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PROCESS INTEGRATION

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PROCESS INTEGRATION

1. NOTATION AND UNITS

		<i>SI</i>	<i>British</i>
A	heat transfer surface area of a heat exchanger	m^2	ft^2
CP	heat capacity flowrate	W/K	$BTU/h^{\circ}F$
ΔT	temperature separation between hot and cold composite curves	K or $^{\circ}C$	$^{\circ}F$
ΔT_{min}	minimum allowable temperature difference or approach	K or $^{\circ}C$	$^{\circ}F$
H, h	enthalpy or heat flow rate of a stream	W	BTU/h
$LMTD$	log mean temperature difference	K or $^{\circ}C$	$^{\circ}F$
M_{min}	minimum number of matches for maximum energy recovery	—	—
N	number of streams in a system or section of network	—	—
Q	heat transferred in a match	W	BTU/h
T	temperature, general or of hot streams	K or $^{\circ}C$	$^{\circ}F$
t	temperature of cold streams	K or $^{\circ}C$	$^{\circ}F$
TI	interval temperature	K or $^{\circ}C$	$^{\circ}F$
U	overall heat transfer coefficient for a match	$W/m^2 K$	$BTU/ft^2 h^{\circ}F$
α	film heat transfer coefficient including fouling	$W/m^2 K$	$BTU/ft^2 h^{\circ}F$

Subscripts

$C, cold$	cold stream
H, hot	hot stream
i	index for individual stream
min	minimum value
s	all process and utility streams

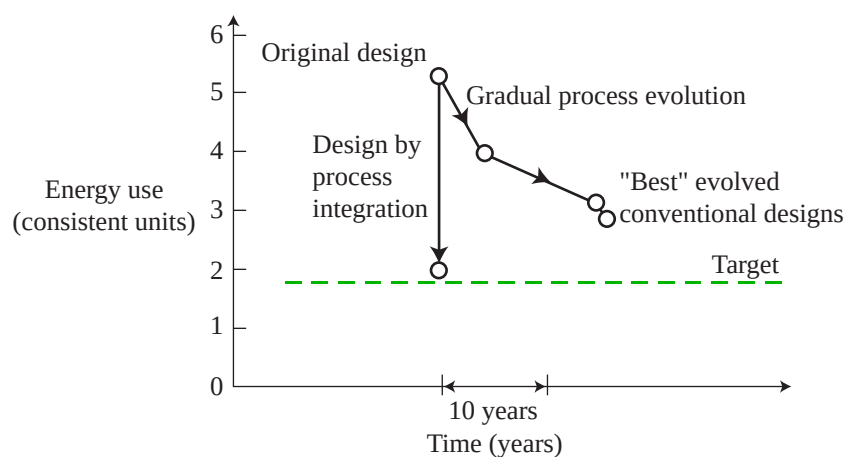
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2. INTRODUCTION

This Data Item introduces Process Integration, the most significant tool for energy analysis that has appeared in recent years. Its key advantages are:

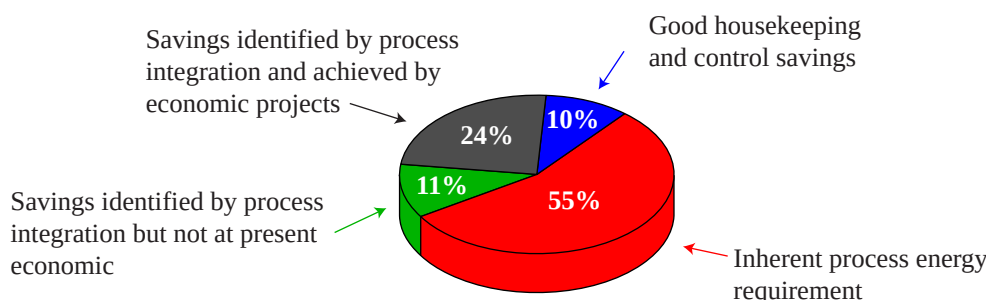
- (i) a definite target for the energy use of a process plant is found and
- (ii) it gives systematic design methods to achieve this target.

The importance of this systematic approach, in contrast to past methods of installing energy efficiency projects piecemeal, is illustrated by Sketch 2.1. Over a period of many years, the energy use of the chemical process shown was reduced in successive designs. The learning curve thus obtained is typical of process plant development. However, if Process Integration techniques had been available initially, the target could have been found and the ultimate design identified in one step. Process Integration, when eventually applied, still identified a practical and economic saving of 30%.



Sketch 2.1 Beating the learning curve by Process Integration

Process Integration targets should be distinguished from good housekeeping targets set by management to try and reduce wastage. The latter targets are chosen by guesswork and experience and are “making the best of what you’ve got”. Process Integration targets are rigorous and are based on a thermodynamic analysis of the process. They show ways of improving the flowsheet so that the plant inherently requires less energy to produce the same quantity and quality of product. Sketch 2.2, using averages from a large number of case studies, shows energy savings identified by Process Integration compared with those from good housekeeping and control measures. These savings were for heat recovery projects. On many plants combined heat and power (CHP) schemes, which can also be identified by Process Integration techniques and are covered briefly in Section 10.4, offer even greater reductions in energy costs.



Sketch 2.2 Typical process energy pie chart

This Data Item introduces the concepts and applies them to heat recovery, in particular to the design of heat exchanger networks and the associated site heating and cooling or utility systems. The emphasis is on the practical application of the techniques and is illustrated by a major case study which shows the methodology being applied to a real situation. This Data Item may be used to carry out simple studies or as a guideline when working with Process Integration consultants, enabling their methods to be followed and their findings understood.

Process Integration is a systematic method and the stages of any study can be clearly delineated. The stages, discussed in Sections 5 to 8, are:

- (i) collect process data,
- (ii) form heat and mass balances,
- (iii) extract the Process Integration stream data,
- (iv) select the minimum temperature approach between hot and cold streams,
- (v) calculate energy targets and the pinch point,
- (vi) examine possibilities for process change and recalculate targets if necessary,
- (vii) design an ideal heat exchanger network to achieve the targets,
- (viii) relax this network to give a variety of practical energy-saving projects,
- (ix) do an economic evaluation and select the best possibilities.

The proposed projects are compared and evaluated by conventional detailed design methods. Process Integration provides an overall energy strategy and enables the most cost effective projects to be identified rapidly. Time spent in the analysis is more than recouped by not needing to evaluate large numbers of possible designs in order to choose between them whilst, at the same time, obtaining a deep understanding of the energy flows within a process and how they relate to one another.

3. HOW TO USE THIS DATA ITEM

The detailed description of Process Integration techniques is contained in Sections 5 to 10, which are arranged in the order in which the stages are met in a study: data collection, targeting, network design and utility systems.

A rapid overview of the techniques may be obtained by reading first the following Sections: 4 (basic terminology), 6 (targeting), 7 (the pinch) and 13 (conclusions). These will give an understanding, before the methodology in Sections 5 to 10 is studied in detail, of why the pinch technology approach is worthwhile and where its advantages lie.

