Heat and Power Networks in Process Design

Part I: Criteria for Placement of Heat Engines and Heat Pumps in Process Networks

The general problem of heat and power integration in process networks is complex and to date not fully understood. The subject covers site combined heat and power, on-plant power generation, heat pumps, and refrigeration systems. This paper is the first of a two-part series and explains the concept of "appropriate" heat engine and heat pump placement in process networks based on a fundamental new insight. "Appropriate" placement takes advantage of integration opportunities with the remainder of the process and yields marginal efficiencies far greater than could be achieved through stand-alone heat engines. Conversely, "inappropriate" placement can never offer an advantage over stand-alone systems. Part II describes procedures for preliminary design, involving heat engine, and heat pump equipment selection and performance assessment.

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SCOPE

For a structured approach to process design, it is useful to regard a process as comprising a set of interacting subsystems. Synthesis of the best practical flowsheet then involves understanding subsystem design and the subsystem interactions. Using this approach, the process can be broken down into as many subsystems as convenient for understanding the problem. Figure 1 shows the chemical process divided into three subsystems: the main chemical processing steps (chiefly reactors and separators); the power-producing and consuming units; and the heat recovery network.

For the main processing steps, a satisfactory systematic approach to system design has yet to be developed. In practice, therefore, these parts of a process are designed by experience, fixing the interactions shown as 1 and 2 in Figure 1. In recent years, understanding of the heat recovery network problem has improved greatly to such an extent that, best practical networks can now be designed with confidence (for example, Linnhoff et al., 1979). This has been brought about largely through understanding a hitherto undiscovered phenomenon referred to as the heat recovery "pinch." Systematic design of networks of course involves the definition of all interactions around the "Heat Recovery Network," Figure 1, including the interaction with the power system. Stand-alone power systems are also well understood; for example, Nishio et al. (1980) recently published a structured approach to steam power system design. However, past attempts at finding a method for systematic design of the combined heat recovery and power problem (eliminating interaction 3 in Figure 1) have been few, and inevitably based on heuristics (for example, Menzies and Johnson, 1972). A truely systematic approach has not been presented to date in the literature.

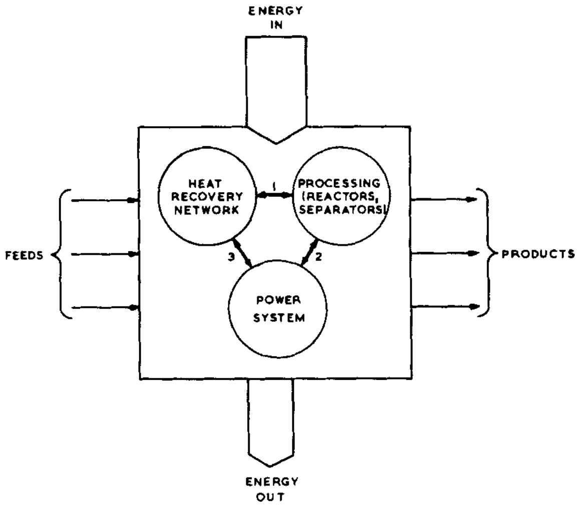

Figure 1. Structured approach to process design.

This paper presents a significant new insight which will add fundamentally to the designer's understanding, and so form the natural basis of any attempt to design integrated total heat and power systems.

CONCLUSIONS AND SIGNIFICANCE

We now exactly understand when in the design of combined heat and power systems we can get efficiencies of 100% (i.e., shaft work from fuel on a one to one basis) and when we end up converting shaft work into cooling water! Previously, recognition of these general conditions was not possible because the heat recovery pinch was not understood. Now that the significance of the pinch is known, the new insight into heat and power integration follows. It is fundamental and so should form

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the natural basis for analyzing integrated heat and power systems designs. For this reason too, it is likely to form the basis of future synthesis procedures.

What is required next is a procedure for predicting the most appropriate heat engine and heat pump technology, and the best practical integration of that technology with any given process heat recovery situation. Such a procedure is developed in Part II as well as an industrial case study. In this case study, a traditional design is shown to pay a 40% energy penalty when compared with the performance predicted by the procedure.

HEAT RECOVERY NETWORK PROBLEM

To understand the present paper, the essential features of the heat recovery problem and of heat engines and heat pumps must be appreciated. Consider the heat recovery network problem first. Much work has been done on this problem, and it has recently been reviewed by Linnhoff et al. (1979) and Nishida et al. (1981). Important results from the work are:

(i) Prediction of rigorous heat recovery targets based on thermodynamic analysis

(ii) Methods for synthesis of minimum cost solutions, in particular analysis of energy vs. capital tradeoffs

(iii) Prediction of the energy recovery bottleneck or "pinch".

