THINKING THERMODYNAMICS

Adrian Finn, Grant Johnson, and Gareth Davis, Costain, UK, look at the ways in which plants can reduce carbon emissions by improving energy efficiency.

As the process industries gear up to be a big part of the solution to tackling climate change – such as through the blueprint for net zero carbon, Roadmap 2035 – reducing carbon emissions from operating plants is a key focus.[1] There is a significant opportunity to do this by improving process plant energy efficiency. Energy efficiency offers not only the opportunity to reduce carbon emissions but to also optimise asset operations and reduce operating costs.

Many hydrocarbon processing plants have been operating for years, often with feedstock compositions and operating conditions different to what they were originally designed for. Low cost and relatively simple modifications can sometimes reduce energy consumption and thus carbon emissions. Such modifications can be identified by taking a systems thinking view during plant analysis and applying guidelines based on thermodynamic principles.

Guidelines based on thermodynamic principles can identify which parts of a process plant are contributing the most significant carbon emissions, and help identify improvements to be quantified by process simulation, process design and cost estimating. Such guidelines have been invaluable on many energy efficiency and debottlenecking projects in integrated processing plants.

Energy-saving techniques and practices based on thermodynamic principles have especially been used on integrated cryogenic gas plants. Cryogenic processes need refrigeration, usually from power input, so energy consumption dictates the size of compression or refrigeration machinery. Lower energy consumption gives large capital savings on new plants as well as operating cost savings and lower emissions. By way of example, cryogenic air separation was using double-effect distillation (the condenser of one column cascades heat to the reboiler of another) over a century ago. Multistream, countercurrent heat exchangers have been employed for over 60 years to effectively recover energy from cold streams. Pressure energy from process gas is effectively used to generate refrigeration, so that many cryogenic processes are auto-thermal, requiring no machinery. Examples from cryogenic gas processing offer opportunities for energy efficiency improvements across the process industries.

'Pinch analysis' is a structured, plant efficiency evaluation method based on thermodynamic principles.[2] All good energy efficiency evaluation methods are systematic, whilst they enable the process engineer to be 'in control' to ensure plant designs are safe, flexible in operation and controllable.[3]

Thermodynamic principles

The first law of thermodynamics states that for any process, energy has to be conserved, i.e. the energy supplied to a process stream, plus the 'work' supplied, equals the enthalpy change.

$$\Delta H = Q + W \qquad (1)$$

Where:
Δ = Change
H = Enthalpy (W)
Q = Heat (W)
W = Work or work equivalent (W)

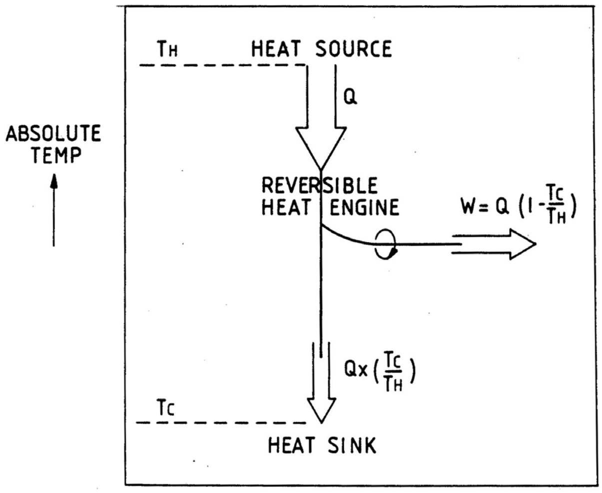

Figure 1. The Carnot principle.

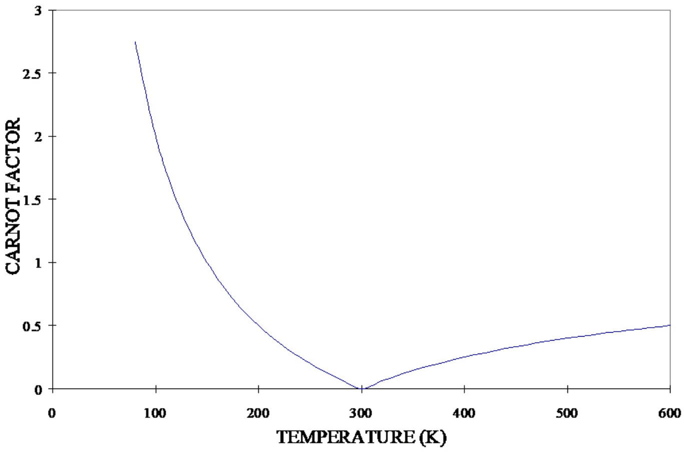

Figure 2. Carnot factor vs temperature.

