Low Temperature Separation Systems

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Distillation is the competitive process for separating the components of a gas mixture such as natural gas or the effluent of the reactor in an olefin plant. To purify the elements of a light hydrocarbon-mixture economically, reliably, and environmentally benign, efficient separation equipment with the appropriate operating conditions should be selected throughout the separation train. This pursues an integration effort to reduce the primary energy consumption of the system and optimise the quality of the required energy. Nevertheless, the demand for utility at below ambient temperatures will not disappear. Hence, refrigeration systems should be provided for such processes.
Conceptualising the relevant processes of a gas plant, to identify the promising options, results in the study of the following building blocks and their interactions.

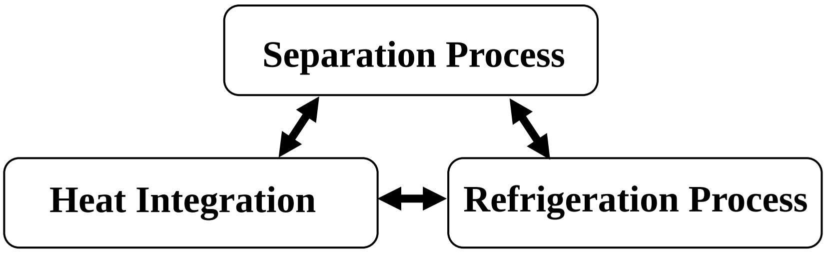


Figure 1: Building blocks of a cryogenic plant design methodology

In this writing, important interactions between the separation system and the refrigeration process are highlighted.

1. Separation and refrigeration system interact in a complex but effective manner

A refrigeration cycle accepts heat from the process at a range of (absorption) temperatures, raises its quality through compressors and rejects the absorbed heat and the added shaft-power, through compression, to a sink at a higher (rejection) temperature. The closer the rejection temperature to the absorption temperature, the lower the pressure ratio in the compressor, and hence, the power consumption of the refrigeration system will be low. On one hand, an option for the refrigeration system is always to upgrade the absorbed heat from the process to the ambient temperature. On the other hand, often the background process can offer heat sinks at a range of temperatures, below the ambient temperature. The refrigeration system can utilise these sinks and reject at least part of the absorbed heat back to the process at a lower temperature compared to its other option: ambient temperature. The main contribution of the described integration between the separation and refrigeration system is the reduction in shaft power for the refrigeration system.

The interactions between the refrigeration and separation system should be considered at the early stages of the design. This is, first, to ensure the maximum exploitation of the integration opportunities. Second, considering these interactions may affect the process heat integration decisions. For instance, it may prove more beneficial to integrate a particular sink in the separation process with the refrigeration system rather than matching it with a source in the separation process (Colmenares and Seider, 1989). Hence, heat integration opportunities should be evaluated and compared globally and simultaneously in the process. Concluding fact is that the process screening procedure is reliable only when the separation design, refrigeration design, and heat integration are carried out simultaneously (Wang and Smith, 2005).

2. Refrigeration system

Low temperature (sub-ambient) processes require heat rejection to the refrigeration systems. The result is that the operating costs for such processes are usually dominated by the cost of power to run the refrigeration system. Simple cycles (i.e. cycles which absorb heat at one temperature and pressure level and also reject the heat at a single temperature and pressure level) can be used to provide cooling as low as typically-40ºC. For lower temperatures, complex cycles are normally used.

In practice, cascades of cycles with multistage compression and expansion are optimised to reduce the overall power requirement of the refrigeration system. In literature, much work has been done on synthesis and optimisation of cycles with multi-absorption levels (Colmenares and Seider, 1989; Del Nogal et al., 2006; Shelton and Grossmann 1986a; Ibid. 1986b; Vaidyaraman and Maranas, 1999). This arrangement improves the energy demand of the system by better managing the vapour generated from expansion. Installation of a liquid-vapour separator after the throttle valve leads the vapour directly to the high-pressure compression stage and therefore, reduces the vapour flow in the low pressure compression stages. Moreover, such structures will optimise the load provided by the refrigeration system at different temperature levels by optimising the refrigerant flow at each level.

Recalling our discussion in the previous section, the energy demand of the refrigeration system can be further optimised by considering multiple rejection levels. Refrigeration cycle then benefits from different sinks provided by the process at a variety of temperatures. For instance, let’s consider the following cycle: a mixed refrigerant (ethylene 0.37, propylene 0.63) is providing 26.6 MW of cooling duty at -49 ºC. In case one (Figure 2), all the absorbed heat is rejected to ambient at 40 ºC. The shaft power required for this cycle is 34.25 MW. In case two (Figure 3) another sink has been provided for the same cycle, enabling the cycle to release 23.87 MW of its rejection duty at -20 ºC. The remaining refrigerant vapour is compressed further in the second stage of the compressor and is condensed by cooling water at 40 ºC. The shaft power consumption for this case is 12.45 MW, almost a third of the former case. Moreover, the cooling water duty is also decreased by 45.66 MW. The example illustrates that integrating the process with the refrigeration system and optimising the refrigerant flowrate in the cycle result in significant energy savings in the process.

