"Pinch technology is based on thermodynamic insights which do help to clarify many options while keeping the designer in control of the design procedure."

Design Energy Recovery Systems with Confidence-Use Pinch Technology Targets

by
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ABSTRACT

In designing a network of heat exchangers for the recovery of waste heat, there is usually a "pinch" at which the minimum approach temperature difference limits energy recovery. Pinch technology emphasizes the importance of utility and other targets, which are independent of the network design, and thus allow a very useful comparison with the requirements of actual networks.

Methods for determining utility and area targets are surveyed. These can be applied both to new designs as well as for determining the scope for energy conserving retrofits. It is pointed out that significant improvements in utility targets can often be achieved by appropriate exploitation of process flexibility. Thus, it is essential that for a successful application of these techniques, experts in the technology working closely with personnel who are also experts in the processes being studied are required.

INTRODUCTION

The pinch point in a heat exchanger network (HEN) is the location where the network is most constrained. This constraint arises from the minimum approach temperature ΔT_{min} specified for heat exchanger design. Thus, a HEN which satisfies the energy target of pinch technology will be so designed that exchangers at the pinch point temperature would have approach temperatures equal to ΔT_{min}.

The Institution of Chemical Engineers "Guide on Process Integration for the Efficient Use of Energy" [Linnhoff et al. (1982)] contains a most valuable summary of the targeting procedures, as well as the pinch design method [Linnhoff and Hindmarsh (1983)] and points the way to the appropriate integration of heat and power systems. The significance of the pinch point as a bottleneck for process integration had earlier been recognized by Umeda et al. (1979) who suggested process changes for reducing the impact of this bottleneck. However, it was only during the early '80s that the full importance of the pinch was realised and the work of Linnhoff was clearly identified with "pinch technology" [see e.g., Linnhoff and Vredeveld (1984)]. There are now systematic techniques for effective designs leading to substantial energy savings. In the Linnhoff and Vredeveld study, Union Carbide experience was quoted to be averaging 50 percent energy savings on grass roots designs or for retrofits, paybacks being less than one year. Thus although much of the initial work is in two university theses [Hohnmann (1971) and Linnhoff (1979)] based on the seemingly academic subject of thermodynamics, it has been gratifying to see this work so successfully used throughout the process industries.

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The following sections summarize some of these procedures and highlight the work of Linnhoff. His approach is partly heuristic and so does not guarantee optimum networks. However, pinch technology is soundly based on thermodynamic insights which do help to clarify many options while keeping the designer in control of the design procedure.

PINCH TECHNOLOGY

A flow diagram for the palm oil steam refining process is given in Figure 1. In HEN analysis cold streams are streams which require heat to achieve their required target temperature (TT). Hot streams are those streams which require some cooling in changing from supply (TS) to target temperatures. For the palm oil process the crude palm oil is a cold stream as it requires heating from 45° to 90°C for acid and clay treatment. The treated oil is a second cold stream and is heated from 80°C to 260°C. Apart from a small amount of fatty acids which are removed by distillation (and are ignored here) the only product from the steam distillation process is the refined oil which is a hot stream and is cooled from 260° to 50°C. Having identified the three significant streams in this problem with mass flowrate and heat capacity data, the enthalpy changes for these streams can then be calculated. The data has been analyzed elsewhere [Wood and Hasan (1987 a, b)] and it was found that substantial energy savings could be achieved, especially for the situation where such a refining process is integrated with an associated refrigerated crystallizer for the production of high and low melting point fractions.

