come up with workable ideas creating additional project value. Heat integration is a most promising option to contribute to this objective by reducing energy cost. As shown in Figure 2, candidate pairings of columns are easily identified by looking at the vapor pressure curves of top and bottom products by stepping of the driving temperature difference for heat transfer (here: 10 K) and the pressure drop of internals. Using this diagram to design a VRC system gives a pressure ratio of about 1.9 for the compressor.

2.1 Basics

As outlined above, design of an optimal sequence of simple columns should be the first step. Though rather obvious, some simple prerequisites are often overlooked. Only the best VLE data and efficiency estimates available should be used and validated using experimental data from laboratory, similar industrial separations or F.R.I. data. Next, utility information for the chosen site should be evaluated. Availability, pressure / temperature rating and cost will limit the acceptable solution space for optimizations.

In a business engineering alignment meeting, the relevant range of feed composition should be discussed and clearly defined.

Reactor selectivity and conversion data need to be challenged, start-of-run / end-of-run conditions need to be defined. Based on these accepted findings, a clear concept for the load ranges, design margins, and fouling factors is to be developed.

2.2 Heuristic methodology

A heuristic methodology successfully exercised in many investment projects can be outlined as follows:

- Find the best sequence of simple columns and look for improvements like side or divided wall columns.
- Perform a first Pinch Point Analysis to find obvious heat integrations like bottoms-feed exchangers.
- Look for candidate columns for heat integration by changing operating pressures, see Figure 2. Higher pressure reduces relative volatility and increases energy demand. Therefore, it is preferable to increase the pressure of easier separations.
- Check, if the energy balance in a chosen pairing is insensitive to changes in operating conditions e.g. feed composition to avoid cross-overs in energy demand and supply: If the HSC or HRC are “infinite” heat sources or sinks, respectively, heat integration will not substantially increase control loop interactions.
- Only supply either a trim condenser or a trim reboiler, never both, as indicated in Figure 3. A superfluous exchanger will run at full capacity most of the time and simply reduce the degree of heat integration. To balance heat demand and supply, it may be more economical to over-design the capacity of one of the columns instead.
- Re-run the Pinch Point Analysis to prove that the modifications applied so far are consistent.
- Check the plant layout for feasibility of proposed heat integrations (e.g. proximity, height alignment).
- Perform detailed equipment sizing calculations for column internals, heat-exchangers, and pumps. Include load-dependent pressure drops and heat-transfer calculations into the simulation, see section 3.1.
- Revise plant layout to accommodate some new, probably large exchangers.
- Position condenser, reflux drum and pump to ensure sufficient NPSH without wasting column height.
- Design the control system and check for sufficient instrumentation. Instrumentation allowing closed mass and heat balances around integrating exchangers is strongly recommended.
- Perform a simulation crash test of the integrated system to find out how it will behave at start-up, i.e. under partial load, with per definition clean heat-exchanger areas, see Figure 4.
- Discuss the control system and instrumentation to accommodate operators’ needs (section 3.1).
- Design the safety concept for the coupled system of two or more columns, validate the shutdown or relief system using dynamic simulation (section 3.2) and design the control system using this model.
- After start-up, compare design to reality and learn. This is where know-how is forged.
- Ensure good communication within the project team. Design engineers from all disciplines involved should share a sound understanding of the impact of heat integration on overall project success and protection of the environment.

3. Project example

In a recent project example at Marl, Germany, the energy demand of a larger plant including several other separation steps and reactors was dominated by a superfractionator column separating a close-boiling mixture (Figure 3). Superfractionators typically have low bottoms temperature, making them ideal candidates to serve as the heat receiving column (HRC). Application of the heuristic methodology showed, that more than 40% of its energy demand could be supplied by raising the operating pressure of three other columns in the same plant, as outlined in Figure 1. Column design pressures needed to be increased by 1 to 4 bar. Steam of higher quality was required only in one column. The energy demand of the three HSC was increased by less than 10%.

The Marl site provides a hot-water system. This system collects waste heat from other plants on the site at a temperature sufficiently high to reboil the superfractionator. This system was expanded to supply the remaining duty, see Figure 1.