These results can all be illustrated by reference to "composite *T-H* curves" (Whistler, 1948), as described by Linnhoff et al. (1979). Table 1(a) gives data for an example problem. To construct composite curves, one divides the total set of streams into "hot" streams (streams requiring cooling) and "cold" streams (streams requiring heating). For each subset, the streams' heat capacity flowrates (*CP*) are summed over the temperature range of the entire problem. This has been done in Table 1(b).

From this data can be plotted composite temperature–relative enthalpy curves, which are shown on common axes in Figure 2(a). The amount of "overlap" on the *H* axis is the amount of possible heat interchange in the heat recovery problem. Clearly, this is maximized by shifting the curves horizontally until they just touch at one point. This point identifies the temperature level in the problem at which heat transfer is becoming infeasible (infinite surface area required because $\Delta T = 0$), corresponding to the minimum amounts of hot utility (shown Q_{IN}) and cold utility (Q_{OUT}). Infinite area, however, means infinite cost, and the capital vs. energy tradeoff is explored by shifting the curves apart horizontally. As the curves are shifted, temperature differences become finite, and the values of Q_{IN} and Q_{OUT} increase by equal amounts. Figure 2(b) shows the curves shifted to a minimum temperature difference (ΔT_{min}) of 20°C, giving an increase in Q_{IN} and Q_{OUT} of 15 MW each. For this work, it is important to appreciate the significance of the "closest approach" or "pinch" phenomenon.

Linnhoff's method of "temperature interval" (T.I.) analysis (Linnhoff and Flower, 1978) reveals the significance of the pinch perhaps more clearly than composite *T-H* curves. In the method, the heat recovery problem is divided into a series of temperature intervals whose boundaries are defined by the supply and target temperatures of the streams. An enthalpy balance is performed for each interval, and energy then cascaded from the highest interval

TABLE 1(a). EXAMPLE PROBLEM DATA

Stream No. and Type	Supply Temp. (°C)	Target Temp. (°C)	Heat Capacity Flowrate (MW/°C)
1 (Hot)	300	80	0.3
2 (Hot)	200	40	0.45
3 (Cold)	40	180	0.4
4 (Cold)	140	280	0.6

TABLE 1(b). COMPOSITE CP FOR EXAMPLE PROBLEM

	Temp. Range (°C)	Stream No.	CP (MW/°C)
Hot Streams	40–80	2	0.45
	80–200	1 & 2	0.75
	200–300	1	0.3
Cold Streams	40–140	3	0.4
	140–180	3 & 4	1.0
	180–280	4	0.6

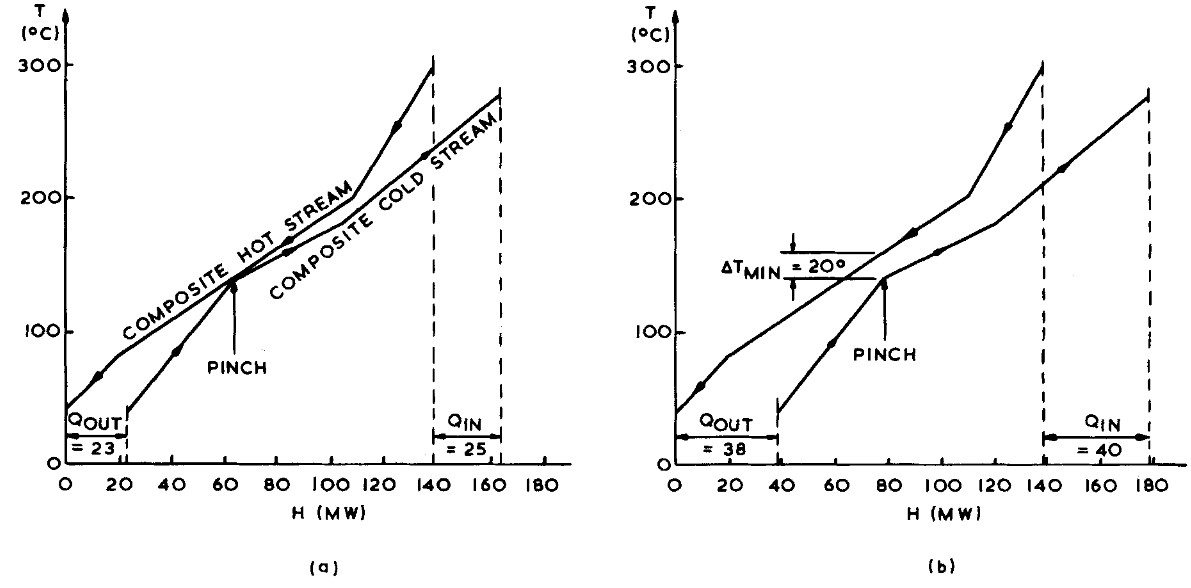
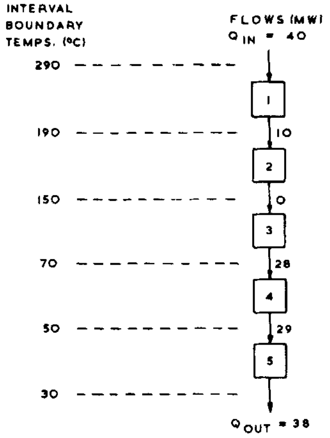


Figure 2. Example problem composite curves.