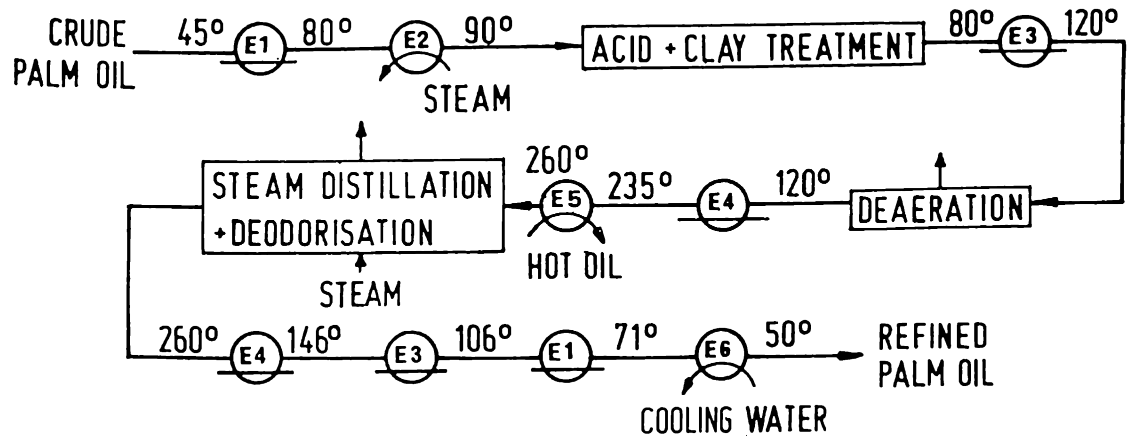

Figure 1. Palm Oil Refinery Process Flow Diagram (El to E6 – Heat Exchangers)

A simple network taken from Ashton and Watt (1985) for another three-stream problem is given in Figure 2 for the stream data in Table 1.

Table 1. Stream Data

Stream Number	CP kW/°C	TS °C	TT °C	Enthalpy Flowrate CP (TT-TS) kW
1. (Hot)	1.0	200	50	–150
2. (Cold)	0.5	50	150	50
3. (Cold)	1.5	100	200	150

The network is designed for a minimum approach temperature difference (ΔT_{min}) of 20°C and has hot utility (steam) requirements of 120 kW and cold utility (cooling water) of 70 kW. By determining the utilities targets, pinch technology provides an objective measure at an early

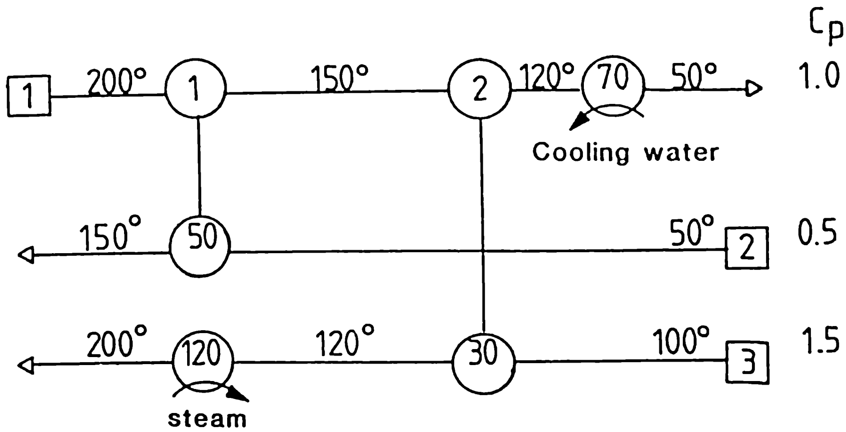

Figure 2. A Simple Heat Exchanger Network.

