The Role of Process Integration in Sub-ambient Processes

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This talk will provide an overview of some of the challenges in sub-ambient process design and how Process Integration has been used in the past to address these challenges. In addition, some recent developments within Process Integration combining the approach, methods and tools of Pinch Analysis with new ways to utilize Exergy Analysis will be presented.

Sub-ambient processes have a number of characteristics that make them quite different from processes operating above ambient temperature:

- A stronger relationship between Thermal and Mechanical Energy since Power is used to produce Refrigeration (cold utility)
- Expensive Cold Utilities (refrigeration)
- Pressure and Phase become more important design variables and must be considered together with Temperature
- Pressurized streams can be expanded to provide additional cooling
- The distinction between Process Streams and Utilities is rather vague, since Process Streams often act as Utilities
- Temperature driving forces are tighter, requiring more accurate process models

Due to these special properties of sub-ambient processes, heat recovery systems cannot be designed separately only focusing on stream temperatures, heat exchangers and hot and cold utilities to balance any heat deficit and/or surplus in the process. There is also a need to consider pressure and pressure changing equipment. In fact, an extended version of the classical heat recovery problem has been proposed [1] for sub-ambient process design:

"Given a set of Process Streams with a supply and target state (i.e. temperature, pressure and the resulting phase), as well as Utilities for power, heating and cooling – design a Network of Heat Exchangers, Expanders, Valves, Pumps and Compressors in such a way that the required Power (or Total Annual Cost) is minimized"

Contrary to the classical heat recovery problem in Process Integration, the Path between supply and target states is not defined in the extended problem definition. Rather, the change in pressure, temperature and possibly phase (the “path”) is an important part of the optimal design problem. A methodology focusing on sub-ambient process design called ExPAnD (Extended Pinch Analysis and Design) has been under development for some time in our group. ExPAnD is addressing the extended problem definition given above; in the beginning with a set of 10 heuristic rules, and later progressing into an optimization framework based on a novel superstructure with heat exchangers as well as equipment for expansion and compression and a Mixed Integer Non-Linear Programming (MINLP) model [2].

Above ambient, $\Delta T_{min}$ is used as an economic parameter trading off operating cost (energy) and investment cost (equipment). In simplified approaches, a single global value is used for
\(\Delta T_{\text{min}}\), while a more industrially relevant approach is to use stream individual contributions \((\Delta T_i)\) to such a specification of minimum allowed temperature difference. In this way, differences in heat transfer coefficients can be accounted for. Below ambient, however, the situation is quite different. Using constant values for \(\Delta T_{\text{min}}\) or \(\Delta T_i\) simply does not work, since the optimal temperature difference will vary with temperature level in such a way that smaller \(\Delta T\) values should be used when moving towards lower (colder) temperatures. The reason is that the amount of work required for cooling a system one degree \(\circ \text{C}\) or \(\text{K}\) increases with lower temperature.

If \(\Delta T_{\text{min}}\) is used as a specification in an optimization model with the objective to minimize required shaftwork to provide the required refrigeration, the optimizer will try to have the driving forces as close to \(\Delta T_{\text{min}}\) as possible in the entire temperature range. The results of this optimization include, in addition to minimum shaftwork, also the required heat transfer area \(A\) (or the lumped parameter \(UA\)). If this amount of heat transfer area (or \(UA\)) is used as a specification in a new optimization, then the driving forces will be un-evenly distributed and the resulting shaftwork will be less than in the first optimization. This clearly shows that when using \(\Delta T_{\text{min}}\) as a specification, the heat transfer area will not be utilized in an optimal way.

If the objective function is changed from minimizing shaftwork in the compressors to minimizing total annual cost, including the cost of equipment, a third result would be obtained, however, this would not change the fact that a \(\Delta T_{\text{min}}\) specification should not be used below ambient temperature. Details from a simple case study will be presented to illustrate and quantify these phenomena.

