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Multi-period Heat Exchanger Network Synthesis with Temperature Intervals and Uncertain Disturbances

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High energy consumption is a major challenge currently threatening many industrial processes. This has made industrial processes such as absorptive CO_2 capture expensive and energy intensive. However, research has shown that the application of Heat Exchanger Networks has the potential of minimizing energy demands in many industrial processes due to its energy recovery advantage. In this study, a sequential procedure is presented for the synthesis of heat exchanger network for multi-period operations with specified uncertainties in flow rates and variations in inlet and outlet temperatures of process streams. The synthesis task in this study was sequentially decomposed into three stages. Temperature interval method was used to determine the loads and minimum utilities required by the network in the first stage. Determination of the minimum number of units was considered in the second stage while the third stage was dedicated to the derivation of a network configuration and sizing of heat exchangers to determine the capital cost using area targeting technique. Efficacy of the proposed methodology was tested using an example from literature. A new heuristic rule was established and the network topologies obtained using the proposed approach testifies to the applicability of HENs for energy minimization during absorptive CO_2 capture.

1. Introduction

Different strategies have been proposed for energy minimization in energy-intensive processes like absorptive CO_2 capture in recent times. For instance, Escudero et al. (2016) developed a heat integration methodology based on Pinch Analysis to assess heat recovery options which were used to minimize the high energy penalty in oxy-fuel power plants. Yoro and Sekoai (2016) proposed the use of promoters and catalysts while the use of additives such as piperazine for energy minimization during absorptive CO_2 capture was suggested in another study by Yoro et al. (2019a). Nevertheless, it has been observed that most of the energy minimization strategies suggested for absorptive CO_2 capture in the literature involve the use of extra mass separating agents, external utilities or inhibitors which are quite expensive (Yoro et al., 2019b). A few studies in the literature have recommended the integration of CO_2 capture devices with power generation plants to minimize energy consumption (Tan and Foo, 2018). None considered a detailed process synthesis approach for effective heat recovery and energy minimization with a keen interest in absorptive CO_2 capture taking into consideration the heat exchanger loads and area costs. Furthermore, absorptive CO_2 capture is energy intensive (Yoro et al. 2018); this high energy requirement ought to be minimized to ensure its economic advantage. Optimization of heat integration processes within CO_2 capture systems could be instrumental in minimizing energy usage. Heat integration leads to reduced energy consumption and an improved heat transfer with adequate material usage in the separation process. Consequently, this study attempts to minimize energy consumption during adsorptive CO_2 capture via optimization of heat integration within the process. A heat exchanger network comprises one or more heat exchangers that jointly satisfy an energy conservation task (Yoro et al., 2019b). Heat exchanger networks (HEN) can determine the least amount of hot and cold utilities required for a process and for recovering process heat in many industrial applications while reducing investment and operating costs (Yeo et al., 2018). Several standard synthesis techniques for HEN in the past have employed mathematical programming approach (Ryu and Maravelias, 2018). It has also been observed that most studies in the past have assumed

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that process parameters such as flow rates, inlet and outlet temperatures of process streams are fixed; thus assuming that heat exchangers have only one period of operation. However, this is not true; because in reality, process variables vary within certain ranges due to changes in environmental conditions and other disturbances which may upset the system. In most cases, these changes are multi-period in nature, which then confirms the need to synthesize a HEN that is capable of handling multi-period scenarios.

Since the early ’90s, substantial contributions in this field have focused more on the synthesis of single period HEN using simultaneous approaches (Kang and Liu, 2017). Very few information is available in the literature on the sequential synthesis of multi-period HEN, especially those with uncertain disturbances in sub-periods which is the focus and most important contribution of this paper. In addition, the application of HEN for energy and area targeting in absorptive CO_2 capture is new and not adequately reported. It is also worthy to note that mixed-integer linear and nonlinear programming models have consistently been solved in a sequence to target energy consumption, number of heat transfer units and capital cost in most HEN synthesis studies in the past (Tan et al., 2017). As far as could be ascertained, no methodology has effectively considered temperature intervals and uncertain disturbances in a sequential manner for HENs synthesis in CO_2 capture studies. Though the aforementioned decomposition-based approaches used for HEN synthesis in the past were helpful, the major limitation associated with the approach is that the interactions between the capital and operating cost of multi-period HEN were often overlooked. Furthermore, it has been identified that the consequence of parametric variations in sub-periods within the HEN structure has also been neglected (Isafiade, 2018). Additionally, limitations of the heat transfer area have continuously been ignored in previously reported methodologies, though it is expected that both the structure and heat transfer area should be taken as design variables for the flexibility analysis of the HEN.

Against this background, this study presents a new sequential-based procedure for the synthesis of optimal HENs for multi-period operations. The proposed procedure considers the effect of parametric fluctuations in sub-periods on the structure of the multi-period HENs to address the major shortcomings observed in previous studies. Area targeting of heat exchangers was also investigated in this study to determine the capital cost of the synthesized network. A case study involving the absorption of CO_2 from a stream of flue gas was used to test the applicability of the proposed technique. Results such as the minimum utility requirement and costs, heat transfer area, cost of heat transfer area and the number of units of the heat exchanger networks were determined at selected fixed parameters for absorptive CO_2 capture. The sequential approach developed in this study is straightforward, unique and can be extended to minimize energy in other CO_2 capture methods (e.g. adsorption and membrane separation) as well as other range of industrial processes.

2. Problem statement

The problem in this study is presented as follows: ‘Given are the operational conditions of a set of process streams which include their supply and target temperatures at periods 1 to 3 with heat transfer coefficients and heat capacity flow rates quantified as exact values. Hot and cold utilities are available in all periods of operation. The task is to synthesize a heat exchanger network (HEN) which is optimally operable for a set of three periods with the least area cost and minimum number of units. The optimal HEN is expected to be defined by the stream matches, number of units, operating temperature of the heat exchangers, area of heat exchangers and the network configuration.

3. Methodology and synthesis procedure for the multi-period HEN

In this section, a methodical procedure is presented to synthesize a multi-period heat exchanger network (HEN) using modified data originally obtained from Isafiade et al. (2015) which adopted a simultaneous approach with a minimum approach temperature of 10 °C. To create a true counter-current profile between the supply temperature (T_s) of the hot stream (H) and the target temperature (T_t) of the cold stream (C) in this study, a minimum approach temperature (ΔT_{min}) of 20 °C was considered and the HEN synthesized sequentially. Process data from Isafiade et al. (2015) were modified in this study to accommodate the minimum approach temperature which forms the first step in using the temperature interval method. To account for uncertain disturbances in the multi-period HEN in this study, every period had different parameters. It was assumed that gas flow rates and temperature are not constant for each period of operation; therefore, heat capacity is not constant as well. The temperature range was divided into temperature intervals for periods 1 to 3 using the inlet temperatures of the process streams as shown in Figure 1. Important process data such as the specific heat capacity of CO_2 were determined from the supply temperatures in each period (see Table 1). All targets (e.g. heat transfer area, heat exchanger loads and the number of units for the HEN) considered in this study were first determined to provide the boundaries for the design problem. In the synthesis stage, hot and cold streams were matched, and the resulting HEN discussed. The heat capacity flow rate at each period was used as the criterion for selecting the matches based on existing thermodynamic rules. Heat transfer area was minimized and an initial network was synthesized showing reduced total cost by following a number of heuristic rules. In the final stage, the synthesized HEN was optimized. Hot utility (HU) and cold utility (CU) introduced in the first period alongside their costs are presented in Table 2 while the minimum utility requirement (MUR) at each period in the network is shown in Table 3.