Temp. interval No. & boundary temps. (°C)	Hot streams (1) (2)	T (°C)	Cold streams (3) (4)	Deficit (1)	Accumulated input (2)	Accumulated output (3)	Maximum permissible input (4)	Maximum permissible output (5)
290		300 — 280						
1	(1),		(4)	+30	0	−30	+40	+10
190		200 — 180						
2	(1), (2)		(3), (4)	+10	−30	−40	+10	0
150		160 — 140						
3	(1), (2)		(3)	−28	−40	−12	0	+28
70		80 — 60						
4	(2)		(3)	−1	−12	−11	+28	+29
50		60 — 40						
5	(2)			−9	−11	−2	+29	+38
30		40						

(MW)

(a)



(b)

Figure 3. Temperature interval analysis by problem table method for example problem.

to the lowest. Just sufficient energy must be added from an external source to ensure that none of the heat flows between intervals are less than zero. In this way, the minimum utility requirements are predicted. Figure 3(a) shows the "Problem Table" (mostly following format and nomenclature of Linnhoff and Flower, 1978) for the example problem introduced in Table 1(a). The numbers in Columns 4 and 5 show the heat flows crossing certain temperature levels. So for example, 40 MW enters the problem from hot utility, 10 MW crosses the 190°C level, etc.

The results of this analysis are shown in Figure 3(b) in diagramatic form. The numbered blocks represent the temperature intervals and the connecting arrows the heat flows. The values of the heat flows are written beside the arrows. This representation we will term the "cascade diagram." Notice in the Problem Table that a minimum approach temperature difference is allowed for by ensuring that hot streams cross temperature interval boundaries at $T_b + \frac{1}{2}\Delta T_{min}$ and cold streams cross at $T_b - \frac{1}{2}\Delta T_{min}$. This departs from Linnhoff and Flower's original system, in that they arranged for hot streams to cross at $T_b + \Delta T_{min}$ and cold streams to cross at T_b. The advantage of the system adopted here is that it allows individual stream ΔT_{min} "contributions" to be assigned. The value of ΔT_{min} in any match is then simply the sum of the matched contributions. *In problems where a global* ΔT_{min} *is applicable*, the contributions become simply $\frac{1}{2}\Delta T_{min}$.

The T.I. analysis reveals the pinch to be a level in the problem of zero heat flow, i.e., no heat passing down through the network. This separates the network into two thermodynamically completely separate regions. Above the pinch, heat is in deficit and must be supplied from an external source. Below the pinch, heat is in surplus and must be rejected to an external sink. To achieve the minimum energy target predicted by the method, no heat must be transferred across the pinch. Any heat transferred across the pinch would have to be supplied from hot utility over and above the minimum requirement, and by enthalpy balance be rejected to cold utility as well.

The pinch was observed independently by Umeda et al. (1978)

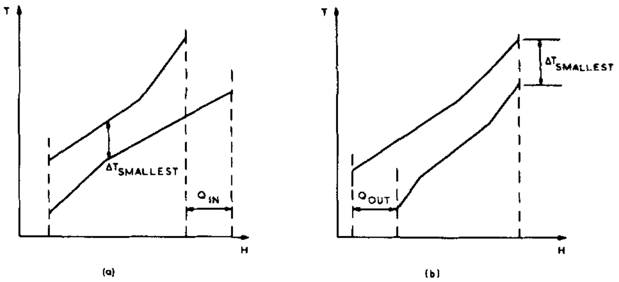


Figure 4. Heat recovery problem types requiring only one utility.

and Linnhoff and Flower (1978). Umeda et al. used composite T-H curves and stated that the pinch constitutes a bottleneck on heat recovery. Linnhoff and Flower used the temperature interval analysis. This analysis prompts the discovery of the full significance of the pinch: heat flow across it is fundamentally linked to excess utility consumption. The implications are wide-spread; see Dunford and Linnhoff (1981), Linnhoff and Hindmarsh (1982), and the present work.

It must be noted that some problems do not have pinches, in that the composite curves can be shifted towards each other until the requirement for one of the utilities disappears, Figures 4(a) and (b). The smallest value of ΔT found in the problem may be quite large, in which case capital cost is insensitive to energy recovery. It is important, however, to compare this type of problem with the type having pinched behavior. The pinch divides the problem into two parts. Thermodynamically, the part problem lying above the pinch is analogous to the heating only case shown in Figure 4(a). Similarly, the part lying below the pinch is analogous to the cooling only case shown in Figure 4(b). This should be born in mind when we come to discuss heat engine integration, because the pinched problem type will be used as the general case for discussion.

