Computational Approach to large Scale Process Optimization through Pinch Analysis

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***Abstract* - Since its debut in the last quarter of the twentieth century, pinch technology has become an efficient tool for efficient and cost-effective engineering process design. This method allows the integration of mass and heat streams in such a way that minimizes waste and external purchase of mass and utilities. Moreover, integrating process streams internally will minimize fuel consumption and hence carbon emission to the atmosphere. This paper discusses a programmable approach to the design of mass and heat exchange networks that can be used easily for large scale engineering processes.**

***Keywords* - Pinch Technology, Engineering Process, Process Integration**

1. Introduction

In many engineering applications, material and energy consumption can be substantially reduced through mutual exchange of resources within the same plant. For example, a cold process stream that needs to be heated can exchange heat from a hot stream that needs to be cooled if the temperature of the hot stream is high enough to attain the temperature needed for the cold stream. The same scenario can be said when there is a mass separating agent MSA that exists in a process and can be used to remove an undesirable substance from a stream within the same process. When there are many energy/mass recipient and giver streams, optimal integration is then done through the pinch technology which guarantees minimal waste and minimal external purchase.

2. Pinch technology

The debut of the pinch technology was first made by the then PhD student Bodo Linnhoff in late 1977 under the supervision of Dr. John Flower at the University of Leeds, UK. It was first applied for matching heat exchangers [1] and then its uses were extended for further applications such as mass exchange [2] and water networks [3], [4]. Pinch analysis has been thoroughly explained in the literature for the different applications [5], [6].

As an illustration of the application of pinch analysis, a process two cold streams and two heat streams as shown in Table 1. Each stream has a supply temperature and a target temperature; in the absence of any integration, the target temperature can only be achieved through the purchase of external cooling and external heating. In that situation, there will be a demand for 6 kW of heating utility and 7 kW of cooling utility.

Figure 1. shows an attempt to integrate the process streams in a manner that will decrease the demand for external utilities. Most important in heat

exchange is the existence of thermal driving force, i.e. flow from high to low temperature and also the fact that energy has to be balanced. Figure 1. suggests that the 1 kW heating requirement can be supplied from the first hot stream and hence decreasing the cooling utilities by 1 kW.

With this integration, it is obvious from the figure that the total external heating is now 5 kW and the external cooling requirement is 6 kW. The stream representation in the diagram is so insightful and indeed it is the lead to the pinch analysis. The straight line segments representing each stream can be slid vertically as the vertical projection is the representation of the heat load requirement. The horizontal projection is what needs to be fixed since supply and target temperatures cannot be changed.

Sliding the cold stream segments further downward will increase the overall and hence better saving opportunity.

Table 1. Cold and hot stream temperatures and load.

Cold streams			
No.	Supply Temp. (°C)	Target Temp. (°C)	Load (kW)
1	20	50	1
2	50	70	5
Hot streams			
No.	Supply Temp. (°C)	Target Temp. (°C)	Load (kW)
1	120	70	2
2	70	20	5