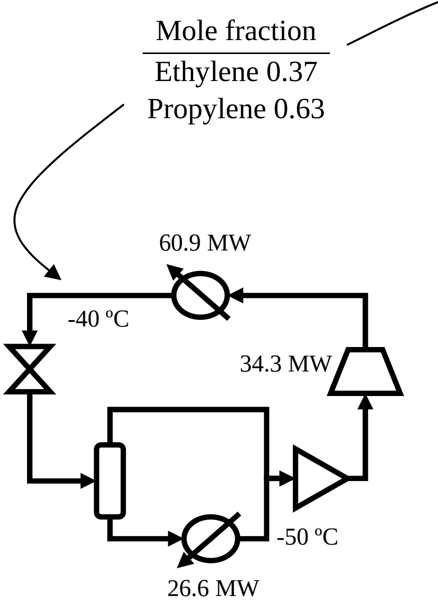


Figure 2: Simple mixed refrigeration cycle

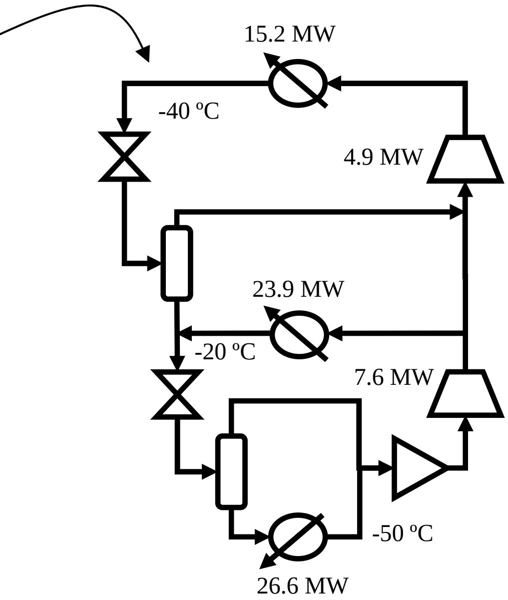
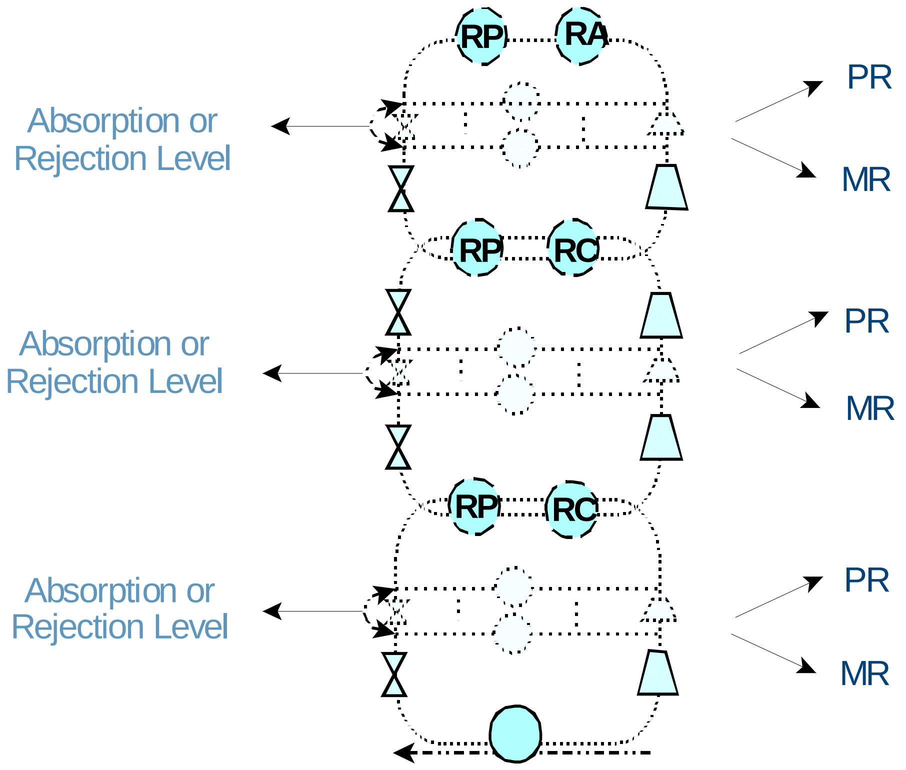


Figure 3: Mixed refrigeration cycle with multiple rejection levels

To accommodate this potential in the refrigeration cycle, the refrigeration superstructure should allow multiple rejection and absorption levels to appear at any order throughout the cycle. In addition, each cycle should be allowed to cascade itself against an upper cycle, in case it is not balanced with the process sink opportunities alone. Figure 4 shows such superstructure graphically.