Pitfalls in using the techniques are discussed in Section 11 and some important refinements to the methods introduced. Section 12 concentrates on a major case study which is treated in detail, and also includes a shorter example that illustrates total site integration. Section 13 is a one page summary of conclusions.

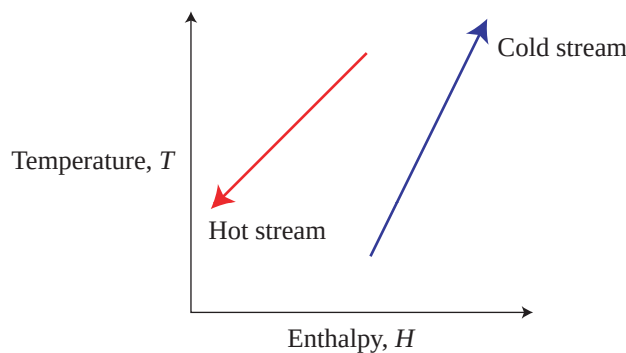
A comprehensive glossary of terms will be found in Section 14, while Section 15 lists derivations and a wide range of references on more specialised aspects.

4. REVIEW OF BASIC TERMS

The prime objective of Process Integration is to analyse the heat flows in a process and thus minimise the overall capital and operating cost of the plant. It is necessary first to understand the essential elements of heat transfer theory as they are applied in the context of Process Integration.

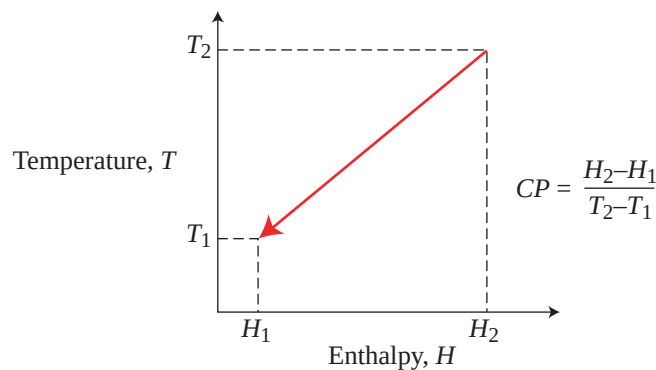
4.1 What is a Stream?

A stream, in the context of Process Integration, is any material flow that undergoes a change in heat content, or enthalpy. A hot stream is one that cools down as part of the process, while a cold stream is heated. Change in heat content can occur on account of either sensible cooling or heating of a gas or liquid or phase changes where latent heat is released or absorbed. For convenience, the enthalpy changes of a stream are represented by means of a graph of temperature against enthalpy as shown in Sketch 4.1.



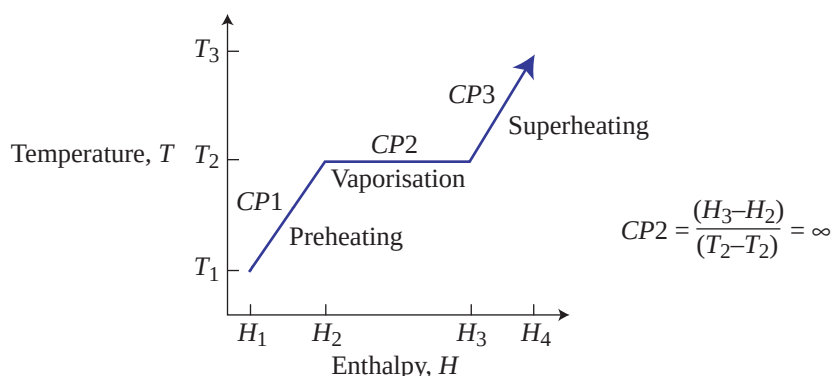
Sketch 4.1 *T-H* representation of streams

As the analysis addresses the problem of heat flow rather than mass flow, it is also convenient to represent the magnitude of this flow in terms of the heat capacity flowrate, *CP*. This is the mass flow rate multiplied by the specific heat capacity, and is expressed in terms of enthalpy change per unit temperature rise or fall per unit time. The value of *CP* is the inverse of the gradient of the line on the *T-H* diagram as shown in Sketch 4.2.



Sketch 4.2 Stream *CP* value

It follows from this that the *CP* of a stream that undergoes a phase change at constant temperature is infinite, and this is shown as a horizontal line in the *T-H* diagram, Sketch 4.3.

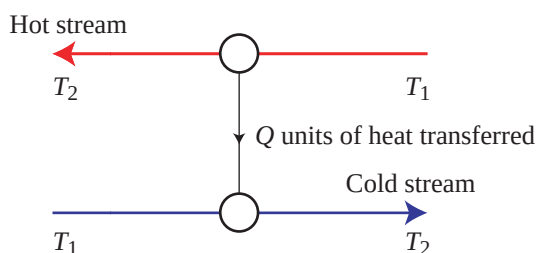


Sketch 4.3 Infinite *CP* for stream isothermal phase change

4.2 Heat Exchangers and Heat Exchanger Networks

A heat exchanger is a unit in which heat is transferred from a hot stream to a cold stream. A more correct term of reference is a heat exchange match between two streams, as this makes no assumption regarding the type of exchanger or the number of units needed to fulfil a particular duty.

A series of matches in the same process or serving a common set of streams is known as a heat exchanger network. The design problem is to devise a network that uses as little external energy as possible and as few matches as possible. As network design and optimisation are important features of Process Integration, a special diagrammatical representation of heat exchanger networks has been devised, as shown in Sketch 4.4. This shows a simple system consisting of two streams and a single heat exchanger. The top line running from right to left* is the hot stream being cooled from T_1 to T_2 , while the bottom line running from left to right* is the cold stream being heated from t_1 to t_2 . The match itself is shown as a dumb-bell shape of two circles joined by a vertical line, with the heat load of the match, Q , also marked. This representation is particularly convenient for comparing different arrangements of matches for the same process.



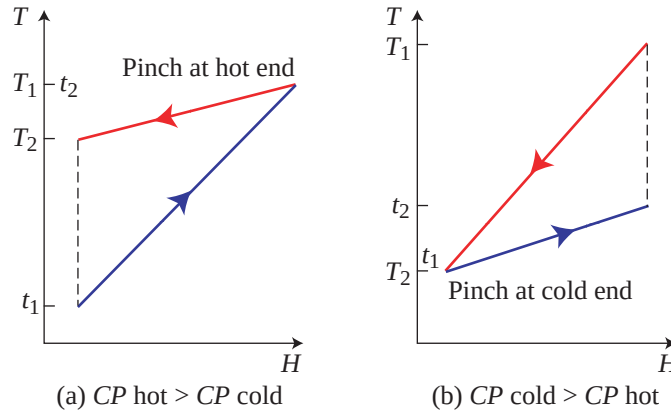
Sketch 4.4 Grid notation for heat exchangers

4.3 Minimum Temperature Approach Between Streams

In order to design an efficient plant it is necessary to know how much heat can economically be transferred in any one match. This is governed by the temperature difference between the hot and cold streams within an exchanger. One of the key concepts to understand in Process Integration is that of the minimum allowable temperature approach or difference, ΔT_{min} . This is best illustrated by the use of temperature-enthalpy graphs as follows.