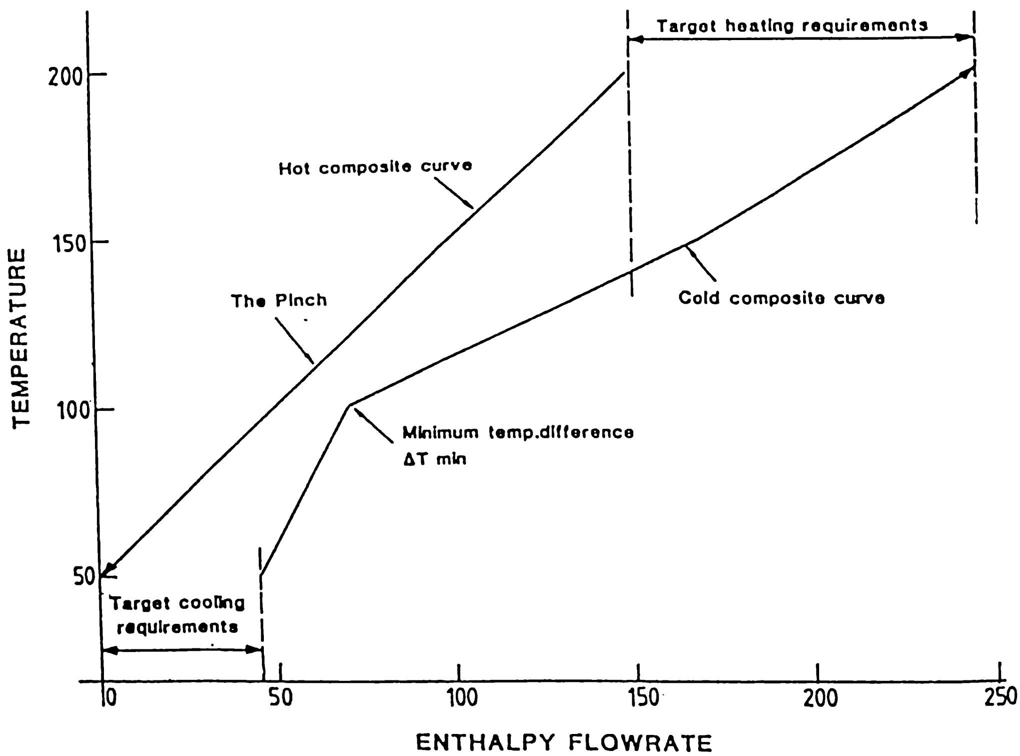

Figure 3. Using Composite Curves to Determine the Energy Targets and Pinch Location

stage of a network investigation for comparison with the performance of actual plant or network designs. For heat exchange between two streams, the maximum heat load for a fixed minimum approach temperature difference is easily obtained by plotting the two streams on a temperature/enthalpy flowrate (T-H) diagram. With multi-stream problems, a similar technique can be used. All hot streams are combined together into the hot composite curve and the cold streams into the cold composite. These two curves can be adjusted relative to each other along the enthalpy axis, so that the minimum temperature difference is ΔT_{min} (as shown in Figure 3 for the example considered). The overlapping region gives the maximum enthalpy that can be transferred from the hot to the cold streams and the minimum utility requirements are also readily obtained from this diagram. In this case the utility targets are 95 and 45 (i.e., 20 percent reduction in the hot utility requirement from the network of Figure 2). Moreover, these targets are achievable and a network satisfying the

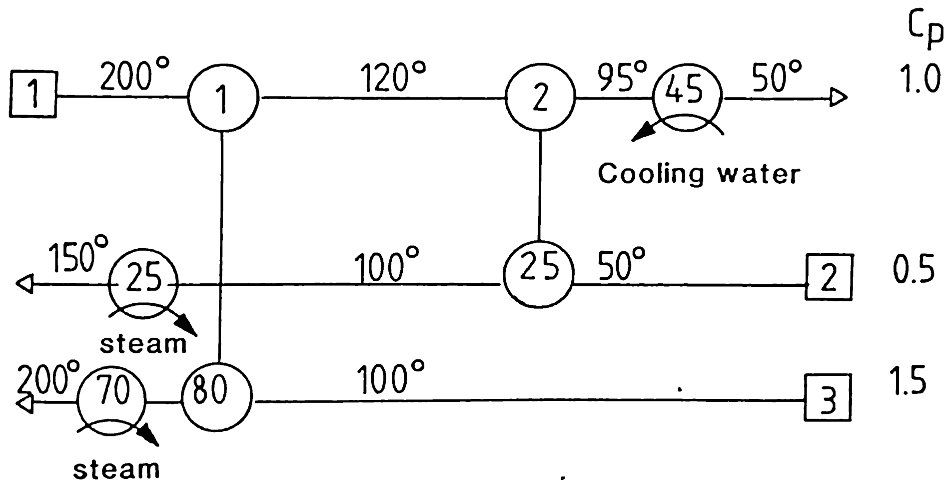

Figure 4. An Alternative Heat Exchanger Network which Satisfies the Energy Targets

targets and obtained with the aid of the pinch design method [Linnhoff and Hindmarsh (1983)] is given in Figure 4. Thus although 45 kW of the available enthalpy in the hot stream are rejected, it is not possible (for the specified ΔT_{min} of 20°C) to recover any of this waste heat and further reduce the steam load. This is because the design given in Figure 4 satisfies the energy targets obtained as shown in Figure 3.

Networks which do not achieve the utilities target for a given ΔT_{min} violate one or more of the following "golden rules" of pinch technology.