Thereby the full reboiler duty of the superfractionator could be supplied by waste heat streams only.

3.1 Operability

Special consideration needs to be given to the integrating heat exchangers under varying load and start-up conditions. Besides the usual design margins on heat exchanger area, two more effects come into play: the plant is normally taken into operation at partial load and – by definition – clean heat exchanger surfaces. These three effects will superimpose to reduce the temperature difference required at start-up. Consequently, it may be difficult or impossible to sustain the design top pressure in the HSC. To avoid unpleasant surprises during start-up, it is recommended to perform detailed simulations of the integrating heat-exchangers under the conditions expected at start-up to ensure stable operation, e.g. circulation in thermosiphons. Kettle reboilers have shown excellent stability even at very low temperature difference.

As long as stable evaporation is ensured, the heat transfer coefficient will decrease somewhat with smaller driving temperature difference. Application of fouling factors, however, considerably increases the calculated heat exchanger area. Figure 4 shows that the top pressure of one HSC column changes by about 1 bar at 50 % load and that the set-points for 100 % load are different for clean and dirty surfaces (assuming full utilization of exchanger area). Since fouling is a slow process, only one condition has to be dealt with at the same time and the pressure set-point can be adapted as needed.

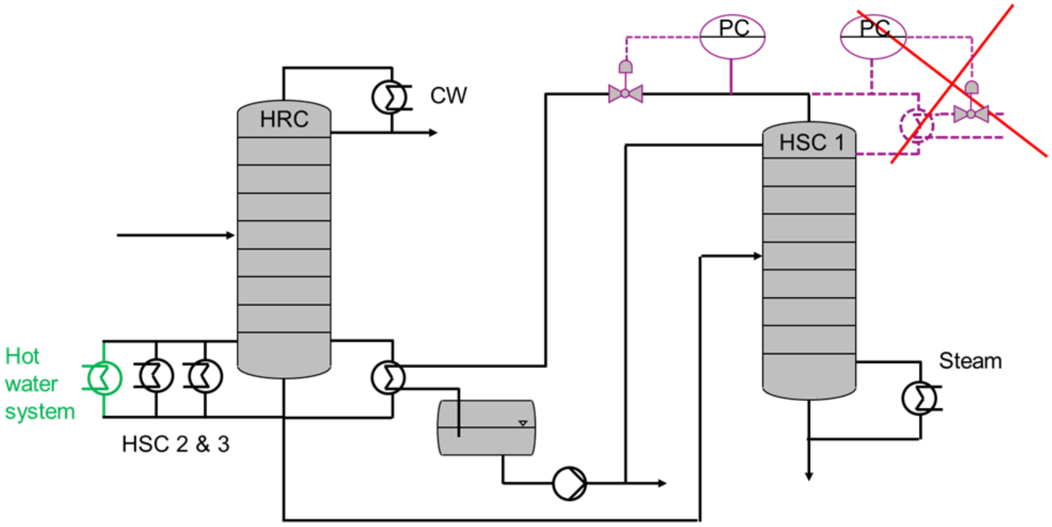
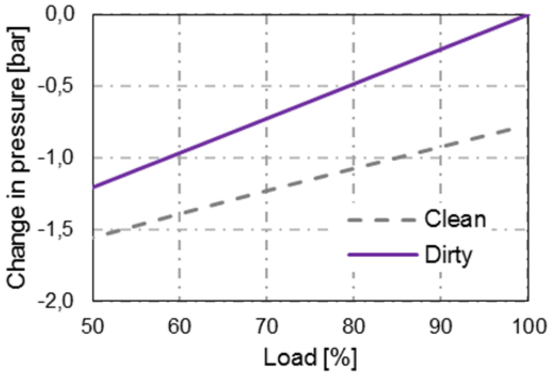


Figure 3: Example project: Flowsheet of the superfractionator as HRC one HSC and other heat inputs.