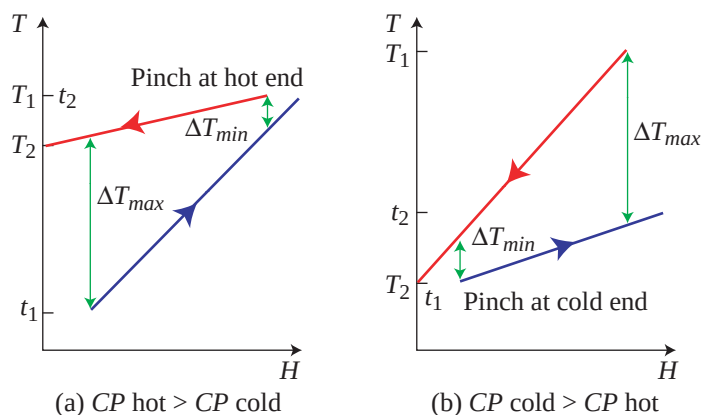
* It is common elsewhere to show the streams flowing in the opposite directions on heat exchanger network diagram. However, the convention chosen in this and other ESDU Data Items on process integration is chosen to be consistent with the stream directions on *T-H* diagrams.

Consider first of all a hot stream transferring heat to a cold stream. The CP values of both streams are known, together with the supply temperatures T_1 and t_1 respectively. The first questions are: what is the maximum amount of heat that can be transferred and what will then be the temperature of each stream? This is shown in Sketch 4.5 for two cases. In case (a) the hot stream has the larger CP and therefore, given an infinitely large exchanger, the temperature of the cold stream will reach the initial temperature of the hot stream, while in case (b), where the cold stream has the greater CP value, the opposite occurs. The point at which the lines meet shows the limit of temperature change and heat recovery is constrained, or pinched, at this point.



Sketch 4.5 Limiting heat transfer cases showing maximum energy recovery

The next step is to establish how much heat can be exchanged in a practical situation, using real equipment. For this, a finite minimum temperature difference, $\Delta T_{\min}$, must be selected, shown in Sketch 4.6 by moving the lines for the hot and cold streams apart horizontally to create a temperature difference at the pinched end of the match. Now, a real heat exchanger can be envisaged in each case, exchanging heat, Q , from the hot to the cold stream, where the minimum temperature difference, $\Delta T_{\min}$, has been specified for each match. Note that the heat transferred between the streams is now lower than in the limiting case and the larger the temperature difference selected, the lower will be the quantity of heat transferred. The basis of design optimisation is balancing heat recovery against exchanger size to minimise the combination of operating and capital cost. It is covered later in this Section and in more detail in Section 9. Again, in case (a) of Sketch 4.6, the limiting factor is the temperature difference at the hot end of the match, while in case (b) it comes at the cold end. The practical design for heat recovery, and the constraining point, or pinch, is therefore dependent on the chosen value of $\Delta T_{\min}$. The concept of a pinch is extremely important within the wider context of heat exchanger network design. Its prime significance is as described here: the limit of practical heat transfer enabling the maximum energy recovery to be found, and giving a target for heat exchange and residual heating and cooling.

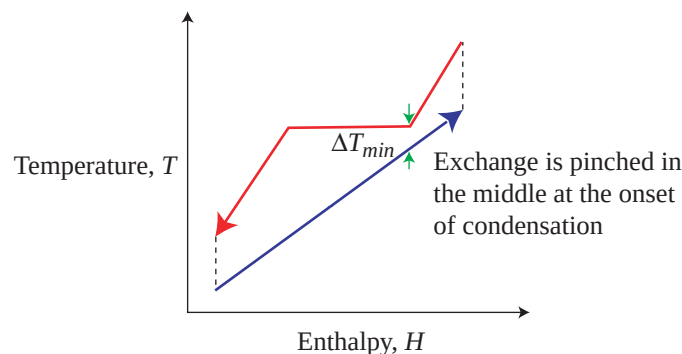


Sketch 4.6 Maximum energy recovery with a real $\Delta T_{\min}$

The value of ΔT_{min} should not be confused with the logarithmic mean temperature difference, $LMTD$, which is used to represent the average temperature difference throughout the match for the design of a pure counter-current, single pass exchanger. The $LMTD$ is used in the equation

$$Q = U \times A \times LMTD,$$

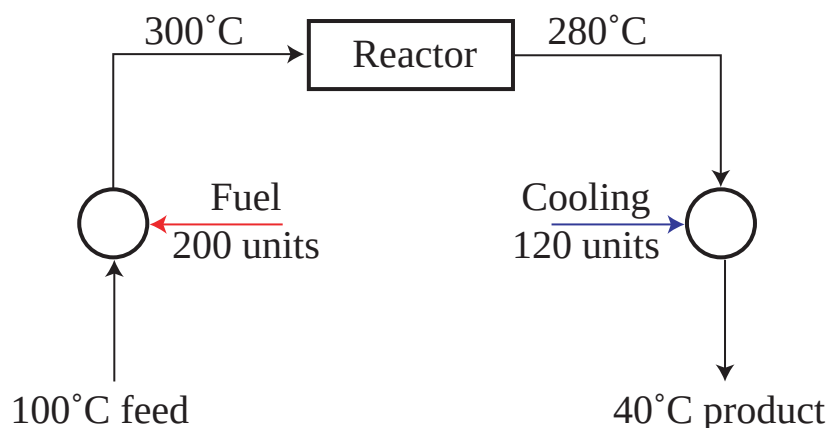
where Q is the heat transferred in an exchanger of area A , with an overall heat transfer coefficient, U , at an effective temperature difference given by the $LMTD$. In a real case, a factor usually between 0.8 and 1 would be included to allow for the fact that pure counter-current heat exchange is usually not attainable in practice. $LMTD$ represents an average overall temperature difference, while ΔT_{min} is the minimum allowable temperature difference anywhere in the exchanger. It is possible for a minimum temperature difference to be observed in the middle of a match, particularly if a phase change occurs, as shown in Sketch 4.7 and not necessarily at one end of an exchanger. This indicates the importance of understanding the nature of the heat transfer operations and the physical states of the materials involved.