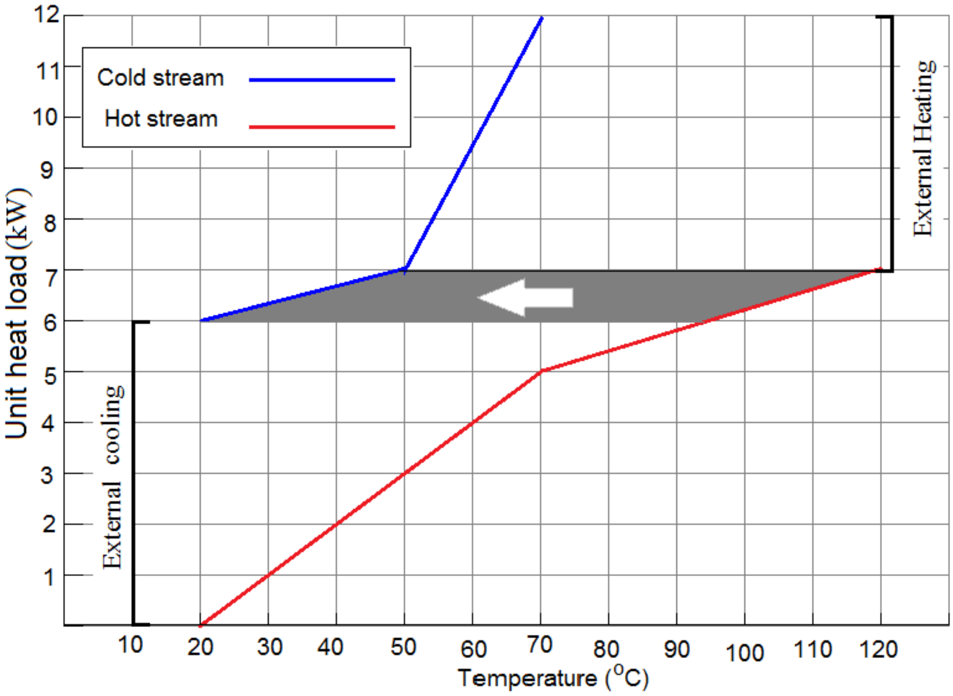

Figure 1. Partial integration of the four process streams.

Figure 2. shows the optimal integration which is also called the pinch analysis diagram. The cold curve is further slid downward until it touches the hot curve, further lowering would is not possible for breaching thermodynamic feasibility and suggests heat to flow from lower temperature to a higher one.

The point at which the cold stream curve pinches the hot one is the pinch point (50 °C) and its significance comes from the fact that any purchase of external cooling above the pinch is regarded a loss of saving opportunity and any purchase heating utility below the pinch is a loss of integration opportunity.

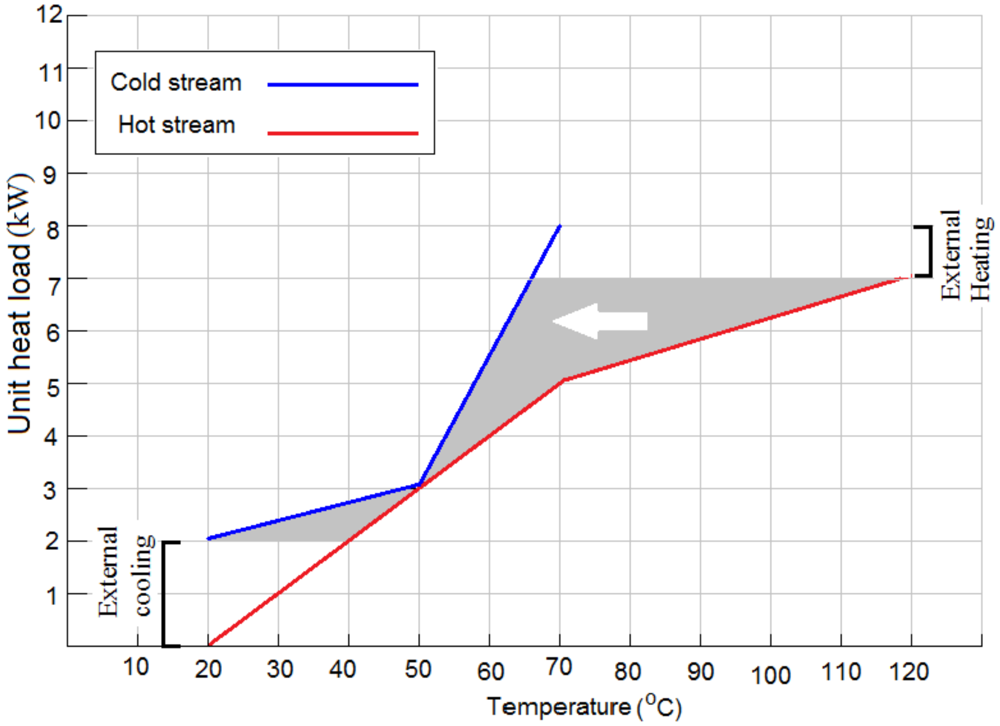

Figure 2. The thermal pinch diagram for the process streams.