From a purely thermodynamic point of view, floating pressure (i.e. no pressure control) in a HSC is sufficient. Floating pressure, however, also implies floating tray temperatures – a situation well outside operator experience. In order to provide effective pressure control, flooded condensers (Luyben, 2017) may be designed. In the present example, control valves were introduced in the HSC's overhead lines. Figure 5 shows the top pressure of a HSC and the actual condensation pressure in the integrating exchanger. In most cases, stable column pressure was achieved. Whenever the temperature difference is insufficient, the control valve is fully open and the column switches to floating pressure operation. After the operators have experienced a few of these situations as unproblematic, confidence in the integrated system is established. Note, that the trim condenser of the HSC has been eliminated, see Figure 3.



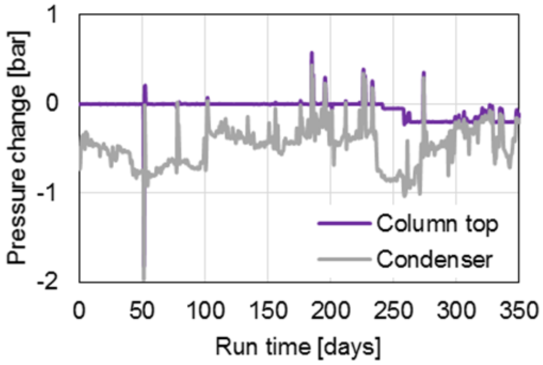


Figure 4: Change of HSC top pressure with load and fouling condition.

Figure 5: Pressure control of HSC.

3.2 Safety concept

A shutdown system limits the pressure of the superfractionator in the case of cooling failure. Shutting down several individual heat inputs at the required safety integrity level (SIL) is problematic with the accepted valve failure rates. To evaluate the shutdown system, a dynamic model considering realistic models for tray holdup and liquid dumping was developed (Bodizs et al. 2014). To simulate a cooling failure, the HRC's condenser duty is set to 0 after 1 min, Figure 6 a). Column pressure and bottoms temperature quickly rise. With a short time lag, the HSC's pressure also rises to keep up the temperature difference required for heat transfer. 4.6 min after the cooling failure, the pressure of the HRC reaches the trip value of its own shutdown system. All heat inputs are shut down with a valve closing time of 15 s, with exception of the duty from one HSC see Figure 6 b). Less than 2 min later, this HSC also reaches its own trip pressure and the last external heat input to the HRC is also shut down. Since there is still some heat transfer in the integrating condenser / reboiler, the HSC's pressure quickly starts to fall, while the HRC's pressure still slowly rises. About 10 min after the cooling failure, the temperature difference driving heat transfer in the reboiler / condenser falls below 5 K. The trays in the HRC have dumped all their liquid holdup and its pressure has almost reached the final value.

The safety concept for heat integrated columns needs to consider the interaction within the whole system. As the simulation results show, it is sufficient to design SIL-qualified shutdown systems for each individual column. In the example presented, the HSC with the highest duty shuts down on its own high-pressure trip. Note, that the pressure control valve in the overhead line may also be utilized in the shutdown system.