Sketch 4.7 ΔT_{min} within a pinched exchanger

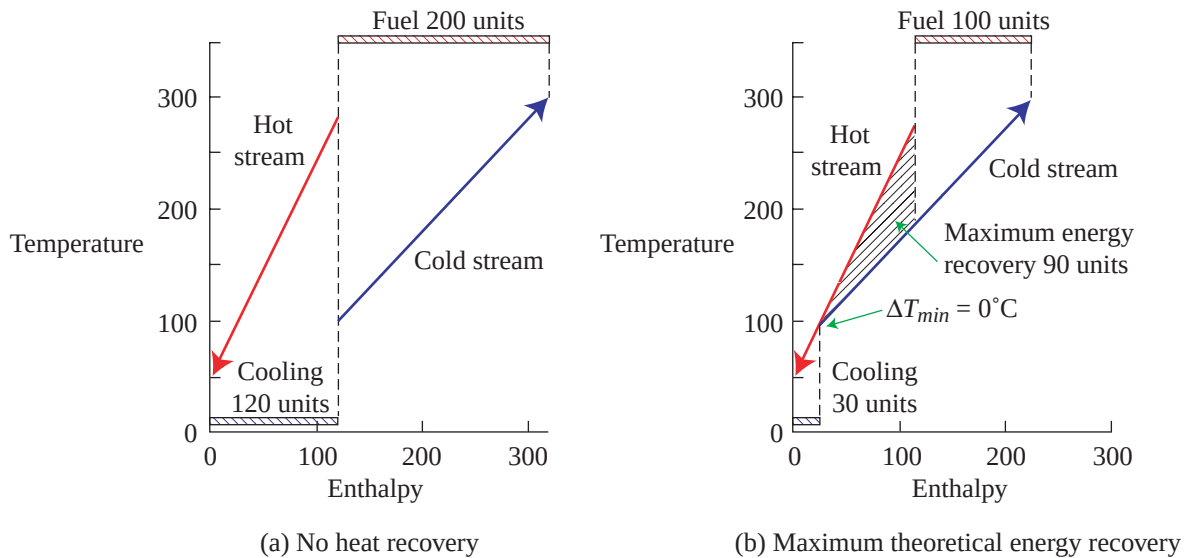
4.4 A Simple Example

A simple example is now developed to show how these basic concepts are put to use. Sketch 4.8 shows an imaginary process consisting of a feed to a reactor that needs to be heated, and a product from the reactor that needs to be cooled. The problem is to decide how much heating, cooling and heat exchange is needed for the process.



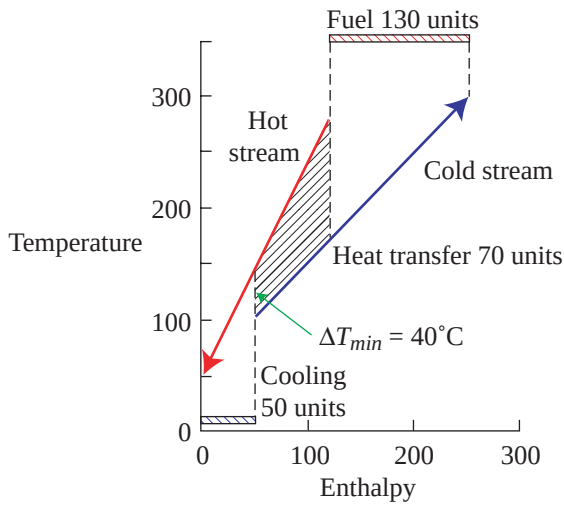
Sketch 4.8 Example process flowsheet

The ideal starting point is the T - H diagram. Firstly, imagine that all the heating needs are supplied by fuel, and all the cooling needs by cooling water. This can be represented by the diagram shown in Sketch 4.9(a), However, using the idea of maximum energy recovery developed earlier, it is possible to view the limiting energy recovery situation, without regard to practical heat exchange, as shown in Sketch 4.9(b). Here the two lines representing the streams touch, at which point there is no temperature difference to drive heat transfer. These two diagrams therefore represent the limiting cases.

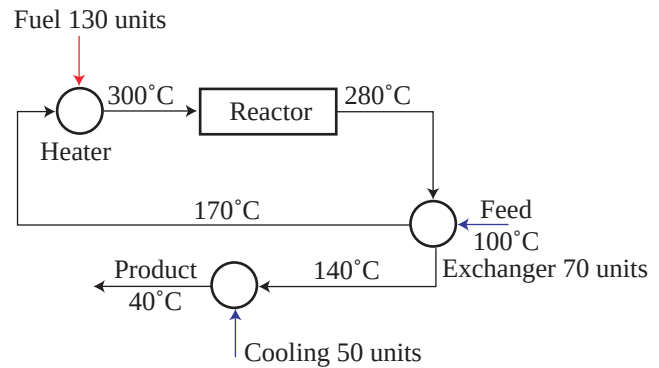


Sketch 4.9 Example T - H diagrams – limiting cases

However, if the minimum allowable temperature difference is 40°C , a real opportunity for heat exchange is revealed as shown in Sketch 4.10 (a). The overlapping region of the T - H diagram shows the amount of heat exchange feasible with this value of ΔT_{min} , and, by a simple heat balance, the remaining heat needed by the cold stream must be met by supplying fuel while the surplus heat in the hot stream, after heat exchange, must be removed using cooling water. This simple heat balance approach, based only on a knowledge of temperatures, enthalpies and flowrates, provides the means to determine, before design, the energy requirement for the process. This becomes the target energy consumption for the chosen value of ΔT_{min} , and can be used as a measure of how well a process is designed. For a new plant the target can be used to check whether or not a design is energy efficient, while for an existing plant it can be used to evaluate current performance and to justify new investment if needed. In the example chosen, the obvious solution is to install a heat exchanger transferring heat from the hot product to the cold feed as shown in Sketch 4.10(b). This reduces the amount of fuel needed to heat the feed from 200 units to 130 units, a saving of 35%. Note that this is also accompanied by an equal reduction in cooling water need. Cooling costs should not be neglected. Indeed, in many low temperature processes involving refrigeration, they may outweigh the heating costs and significant savings can be achieved.



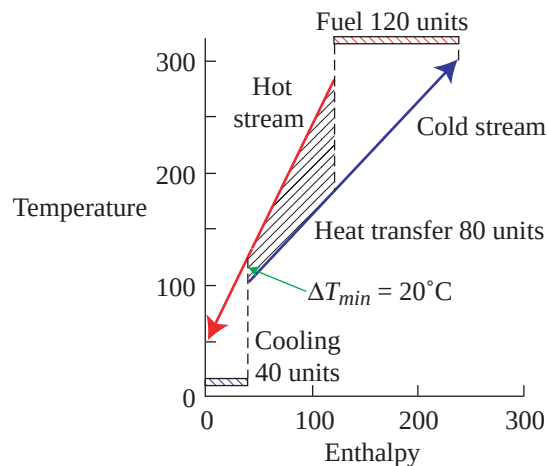
(a) Energy targets for $\Delta T_{min} = 40^\circ\text{C}$



(b) Process flowsheet $\Delta T_{min} = 40^\circ\text{C}$

Sketch 4.10 Example T - H diagram and flowsheet for $\Delta T_{min} = 40^\circ\text{C}$

The effect of altering the value of ΔT_{min} is illustrated in Sketch 4.11. If the value is chosen to be 20°C instead of 40°C , the lines on the T - H diagram are closer together. This results in a greater area of overlap, representing increased heat recovery and less energy requirement, but at the cost of a larger heat exchanger. This is in effect a tool for selecting the optimum level of heat recovery based on a knowledge of energy and equipment costs and nothing else at this stage.