Another important category of refrigeration systems to be considered is mixed refrigerant systems. The advantage of mixed refrigerants over pure refrigerants is that they undergo isobaric phase change along a range of temperatures within the dew and bubble temperatures of the mixture. Given the correct refrigerant pressures, flowrate and composition, this allows a good match between the process and refrigerant temperature profiles (an indicator of cycle efficiency) with a simpler configuration than multilevel pure refrigerant cycles (Del Nogal et al., 2006). Simple configuration of mixed refrigerant cycles results in less rotary equipment involved in the process, which adds additional value to the design in terms of the reliability of the operation. Refrigerant composition is an important degree of freedom both at the design stage and during operation. However, considering the composition changes in a cycle with multiple absorption and rejection levels will make the design significantly complex.



RP: Rejects to process RA: Rejects to ambient RC: Rejects to another cycle
PR: Pure refrigerant MR: Mixed refrigerant

Figure 4: Superstructure for cascades of multistage (absorption and rejection) refrigeration cycles

All in all, in the synthesis and optimisation of the refrigeration system, number and type of cycles (mixed or pure); refrigerant composition; number of refrigeration levels; their temperature and nature (absorption and rejection levels); and the cascading strategy should be considered.

3. Simultaneous design of the refrigeration and separation system

Important interactions between the separation and the refrigeration system which were discussed before highlighted the necessity of simultaneous design of refrigeration and separation systems. When screening various separation sequences, an accurate judgement of the refrigeration system performance is required. Different levels of complexity can be employed:

A. Refrigeration systems can be evaluated using simple models such as Carnot model.

Carnot model evaluates the required shaft power of the refrigeration system considering the temperature range between which the specific source and sink operate:

$$W = \eta Q_C (T_H - T_C) / T_C$$

Eta is the Carnot efficiency and is assumed based on the engineering insights. This approach is fast and can be modified to take into account both pure and mixed refrigerants. Mixed refrigerant options can be implemented by descretising the temperature range that the process stream is covering (Figure 5). The main drawback of this method is that it cannot reflect different refrigerant characteristics. Moreover, even though the strategy for the refrigeration system (i.e. whether to use mixed or pure cycles or a combination of them) can be extracted from this part of optimisation, the design and structure of the refrigeration system remain unsolved.

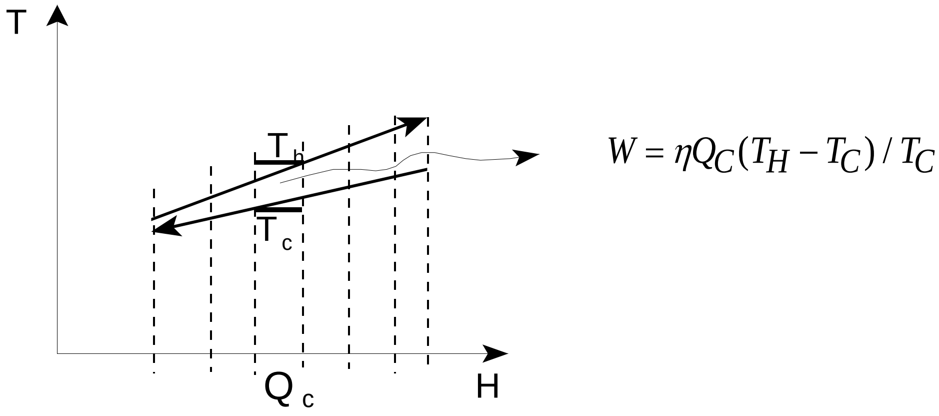


Figure 5: Performance of mixed refrigerants is considered by descretising the range that the process streams cover.

B. Cascades of simple cycles can be simulated to calculate the power demand of the system.

A method has been developed for servicing each source below ambient in the system where a simple cycle becomes responsible (Wang and Smith, 2005). The simple cycles reject their heat to the process depending on the process sink capacities at below ambient temperatures. The rest of the heat is rejected through cascades to the ambient utility. Considering full integration between the process and refrigeration system results in designs with high thermodynamic efficiency. However, there are two disadvantages with this approach:

- The resulted refrigeration system design is not practical. Since only simple cycles are employed and the cycles are not integrated to form multi-level refrigeration cycles, the designs are too complex to be considered in practice.

- Mixed refrigerants are not taken into account and hence, separation sequences requiring sloped refrigeration cannot take advantage of mixed refrigerants.

C. Cascades of mixed and pure cycles with multistage absorption and rejection level can be optimised.

Indeed, this approach will be robust and gives the most accurate evaluation of the refrigeration system. All the main optimisation parameters discussed in section 2 should be considered. Obviously, the approach needs to accept the designer’s fixed parameters. But capturing the complexity of simultaneous optimisation of heat integrated separation and refrigeration system remains a challenge. Stochastic optimisation approaches are employed to overcome this highly nonlinear problem.

5. Conclusion

Low temperature processes require heat rejection to refrigeration systems. The result is that the operating costs for such processes are usually dominated by the cost of power to run the refrigeration system. For large-scale systems, multiple levels of refrigeration, cascaded systems and mixed refrigerants are used. This, coupled with a high degree of heat integration, makes the design of such systems extremely complex because of the complex interactions that occur. Different systematic approaches have been developed for the design of complex low temperature systems. Each of these methodologies has advantages and disadvantages. Therefore, according to the context and the level of accuracy required, the best approach can be selected.

6. References

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