HEAT ENGINES AND HEAT PUMPS

A heat engine is a device which absorbs heat Q_1 from a source at temperature T_1, rejects heat Q_2 to a sink at temperature T_2, and does work W. By the First Law of Thermodynamics,

$$W = Q_1 - Q_2 \tag{1}$$

See Figure 5(a) and by the Second Law,

$$W \leq \alpha \cdot Q_1 \tag{2}$$

where

$$\alpha = \frac{T_1 - T_2}{T_1} \tag{3}$$

The equality in Eq. 2 applies to Carnot (reversible) cycles. For real

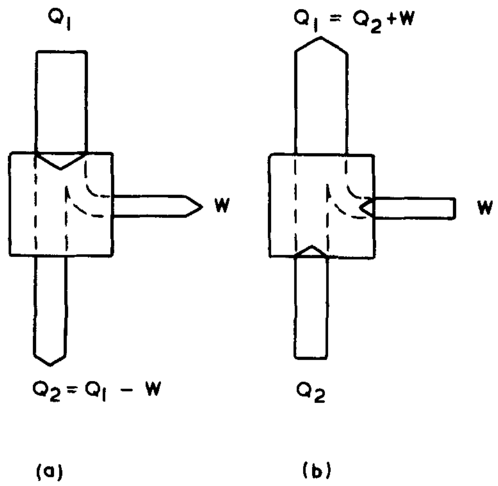


Figure 5. Schematic representation of heat engines and heat pumps.

(irreversible) heat engines, Eq. 2 can be rewritten, introducing a machine efficiency η_E, as

$$W = \eta_E \cdot \alpha \cdot Q_1 \qquad (4)$$

with $\quad 1 > \eta_E \geq 0$

The value of η_E depends on two main irreversibilities, namely temperature differences involved in accepting Q_1 and rejecting Q_2, and anisentropic compression and expansion of the engine working fluid.

In a chemical process, heat sources and sinks are often defined by a set of variable temperature process streams. A heat engine operating between variable temperature source and sink can be regarded as the sum of infinitely many cycles with constant temperatures T_1, T_2. The value of α is then defined by the process streams.

A heat pump is simply a heat engine running in reverse. Thus it accepts heat Q_2 at T_2, requires work W, and rejects Q_1 at T_1, Figure 5(b). Again, by the First Law of Thermodynamics, Eq. 1 applies, and by the Second Law,

$$W \geq \alpha \cdot Q_2 \qquad (5)$$

where

$$\alpha = \frac{T_1 - T_2}{T_2} \qquad (6)$$

Equation 6 defines what is often termed the "coefficient of performance" of a heat pump. The equality in Eq. 5 applies to a reversible cycle. For real heat pumps, one can write

$$W = \frac{\alpha \cdot Q_2}{\eta_E} \qquad (7)$$

where $\quad 1 > \eta_E \geq 0$

Now we have all that we need to start.

THE BASIC IDEA: PLACE YOUR ENGINE OR HEAT PUMP RELATIVE TO THE PINCH.

Heat Engine Placement above Pinch

The basic idea presented in this paper is as simple as it is fundamentally important. It can be illustrated using, Figure 6(a), the heat engine representation as shown in Figure 5(a), and the cascade diagram shown in general form in Figure 6(b). To solve the heat recovery problem in Figure 6(b), a total quantity of heat (F_1) is required from an external source. Now consider Figure 6(c). Suppose the heat (F_1) is supplied from the exhaust of a heat engine such as shown in Figure 6(a). Then,

Total heat supply to integrated system	$= Q$
Heat supplied to heat recovery network	$= F_1 = Q - W$
Marginal heat supplied to engine	$= Q - F_1$
	$= W$

Hence, work W is produced from marginal heat W, i.e., at an efficiency of 100%!

In Figure 6(a), the heat engine operates alone, and the rejected heat $Q - W$ is unused. In Figure 6(b), the heat recovery network operates alone, in that it accepts heat directly from a high-temperature source. In Figure 6(c), energy degradation is better controlled than in either (a) or (b). The heat recovery network accepts heat from source after a temperature difference has been exploited to produce work. Also, the heat engine is not allowed to reject heat directly to the environment. Hence the integrated system is more efficient than the separate systems. A straight comparison leads to the 100% efficiency conclusion in this case.

Note that there is a definite limit to the amount of work that can be generated through integration in a given process at 100% efficiency. If the required heat engine design is such that $Q - W$ is greater than F_1, some of the engine exhaust heat has to pass into cooling water. If, instead, the excess exhaust heat were to be absorbed by the process, this would entail cascading heat across the pinch and, as previously stated, such heat would be passed to cold utility too. So work generation beyond the limit given by $F_1 = Q - W$ cannot be of a better efficiency than stand-alone engine efficiency.

