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Implementation and Pitfalls of Process Integration

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Process Integration (PI) is a powerful tool for designing and optimising processes for energy efficiency and sustainability. Sometimes its simplicity is misunderstood. Even PI has some potential pitfalls related to the problem formulation and data extraction. Regardless of the precision used, the results largely depend on solving the correct problem – i.e. if the formulation reflects the reality adequately and if the appropriate data have been extracted. An incorrect data extraction has been the reason for conclusions that PI did not work. When revisiting most of those problems, it becomes obvious that it was not a fault of the PI methodology, but an inexperienced user.

1. How to Proceed to Achieve a Credible Solution

The first issue is: How to start and to progress with a PI study? Kemp (2007) summarized the steps, which had been further developed based on the authors' experience. They are related to the HI, but could be used for mass/water integration:

1) Get familiar with the process. The efficient way is to closely liaise with the process designer (grassroots design) and/or plant manager (operating plants).
2) Mass and heat balance – based on the process flowsheet data, as well as calculations and/or measurements from the running plant (for a retrofit).
3) Select the streams. This is a key step and not as straightforward as it seems.
4) Remove all existing units related to the PI analysis. For HI remove all heat exchangers; for mass/water integration – all mass/water exchanging units. This is crucial – otherwise the optimised design would be the same as the initial.
5) Extract the stream data for the PI analysis. For HI thermal data are needed or for Water Integration – contaminants and water flowrates.
6) Select by a qualified guess/experience an initial value of ΔT_{min} for the heat integration. This can be later optimized at the various stages of the design.
7) Perform the Pinch Analysis, obtaining the Pinch location and the utility targets.
8) Design the initial HEN, starting with the maximum energy recovery.
9) Check for cross-Pinch heat transfer and inappropriately placed utilities.
10) Check the placement of reactors, separation columns, heat engines and pumps.
11) Investigate the potential for the process modification for both energy minimisation and capital cost reduction. Investigate potential benefits of +/- principle and Keep Hot Stream Hot and Keep Cold Streams Cold principle.

12) Investigate the integration with the other processes - Total Site Analysis
13) Evaluate pressure drop effects (trade off between heat saving and pumping cost) and the lay-out implications – piping cost , heat and pressure drop losses.
14) Make the pre-selection of heat exchange equipment and preliminary costing. Provisions based on the assessment of the future energy prices are needed.
15) Perform an optimisation run of the pre-design plant/site djusting ΔT_{min}
16) Based on the optimisation adjust and extract more precise data and return to 7) perform additional loops with screening and scoping, potential simplification.
17) Consider real plant constraints, including safety, technology limitations, controllability, operability and flexibility, availability and maintainability.
18) Very important for PI design are start-up and shut-down issues. Some early designed highly integrated plants suffered those problems.
19) Second optimisation run for the final tuning. If needed return to any appropriate previous step for adjustment.
20) The design is ready for detailing. However the optimisation is a never ending procedure – with changing operating conditions and/or economical environment the design should be re-optimised.

2. Data Extraction

The data extraction is a crucial step. It can be performed automatically (Linnhoff and Akinradewo, 1998) from simulation data. Several software packages have been offering this option, e.g. SuperTarget®. However, this has to be done carefully. Poor data extraction can easily lead to missed opportunities for improved process design. If the data extraction accepts all the features of the existing flowsheet then there will be no scope for improvement. From 1998 the methodology has developed and attempts for the automatic data extraction were made, but the rules and experiences are still valuable. The basic rules are: (i) When a stream is a stream? (ii) How precise data we need at specific steps? (iii) How to handle considerable C_p changes? (iv) What is the further know-how (rules) for the data extraction? (v) How to calculate heat loads, capacities and temperatures of an extracted stream? (vi) How “soft” are the data in the flowsheet/plant? (vii) Where to find data for the capital and running cost?

2.1 When a stream is a stream?

This is one of the key issues for proper problem setup. Streams not gaining or providing heat should not be considered. This rule considerably simplifies the problem. There are also some streams which should not be included into the PI problem – e.g. for distance, safety, product purity, or operational reasons. When deciding which streams are going to extracted, the following question should be answered: When a stream is a stream? Let us consider the example in Figure 1. It has been introduced by Linnhoff et al. (1982, 1994) and has been used with some modifications in follow-up books (Smith, 1995, 2005; Kemp, 2007) and in many courses based on UMIST/The University of Manchester teaching materials. It shows a part of a flowsheet in which the feed stream is heated by a recuperating heat exchanger to 45 °C and enters to a processing unit. After leaving this unit, the stream is heated again by two heat exchangers and enters a reactor. The reactor operation requires the feed stream to be at 160 °C. The options for how many streams we should extract are: (i) one from 10 °C to 160 °C; (ii) two from 10

°C to 45 °C and 45 °C to 160 °C; or (iii) three from 10 °C to 45 °C, 45 °C to 80 °C and 80°C to 160 °C?

