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Recent Methods for Retrofitting Heat Exchanger Networks with Heat Transfer Intensifications

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This paper presents an overview of recent optimization approaches for retrofitting heat exchanger networks (HENs) with heat transfer intensified techniques. The developed methods includes the heuristic rules for finding suitable enhanced exchangers in HENs, and the SA-based optimization method and MILP-based iterative mathematical programming method for optimizing HEN retrofit problems. An industrial case is investigated with the different optimization methods in several typical retrofit scenarios, providing a better understanding of implementing intensification techniques in suitable exchangers to achieve the best energy saving in a whole retrofitted HEN.

1. Introduction

The most efficient way to decrease energy consumption and the release of greenhouse gases from the process industries is to increase heat recovery. The cleanest energy is the energy saved by improved efficiency. In major process industries including oil refining, petrochemical processes, food, cement, steel, pulp and paper, where very substantial energy savings can be made. Calculations indicate that the energy consumption could be decreased by 30 % purely by using intensification technology in the critical parts of the heat recovery system (Pan et al., 2012). Various new ways have recently been developed to significantly enhance heat exchanger performance. These techniques do not need to be applied through the whole heat recovery system, but mainly at those critical parts that limit the system performance.

Recently, the approaches of implementing heat transfer intensification techniques have be considered in more details. Pan et al. (2011) firstly proposed a novel MILP-based method to solve HEN retrofit problems with intensified heat transfer techniques. Wang et al. (2012a) proposed a detailed model for predicting exchanger performances and developed five heuristic rules to identify suitable heat exchangers for intensification. For modelling detailed intensified techniques, Pan et al. (2013a) focused on the recent achievements of tube-side and shell-side enhancement techniques, considered different techniques in the same cases to compare their performances, and investigated their combinations. Intensified heat transfer techniques are also considered to reduce fouling effect in enhanced exchangers (Pan et al., 2013b). To combine the advantages of intensification and the conventional retrofit methods, Pan et al. (2013c) successfully found valid retrofitted structures for retrofitting HEN with heat transfer intensification, which can achieve significant energy saving without expensive cost from too many modifications. Sreepathi and Rangaiah (2014) proposed several exchanger reassignment strategies for HEN retrofitting. One of those was developed and used in multi-objective optimization. Liu et al. (2014) applied hybrid genetic algorithm to obtain the optimal retrofitted HEN with full utilization of the existing heat exchangers and structures. Kang and Liu (2014) presented a retrofitting approach for heat exchanger networks (HENs) for single-period and multiple-period operations, aiming at the improvement of operation flexibility of HENs.

Based on the aforementioned researches, this paper provides an overview of recent optimization approaches for retrofitting heat exchanger networks (HENs) with heat transfer intensified techniques. The conventional approaches (heuristic based, simulated annealing based and MILP-based) are investigated in an industrial case study to illustrate their efficiencies of solving HEN retrofit problems with heat transfer intensification.

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2. Conventional approaches of retrofitting HENs with heat transfer intensification

The existing methods for retrofitting HENs can be divided into three categories, thermodynamic analysis (e.g. Heuristic Rules), stochastic optimization methods (e.g. Simulated Annealing), and deterministic programming methods (e.g. MILP). The optimization procedures and required models of the most efficient approaches based on the above categories are briefly introduced in this section. More details of these methods have been reported by Wang et al. (2012a), Wang et al. (2012b) and Pan et al. (2012).

2.1 Heuristic rule approach

The heuristic rules proposed by Wang et al. (2012a) are used to consider aspects of the reduction in the use of utilities, and the selection of suitable heat exchangers to be enhanced. Retrofit problems can be dealt without involving complex calculations. The optimization procedure includes five steps (namely five rules):

- **Rule 1: searching for exchangers in utility path.** The candidates for intensification should be on utility path. The exchangers on the same stream with a utility exchanger can affect the duty of the utility exchanger directly.
- **Rule 2: sensitivity analysis.** Based on the heat exchangers selected with Rule 1, sensitivity tables are used to quantify impact of heat transfer intensity on utility consumption of the HEN. High sensitivity exchanger can be a good candidate for intensification.
- **Rule 3: checking pinching match.** Pinching match is the bottleneck of heat recovery network. Normally, the pinching match will have a very small heat transfer temperature difference.
- **Rule 4: enhancing candidates in sequence.** Once the best exchanger selected based on Rule 2 is enhanced, sensitivity analysis (Rule 2) is applied again to all candidate exchangers to find the next best one.
- **Rule 5: enhancing pinching match.** Enhancing pinching match can be considered in the situation of no good candidate for the heat transfer enhancement, or the potential for energy savings from enhancing promising candidates may be very low.

Based on the heuristic rules 1-5, suitable candidates in HEN are selected, and the optimal solution of HEN retrofit can be obtained.

2.2 Stochastic optimization method

Stochastic optimization methods are optimization methods that generate and use random variables. Simulated annealing (SA) is a generic probabilistic metaheuristic for the global optimization problem of locating a good approximation to the global optimum of a given function in a large search space. The SA-based optimization method adopted in this paper is based on the approach proposed by Wang et al. (2012b).

In the SA method, continuous variables include exchanger duties, stream flowrates, stream temperatures, and exchanger heat transfer coefficients; while discrete variables include adding intensification techniques, deleting intensification techniques. Thus, adding intensification techniques and deleting intensification techniques are described as the SA moves, which can create a network with a small random difference from the trial situation as follows:

- Intensification is randomly added to tube side or shell side or both in an exchanger with an increasing ratio of heat transfer coefficient.
- The maximum increasing ratio of heat transfer coefficient according to enhancement device is described in constraints. Moreover, the maximum number of exchangers to be enhanced can be set as too many modifications on exchangers are not common in practical industry.
- The objective function is to minimize the energy consumption or the total retrofit cost of networks.
- After a SA move is made, the new network will be accepted if the objective value is improved; otherwise, the new network will be denied.

Repeat the above procedure in a sufficient long computing time, an optimal retrofitted network with heat transfer intensification can be found.

Two calculation approaches (duty-based and area-based) are used for determining heat exchanger performances. In duty-based approach, the inlet temperatures, stream capacities and heat load in an exchanger are known, thus exchanger area can be calculated directly from Eq(1)-Eq(3), where EX is the set of all exchangers, HTI_{ex}, HTO_{ex}, CTI_{ex} and CTO_{ex} are inlet and outlet temperatures of hot and cold streams in exchanger ex, Q_{ex} is the duty of exchanger ex, $HFCP_{ex}$ and $CFCP_{ex}$ are heat-flow capacities (the multiplication between heat capacity and flow-rate) of hot and cold streams in exchanger ex, $LMTD_{ex}$ is the logarithmic mean temperature difference of exchanger ex, EXA_{ex} is area of exchanger ex, and U_{ex} is the heat transfer coefficient of exchanger ex.

$$HTO_{ex} = HTI_{ex} - \frac{Q_{ex}}{HFCP_{ex}}, \quad \forall ex \in EX \tag{1}$$

$$CTO_{ex} = CTI_{ex} + \frac{Q_{ex}}{CFCP_{ex}}, \quad \forall ex \in EX \tag{2}$$

$$EXA_{ex} = \frac{Q_{ex}}{U_{ex} \times LMTD_{ex}}, \quad \forall ex \in EX \tag{3}$$

In area-based approach, exchanger area is known and fixed, but heat load (Q_{ex}) is unknown. The calculation of heat load (Q_{ex}) requires a iterative procedure of Eq(1)-Eq(3), and an estimated value of heat load is needed in the initial condition. Even though the area-based approach leads to a longer computing time, it presents practical HEN retrofit process with heat transfer intensification directly, and avoids minimum approach temperature violation.

2.3 Deterministic programming method

A deterministic algorithm is an algorithm which, given a particular input, will always produce the same output, with the underlying machine always passing through the same sequence of states. MILP-based iterative methods proposed by Pan et al. (2012) have been widely used for retrofitting HENs with heat transfer intensification recently. The optimization approach includes an MILP-based model and an iteration algorithm.

First of all, logarithmic mean temperature difference (LMTD) is initialized with initial stream temperatures, as shown in Eq(4), where HTI'_{ex}, HTO'_{ex}, CTI'_{ex} and CTO'_{ex} are inlet and outlet initial temperatures of hot and cold streams in exchanger *ex*.

$$LMTD'_{ex} = \frac{(HTI'_{ex} - CTO'_{ex}) - (HTO'_{ex} - CTI'_{ex})}{ln[(HTI'_{ex} - CTO'_{ex})/(HTO'_{ex} - CTI'_{ex})]}, \quad \forall ex \in EX \tag{4}$$

Then, a set of binary variables is proposed: EEX_{ex} =1, if an intensification technique is implemented in exchanger *ex*; otherwise, it is 0. Thus, the heat transfer coefficients of intensified exchangers can be formulated as:

$$U_{ex} \geq MINU_{ex} \times (1 - EEX_{ex}), \ \forall ex \in EX \tag{5}$$

$$U_{ex} \leq MAXU_{ex} \times (1 - EEX_{ex}), \ \forall ex \in EX \tag{6}$$

where $MAXU_{ex}$ and $MINU_{ex}$ are the upper and lower bounds of heat transfer coefficient when a intensification technique is implemented in exchanger *ex*.

The constraints of heat transfer (HBA_{ex} and HBB_{ex}) and energy balance (AEB_{ex} and BEB_{ex}) in an exchanger are shown in Eq(7)-Eq(10).

$$HBA_{ex} \geq HFCP'_{ex} \times (HTI_{ex} - HTO_{ex}) - EXA_{ex} \times U_{ex} \times LMTD'_{ex}, \ \forall ex \in EX \tag{7}$$

$$HBB_{ex} \geq EXA_{ex} \times U_{ex} \times LMTD'_{ex} - HFCP'_{ex} \times (HTI_{ex} - HTO_{ex}), \ \forall ex \in EX \tag{8}$$

$$AEB_{ex} \geq HFCP'_{ex} \times (HTI_{ex} - HTO_{ex}) - CFCP'_{ex} \times (CTI_{ex} - CTO_{ex}), \ \forall ex \in EX \tag{9}$$

$$BEB_{ex} \geq CFCP'_{ex} \times (CTI_{ex} - CTO_{ex}) - HFCP'_{ex} \times (HTI_{ex} - HTO_{ex}), \ \forall ex \in EX \tag{10}$$

The minimum temperature difference (ΔT_{min}) is restricted in Eq(11) and Eq(12).

$$HTI_{ex} \geq CTO_{ex} + \Delta T_{\min}, \ \forall ex \in EX \tag{11}$$

$$HTO_{ex} \geq CTI_{ex} + \Delta T_{\min}, \ \forall ex \in EX \tag{12}$$

The stream temperature differences ($DAHTI_{ex}$ and $DBHTI_{ex}$) are presented in Eq(13) and Eq(14). Other temperature differences, such as $DAHTO_{ex}$, $DBHTO_{e}$, $DACTI_{ex}$, $DBCTI_{ex}$, $DACTO_{ex}$ and $DBCTO_{ex}$ are formulated in the same way.

$$DAHTI_{ex} \geq HTI_{ex} - HTI'_{ex}, \ \forall ex \in EX \quad (13)$$

$$DBHTI_{ex} \geq HTI'_{ex} - HTI_{ex}, \ \forall ex \in EX \quad (14)$$

Eq(15) presents energy saving (*QS*) after in the retrofit, where EX_{hu} and EX_{cu} are the set of all exchangers consuming hot and cold utilities; $OCTI_{ex}$ and $OHTI_{ex}$ are the original inlet temperatures of cold stream and hot stream in exchanger *ex* before retrofit.

$$QS = \sum_{ex \in EX_{hu}} \left[CFCP'_{ex} \times \left(CTI_{ex} - OCTI_{ex} \right) \right] + \sum_{ex \in EX_{cu}} \left[HFCP'_{ex} \times \left(OHTI_{ex} - HTI_{ex} \right) \right] \quad (15)$$

The objective of the MILP-based method is to minimize the summation of difference in energy balances, heat transfers and stream temperatures with the restrictions of an estimated energy saving value (*QS'*), as shown in Eq(16) and Eq(17).

$$QS \geq QS' \quad (16)$$

$$\begin{aligned} Obj = & \left[\sum_{ex \in EX} \left(DACTI_{ex} + DBCTI_{ex} + DACTO_{ex} + DBCTO_{ex} \right) + \sum_{ex \in EX} \left(HBA_{ex} + HBB_{ex} \right) \right] \\ & + \left[\sum_{ex \in EX} \left(DAHTI_{ex} + DBHTI_{ex} + DAHTO_{ex} + DBHTO_{ex} \right) + \sum_{ex \in EX} \left(AEB_{ex} + BEB_{ex} \right) \right] \end{aligned} \quad (17)$$

The MILP-based model for maximum energy saving consists of an objective function given in Eq(17) and model constraints given from Eq(4)-Eq(16).
Since the MILP-based model has been built, an iteration algorithm (two iteration loops) is used to find the optimal solution for HEN retrofit problems. In the first loop, the MILP-based model is solved repeatedly to obtain a feasible solution for HEN retrofit under certain energy saving. In the second loop, the maximum value of energy saving is searched, and the feasible solution under the maximum energy saving can be found by using the procedure proposed in the first loop.