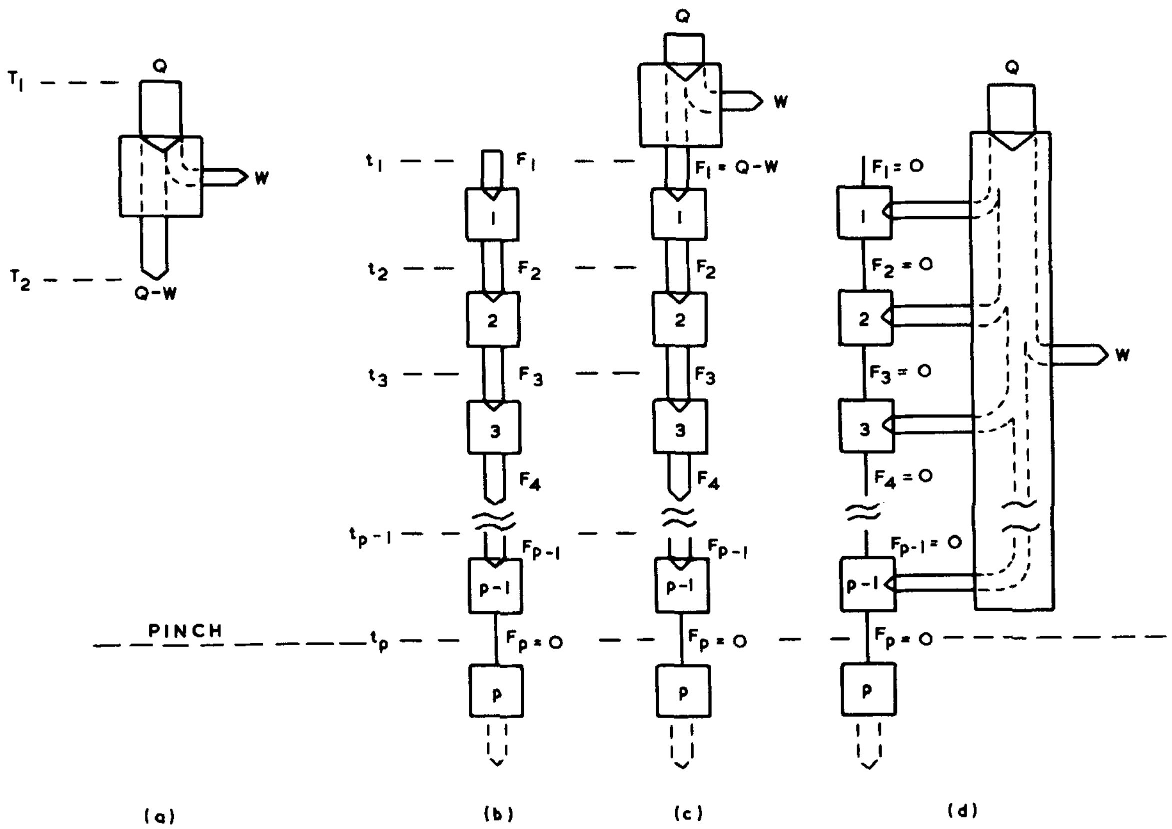


Figure 6. Integration of heat engine above the pinch.

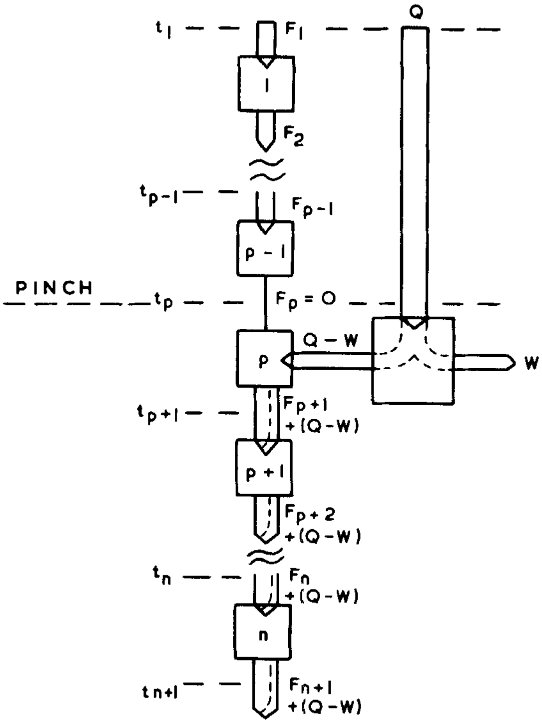


Figure 7. Integration of heat engine across the pinch.