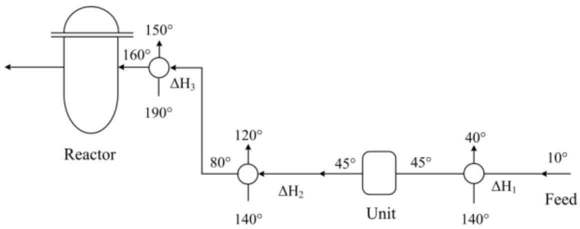

Figure 1: An example –A flowsheet fragment

If option (iii) is applied, the resulting design would be exactly the initial one, having again three heat exchangers with identical heat duties. This is the case for which critics of the PI concluded that no improvement was obtained. Option (ii) offers more degrees of freedom – the first HE would be the same as in the current flowsheet but the rest of the design could be modified. Extracting two streams would be the case when the processing unit demands the feed temperature close to 80 °C. Option (i) would provide the most degrees of freedom and scope for improvement, but it requires that the processing unit feed could be at any temperature between the supply 10 °C and the target for the reactor 160 °C. If the processing unit is a filter as Smith (2005) assumed, there would be some restriction on the filter supply temperature – for high temperatures the filter might experience a problem. If the processing unit is just storage, as Linnhoff et al. (1982, 1994) assumed, the temperature restriction might be different. This simple example demonstrates that stream extraction can't be fully automatic, but requires more assessment related to processing units and their performance.

2.2 How precise data are needed at specific steps?

This is a very frequent question. Many excuses for not performing PI analysis claim that a running plant has not got sufficiently precise data. PI starts with rough assumptions, which are further corrected in several loops. PI and initial optimisation are more about screening and scoping than detailed design. The goal is to get an answer to the question what potential for energy saving there is and in which direction the optimisation should proceed? If that potential is about 15 %, this is sufficient and it doesn't matter too much if the precise figure would be 13 % or 17 %. In the regions close to the Pinch the data should be as precise as possible (Linnhoff et al., 1982). At the start the designer might have only a vague idea of where and at what temperature the Pinch will occur. The data extraction has to start from rough assessments and being corrected.

2.3 How to handle considerable C_p changes and the latent heat?

From Figure 1 it is obvious that phase changes are very likely to occur when the temperature rises from 10 °C to 160 °C. Also C_p is changing with the temperature. Just to use constant C_p would be unrealistic. To deal with this problem, a segmentation technique was developed. It has been used e.g. in STAR (2010). It is important how many segments to define and at which temperatures they should start and end. Each segment increases the complexity and should be kept at minimum.

2.4 What are the data extraction rules?

Some data extraction rules were introduced very early by Linnhoff et al. (1982, 1994) and used with some modifications in follow-up books (Smith, 1995, 2005; Kemp, 2007; Klemeš et al., 2010) and many courses based of UMIST teaching materials e.g. (CPI, 2004). Most have been heat integration related, however, the principles can be analogically applied for the mass/water integration as well. The rules are as follows:

(i) *Non-isothermal mixing*. When two or more streams, with different temperatures, are mixed, this represents a heat exchange with a degradation of the higher temperature. It can also result in cross-Pinch heat transfer.

(ii) *Heat losses.* In most cases the heat losses are neglected. This is not correct for situations where streams are long or subject to very different temperatures. The solution is to introduce hypothetical coolers / heaters representing the losses.

(iii) *Extracting utilities.* The utilities should never be extracted from the existing plant or flowsheet. Such action would likely result in the same utility use and neglect more efficient options – e.g. utilities generation. However, attention should be paid that e.g. steam is not always a utility. In some cases is also used as process stream – an example is stripping steam in separation columns.

(iv) *Generation of utilities.* The HI analysis using the Grand Composite Curve may indicate valuable options for using otherwise wasted heat or cold to generate utilities. Many mistakes have been caused by just matching the evaporation neration line without making provisions for preheating and superheating.