The same discussion above can be made for the different applications where external purchases can be minimized by allowing process streams to exchange mass and energy. For example, in mass exchange processes, streams which are rich of a given impurity might have locally available mass stripping agents (MSA) that can take in the impurities from the rich streams.

2.1 General approach

In the general situations where pinch analysis is applicable, there will be a number of donor streams and another set of recipient streams with a load to be exchanged from the donor to the recipient. The exchange process will impact a given property of each stream. It is desired that the property is changed from a supply value to a target value by exchanging the right amount of (energy or mass) load. The exchange process is administered by a driving force represented by either a temperature gradient or an equilibrium function.

3. Problem statement

For *D* donor streams with their flow rates $F_{d,i}$, the supply property p_i^s needs to be set to the target property p_i^t for all i=1,2,… D by exchanging load with *R* recipient streams with their flow rates $F_{r,j}$, the supply property u_j^s needs to be set to the target property u_j^t for all j=1,2,… R. The function for the minimum driving force between the two sets of streams is also provided.

4. Methodology

An algorithmic approach is used as the methodology for finding the pinch point and minimum excess and external loads.

1. For all u_j^s and u_j^t j=1,2,3…R (for all recipient streams), express the recipient property on the donor property scale (p_j^s and p_j^t) using the minimum allowable property and property relation function. For example, in mass exchange, the concentration of the recipient stream (the lean stream) is expressed as: $y_j = m_j(x_j + \varepsilon_j) + b_j$ while in heat integration the recipient stream will be the cold stream whose temperature will be expressed as $T_j = t_j + \Delta T_{Min}$.
2. Establish the set P of all unique supply and target compositions in the problem:
   $P = \{p_i^s \cup p_i^t \cup p_j^s \cup p_j^t\}$ for i=1,2,3…D

and j=1,2,3,…R

3. Sort P in a descending order such that $P = \{p_1, p_2, p_3, \dots, p_N\}$: $p_1 > p_2 > p_3 > \cdots > p_N$ Where N is the total unique elements representing the set of all supply and target values.
   In P, each interval between two consecutive elements can be thought of as a single exchange unit that will integrate all donor and recipient streams whose supply and target properties overlap with this interval. For N elements in a set, the number of intervals will be N-1.
4. For each donor stream with composition interval $[p_i^s, p_i^t]$, split the interval into segments such that: $[p_i^s, p_i^t] = [p_i^s, p_1^{'}] \cup [p_1^{'}, p_2^{'}] \cup [p_2^{'}, p_3^{'}] \cup \dots \cup [p_r^{'}, p_i^t]$ where $p_i^t < p_1^{'} < p_2^{'} \dots < p_k^{'} < p_i^s$ and $\{p_1^{'}, p_2^{'}, p_3^{'} \dots p_k^{'}\} \in P$ and calculate the total load to be exchanged in each interval from $L_{d,n} = \Sigma L_{i,n} = \Sigma f(F_{d,i}, (p_u - p_l)_n)$ for all donor streams i=1,2,3,..D whose property range coincide with that interval and n=1,2,3,…,N-1, where p_u and p_l are the upper and lower limits of the interval.
5. Perform the same segmentation for recipient streams $[p_j^s, p_j^t]$ by splitting the interval into segments and calculate the load in each interval from:
   $L_{r,n} = \Sigma L_{j,n} = \Sigma f(F_{r,j}, (p_u - p_l)_n)$
   for all recipient streams j=1,2,3,..R whose property range coincide with that interval and n=1,2,3,…,N-1, where p_u and p_l are the upper and lower limits of the interval.
6. Initiate excess load value: L_{excess}=0
   For n=1,2,3 …N-2 (all intervals except the last)

If $L_{d,n} \geq L_{r,n}$

Add the surplus ($L_{d,n} - L_{r,n}$) to the recipient load in the next interval such that: $L_{r,n+1} = L_{r,n+1} + (L_{d,n} - L_{r,n})$