Sketch 4.11 Example T - H diagram for $\Delta T_{min} = 20^\circ\text{C}$

Being aware of this balance between energy and capital costs, together with the concept of a pinched or constrained heat exchanger which was introduced in the previous Section, is the key to optimising the design of the heat recovery system. This simple example illustrates the fundamental aspects of Process Integration, although none of the concepts has been explained at this stage. In later Sections they will be developed in detail, using a real example to illustrate the practical use of the techniques.

5. DATA REQUIREMENTS

The collection of data and the arrangement of them into the form necessary for a Process Integration analysis is one of the most important and difficult phases of the study. The aim is to find the temperature-enthalpy relationships for each stream. It is more important to obtain a consistent set of data than a highly precise one, and it is worthwhile to cross-check between as many different readings and different sources as possible to ensure this. Process Integration is a broad-brush analysis allowing all possibilities to be screened rapidly and an initial solution to be found. Consequently quite rough data will suffice as long as they are not self-contradictory. The initial solution can then be fine-tuned and, if new heat exchangers are found to be necessary, further data can be collected to aid the detail design.

The data collection phase usually has the following stages in a study of an existing plant. New plants are much simpler to study as design data can be used for stages 1 to 3 below.

- (1) Obtain, or draw up, a plant flowsheet that shows all the main process flows requiring heating or cooling. Details of ancillary equipment such as pumps and valves are not required.
- (2) Collect data on feed rates, production throughput, flowrates, reflux and recycle ratios, fluid densities, and form a mass balance. This will show all the mass flows in the plant.
- (3) Collect data on temperatures, fuel use, heat exchanger ratings and performance, and specific heats. Use this to form a heat balance, analogous to the mass balance but showing temperatures and heat flows.
- (4) Use the heat and mass balances to extract the stream data. These are the data in the form required for the Process Integration analysis and consist of a series of streams requiring heating or cooling. For each of these, temperature-enthalpy data are required.

Nearly always, some of the recorded data will have to be modified to give consistent balances – particularly for the heat balance. In general, temperature recordings and specific heat and density data for simple mixtures are likely to be more accurate than recorded flowrates or steam consumption figures. All data should be recorded together, over as short a period as possible. The case study described in Section 12.1 is a good illustration of data collection in action. Note the wide variety of data that are potentially useful for the analysis. Sketches 12.1 and 12.2 show the minimum information required for Stage 1 of the analysis.

Stage 2, the mass balance, is usually relatively straightforward. Flowrates can be recorded and compared with the average calculated from annual production rates, making sure that the actual working year and plant running times are used in the calculation rather than the calendar year. Flow recorders are subject to considerable random error so that some readings may have to be changed to get a consistent balance. The cross-check with annual figures should indicate whether the data collected are representative of normal plant operation.

Stage 3, the heat balance, is more difficult. Calculated heat loads and enthalpies will depend on data for the temperatures, mass flowrates and specific heat capacities of the flows. Errors will be cumulative. There will also be heat losses to allow for. Where the plant parameters change appreciably during running, for example due to fouling, recordings should be made for the two extreme cases and in the middle. The main analysis should be based on the mean case, but the proposed solution can also be checked against the two extreme situations. Again, comparison can be made with annual figures such as furnace fuel consumption and steam production, but allowances must be made for production and distribution losses, furnace inefficiency and fuel used in non-productive periods such as startup, shutdown and standby.

Where difficulty is found in obtaining sufficient data, a detailed energy audit or energy survey will be needed which may require the use of specialist consultants.

Stage 4, the stream data extraction, is usually the trickiest part of all. The plant flows that constitute streams must be defined and the temperature-enthalpy relationship calculated (usually in linearised sections) with allowances for heat losses.

A stream is defined as any process flow that takes in or gives out heat but does not undergo a change in composition. There are three possibilities:

- (i) sensible heating or cooling, in which the enthalpy change takes place over a range of temperatures,
- (ii) isothermal phase changes, typified by the condensation or boiling of a single vapour, in which a large enthalpy change due to latent heat occurs at nearly constant temperature,
- (iii) non-isothermal phase changes, typified by the condensation or boiling of mixed vapours with or without inert gases present, in which the enthalpy change, due to both latent heat removal or absorption and sensible heat changes occurs over a temperature range.

It is important to note the precise definition of a stream in Process Integration analysis; in particular, if a process flow undergoes a change in composition, for example by passing through a separator or in some other unit operation, it becomes a different stream. The first stream should be taken to the feed point of the unit operation and a separate product rundown stream specified. The internal workings of the unit operation should be ignored at this stage. However, any heat that is supplied to or released by the unit operation, as in reboilers, condensers and pumparounds, must be included in the analysis. These are recycle streams that are not undergoing a change in composition. Beneficial changes in the operating conditions of particular unit operations can be identified separately, if required, by advanced Process Integration techniques.

Next, the enthalpy data are collected. Enthalpy values at the initial (supply) and final (target) temperatures of each stream are required, and allowance must be made for:

- (a) non-linear stream heat capacities, especially where there is partial vaporisation or condensation,
- (b) heat losses, assumed unavoidable, from exchangers and pipework.

Streams can often be split into linear segments with break points at the beginning and end of existing heat exchangers. This will be adequate at this stage. If a closer approximation proves to be necessary in certain regions later, more data points can be evaluated but initially it is pointless to go into too much detail. This is especially true if the targeting is being done by hand calculation, when the number of temperature points should be kept to an absolute minimum to avoid lengthy and tedious calculations.

Heat losses must also be accommodated. They reduce the heat available from hot streams and increase that required by cold streams. Heat losses from heat exchangers are assumed to stay at their initial levels for the purpose of the Process Integration analysis. Good housekeeping measures to reduce these losses should be considered separately. There are also temperature discontinuities that must be removed to give smoothly jointed composite curves (*q.v.*). This is done by taking the higher of the two temperatures for cold streams and the lower for hot streams, which ensures a conservative result.

6. ENERGY TARGETS

6.1 Introduction

The brief description of Process Integration in Section 4 showed that rigorous energy targets could be set for a process. This Section gives details of how they can be calculated.

There are two possible methods. A graphical construction on the temperature-enthalpy plots, based on the diagrams in Section 2, can be used. This is cumbersome. It is preferable to use the heat cascade calculation method which is outlined in Section 6.3. However, the graphs are still useful for understanding the energy flows in a plant.

6.2 The Composite Curves

Section 4 showed how a single hot and cold stream could be plotted on a $T-H$ graph and used to derive targets for the minimum heating and cooling requirements and the maximum heat exchange at a given ΔT_{min} . However, for a real process this analysis must be extended to cover the general case of many hot and cold streams.