(v) *Extracting at the effective temperature***.** In some cases a stream cannot be extracted directly as it still has to be used by a related process. E.g. a hot stream should be extracted at temperatures at which the heat becomes available. A good example has been presented by Smith (2005) for a reactor using a quench liquid.

(vi) *Forced and prohibited matches.* There could be matches in a heat exchanger network, which should be either prohibited, e.g. for the danger of contamination, or those which must be secured. Software tools usually offer such an option. If not this can be secured by an appropriate penalty/bonus in the objective function.

(vii) *Keeping streams separate only when necessary.* If streams can be merged then it may be possible to eliminate some heat exchanging units.

2.5 How Can the Heat Loads, Heat Capacities, and Temperatures of an Extracted Stream Be Calculated?

When a stream has been extracted, next problem is how to calculate the heat related data. There are common engineering practices available for running plants as the measurements with the following data reconciliation (Klemeš et al. 1979; BELSIM, 2003). Another option is to use a flowsheeting simulation model. These options are time consuming and at the early design stage the process structure is likely to evolve. For this reason it is possible to use a simplified approach based on the extracted data. The experience shows that at the initial stage they are sufficient.

2.6 How "soft" are the data in a flowsheet/plant

Inexperienced persons are trying to stick the temperatures shown in the PFD and then perform the PI analysis. This approach usually ends up overlooking many opportunities. It is better to question every temperature, discuss them with the plant designer/manager, and establish which temperatures are absolutely crucial to be achieved ("hard" data) while the rest (the “soft” data) can be compromised. In practice most data are in some way soft and this can be used beneficially. Streams leaving the plant are usually characterized by soft data and are suitable for optimisation via the +/- principle. Data softness is related to changing conditions and to flexibility, operability, and resilience.

2.7 Data for the capital and running cost?

The need to find cost data arises when the appropriate ΔT_{min} should be selected. The optimum ΔT_{min} depends on economic parameters. Estimating capital cost is time consuming. They are approximate methods (Taal et al., 2003) for the initial stage when little is known about the design and materials required or the temperature, pressure and composition of streams. Equipment cost may vary regionally and may be related to market conditions. It is difficult to estimate operating cost, which is affected by labour, taxation, and is mainly a function of energy cost. A potential pitfall is using the current price of energy. It is better to use the anticipated average energy price for the life span of the plant; in case of retrofit – for the expected payback period. In a number of works this rule was not followed. The question is then where to find energy price projections for the time within five or ten years? Even the forecasts from qualified institutions were not fulfilled. One of the potential approaches is to use scenarios and target the most flexible design which would provide a balanced optimum for various situations.

2.8 Integration of renewables – fluctuating demand and supply

Renewables availability varies significantly with time and location. The energy demands of sites vary significantly with time of the day and period of the year. The advanced PI methodology using the time as another problem dimension is a potential solution to deal with this problem. A basic methodology has been developed previously for HI of batch processes – Time Slice and Time Average Composite Curves (Kemp and Deakin, 1989). It has been recently revisited by Foo et al. 2008. A novel approach has been extending the HI of renewables by Perry et al. (2008) and Varbanov and Klemeš (2010). Dealing with variation and fluctuation brought another complexity into data extraction. Important is the specification of the time intervals - Time Slices.

3. Results Interpretation

Beside data extraction, correct interpretation of the results is a very important step in PI analysis and optimisation. The results are usually presented by a printout and in most cases by a Grid diagram or PFD supported by tables. Many software tools developed an interface for transferring the extracted data to minimise misinterpretations. A difficult part is the results assessment and possible further development/correction from the viewpoint of the process technology. It depends on the issues of data uncertainty, data “softness”, flexibility, operability, controllability, safety, availability and maintenance. It is advisable not to stick with one solution, but to explore different scenarios related to various operating conditions and to test the sensitivity of the design.

4. Conclusions - Making it Happen

Even when a sustainable and near optimum design is developed it still has to be put into practice. This involves selling the projects, which could be in many cases unconventional to the investors and contractors. This used to be a problem at the beginning of the PI history. PI has since proven itself and gained in popularity and decision makers have become more receptive. Among pioneers have been the members of UMIST and later The University of Manchester “PI Research Consortium”. However, the close and smooth joint effort and collaboration amongst the PI specialists, plant designers, plant management and the owners/contractors is still a major issue.

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