Table 1: Process stream data (Modified from Isafiade et al., 2015)

Stream	T_s (°C)	T_t (°C)	F(kW/°C)	Cp (kJ/kg.°C)
Period 1				
H1	249	100	10.55	1.02
H2	269	128	12.66	1.04
C1	96	170	9.14	0.92
C2	116	270	15.00	0.94
Period 2				
H1	229	120	7.03	1.01
H2	249	148	8.44	1.02
C1	96	170	9.14	0.92
C2	116	270	15.00	0.94
Period 3				
H1	249	100	10.55	1.02
H2	269	128	12.66	1.04
C1	106	150	16.10	0.93
C2	96	250	10.00	0.95

Table 2: Utility data

Stream	T_s (°C)	T_t (°C)	Cost ($/y)
HU	320	300	28,800
CU	20	40	630

Table 3: Minimum utility, pinch temperature and number of units

Period	Pinch (°C)	MUR (kW)		Number of HE units
		Hot	Cold	
1	170	483.13	648.59	5
2	116	482.82	665.60	5
3	106	240.54	483.74	5

The temperature interval diagram in Figure 1 was obtained using information from Tables 1 and 2. Periods 1 to 3 were specified in Table 1 to show that in a multi-period network, operating parameters fluctuate from period to period. Hot and cold utility streams were included in Figure 1 to subsequently generate a balanced Composite Curve for both the hot and cold sides. The resultant balanced composite curve was used to size the heat exchangers and coolers in the network using an area targeting technique. Utility loads were determined at each period by means of enthalpy calculations while temperature intervals from periods 1 to 3 were used to determine the minimum utility requirement (MUR) of the network. Total annualized cost (TAC), which is the total annual value of the net present cost (annual operating cost) was calculated by summing the costs of hot and cold utilities required by the network on an annual basis.

4. Energy and area targeting for the HEN design

Hot and cold utility targets in the periods form the minimum utility requirement (MUR) of the network presented in Table 3. Also obtainable in Table 3 are the Pinch temperatures for each Period. From these Pinch temperatures, a global Pinch temperature for the network (170 °C) could be selected and used for subsequent designs. But in this study, the different Pinch Point temperatures were maintained in each period.

$$N = (S_{AP} - 1) + (S_{BP} - 1) \quad (1)$$

$$A = Q / U.\ LMTD \quad (2)$$

$$\text{Capital cost} = 1000\ (\text{number of shells/streams}) + 500A^{0.6}\ \$/y \tag{3}$$