The method is to take a temperature range or interval and, within each interval, to add together the heat capacity flowrates and enthalpies of all the hot streams present to give a combined curve, known as the hot composite curve. In the same way, all the cold streams in the interval can be combined together to give the cold composite curve. The targets can then be read off in just the same way as in Sketch 4.10(a).

It is straightforward, though sometimes tedious, to construct the composite curves by hand from the stream data. As an example, take the set of stream data listed in Table 6.1.

TABLE 6.1 Stream data for example problem

	1	2	3	4
Stream	Temperature °C	Enthalpy MW	Heat Capacity Flowrate (CP) MW/K	Interval Temperature °C
HOT STREAM				
A	199	1.35	0.0101 0.0109	189
	123	0.58		113
	70	0		60
B	144	1.51	0.0150 0.0169 0.0110	134
	112	1.03		102
	70	0.32		60
	41	0		31
C	123	3.02	0.0773 0.0362	113
	112	2.17		102
	52	0		42
D	204	0.12	0.0020	194
	144	0		134
COLD STREAM				
X	21	0	0.0218 0.0241 0.0253 0.0263 0.0376	31
	60	0.85		70
	92	1.62		102
	111	2.10		121
	138	2.81		148
	179	4.35		189
Y	152	0	0.0313	162
	302	4.70		312
Z	254	0	0.0146	264
	319	0.95		329

Note: $\Delta T_{min} = 20^{\circ}\text{C}$

Interval Temperatures are defined as follows:

for Hot Stream, $TI = T - \Delta T_{min}/2 = T - 10$,

for Cold Stream, $TI = T + \Delta T_{min}/2 = T + 10$.

The cold composite curve for the cold streams, X to Z, is formed as follows.

- (1) Make a list of all the temperatures at which streams begin or end or change heat capacity flowrate, *CP*. Then rank them in ascending order, as in the first column of Table 6.2.
- (2) List all the heat capacity flowrates of streams that have temperatures within each temperature interval. This is the second column of Table 6.2.
- (3) Where more than one cold stream exists in an interval, as between 152°C and 179°C and between 254°C and 302°C, add together the *CP*s to give the total in column 3.
- (4) Multiply the total *CP* by the temperature change from beginning to end of the interval. This gives the change in enthalpy of all the cold streams over the interval (column 4).

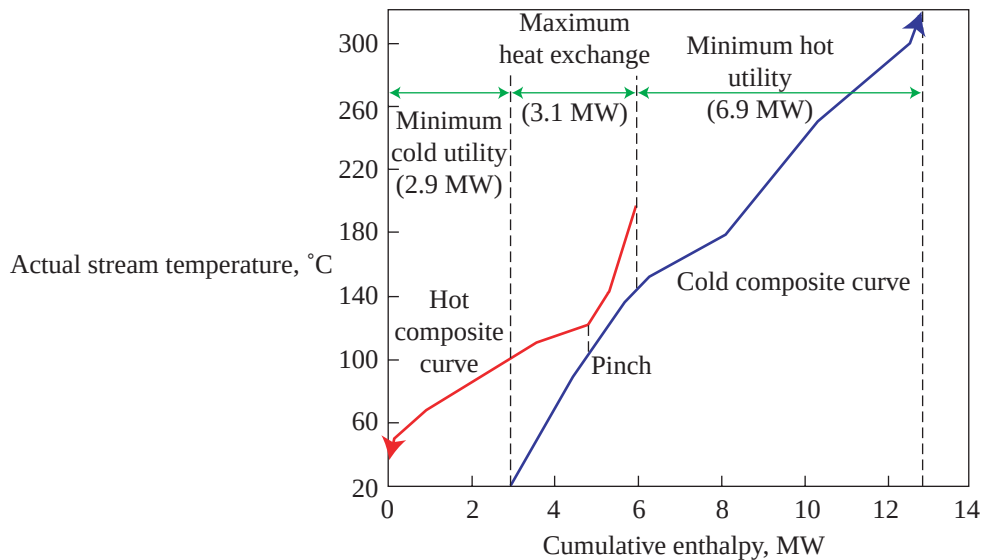
Starting from zero at the bottom end temperature, add the enthalpy increments for each temperature interval successively to give a cumulative enthalpy as shown in the fifth and last column of Table 6.2. This is the cold composite curve.

TABLE 6.2 Calculation of Cold Composite Curve

1	2	3	4	5
Temperature	Heat Capacity Flowrate, MW/K		Enthalpy, MW	
°C	Individual Streams X + Y + Z	Total CP_i	Increment	Cumulative
21				0
60	0.022	0.022	0.85	0.85
92	0.024	0.024	0.77	1.62
111	0.025	0.025	0.48	2.10
138	0.026	0.026	0.71	2.81
152	0.038	0.038	0.53	3.34
179	0.038 + 0.031	0.069	1.86	5.20
254	0.031	0.031	2.35	7.55
302	0.031 + 0.015	0.046	2.20	9.75
319	0.015	0.015	0.25	10.00

The hot composite curve is derived in precisely the same way using the hot streams, A to D.

The shapes of the hot and cold composite curves have now been established, but they must be set the correct distance apart, ΔT_{min} , to give the correct targets. This is done by sliding the cold composite curve horizontally to the right relative to the hot composite until the two curves do not cross over and are ΔT_{min} apart at their point of closest approach. For this example, with a ΔT_{min} of 20°C, the result is shown in Sketch 6.1. The cold composite has been moved by 2.9 MW, and this gives the cold utility target. The hot utility target can be read off as 6.9 MW, and the maximum possible heat exchange at this ΔT_{min} is 3.1 MW.

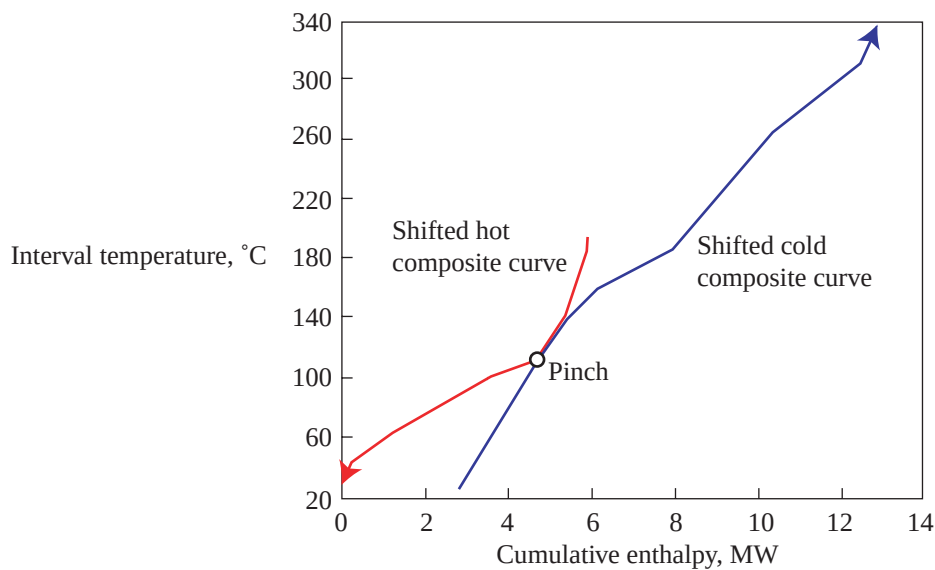


Sketch 6.1 Composite curves

6.3 Interval Temperature

The minimum utility requirements can be calculated mathematically more readily than by using the graphical procedure. To do this, it is necessary to introduce the concept of interval temperature.