1. Don't transfer heat across the pinch (i.e., take heat from a hot stream above the pinch temperature to heat a cold stream below the pinch temperature).
2. Don't use cold utility above the pinch.
3. Don't use hot utility below the pinch.

The reason why the network of Figure 1 does not achieve the utility target for $\Delta T_{min} = 20°$ is that half of the load of exchanger 1 is across the pinch. There is, therefore, an energy penalty of 25 enthalpy units compared to the utility target.

PROCESS FLEXIBILITY AND UTILITY TARGETS

Most processes have flexibility and there is, therefore, a strong economic incentive to determine those process conditions which will reduce utility consumption. Without utility targets this is a tedious procedure as it is necessary to design and assess many networks. However, with pinch technology, the impact of alternative process conditions may be readily assessed simply by redetermining the utility targets for the revised stream data without the need for many network designs. (Rather than use the composite curves, as explained above, it is more convenient to use the Problem Table procedure of Linnhoff and Flower (1978) which has been incorporated into computer programs*). Moreover, the location of the pinch often provides considerable insight into how process conditions should be changed so as to achieve lower utility targets. This follows from application of the plus/minus principle [Linnhoff and Vredeveld (1984)] which ensures that utility targets will be reduced if some of the following can be achieved:

1. Increased duties of hot streams above the pinch (plus).
2. Decreased duties of cold streams above the pinch (minus).
3. Decreased duties of hot streams below the pinch (minus).
4. Increased duties of cold streams below the pinch (plus).

*E.g. HENTARG which is obtainable from Engineer C. S. Baduria, Office of Energy Affairs, Fort Bonifacio, Metro Manila (Phone: 857487).

Sometimes a process change involves two changes simultaneously. Thus, a pump around reflux stream (which is extensively used for heat recovery on crude oil distillation units) may be initially available at a temperature above the pinch and be cooled to a temperature below the pinch. Then if the flowrate of this stream is increased, while the enthalpy change is kept constant, the target temperature will also increase. The result of this change in flowrate is to increase the duty of this stream above the pinch while simultaneously reducing the duty below the pinch. However, for this change to have any impact on the utility target, it is necessary that the original supply and target temperatures be on opposite sides of the pinch. There will be no impact on utility targets if such changes to mass flowrates are made to pump around reflux streams which are either completely above or completely below the pinch. Thus, the pump-around streams which have potential for reducing utility targets are readily obtained by inspection once the location of the pinch is known. Increasing the flowrates of such pump-around streams reduced the hot utility target by 10 percent, and provide the basis for a cost effective retrofit on a modern crude oil distillation unit [Wood (1982)].

THE GRAND COMPOSITE AND PROCESS INTEGRATION

The grand composite curve may conveniently be plotted from energy flows and temperatures obtained from the Problem Table targeting method. It represents the net energy requirement of the process as a function of temperature and is obtained by enthalpy balance on the hot and cold streams for networks supplied with target utilities. At the pinch temperature the energy flow is zero. An example of the grand composite is shown in Figure 5 [Hill (1985)]. Above the pinch the