Using the concept of Exergy is obvious in processes with a strong focus on work/power, such as power stations, CHP systems and sub-ambient processes. As already mentioned, in sub-ambient processes external cooling in the form of refrigeration is produced by compression (i.e. work) and expansion. Thus, the link to Exergy (defined as the maximum work that can be produced when a system comes into equilibrium with the environment through reversible processes) is obvious.

In fact, the concept of Exergy has been used quite extensively in established Pinch Analysis and Process Integration. Since the Exergy (work potential) of Heat can be obtained by multiplying the Carnot factor with the amount of Heat (or Enthalpy change), exergy losses in power stations, low temperature (sub-ambient) distillation systems and refrigeration cycles can be represented in Temperature – Enthalpy (Heat) diagrams by simply replacing Temperature by Carnot factor as the y-axis (ordinate). With Heat as the abscissa (x-axis) and Carnot factor as the ordinate, the area between the curves (hot and cold Composite Curves, or utility and process Grand Composite Curves) is a direct and quantitative representation of the exergy losses in such processes.

This is exactly what was done in the early 1990s [3], when the Exergy Composite Curves and the Exergy Grand Composite Curve were introduced. Similarly, for low-temperature distillation processes, the Column Grand Composite Curve also had its Exergy version [4]. While these representations are excellent visual aids for suggesting design modifications in distillation columns (such as feed preheat, use of side reboiler or side condenser) and refrigeration cycles (the effect of introducing more levels), their construction is more difficult due to the non-linear relation between temperature and Carnot factor. In addition, quantitative information about exergy losses and target values for best performance are not explicitly available.
Similar to Energy, Exergy also comes in a large number of different forms. In the Process and Energy Industries, Chemical Exergy and Thermo-mechanical Exergy (also referred to as Physical Exergy) are the most important Exergy forms. In sub-ambient processes, there are very few chemical reactors, thus the need for including Chemical Exergy is limited to changes in composition due to separation. In a majority of cases, focusing on Thermo-mechanical Exergy is sufficient, and it has been shown that a decomposition of this exergy form into Temperature-based Exergy and Pressure-based Exergy will enable a better analysis and understanding of various sub-ambient processes.

The Temperature-based Exergy of a Process Stream as well as the Exergy of Heat has a rather special behavior below ambient temperature. Above ambient, the idealized Carnot cycle and the corresponding Carnot efficiency (or factor) provides a limit for how much work that can be developed from a given amount of heat. This maximum amount of work is by definition the Exergy of that heat. All real power cycles produce less work than the Carnot cycle. Even for the ideal Carnot cycle, the maximum amount of work produced (i.e. the Exergy) is always less than the amount of Heat. Assuming the ambient (environmental) temperature is 298 K, the maximum amount of work that can be produced from say 100 kW of heat is 40.4 kW, 70.2 kW and 85.1 kW if the heat is available at 500 K, 1000 K and 2000 K respectively. In contrast, below ambient temperature heat (or better cold thermal energy) is more valuable than work for temperatures below half of the ambient temperature (149 K).

The main objective of the research in our group has been to move Exergy Analysis from being a post-design analysis tool to become a targeting and synthesis tool in the conceptual design stage. Our strategy has been to try to develop Graphical Tools similar to the ones used in Pinch Analysis, and the results so far have been new linear Exergy Composite Curves and a linear Exergy Grand Composite Curve. The basis for these new linear graphical tools is the Exergetic Temperature [5], a new energy quality parameter that enables easier graphical representations. Being linear means that these diagrams are easier to construct than the existing Exergy curves based on the Carnot factor, and they provide explicit information about Exergy targets as well as guidelines for design.

A more careful definition and identification of Exergy Sources and Exergy Sinks has also enabled the development of a new general and reliable (in the sense of measuring real quality of the processes studied) exergy efficiency parameter referred to as the Exergy Transfer Effectiveness (ETE). Case studies have shown that there are considerable discrepancies between the various exergy efficiency definitions put forward in the literature. This is particularly true for sub-ambient processes [6].

The presentation will illustrate the different concepts that are discussed by using sub-ambient industrial processes of high importance, such as Air Separation Units (ASUs) based on cryogenic distillation and liquefaction processes for natural gas to produce LNG.

References:


