CHEMICAL ENGINEERING TRANSACTIONS
VOL. 76, 2019

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Petar S. Varbanov, Timothy G. Walmsley, Jiří J. Klemeš, Panos Seferlis

ISBN 978-88-95608-73-0; **ISSN** 2283-9216

DOI: 10.3303/CET1976205

Total Site Heat Integration Considering Optimum Pressure Drops

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In this study, a new methodology is developed for Total Site Minimum Energy Requirement (MER) targeting, in which optimum stream pressure drops (ΔPs) are considered for each individual process. To validate the accuracy of the methodology, two Total Site (TS) systems comprising processes A and B and processes C and D are selected and evaluated using two different approaches; I) considering streams' assumed heat transfer coefficient (conventional method) and II) considering streams' allowable ΔPs. In the second approach, the possibility of pumps/compressors replacement is first investigated for each individual process, through exploring a 3-way trade-off between energy consumption, area requirement and hydraulic system. The resulting data are then used to construct a Total Site profiles (TSPs) for MER targeting. These profiles depict that the hot and cold utility values, when ΔPs are optimized, are much less than those obtained in conventional method using assumed coefficients. Moreover, the TS energy targets that are estimated in this method are more realistic and compatible with the results of detailed design stage.

1. Introduction

Total Site Heat Integration (TSHI) is a method for integrating heat recovery through different processes in an industrial complex. The aim of this technique is optimum design of a central utility system for the entire site within the framework of multiple processes. It has been proved that TSHI can lead to applicable designs. Many researchers have focused on this subject for improving conventional TSHI methods to achieve more accurate results. Nemet et al. (2012) studied the conventional TSHI method suggested by Klemes et al. (1997) and considered the capital costs for utility generation and consumption levels. Fodor et al. (2012) presented a TS targeting method by considering stream specific minimum temperature difference (ΔT_{min}) for individual processes and between process streams and utilities. The distinction of the suggested method is considering the effect of heat transfer coefficients of streams and utilities during TS targeting. Tarighaleslami et al. (2017) demonstrated a TSHI targeting method with more precise targets requiring isothermal and non-isothermal utilities.

ΔP is an important parameter for feasible synthesis of heat exchanger networks (HENs) and its consideration can be extended to TS problem. Limited researchers have considered the ΔPs in utility transmission lines between processes in TS problem, i.e. elevation ΔPs, frictional ΔPs, and ΔPs related to distances between plants. Chew et al. (2013) has considered the equipment pressure rating for HENs and selected the appropriate pressures for industrial implementation of TSHI. Wang et al. (2013) studied the ΔP arising from distance between plants by economic analysis of TSHI. An improved algorithm for defining TS minimum utilities was extended by Liew et al (2014) by considering ΔP impact on utility temperatures. Synthesis of TS by employing a stochastic multi-period mixed-integer nonlinear programming model was carried out by Nemet et al. (2015). The purpose of their work is to enhance TS modelling by including proper pressure levels for intermediate utilities. Another study by Chew et al. (2015) investigated the significance of ΔPs due to elevation changes and frictional losses in utility transmission lines within TS. It is concluded that considering pressure drop by this method leads to more realistic targeting results in utility distribution network estimation.

None of the current works have addressed the ΔPs arising from heat exchange in Total Site Heat Exchanger Networks, when targeting for MER. It was verified that use of assumed values for film heat transfer coefficient in targeting stage of HENs leads to inconsistency between targeting, synthesis, and detailed design results for

Paper Received: 22/03/2019; Revised: 17/05/2019; Accepted: 14/06/2019
Please cite this article as: Faramarzi S., Tahouni N., Panjeshahi M.H., 2019, Total Site Heat Integration Considering Optimum Pressure Drops, Chemical Engineering Transactions, 76, 1225-1230 DOI:10.3303/CET1976205

both retrofit and grass-root design (Polley et al, 1990; Polley and Panjeshahi, 1991). To ensure that the results of synthesis stage are compatible with those finally achieved after exchangers detailed design, it is needed to apply the area targeting algorithm based on allowable stream ΔPs.

2. Methodology

The design of heat recovery networks is generally concluded in a number of stages. First, there is a targeting stage where the economics of heat recovery are evaluated in order to set the recovery level. This involves the trading-off energy and network capital costs. The second stage involves network synthesis. Here the topography of the heat recovery system required to realize the targeted energy recovery is determined. Finally, the detailed design of the exchangers within the recovery system is undertaken. Delay in considering ΔP in above procedure can lead to inconsistent results between network synthesis and detailed design, with respect to surface area of the exchangers as well as incorrect capital-energy trade-off and network optimization in both grass-root and retrofit designs. Consequently, for decreasing difference in results of HEN synthesis and detailed design, we need a network area algorithm based on streams ΔPs (not assumed heat transfer coefficients) leading to consistent results.
As a result, for the first part of the methodology employed in this research, area algorithm based on streams ΔP (Polley and Panjeshahi, 1991), is used in targeting of individual processes of TS to get close to the optimum point of energy and area consumption. The equation (1) states the economic objective function.

$$\textit{Total cost} = f(\Delta P_1, \Delta P_1, \ldots, \Delta P_n) = CC_{Exch} + CC_{Pump/Comp} + OC_{Power} + OC_{Energy} \tag{1}$$

Where CC_{Exch} is the capital cost for all exchangers, $CC_{Pump/Comp}$ is the capital cost for purchasing pumps/compressors, OC_{Power} is operating cost for consumed electricity in pumps/compressors and C_E is the cost of utilities. This is a 3-way trade-off between energy consumption, area requirement and hydraulic system. The objective cost function is minimized and then the optimum ΔT_{min} for intra process streams ($\Delta T_{min,pp,opt}$), optimum stream ΔPs, minimum utility requirements and minimum area for each process are obtained. The ΔP values are not the allowable pressure for each stream. Instead, the application of smaller/bigger pumps/compressors is considered (Panjeshahi and Tahouni, 2008). The results are obtained using PILOT software (Panjeshahi, 2012) programmed for targeting and design of HENs. Equation (2) states the conventional way to calculate minimum area for a HEN, where A_j is area contribution of stream j. Given the relationship between ΔP and film heat transfer coefficient in equation (3), we can calculate the network area predictions on stream pressure drop rather than assumed heat transfer coefficients. In equation (3), ΔPj, Kj, Acj and hcj are specified ΔP of stream j, constant value relating to stream j, exchanger area installed on stream j (contact area) and clean heat transfer coefficient of stream j. By simultaneously solving the equations (2) and (3), the heat transfer coefficients will be omitted. Then equation (4) estimates the network area based on ΔPs, where A_{cj}, K, C_{PK} and A_K are contact area of stream j, number of opposing streams to stream j within that interval, specific heat of stream k and area contribution of stream k (Polley and Panjeshahi, 1991).

$$A_{min} = \sum_{j=1}^{J} A_j \Rightarrow A_j = \sum_{i=1}^{I} \left(\frac{q_{ji}}{\Delta T_{LM,i}} \right) \left(\frac{1}{h_j} \right) \tag{2}$$

$$\Delta P_j = K_j A_{cj} \left(h_{cj} \right)^m \tag{3}$$

$$A_{cj} = A_j + \sum^{opposing\,streams} \frac{CP_k}{\sum CP_k} \tag{4}$$

By implementing the algorithm in process level, stream ΔPs are optimised and the output of this step is used for energy targeting within the processes of TS. The new proposed method for TS targeting is summarized in Figure 1.
<u>Step 1:</u> Data extraction including process, physical property and cost data for each process.
<u>Step 2:</u> Targeting the intra-process heat recovery for each individual process based on area algorithm (Polley and Panjeshahi, 1991). Thus, by implementation a 3-way trade-off between area, energy and ΔP, the optimum process to process ΔT_{min} ($\Delta T_{min,pp,opt}$) is identified. Also, the Pinch location, heating and cooling utility demands, total annualized cost, minimum area and Grand Composite Curve (GCC) for each process are known.

Afterwards the heat source/sink segments from the GCC of individual processes are extracted and heat recovery pockets on the GCCs are removed due to the potential for internal process heat recovery. It is noted that the sink / source parts in GCC have been shifted by ±1/2 $\Delta T_{min,pp,opt}$ (T*) in each individual process.

Step 3: Targeting the utility generation and consumption for TS. To do this, the ΔT_{min} between process and utilities ($\Delta T_{min,pu}$) is selected based on the method suggested by varbanov (2012). The utility temperatures are sketched based on heat source and sink segments. This stage prepares TS Problem Table Algorithm (PTA), which is in the similar way of individual processes PTA. The shifted temperatures, T*, are first shifted back to their original values, and then shifted again by $\Delta T_{min,pu}$ to make sure ΔT_{min} between process and utilities is maintained (equation 5). Then, TSP are illustrated by combining site heat source and sink parts. In the final part, utility generation and consumption is analysed from highest temperature level of hot utility and moves toward the lowest temperature level for maximization of utility generation.

$$Site\ Sink: T^{**} = T^{*} - 0.5\Delta T_{min,pp,opt} + \Delta T_{min,pu} \quad (and) \quad Site\ Source: T^{**} = T^{*} + 0.5\Delta T_{min,pp,opt} - \Delta T_{min,pu} \tag{5}$$

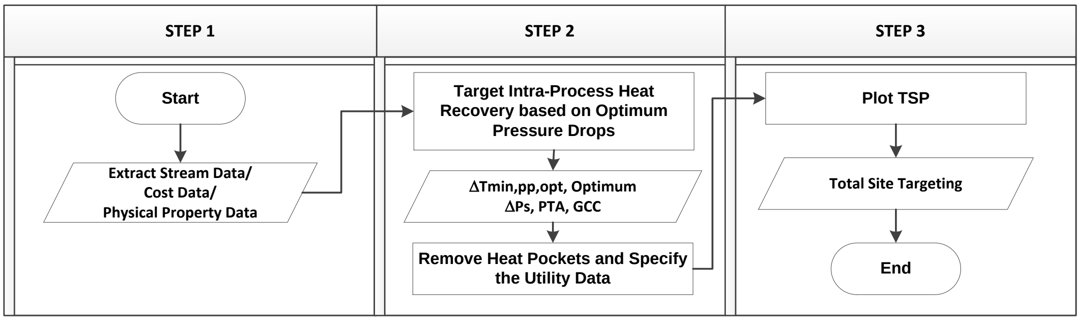

Figure 1. Flowchart of the modified TSHI method

3. Case Study

In this research, two TS examples have been studied applying the new proposed procedure. Each case study is TS consisted of two individual processes. The stream data of both processes are shown in Tables 1 and 2The first case study includes two processes A and B., which are the modified examples from literature (Canmet ENERGY, 2003 and Kemp, 2007). Also, the cost data is represented in Table 3.

Table 1. Stream data for process A

Stream	Ts (°C)	Tt (°C)	CP (kW/°C)	h (W/m^2.°C)	Allowable ΔP (kPa)
A1 Hot	200	100	20	500	120
A2 Hot	150	60	40	250	80
A3 Cold	50	120	70	500	20
A4 Cold	50	220	15	250	30

Table 2. Stream data for process B

Stream	Ts (°C)	Tt (°C)	CP (kW/°C)	h (W/m^2.°C)	Allowable ΔP (kPa)
B1 Hot	200	50	3	250	120
B2 Hot	240	100	1.5	250	80
B3 Hot	200	119	23	250	90
B4 Cold	30	200	4	250	20
B5 Cold	50	250	2	250	20

Table 3. Cost data for process A and B

Hot utility ($/y)	Cold utility ($/y)	Heat exchanger ($)	Plant life time (y)	Payback time (y)	Interest rate %
30	7	0+1000(A)	20	3	30

The related data for the second Total Site case study including two processes C and D as well as cost data are shown in Tables 4, 5 and 6. Process C is a modified example by Nie and Zhu (1999) and process D is an aromatics plant studied by Polley and Panjeshahi (1991).

Table 4. Stream data for process C

Stream	Ts (°C)	Tt (°C)	CP (kW/°C)	h (W/m^2.°C)	Allowable ΔP (kPa)
A1 Hot	180	30	59.8	1282	200
A2 Hot	270	40	114.4	2066	25
A3 Hot	350	30	33.8	895	6
A4 Hot	380	50	145.6	1115	13
A5 Hot	150	100	657.8	1217	26
A6 Hot	290	190	384.8	1076	34
A7 Cold	20	390	520	1300	350

Table 5. Stream data for process D

Stream	Ts (°C)	Tt (°C)	CP (kW/°C)	h (W/m^2.°C)	Allowable ΔP (kPa)
A1 Hot	327	40	100	500	120
A2 Hot	220	160	160	500	80
A3 Hot	220	60	60	500	90
A4 Hot	160	45	400	500	60
A5 Cold	100	300	100	500	20
A6 Cold	35	164	70	500	20
A7 Cold	85	138	350	500	30
A8 Cold	60	170	60	500	15
A9 Cold	140	300	200	500	80

Table 6. Cost data for process C and D

Hot utility ($/y)	Cold utility ($/y)	Heat exchanger ($)	Plant life time (y)	Payback time (y)	Interest rate %
40	7	$0+800(A)^{0.83}$	20	3	15

4. Results and discussion

The targeting results for individual processes A and B are demonstrated in Table 7, separated for two different area algorithms based on fixed-heat transfer coefficients (conventional method) and the optimum ΔPs. Next, the results for TS MER targeting are shown in Table 8. The $\Delta T_{min,pu}$ for this TS is selected of 20°C. Also, the net amount of utilities is shown in Table 9. Moreover, TSPs for targeting based on fixed-heat transfer coefficients and optimum ΔPs are illustrated in Figures 2 and 3, which clearly shows the results.

Table 7. Results of targeting for individual process A and B

	Process A		Process B	
	Fixed h	Optimum ΔP	Fixed h	Optimum ΔP
Hot utility (kW)	3,870	2,410	418	208
Cold utility (kW)	2,020	560	1,861	1,651
A_{min} (m^2)	515.53	201.97	142.02	50.66
Total annualized cost ($/y)	285,717	151,368	68,399	33,076
$\Delta T_{min,pp,opt}$ (°C)	57	24	63	28

Table 8. TS targeting for case study I (process A and B)

	Fixed h	Optimum ΔP	% of change	CO_2 Reduction (t/y) (EPA, 2019)
Hot utility (kW)	1,707.95	1,328.6	23	1094.6
Cold utility (kW)	2,591.04	921.39	70	4817.6

Table 9. Utilities for MER targeting of first TS (processes A & B)

Utilities	fixed h (kW)	Optimum ΔP(kW)
HPS (300 °C)	820	772
MPS (200 °C)	647.95	96
LPS (120 °C)	240	460
CW (10-30 °C)	2591.04	921.39

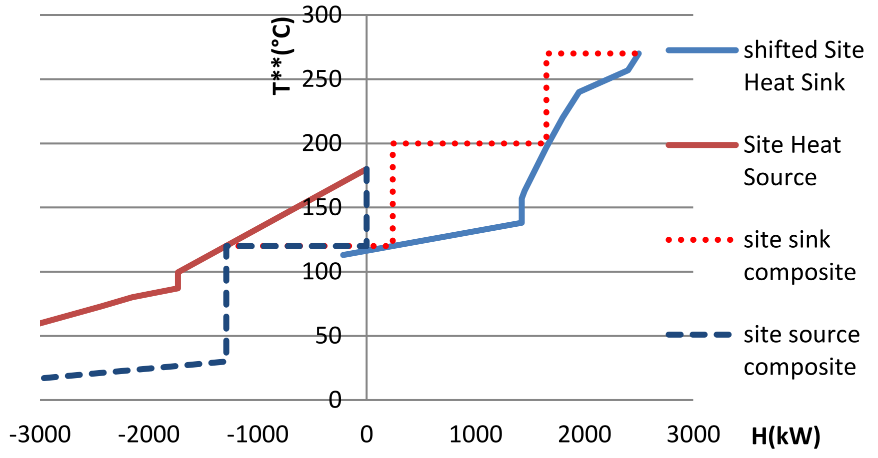

Figure 2: TSP for case study I (fixed h)

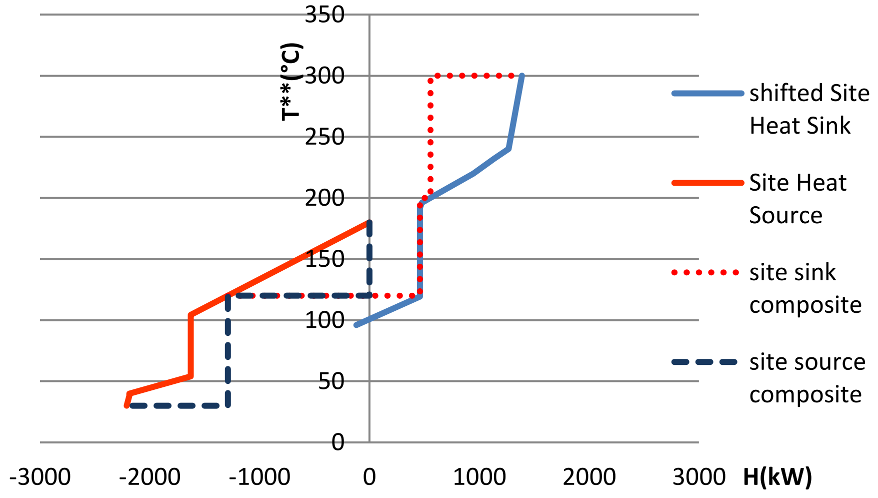

Figure 3: TSP for case study I (optimum ΔP)

The relevant results for targeting of second case study are summarized in Tables 10 and 11 ($\Delta T_{min,pu}$ =20°C).

Table 10. Results for targeting of individual process C and D

	Process C		Process D	
	Fixed h	Optimum ΔP	Fixed h	Optimum ΔP
Hot utility (kW)	44,148	51,428	24,480	21,680
Cold utility (kW)	17,264	24,543	32,200	29,400
A_{min} (m^2)	10,456	20,699	12,889	8,639
Total annualised cost ($/y)	2,396,375	3,234,659	1,831,839	1,511,927
$\Delta T_{min,pp,opt}$ (°C)	14	28	25	20

Table 11. TS targeting for case study II (process C and D)

	Fixed h	Optimum ∆P	% of change
Hot utility (kW)	64,677.32	59,069.72	9 %
Cold utility (kW)	45,512.12	39,912.30	13 %

5. Conclusions

This study developed a new method for targeting of TSHI, considering the streams optimum ∆Ps. The results depict the amount of hot and cold utility for MER targeting of TS have been decreased, when we consider the streams optimum ∆Ps for exact targeting of individual processes. This achievement emphasizes that not considering the ∆Ps of heat exchangers will result in imprecise results.

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