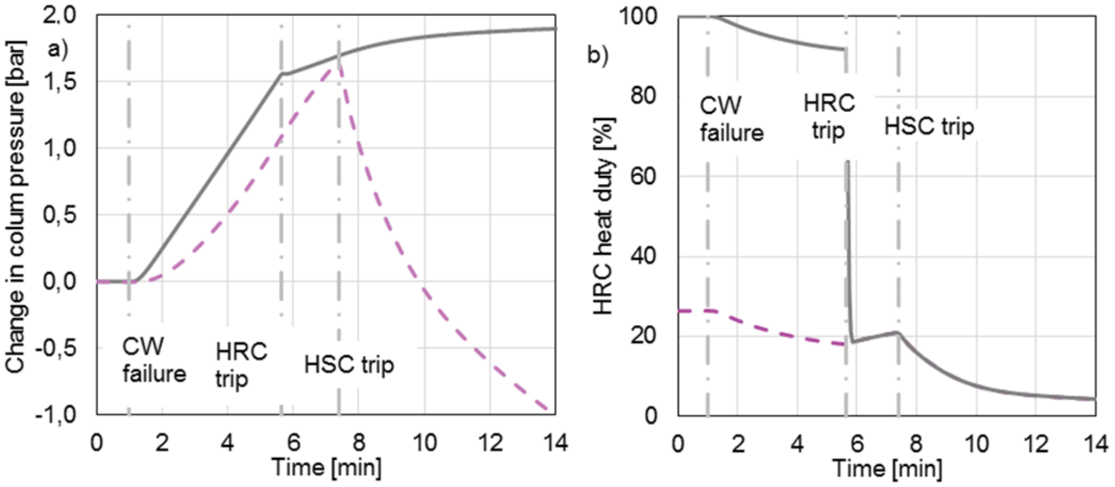


Figure 6: Dynamics of column system shutdown: a) Change of column pressures b) total heat duty of HRC and contribution of one HSC in relative terms. Solid line: HRC, broken line: HSC.

3.3 Economics & environment: Life cycle cost & CO_2 reduction

Cost savings caused by reduced utility consumption seldom come for free. In most cases, heat integration will increase equipment costs for thicker shells, taller columns and larger heat exchanger areas. Furthermore, additional cost for detailed design, instrumentation, piping, insulation and advanced process control is to be expected. Keeping in mind that the plant will not always run at design capacity, it is probably reasonable to set a target for the payback time at about 5 years as an upper margin for additional investment. Thoroughly designed heat-integrated systems will in most cases easily beat this target.

Besides savings of inside battery limits running costs, further savings may be possible in utility production and supply. If utility availability on-site is already tight, new projects will cause considerable investment in steam or cooling water supply. In the example process, expenses for a new cooling tower could be saved. This reduction in investment will pay many bills for thicker vessel shells.

An initial estimate showed VRC as the most economical alternative for the superfractionator by itself, as long as the comparison was limited to capital versus utility cost for steam or electricity. From a project and company-wide point of view, however, the chosen path of integrating waste heat was more economical. Cost for hot water duty is income for other plants within the company, condensation duty from within the plant comes almost for free.

The carbon footprint of the new plant was minimized.

3.4 Pitfalls

Even the most thorough project definition will not cover all eventualities. Unexpected high or low boilers occurring in the feed or produced in reactors may reduce the driving temperature difference in integrating exchangers. Providing ample venting capability and margins in vessel design pressure helps to mitigate this risk.

Pressure control in the HSC's overhead line led to a very fast trouble shooting success during start-up. Operators forgot to adapt the top pressure set-point to partial-load conditions. In the attempt to maintain column pressure at the now too high value, the controller caused an excessive pressure drop in the overhead control valve. Consequently, the pressure in the reflux drum was so low, that the available head of the reflux pump was insufficient to return the reflux to the column. Trouble-shooting was limited to lowering the pressure set-point.

4. Conclusions

Heat integration of distillation columns offers a significant potential to reduce energy costs and carbon footprint in process plants and constitutes a large step towards more environmentally friendly and sustainable processing plants. Heat integration of columns is shown to be a most practical tool to contribute to these goals. Compared to other energy saving techniques like VRC, heat integration can be realized with relatively low capital expenditure using little additional and only standard equipment. Furthermore, the conceptual design for heat integration is straightforward. Once the energy and cost savings potential is estimated, however, the easy part is over. The engineering team is challenged to bring the design to life avoiding the pitfalls lurking in the intensified interactions between equipment design, plant layout, instrumentation, process control and safety concept.

A heuristic methodology is provided helping the practitioner to find cost-effective, reliable designs for heat-integrated columns near the energy optimum.

In order to master the increased project complexity caused by a heat-integrated distillation sequence, the designers need to begin to tackle these questions as early as possible. In an industry striving towards more sustainable process plants, first energy saving considerations should be an integral part of any feasibility study and solid estimates should be performed in the pre-basic engineering phase at the latest.

Designing a heat-integrated plant is a team effort. Experts from the disciplines simulation, process and equipment design, control, plant layout, piping and operations need to work hand in hand in finding and realizing elegant solutions.

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