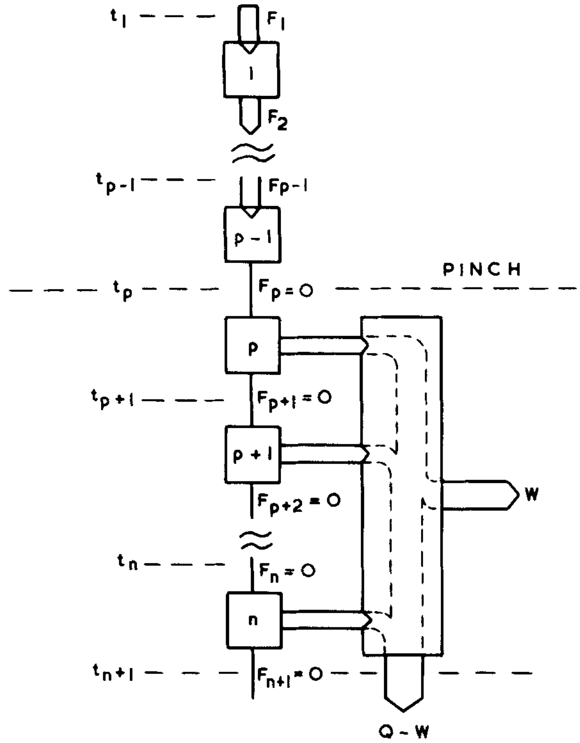


Figure 8. Integration of heat engine below the pinch.

In the situation where the maximum heat flow into the process (F_1) is fixed, W is maximized by maximizing $\eta_E \cdot \alpha$. The temperature efficiency α is a function only of source and sink temperatures. Where the source or sink is a chemical process involving many streams, it is a complicated function of temperature, but for a given process it is fixed. In an integrated heat and power system, therefore, maximizing W is achieved by maximizing η_E, primarily by reducing the temperature differences in the engine exchangers which accept and reject heat. For a given temperature of supply for Q, Figure 6(d) shows how η_E may be maximized against the process sink while still producing work at 100% marginal efficiency. The engine exhaust supplies each temperature interval above the pinch with exactly the quantity of heat required by each interval between the interval boundary temperatures. From the Problem Table algorithm, the individual interval requirements are simply the interval heat balances, i.e., $\Sigma_j(\Delta H)_j$ for all streams j existing within an interval i. Hence for the total problem heat balance,

$$Q - W = \sum_{i=1}^{p-1} \sum_{j} (\Delta H)_{i,j} \tag{8}$$

The total quantity of exhaust heat is unchanged, but its *levels* have now been minimized to maximize η_E and hence W.

Now notice two things of interest.

1) As η_E increases, work output increases but at the same marginal efficiency of 100%. Thus we arrive at the conclusion that as engine efficiency is changed this has an impact *not* on the efficiency of work generation but on the quantity of work that can be generated.

2) In supplying heat as in Figure 6(d), after engine integration all process internal heat flows above the pinch are reduced to zero, indicating that all surplus temperature driving forces have been consumed. Note also that in the general case, some $\Sigma_j(\Delta H)_j$ may be negative, indicating that in these intervals the heat engine cycle should be absorbing heat. Clearly, in the general case such a "perfect fit" heat engine would be impractically complex. Arriving at the best practical compromise will be discussed in Part II.

Heat Engine Placement Across Pinch

Figure 7 shows a heat engine exhaust integrated below the process pinch, with the engine heat supply coming from above. The exhaust heat $Q - W$ has to be cascaded through all temperature intervals below the pinch until it emerges from the lowest interval n to be rejected as waste heat. Thus overall, the heat engine takes on additional heat Q and rejects additional heat $Q - W$ in producing work W. There is no benefit accruing from integration when compared to stand-alone engines. We, therefore, define placement across the pinch as "inappropriate." Notice that no matter how the engine exhaust heat is distributed between the intervals below the pinch, no benefit over stand-alone placement will ever be obtained.

Heat Engine Placement Below Pinch

Lastly consider Figure 8, in which the heat engine takes its heat from below the pinch and rejects heat below. Heat extraction load and levels are shown maximized, such that work generation is maximized. Because no heat is transferred across the process pinch, the hot utility requirement for the process (F_1) is unchanged. Hence waste heat below the pinch is converted into work at 100% efficiency; the heat engine is, therefore, once more "appropriately" placed. The figure demonstrates work generation at the "expense" of waste heat load reduction.

Heat Pump Placement

"Appropriate" placement of heat pumps involves the same logic but leads to opposite criteria to those for heat engines. Namely, energy savings are not realized unless a heat pump is placed across the pinch. In Figure 9(a), a heat pump is shown taking heat from an interval above the pinch and rejecting heat to a higher interval. This establishes a closed loop of heat circulation Q, with the work input replacing hot utility on a one to one basis. Clearly, no net energy saving can result and in most industrial contexts, a "conversion" of electricity to heat would take place. In Figure 9(b) a heat pump is shown placed below the pinch. Again, a heat circulation of Q is established, only now the shaft work is converted to additional cold utility. It would seem that such a task would be more suited to a simple immersion heater! Clearly we are on safe grounds to term the heat pumps in Figures 9(a) and (b) as inappropriately placed.