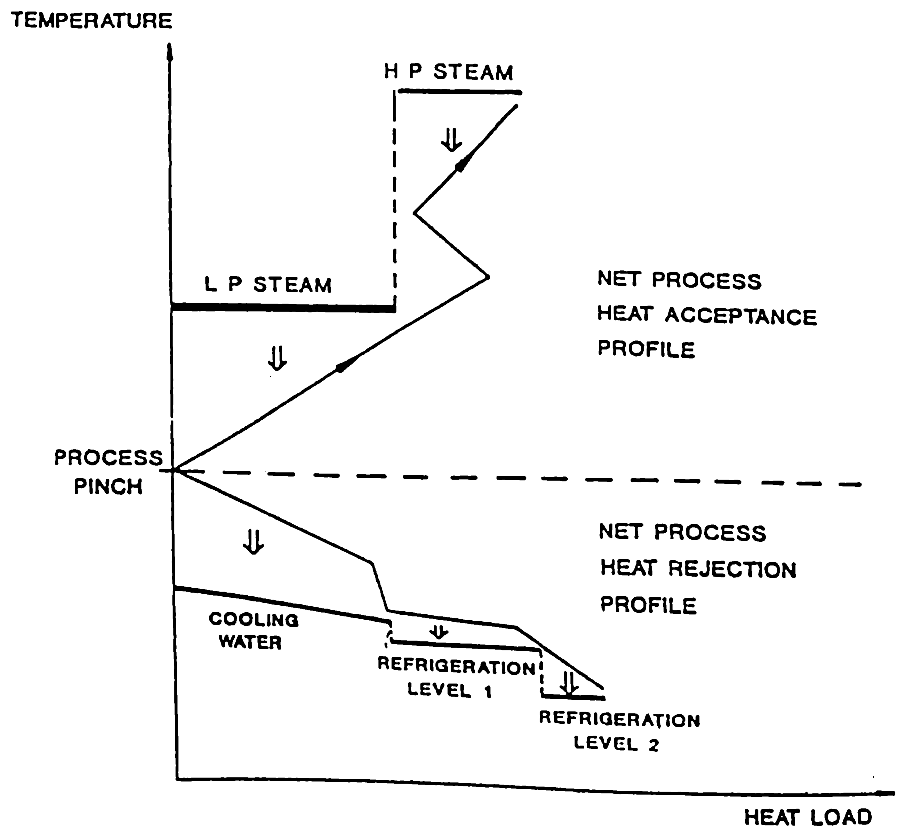

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Figure 5. Use of Grand Composite Curve and Location of Hot and Cold Utility Loads

process is a net sink for energy and so the grand composite curve can be used to select the appropriate levels and flows of hot utilities (e.g., utility steam pressures). Similarly below the pinch the process is a net source of energy which is transferred to appropriate cold utilities or sometimes this energy can be used for steam raising. Utilities may be linked to systems for producing electrical or mechanical power and Townsend and Linnhoff (1983) used the grand composite curve to determine appropriate integration of heat and power systems.

The grand composite curve has also been found to be useful for determining how best to intergrate the energy flows of distillation columns into a "background (or remaining) process". Columns require heat to satisfy reboiler duties but usually similar energy flows are rejected from condensers. Ideally, the distillation column should be able to borrow heat from the background process and return heat into the process on the same side of the pinch. Thus, the temperature span between the reboiler and condenser should not cross the pinch, and adjustment of column pressure may be successful in moving a column away from the pinch, thus reducing the utility target for the combined process [Linnhoff, Dunford and Smith (1983), Hindmarsh and Townsend (1984)].

As well as investigating the integration of a distillation column with the rest of the process, it is of course possible to separate other items and compare them with the remaining grand composite curve. In this way the most appropriate conditions can be obtained for reducing the utility targets. This technique has been used with evaporators and flash systems as well as chemical reactors. A study showing how to determine the most suitable flash pressure or whether greater energy savings would be achieved with additional flash stages has recently been presented [Kemp (1987)]

CAPITAL TARGETS

The procedures discussed previously have led to very significant energy savings. However, it is of course not the desired objective to minimize energy costs, but the total operating costs including plant capital charges should be optimized. If the utilities are supplied at the minimum temperature difference then a further pinch is introduced and the added complexity of some networks which feature such utility pinches can add very significantly to plant capital costs. Furthermore, it has been implicitly assumed that ΔT_{min} is known. However ΔT_{min} will depend on the shape of the composite curves as well as the environment for heat transfer (e.g. gas/gas exchange, refrigerants, corrosive fluids, etc.). Thus, for the same environment, the optimum ΔT_{min} will be smaller for composite curves which are strongly pinched compared to those which are approximately parallel. Therefore, network optimization has to be carried out for various values for ΔT_{min}. This procedure can be abbreviated if the network cost (area) can be predicted from stream data alone.

If the overall heat transfer coefficient (U) for all exchangers in a network is constant, then heat exchange which exactly follows the composite curves gives a network of minimum area. This area target is given by [Nishida et al. (1971), Hohmann (1971)]

$$A_{MIN} = \frac{1}{U} \sum_{j}^{\text{INTERVALS}} \frac{\Delta H_j}{(\text{LMTD})_j}$$

With most networks this target can only be exactly achieved with considerable complexity involving many small exchangers and intricate patterns of split streams. However, many networks almost achieve the area target (assuming counter current heat exchange: with multi-tube pass exchangers, there is of course extra area required because of the mean temperature difference correction factor).