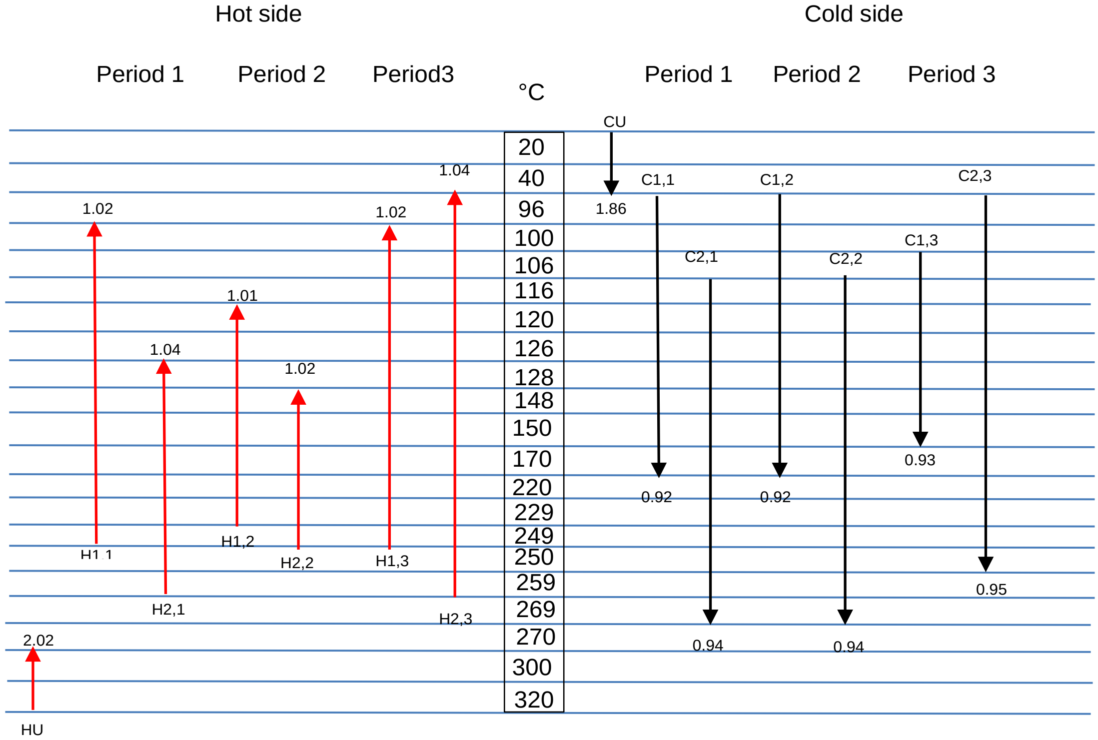

Figure 1: Temperature intervals for hot, cold and utility streams

In Eq(1) to Eq(3), N is the minimum number of units, S_{AP} is the number of streams above the pinch, S_{BP} is the number of streams below the pinch, A is area, Q is the heat load, U is the heat transfer coefficient and LMTD is the log mean temperature difference. Pinch decomposition and matching of hot and cold streams were carried out to determine the minimum number of units using Eq(1) and the optimal network design showing energy loads in each period is presented in Figure 2. The area of each heat exchanger in the network was determined from Eq(2) while the capital cost was calculated from Eq(3) and presented in Table 4.

Area targeting is a vital component that determines the capital cost in HEN. It also plays an important role in capital energy trade-off which determines the optimum ΔT_{min}. Area targeting for the HEN in this study was carried out graphically using balanced Composite Curves considering streams with a common heat transfer coefficient. From the balanced Composite Curve shown in Figure 3, information about the energy targets and heat transfer area costs of the HENs in this study was deduced. The total annualized cost, capital cost and total heat transfer area for the HENs in this work is presented in Table 4 and compared with previous studies. Maximum area targets for heat exchangers per stream match at each period is presented in Table 5. Since the segments of the hot and cold composite curves are straight lines, unknown temperatures at the vertices were calculated based on the Cp values using linear interpolation technique. The area of the heat exchangers in each period was calculated from the respective LMTD's according to Eq(2) and shown in Table 5. Differences observed with reported values in Table 4 could be attributed to the higher value of ΔT_{min} considered in this study. An increase in ΔT_{min} decreases the area targets of the network, but with an increased energy cost. The heat exchanger in period 1 (see Figure 2) can serve in the three periods which explains why the synthesized HEN is a multi-period network. No heat exchanger (cooler) was needed in period 2 (as depicted in Figure 2) because both hot and cold streams in the period can directly get to their target temperatures without using hot or cold utilities. Interestingly, the application of the proposed technique in this study could be extended to other CO_2 capture techniques/systems to optimally minimize their energy consumption.

Table 4: Comparison of Capital cost, TAC and total heat exchanger area compared with literature

	Cost ($/y)	References	Total HEN area (m^2)	References
Capital cost (CC)	16,090.62	This study	1137.79	This study
	Not reported	Isafiade et al. (2015)	Not reported	Isafiade et al. (2015)
Total annualized cost (TAC)	29,430.00	This study		
	62,710.46	Isafiade et al. (2015)		