Else

Add the deficit ($L_{r,n} - L_{d,n}$) to the excess lean, such that:

$L_{excess} = L_{excess} + (L_{r,n} - L_{d,n})$

Update the pinch point concentration value

$p_{pinch} = p_{n+1}$

End If

End Loop

7. For the last interval (N-1)

If $L_{d,N-1} \geq L_{r,N-1}$

The surplus rich ($L_{d,N-1} - L_{r,N-1}$) will be offset by an external supply:

$L_{external} = (L_{d,N-1} - L_{r,N-1})$

Else

Add the deficit ($L_{r,N-1} - L_{d,N-1}$) to the excess load, such that:

$L_{excess} = L_{excess} + (L_{r,n} - L_{d,n})$

and let

$L_{external} = 0$

End If

For the different applications, Table 2. shows representative data necessary for each application.

Table 2. The analogy of the different counterparts in the different applications of pinch analysis technique.

	Heat integration	Mass Integration	Material recycler
Property (p)	Temperature (T_{cold}, T_{hot})	Concentration (x, y)	Concentration (c)
Donor stream	Hot stream	Rich stream	Source stream
Recipient stream	Cold stream	Lean stream	Sink stream
Load exchanged (L)	Heat	Mass	Mass
Load function (f)	$Q = m\dot{C_p}\Delta T$	$M_{rich} = \dot{m}\Delta y$ or $M_{lean} = \dot{m}\Delta x$	$M_{source} = \dot{W}c$ or $M_{sink,max} = \dot{G}c^{Max}$
Minimum allowable property difference	ΔT_{Min}	ε	-
Property relation function	$T_{hot} = T_{cold} + \Delta T_{Min}$	$y = m(x + \varepsilon) + b$	-

5. Illustrative Example

A process has 22 lean streams and 28 streams rich of a given composition. The equilibrium equation for this composition is given by the linear function $y = m(x + \varepsilon) + b$ where ε is the minimum allowable concentration difference.

The above procedure was coded in Matlab™ and revealed that for optimal integration, the minimum excess load is 0.429 kg/s with the minimum external outsourcing of MSA being 0.523 k/s. The pinch point was found at y=0.099.

These outputs were corroborated by using the rigorous pinch diagram shown in Figure 3 with the above outputs clearly observed on the diagram.

Table 3. A process with 22 lean streams and 28 rich streams of a given composition.

Lean streams							Rich streams			
No.	Flow rate (kg/s)	x^s	x^t	m	ε	b	No.	Flow rate (Kg/s)	y^s	y^t
1	2.0	0.292	0.213	0.14	0.069	0.002	1	3.6	0.122	0.066
2	4.7	0.039	0.071	0.36	0.051	0.006	2	3.5	0.071	0.045
3	1.9	0.073	0.114	0.30	0.028	0.008	3	5.1	0.072	0.038
4	0.3	0.292	0.227	0.12	0.050	0.018	4	0.2	0.073	0.050
5	2.6	0.096	0.105	0.46	0.005	0.003	5	0.7	0.052	0.034
6	7.2	0.100	0.144	0.20	0.099	0.007	6	3.1	0.069	0.057
7	2.7	0.098	0.129	0.37	0.002	0.011	7	4.1	0.073	0.039