In Figure 9(c) a heat pump is shown taking heat from below the pinch and rejecting it above. Now, surplus heat available below the

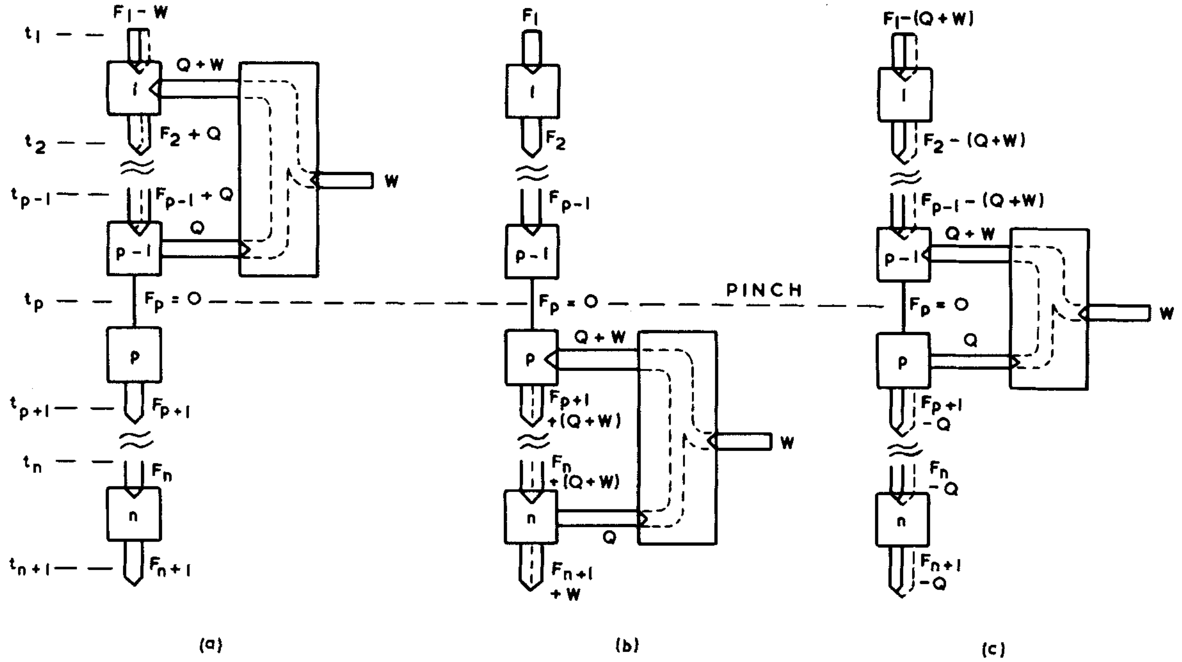


Figure 9. Integration of heat pumps into heat recovery networks.

pinch is made to supply heating requirement above. The net result is hot utility reduced by $Q + W$ and cold utility reduced by Q; in other words, exactly the same benefit as would be obtained from a stand-alone heat pump. The limits on energy saving by appropriate integration are posed by $Q + W \leq F_1$ *or* $Q \leq F_{n+1}$. If the heat pump input and output heat flows are greater than these limits, the additional work input to the heat pump must, by overall enthalpy balance, be degraded to cold utility. As before, η_E is maximized by reducing all F_i to zero.

PRACTICAL CONSIDERATIONS

It has already been stated that in the general case it is impractical to design heat and power networks with machine heat intake or output characteristics perfectly matched to a given process. In practice, the best compromise has to be found which satisfies technological and economic constraints. Figure 10 shows the situation where a heat engine is integrated entirely above the pinch, but where the inputs to the intervals from the engine exhaust do not necessarily match the interval requirements. What is required is to find a set of values x_i such that

$$Q - W = \sum_{i=1}^{p-1} \sum_{j} x_i (\Delta H)_{i,j} \leq F_1 \qquad (9)$$

(subject to no $F_i < 0$ after engine placement) to maximize profit accounting for energy and capital cost.

Insights into the characteristics of various types of heat engines and pumps and of the chemical process are required to solve this problem and a procedure is described in Part II. However, it is important to realize that the concept of appropriate placement is completely general and remains valid in practical systems. The effect of the "best design" compromise is simply to reduce the quantity of work available at 100% efficiency.

A further important practical constraint arises because some heat engines, notably open-cycle gas turbines and Diesels, are forced to reject some of their exhaust heat at temperatures extending down to ambient. Hence, appropriate placement of such engines is, in most chemical processes, only possible below the pinch. Placement above the pinch can never be "fully" appropriate because some exhaust heat *has* to cross the pinch to go to ambient. In these cases, there is a tradeoff between the overall efficiency of the integrated system (which departs from 100% the more exhaust heat is rejected below the pinch) and the increased work output obtained through a higher load on the heat engine. In other words,the choice then is to generate little work at an efficiency near 100% or more work at a lower efficiency. This is explored further in Part II.