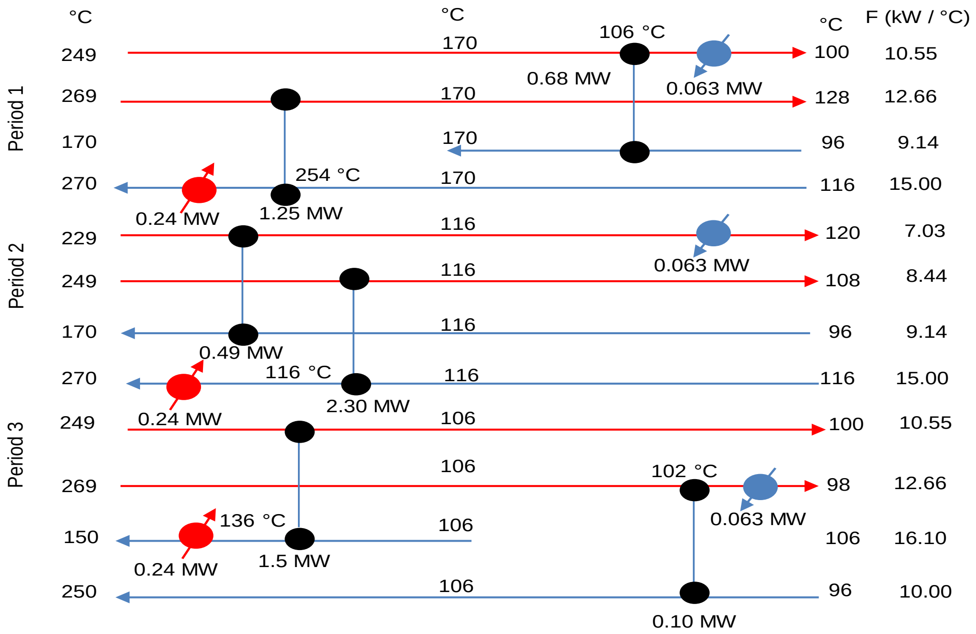

Figure 2: Optimal HEN with operational periods and heat loads

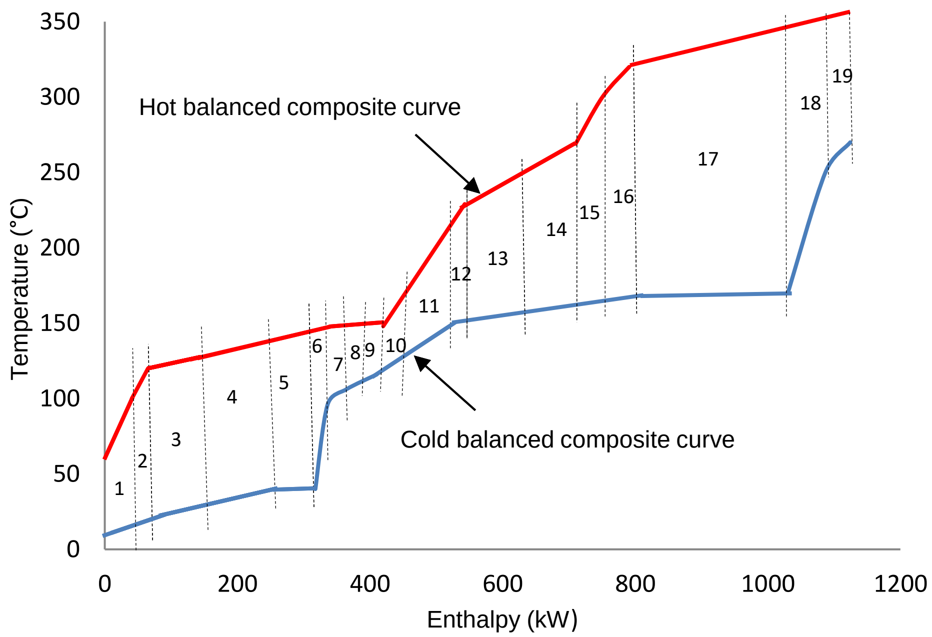

Figure 3: Balanced composite curve for the case study

Table 5: Maximum areas of HEN

Match	Area (m^2)		
	P1	P2	P3
HU_1-C_2	35.45	35.45	35.45
H_2 - C_2	33.75	30.44	33.82
H_1 – C_1	33.75	30.44	33.82
CU_1- H_1	34.40	-	34.40

5. Conclusions

This study has presented a simplified sequential technique to minimize the high energy requirement associated with absorptive CO_2 capture. The technique considered temperature intervals, heat exchanger area sizing and uncertain disturbances in flow rates. The proposed technique in this study revealed a new heuristic rule which showed that the use of feasible matches as initializing matches would result in a multi-period network with a minimum number of units of heat exchangers at each period; thereby paving a way for remarkable energy saving. The proposed technique resulted in an optimal HEN that is flexible with heat transfer devices that are able to accept changes in operating conditions. Finally, the synthesized HEN yielded encouraging results for adsorptive CO_2 capture in terms of capital cost ($16,090.62 /y), utility cost ($29,430.00 /y), heat exchanger areas (1137.79 m^2) and minimum number of units of heat exchangers (5 units) when compared with literature (see Table 4). Results obtained in this study are improvements over previous studies that considered simultaneous techniques with a lesser minimum approach temperature.

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