The gap between the composite curves is regulated by the value of ΔT_{min} and it is useful to remove the gap so that the curves just touch. This is done by adding $\Delta T_{min}/2$ to all the cold stream temperatures and subtracting $\Delta T_{min}/2$ from all hot stream temperatures. The shifted temperature values are known as interval temperatures and are shown in column 4 of Table 6.1. If the composite curves are plotted on interval temperature axes, they will move closer together and will just touch at the one point where the composite curves were ΔT_{min} apart. This is known as the temperature pinch. The shifted composite curves are shown in Sketch 6.2.



Sketch 6.2 Shifted composite curves (interval temperature basis)

Using interval temperatures, therefore, cancels out the effect on the analysis of the minimum temperature driving force needed to achieve heat exchange.

6.4 The Heat Cascade and the Problem Table

With the enthalpy data considered at interval temperatures, the need for make-up utility heating or cooling can be found by taking the difference between the stream heating and cooling loads over each range of temperatures.

If net heat is released at a high temperature, it may be possible to use it at a lower temperature where there is a heat deficit. So a heat cascade is set up over the temperature range of the process. Using this cascade (Table 6.3), which is also known as the Problem Table, the minimum heating and cooling targets can be found. The calculation method is similar to that for the composite curves.

TABLE 6.3 Calculation of Heat Cascade (Problem Table)

1	2				3	4	5	6	
Interval Temperature °C	Heat Capacity Flowrate, MW/K					Heat Increment MW	Total Heat Cascades		
	Individual Streams $CP_{hot}-CP_{cold}$				Total		Infeasible MW	Final MW	
329							0.000	6.900	
					- 0.0146	-0.0146	-0.248		
312							-0.248	6.652	
					- 0.0313 - 0.0146	-0.0459	-2.203		
264							-2.451	4.449	
					- 0.0313	-0.0313	-2.191		
194							-4.642	2.258	
					+ 0.0020 - 0.0313	-0.0293	-0.147		
189							-4.789	2.111	
	0.0101	+ 0.0020	- 0.0313	- 0.0376	-0.0568	-1.534			
162							-6.323	0.577	
	0.0101	+ 0.0020			-0.0376	-0.0255	-0.357		
148							-6.680	0.220	
	0.0101	+ 0.0020			- 0.0263	-0.0142	-0.202		
134							-6.882	0.018	
	0.0101	+ 0.0150			- 0.0263	-0.0012	-0.016		
121							-6.898	0.002	
	0.0101	+ 0.0150			- 0.0253	-0.0002	-0.002		
113							-6.900	0.000	
	0.0109	+ 0.0150	+ 0.0773	- 0.0253	0.0779	0.857			
102							-6.043	0.857	
	0.0109	+ 0.0169	+ 0.0362	- 0.0241	0.0399	1.277			
70							-4.766	2.134	
	0.0109	+ 0.0169	+ 0.0362	- 0.0218	0.0422	0.422			
60							-4.344	2.556	
					+ 0.0110	+ 0.0362	- 0.0218		
42						0.0254	0.457		
					+ 0.0110	- 0.0218	-0.0108	-0.118	
31								-4.005	2.895

Maximum infeasibility (largest negative value) in the infeasible heat cascade is 6.9 MW at an interval temperature of 113°C. This is therefore the minimum amount of hot utility which must be added to the cascade, *i.e.*, the Minimum Energy Requirement (M.E.R.) target. The cold utility target is 4.0 MW less at 2.9 MW. The pinch temperature of 113°C interval temperature corresponds to a hot stream temperature of 123°C and a cold stream temperature of 103°C.

The method, illustrated using the stream data from Table 6.1, again with a ΔT_{min} of 20°C, is as follows.

- (1) Convert all stream temperatures to interval temperatures by adding $\Delta T_{min}/2$ (i.e. 10°C) to cold stream temperatures and subtracting $\Delta T_{min}/2$ from hot stream temperatures. This gives the last column in Table 6.1.
- (2) List all the interval temperatures at which streams begin or end or change heat capacity flow rate, CP .
- (3) Rank these interval temperatures in descending order. This is column 1 of Table 6.3.
- (4) For each temperature interval, add together the heat capacity flowrates of all the hot streams which exist in that temperature interval and subtract the heat capacity flowrates of all the cold streams, to give the net heat capacity flowrates (columns 2 and 3 of Table 6.3).
- (5) Multiply the net heat capacity flowrate by the temperature range of the interval to give the net heat required or released by all the streams in the interval (column 4 of Table 6.3).
- (6) Starting from a zero input at the highest temperature, work down the table, adding on the heat change in each temperature interval to give a heat cascade, or cumulative heat passing through at the particular temperature (column 5).

This preliminary problem table will normally have infeasibilities. These are temperatures at which the net heat cascaded through the system is negative. These infeasibilities must be removed.

- (7) Find the largest negative number in column 5 of the preliminary problem table. Add this amount of heat, Q , as hot utility at the top of the cascade. All the other values in the cascade will also increase by Q , to give a new series, column 6 of Table 6.3. This is the feasible problem table.

The heat Q added is equal to the target hot utility requirement. The pinch is the point at which there is zero net heat flow in the cascade, corresponding to the point where there was the largest infeasibility. This occurs at an interval temperature of 113°C.

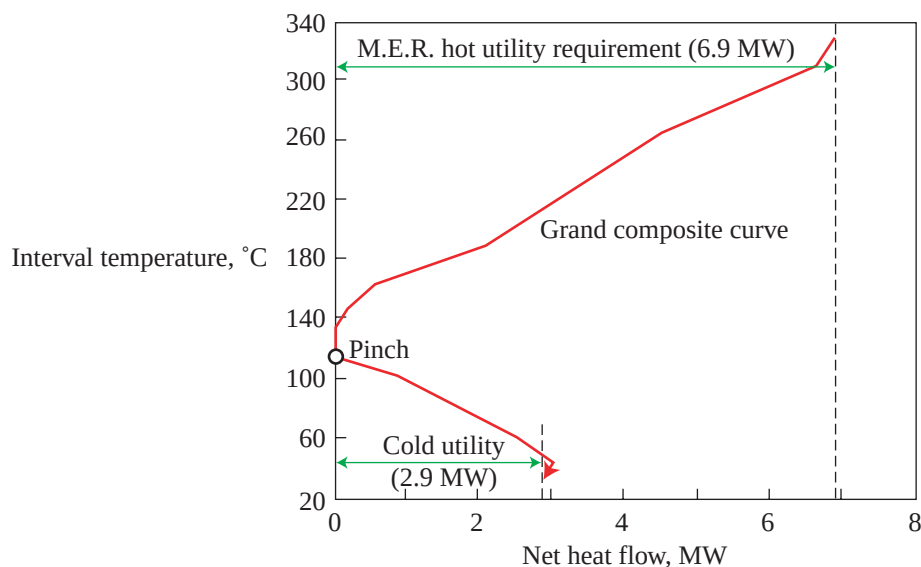
- (8) The first and last values in the final column of the problem table are respectively the minimum hot and cold utility requirements.