Work is especially useful for processes that operate at various pressures and use 'shaft work' or pressure energy. Reduction in the pressure of a gas can supply work, which is needed to separate streams into purer products. Whatever energy is required for, to reduce the work input to a process, available work should be used wisely. It is useful to assess reducing energy consumption by avoiding wasting work.[4]

Sadi Carnot showed that when heat energy produces work, by driving a reversible heat engine, the work delivered is the maximum possible 'ideal' and, as shown in Figure 1, is given by:

$$W = Q\left(1 - \frac{T_c}{T_h}\right) \qquad (2)$$

Where:
W = Work or work equivalent (W)
Q = Heat (W)
T = Temperature (K)
C = Cold (sink)
H = Hot (source)

Equation 2 shows the work attainable from a reversible process, including from a process stream heating (or cooling below ambient) another process stream. If T is less than T0, equation 2 gives the minimum (reversible) work to 'pump' heat from low to high temperature, such as in a refrigeration cycle.

For energy it is better to think work. Work accounts for both the change of energy (duty) and the potential for energy transfer, such as if one stream is hotter than another and can therefore provide heat energy. Work highlights the importance of temperature level for thermal energy transfer and of pressure energy and energy associated with streams of different composition.

Figure 2 shows the work value of a unit of energy vs absolute temperature. At sub-ambient temperatures, work change per unit of energy flow is increasingly larger than for temperatures above ambient. This relationship, of work equivalent of energy, shows why cryogenic plant design benefits so much from thermodynamic guidelines, especially as cryogenic temperatures are often derived from power-intensive machinery.

The concept of the reversible process is useful to provide energy consumption and performance targets for comparing processes. Base-load LNG plants are massive power consumers – up to approximately 250 MW per train. They operate at around 50% Carnot efficiency by exhibiting many energy-saving techniques based on thermodynamic principles.

Clearly, 'lost work' should be minimised as it represents waste – either of work input to the process or work that could have been usefully used or extracted from the process. However, process plants are not built and operated just to be energy efficient. Thus, any energy efficiency proposal should consider capital and operating costs (and potentially carbon taxes) and identify the priority modifications. This may be as one overall plant upgrade or by piecemeal,

Figure 3. Plate and shell exchanger performing the same duty as shell and tube (with thanks to Robert Broad).

staged changes via a roadmap to ensure early changes do not compromise later ones. Some guidelines are required.[5]

Guidelines for energy efficiency

Guidelines based on reducing lost work suggest potential plant improvements by identifying how a process may be closer to fully reversible (which represents the maximum theoretical energy efficiency). They help to screen out early changes that are unlikely to be attractive, so that more time can be spent on the most promising candidates.

Reversibility requires:

- Infinitesimally small changes.
- Keeping at equilibrium.
- Zero driving forces for heat and/or material transfer.

Of course, the above are infeasible in practice and can only be approached. However, they provide targets to aim for. Some parts of an operating plant contribute to lost work that is considered inevitable to achieve process objectives. It may also be difficult to optimise energy supplies, e.g. by changing temperature levels and/or energy loads, due to process requirements. The process engineer should therefore address those parts of the process – usually the separation, heat exchange and utilities – where lost work is avoidable.[2]

The following guidelines should be used to reconcile the plant design heat and material balances with actual operating data to identify process options and potential improvements. Factors such as process control and how the plant is operated (compared to the original design intent) should be included. Process monitoring and energy audits can provide the necessary operational data. Any efficiency issues due to flaring or fugitive emissions should also be considered.

Identify available sources of work

There may be high temperature process streams available for process heating – e.g. flue gas, for combustion air preheat or for heating boiler feed water. Hot streams may be available for process heating, especially if process streams are split to match energy requirements with minimised temperature differences so as to meet their target temperature. This reduces the need for high grade heat. Pinch analyses help in this scenario.

On one Costain project, heat exchange between hot spent regeneration gas from a gas dehydration unit provided regeneration gas preheat. This improved energy efficiency and enabled 20% greater throughput.

An opportunity arises wherever high pressure gas is reduced in pressure. The work available could potentially be used in an expander (of high isentropic efficiency) for gas boosting or to generate electricity or in an ejector for gas boosting.

Pressure let-down of liquid streams is often necessary and can provide work. On an acid gas removal plant with an absorber and regeneration column system, a hydraulic turbine or liquid expander on the rich solution leaving the absorber can provide 50% of the power needed to pump regenerated lean solution.

Using machinery and prime movers of increased isentropic efficiency clearly helps increase overall energy efficiency.

The utilisation of renewable wind power and hydro power is supported by this guideline as a way of providing power and minimising carbon emissions.

In summary, it is important to look broadly for where useful work is available and not being used effectively.

Avoid large driving forces in both energy and material transfer

If a hot process stream heats another process stream using large temperature differences, the potential of the hot stream (its work value) to heat to a temperature close to its starting temperature is lost. Heat is thus degraded unnecessarily and process heating needs more expensive, high-grade heat. Heat exchangers with large temperature driving forces incur an energy penalty elsewhere in the process, often unnoticed. For an existing site, reassessing the utilities and process streams available for heating and cooling is very useful prior to evaluating improved process integration to better recover energy.