8	3.4	0.087	0.130	0.34	0.021	0.011	8	4.1	0.099	0.071
9	3.9	0.209	0.185	0.26	0.070	0.009	9	3.2	0.114	0.034
10	5.1	0.113	0.166	0.24	0.080	0.016	10	4.6	0.053	0.042
11	4.4	0.229	0.204	0.30	0.019	0.020	11	7.3	0.109	0.084
12	2.7	0.184	0.180	0.37	0.054	0.003	12	2.1	0.054	0.043
13	4.3	0.282	0.197	0.31	0.049	0.018	13	7.6	0.041	0.022
14	7.1	0.193	0.181	0.40	0.048	0.012	14	0.2	0.070	0.055
15	4.7	0.091	0.146	0.56	0.017	0.019	15	2.2	0.073	0.058
16	7.9	0.310	0.289	0.32	0.080	0.017	16	0.6	0.064	0.026
17	0.1	0.270	0.195	0.53	0.031	0.018	17	2.3	0.090	0.048
18	0.2	0.345	0.291	0.34	0.069	0.017	18	4.0	0.069	0.040
19	6.6	0.056	0.154	0.58	0.071	0.013	19	1.7	0.057	0.034
20	2.0	0.308	0.215	0.51	0.036	0.016	20	7.6	0.085	0.080
21	4.0	0.149	0.165	0.61	0.056	0.013	21	2.4	0.060	0.033
22	3.1	0.166	0.175	0.59	0.062	0.017	22	1.4	0.047	0.029
							23	1.0	0.029	0.028
							24	2.5	0.044	0.037
							25	2.9	0.071	0.049
							26	2.1	0.164	0.138
							27	5.4	0.022	0.009
							28	1.9	0.102	0.058

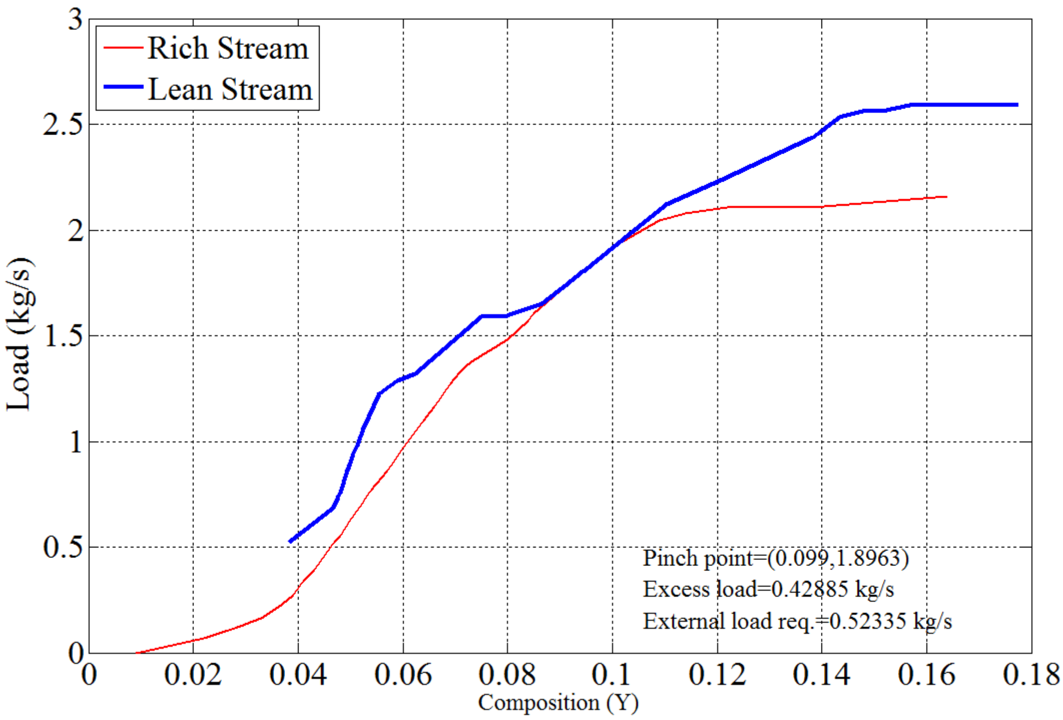

Figure 3. The mass exchange pinch diagram for the illustrative example.

4. Conclusion

Targeting optimum integration using the pinch technology can be achieved using the graphical method, algebraic method and the mathematical linear programming method. The presented algorithm is inspired by the algebraic method and it is useful when dealing with large scale problems that may also include additional constraints that can be easily incorporated into the program code. In some situations, as in dealing with combinatorial and nonlinear constraints, one can use the code with a heuristic technique in order to approximate the optimal solution.

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