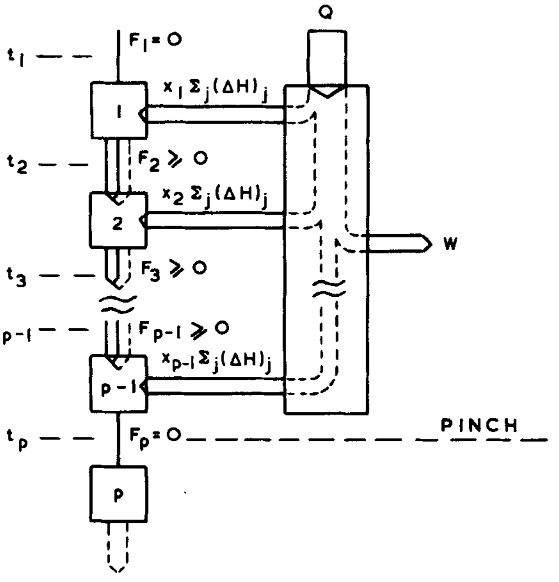


Figure 10. Integration of practical heat engine above the pinch.

CURRENT DESIGN PRACTICE

Present chemical processes are designed with no knowledge of the heat recovery pinch. It is no surprise, therefore, that many processes, for example, have steam systems with condensing turbines that transfer heat across the pinch, wasting energy. We now know that no matter how well-designed and efficient the steam cycle itself may be (and modern systems score on both points), inappropriate placement can cause substantial energy wastage to be designed into the total process, for no good reason other than the designer's unawareness. Note that inappropriate placement may also incur capital cost penalties, because larger equipment may be needed to handle the larger than minimum energy flow (Linnhoff and Turner, 1981).

Similarly, let us think of the number of vapor recompression schemes for distillation columns that have been considered in the past without knowledge of the pinch phenomenon. The appropriate placement concept shows that these schemes can never have a chance of producing net energy savings (compared to a properly integrated process), if the distillation column reboiler and condenser lie on the same side of the pinch. Also, for technical and economic reasons concerned with the heat pumping equipment itself, the temperature difference between boiler and condenser needs to be small. And even if these two criteria are met, the "need" for vapor recompression can be designed out of the system by altering column pressure appropriately, so as to eliminate the problem at source (Dunford and Linnhoff, 1981). Hence, future possibilities for vapor recompression viable in otherwise well-integrated processes seem to be rare.

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NOTATION

CP = heat capacity-flowrate, MW/°C
F = heat flow, MW
ΔH = difference of enthalpy flow, MW
$\Sigma_j(\Delta H)_j$ = enthalpy balance over all streams j, MW
$\Sigma_i \Sigma_j(\Delta H)_{i,j}$ = enthalpy balance over all temperature intervals i of all streams j existing within intervals i, MW
Q = heat quantity or flow, MJ or MW
Q_{IN} = minimum hot utility requirement for heat recovery problem, MW
Q_{OUT} = minimum cold utility requirement for heat recovery problem, MW
T = temperature, K
T_b = interval boundary temperature, °C
ΔT = temperature difference, °C
ΔT_{min} = minimum approach temperature difference, °C
W = Work or power, MJ or MW
α = heat engine or heat pump temperature efficiency, dimensionless
η = total heat engine or heat pump efficiency, dimensionless
η_E = heat engine or heat pump machine efficiency, dimensionless

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Part II: Design Procedure for Equipment Selection and Process Matching

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In Part I, criteria for heat engine and heat pump placement in chemical process networks were derived, based on the "temperature interval" (T.I) analysis of the heat exchanger network problem. Using these criteria, this paper gives a method for identifying the best outline design for any combined system of chemical process, heat engines, and heat pumps. The method eliminates inferior alternatives early, and positively leads on to the most appropriate solution. A graphical procedure based on the T.I. analysis forms the heart of the approach, and the calculations involved are simple enough to be carried out on, say, a programmable calculator. Application to a case study is demonstrated.

Optimization methods based on this procedure are currently under research.

SCOPE

In part I, it was shown that from an understanding of the "pinch" phenomenon in heat recovery networks, the concepts of "appropriate" and "inappropriate" placement for heat engines and heat pumps follow. Appropriate placement of heat engines in integrated process networks makes it possible to produce work from heat at 100% efficiency. Inappropriate placement cannot give efficiencies greater than "stand-alone." Conversely for heat pumps, stand-alone efficiency can be achieved only by appropriate placement, and inappropriate placement is fundamentally wasteful.

Following these discoveries, this paper shows that it is possible to identify a "thermodynamic best" appropriately-placed heat engine or heat pump device in any given heat recovery network. With an appropriately-placed "thermodynamic best" heat engine, work output at 100% efficiency is maximized. However, this engine would involve impractical complexity, both in the heat exchanger network and in the engine cycle design. A method for determining the "best practical" config-

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