The problem table thus gives the utility targets – 6.9 MW hot, 2.9 MW cold – with no need for graphical construction. However, it gives no indication of the heat actually exchanged within the system, only the residual utility requirements. To interpret the results of the analysis thoroughly, the composite curves are therefore needed as well. The heat exchange is then found by back calculation. Here, since the total heat required by the cold streams is 10 MW (from Table 6.2), the heat exchange must be 3.1 MW. The composite curves are also necessary for area and capital cost targeting calculations (see Section 9).

Hand calculation of the Problem Table is long and tedious for all but the simplest processes. Even the case study used illustrates the number of calculations needed and the time involved. The procedure is relatively straightforward and is ideal for computer calculation. Several programs are available that calculate the targets, the composite and grand composite curves, and the pinch. Most of them perform other useful analyses as well. They are listed in the Appendix.

6.5 The Grand Composite Curve

It is useful to plot the heat cascade or the problem table as a temperature – enthalpy graph. The result is the grand composite curve (G.C.C.) and is shown in Sketch 6.3.



Sketch 6.3 Grand composite curve

The grand composite curve is an even more useful tool than the composite curves, especially for the more advanced techniques such as identification of process change. This is because it has significance in three ways.

- (1) It is a plot of the enthalpy difference (horizontal axis) between the hot and cold composite curves with the necessary temperature correction, ΔT_{min} , included.
- (2) It shows the net heat flow through the process, from hot utilities and hot streams to cold utilities and cold streams, at any interval temperature.
- (3) It shows the amount of heat required by or released from the process at any given temperature and thus how much hot or cold utility can be used at different levels.

The other benefit of the grand composite curve is that the pinch point shows up more clearly as it is the point at which the graph touches the temperature axis.

6.6 Interpretation of the Graphs

The temperature – heat load graphs not only give the targets, but also give a feel for the way the process uses energy.

The composite curves are primarily used to show:

- (i) the relative importance of heat exchange and utility heating/cooling,
- (ii) the variation of driving forces with temperature,
- (iii) the basis of the calculation of heat exchanger area (see Section 7).

The grand composite curve primarily reveals:

- (i) the pinch temperature,
- (ii) other areas of low heat flow where design will be tightly constrained,
- (iii) utility use at different temperature levels,
- (iv) the best placement of separation and reaction systems.

Their use is illustrated in the case study and in Section 8 on network design.

7. THE PINCH AND ITS SIGNIFICANCE

7.1 Introduction

Process Integration is often known as pinch technology. The pinch is the key to understanding the Process Integration analysis of a plant, and shows:

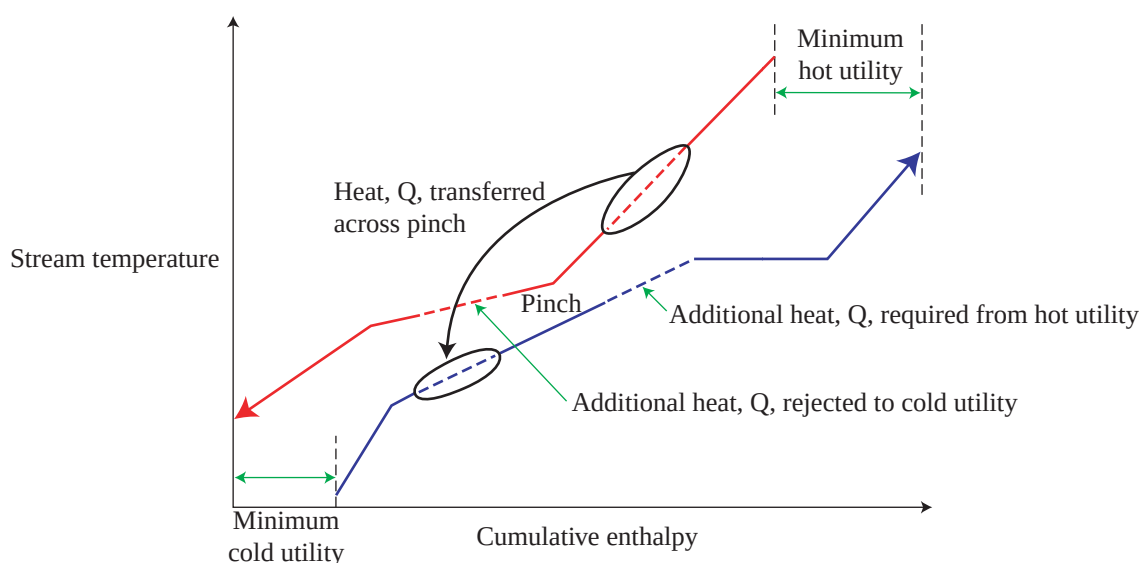
- why and where a plant uses much more energy than it needs and identifies major energy savings, even on “state-of-the-art” processes developed over many years,
- how to design the heat recovery system to achieve in practice the targets identified by using the composite curves and the problem table (see Section 4.4).

7.2 Heat Flow in the Process

Sketches 6.1 to 6.3 show that, at high temperatures, utility heating is required whilst at low temperatures, cold utility is needed and, in between, heat exchange is possible.

Sketch 6.2 shows that when ΔT_{min} is taken into account, the shifted hot and cold composite curves just touch at the pinch. Therefore, none of the hot streams below the pinch point is able to heat any of the cold streams above the pinch. In order to recover heat usefully from hot streams below the pinch, they must heat cold streams which are also below the pinch. Likewise, heating of cold streams above the pinch must be carried out by hot streams above the pinch or by hot utilities.

Suppose, however, that a hot stream above the pinch is used to heat a cold stream below the pinch, as in Sketch 7.1, thereby transferring heat across the pinch. The cold stream could have been heated by a below-pinch hot stream instead and the above-pinch hot stream could have been used to heat an above-pinch cold stream. However, as pointed out in the previous paragraph, the below-pinch hot stream cannot heat the above-pinch cold stream. Both these streams must therefore be satisfied by utilities. The net result is that both hot and cold utility consumption has gone up by Q units as a result of transferring Q units of heat across the pinch.



Sketch 7.1 Heat transfer across the pinch illustrated by composite curves

The reason for this becomes even clearer by inspecting the grand composite curve, Sketch 6.3 and Table 6.3, where it is seen that, when the targets are being achieved, there is no net heat flow across the pinch. If heat,