In practice it is unrealistic to assume a constant value for U as the film coefficients often differ by at least an order of magnitude. For such situations a modified target [Townsend and Linnhoff (1984)] for counter current heat exchange is:

$$A_{TOT} = \sum_{j}^{\text{INTERVALS}} \frac{1}{(LMTD)_j} \left(\sum_{k}^{\text{STREAMS}} \frac{\Delta H_k}{h_k} \right)_j$$

This expression does not guarantee that A_{TOT} is the minimum network area. (This is because it is advantageous to match streams with high film coefficients together and this requirement can overide the benefit of counter-current matching). However, A_{TOT} has been found to be satisfactory for preliminary costing purposes.

RETROFITS

Heat exchanger network designs based on pinch technology techniques are essentially for grass roots designs. These techniques have been adapted with some success for retrofit projects but improvisation is necessary, together with the availability of skilled experienced personnel for a good result. The pinch design method has been used to produce maximum energy recovery designs, from which designs more compatible to the existing design were evolved. However, often, it is difficult to identify a design whose structure suits the existing plant. Another problem is the choice of ΔT_{min}: this can influence network structures as well as the location of cross pinch exchangers. A recent paper [Tjoe and Linnhoff (1986)] which seeks to overcome these difficulties has recently been published and is outlined below.

Using the techniques discussed above, the target energy and area requirements may be predicted as a function of ΔT_{min}. The situation on comparing these predictions with an existing design (A) will be shown diagramatically on Figure 6. The existing design will not be as efficient

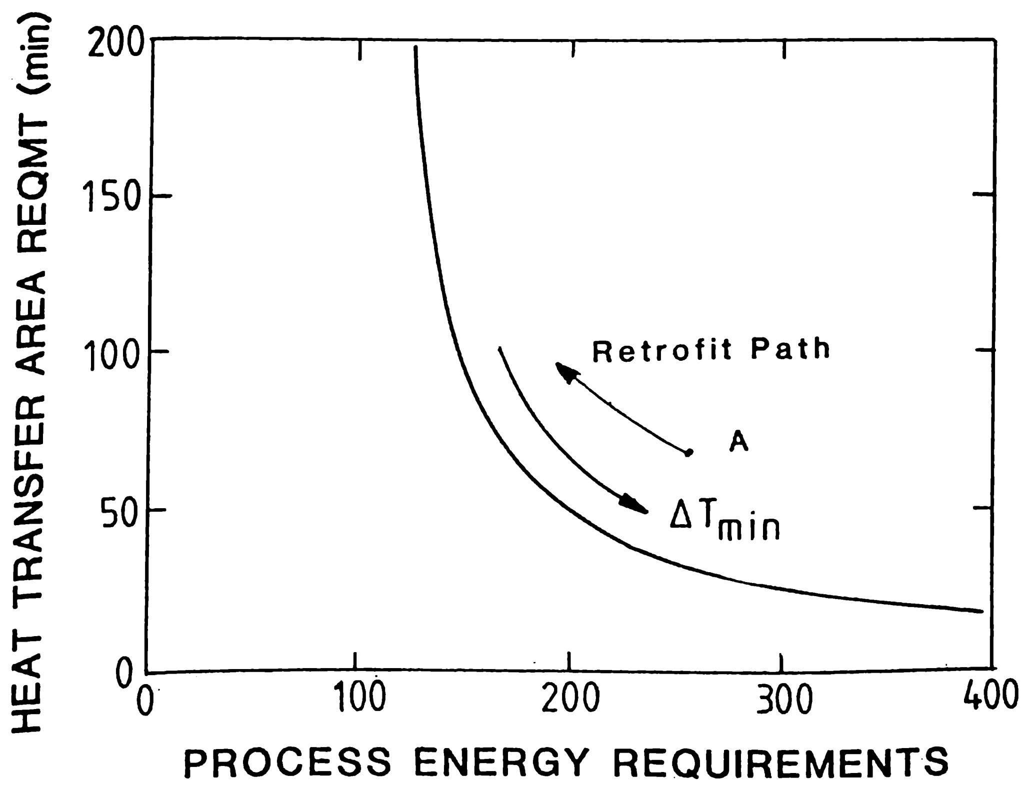

Figure 6. Energy and Heat Transfer Area Targets and ΔT_{min}

as the targets both for energy and area requirements. On modifying an existing design by retrofit it is most likely that additional area will be needed so as to save energy and so the retrofit will follow the path shown. A locus of the path may be obtained by making the conservative assumption that the network after retrofit will use area as effectively as before. Given this path the energy savings and area costs can be predicted as a function of ΔT_{min}. Hence, the size of the retrofit and corresponding value for ΔT_{min} may be found which meets the imposed economic criterion for the project (e.g., two years payback). With the broad scope of the retrofit and ΔT_{min} determined, the detailed retrofit then follows these steps:

1. Identify cross pinch exchangers.
2. Eliminate cross pinch exchangers.
3. Complete the network and reuse the exchangers removed where possible but without cross pinch matches.
4. Evolve improvements by improving the compatibility with the existing network by moving heat loads around loops and along paths.
5. Check the payback period and energy savings.

An alternative approach to retrofits is to use the pseudo pinch approach of Trivedi et al. (1988). Since the temperatures at the pseudo-pinch can be varied, this flexibility can be used to ensure that a resulting energy saving design has a high degree of compatibility with an existing design. Experience with this procedure indicates that it has often easier to use than the method of Tjoe and Linnhoff (1986).

Table 2. Process Integration Reports Available from the ETSU Enquiries Bureau, Harwell Laboratory, Oxon, OX11 ORA, England

Company	Site activities	ETSU ref. no.
Gulf Oil Refining Ltd.	Oil refinery	RD/7/21
Shell Uk Ltd.	Oil refinery	RD/19/26
Tioxide Plc	Titanuim dioxide manufacturer	RD/6/13
Proctor and Gamble Ltd.	Soap and detergent manufacturer	RD/8/19
William Blythe Ltd.	Production of inorganic chemicals	RD/5/20
Cray Valley Products Ltd.	Production of synthetic resins	RD/13/15
Beecham Pharmaceuticals	Solvent recovery unit	RD/16/17
Long John International	Grain whisky distillery	RD/4/9
Tetley Walker Ltd.	Brewing	RD/11/22
Cadbury Typhoo Ltd.	Milk and beverage powder manufacturers	RD/12/23
Van den Berghs and Jurgens	Edible oil refining	RD/14/14
J. Lyons & Co. Ltd.	Food processors	RD/20/27
East Lancashire Paper Mill	Paper manufacturer	RD/15/18
St. Regis International	Paper manufacturer	RD/17/16
Sheerness Steel	Steel works	RD/18/25

INDUSTRIAL APPLICATIONS

The UK Government through the Energy Efficiency Office has subsidized a number of Process Integration studies based on pinch technology. These have been selected to demonstrate the power of Pinch Technology across a wide range of industries. Reports released under this programme are listed in Table 2. Typically the scope for energy savings reported are about 30 percent with payback periods varying from a few months to two years. Many of the reports state that energy saving projects identified by these studies have been or are being implemented.

CONCLUSION

Thus, there is ample evidence to encourage those unfamiliar with process integration pinch techniques that the technology has proven to be of significant benefit. However, the successful application has required specialists expert in the technology working closely with personnel who are also experts in the processes being studied. Few companies have managed to develop an in-house expertise in Process Integration without the direct assistance of personnel who have had a long term involvement with the development of the techniques [Hill (1985)]. It is an objective of the Office of Energy Affairs in the Philippines that appropriate expertise in this technology be developed in this country. Readers who wish to learn more about pinch technology should contact Engineer C. S. Baduria, Office of Energy Affairs, Fort Bonifacio, Metro Manila.

NOMENCLATURE

A	=	Heat Exchanger Surface Area (m^2)
CP	=	Heat Capacity Flowrate (mass flowrate x specific heat) (kW/^oC)
h	=	Heat transfer film coefficient (kW/m^2 ^oC)
H	=	Enthalpy Flowrate (kW)
ΔH	=	CP (TT – TS) (kW)
LMTD	=	Log Mean Temperature Difference (^oC)
TS	=	Stream supply temperature (^oC)
TT	=	Stream target temperature (^oC)
U	=	Overall Heat Transfer Coefficient (kW/m^2 ^oC)
ΔT_{min}	=	Heat Exchanger Network Minimum Approach Temperature Difference (^oC)

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