Pinch analysis succeeds by using thermodynamic principles to identify energy targets. In a process requiring heating and cooling of multiple streams – crude oil heating prior to fractionation, for example – two stream shell and tube heat exchangers inevitably introduce 'losses' because temperature driving forces must be high to avoid multiple shells. By only using shell and tube exchangers, how does energy consumption compare with the lowest possible energy consumption? Pinch analysis identified the value of 'composite curves' (enthalpy change vs temperature) for this. A pinch analysis uses the summated plant cooling and warming streams to give definitive energy targets (exactly as practiced at cryogenic plants for many years). Indeed, it enables appreciation of how multistream heat exchangers would improve energy recovery and reduce energy consumption.

If analysis is limited to heat exchangers handling two streams, then countercurrent heat exchangers and splitting of process streams to minimise temperature driving forces can give significant energy savings.

The use of guidelines to improve plant energy efficiency highlights:

- Use of intermediate reboil in distillation and/or for column feed preheat, thus using lower grade, lower cost heat.
- Use of plate exchangers or spiral heat exchangers, especially in refinery applications, for true countercurrent operation, with cost effective approach temperatures of 3˚C (Figure 3).
- Optimisation of energy supply, including steam temperature levels – avoiding unnecessarily high temperature steam and improving steam system efficiency.
- Use of multiple refrigeration levels – increasing the complexity of refrigeration and heat exchange systems but reducing refrigeration compressor power requirements.

Distillation in particular presents energy-saving opportunities: columns incur large energy degradation, from the reboil heat source temperature to the sink temperature – air or cooling water – of the condenser, and by irreversible mixing of liquid and vapour not in equilibrium. Lower temperature heat may be available for reboil. On distillation columns with more than one feed point, changing column feed location(s) to better match the column feed conditions to the column fluid compositions can be easily assessed by process simulation.

Operation at reduced temperature driving forces does not reduce energy duties but enables the use of energy at less extreme temperatures. Less work is wasted. Capital and energy costs should be carefully assessed to determine optimal modifications. In cryogenic processing, temperature differences for energy recovery of only 2 – 3˚C are commonplace.

Mixing of process streams of dissimilar temperatures and/or compositions reduces energy efficiency and increases energy consumption. Crude preheat trains and other integrated heat exchange systems have benefitted from energy efficiency studies and use of process integration techniques. If the feedstock differs from the original design, process streams of dissimilar temperature may be mixed, so streams are heated when the objective is to cool them (or vice versa). This inevitably increases overall energy consumption and carbon emissions.

Mixing of streams, which subsequently require separation, wastes energy. It is important to be wary of process operations that do not fully align with the overall process objective, as this can be very wasteful.

Stay as close as possible to ambient temperature and pressure

Equation 2 and Figure 2 show that lost work will be relatively high away from ambient temperature. All else being equal, avoid extreme temperatures and high pressures to minimise losses.

This guideline suggests that the operating pressure of a distillation column should normally be set for the condenser temperature to be just above ambient. This normally holds true in isolation but changes if heat integration is feasible, e.g. if a revised column pressure means columns can be thermally linked, so that the condenser of one column rejects heat to the reboiler of another.

The need to meet a wide range of operating pressures with lowest energy consumption, e.g. in gas storage and transmission, leads to consideration of the optimal machinery and power source. Costain has used high-speed electric motors and active magnetic bearings to provide a very wide range of speed variation (potentially as low as 30% of maximum speed) to avoid wasteful suction or discharge gas throttling.

Do not introduce process steps unless strictly necessary

Every step in a process causes losses, so the more steps, the greater the likelihood of losses. Each step should contribute towards the overall process objective, as noted in the discussion of fluid mixing. How does each step affect other steps or parts of the integrated process?

One way of reducing energy for separations is to separate only what is needed and to do it just once. Often, several product streams are recovered separately from a refinery fractionator only to be re-mixed downstream.[6] It is likely that an opportunity for increased energy efficiency is being missed.

Consider the example of burning gas for power generation, the transportation of high voltage electricity and its only eventual use as relatively low voltage power or lighting. The energy eventually used is a fraction of the original energy content of the combusted natural gas. There are very high losses to the end user with very high associated carbon emissions. Fuel switching schemes, which use locally-produced renewable electrical energy, do not just save on what is consumed at the point of use but all associated losses, a much higher value. Considering overall energy efficiency from source energy/power generation, right through to the end user, can be very valuable.[2]

Conclusion

Guidelines derived from basic thermodynamic principles afford insight and understanding to the process engineer. They show where to focus to get the best returns on time and effort from process efficiency studies. By considering departure from reversibility and the high driving forces that lead to lost work, improved energy efficiency and reduced carbon emissions can be identified, quantified, costed and implemented.

References

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