3. Case study

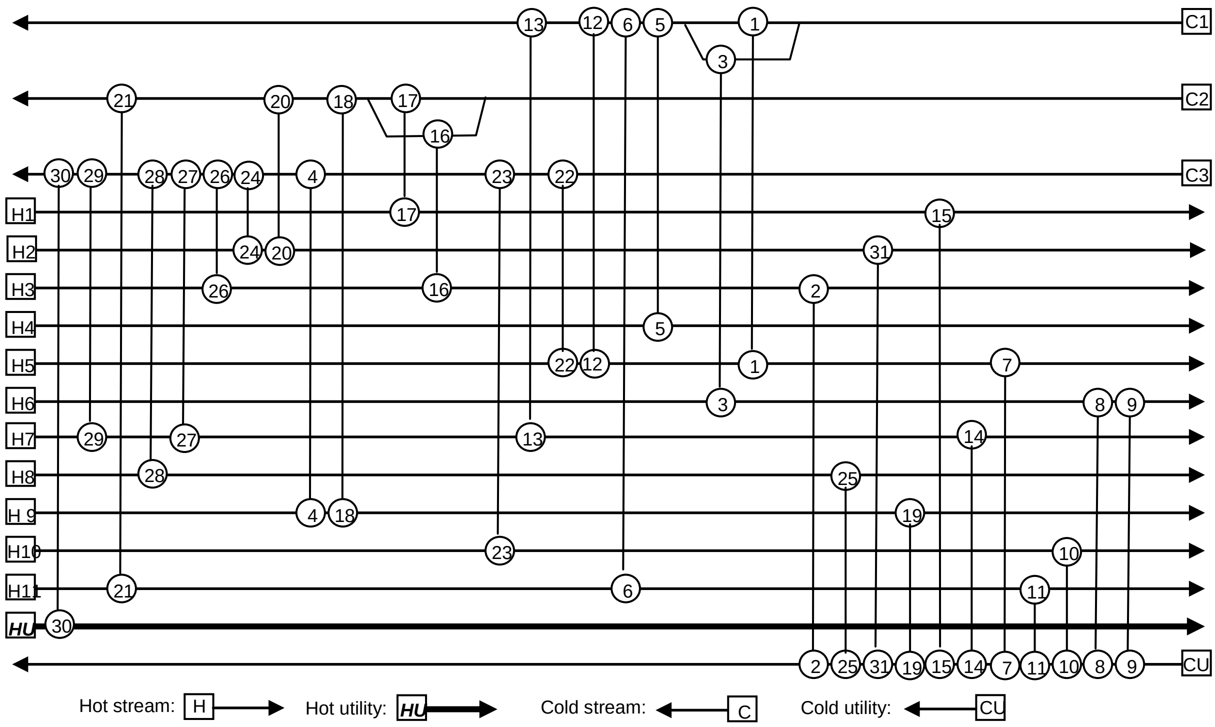

Figure 1: An industrial scale HEN for the case study

The example investigated in this paper is an industrial scale HEN, as shown in Figure 1. The retrofit objective is to reduce the hot utility (HU) consumption, namely, reduce the heat duty of heat exchanger 30 (target exchanger). The stream data and initial exchanger data can be found in Tables 1 and 2. Moreover, the heat-flow capacities of hot utility and cold utility are 93 kW/ºC and 9,652.5 kW/ºC, the inlet temperatures of hot utility and cold utility are 1,500 ºC and 12.45 ºC, the minimum temperature difference approaches (ΔT_{min}) before and after heat transfer intensification are 19 ºC and 5 ºC.

Table 1: Stream details in case study

Stream	C1	C2	C3	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11
FCP (kW/ºC)	323	358.5	474	14.2	181.5	113	100	22.2	39.5	28.0	176	24.5	25.0	69.6
T_{in} (ºC)	33.5	91.34	151	335	253.2	294	212	213	174	364	290	284	240	179
T_{out} (ºC)	95.6	157.3	352	69.4	116.1	130	156	61.7	43.3	65.6	211	65.6	57.8	69.3

Table 2: Exchanger details in original HEN

EXs	HTI_{ex} (ºC)	HTO_{ex} (ºC)	CTI_{ex} (ºC)	CTO_{ex} (ºC)	$LMTD_{ex}$ (ºC)	EXA_{ex} (m^2)	U_{ex} ($kW/m^2 \cdot ºC$)	Duty (kW)
1	117.220	66.284	33.510	40.523	51.660	174.990	0.12509	1130.8
2	131.237	130.000	14.194	14.208	116.416	11.666	0.10292	139.8
3	174.400	76.670	33.510	57.450	74.024	116.660	0.44702	3860.3
4	284.200	174.731	156.731	162.390	54.291	174.990	0.28230	2682.0
5	212.440	156.050	48.986	66.454	125.521	100.000	0.44880	5633.4
6	174.444	85.701	66.454	85.606	45.500	650.000	0.20884	6176.5
7	66.284	61.670	12.998	13.009	50.939	20.000	0.10054	102.4
8	76.670	62.200	12.527	12.586	56.573	30.000	0.33677	571.6
9	62.200	43.330	12.450	12.527	39.535	55.560	0.33933	745.4
10	171.093	57.780	12.586	12.880	90.200	277.800	0.11305	2832.8
11	85.701	69.300	12.880	12.998	64.218	55.560	0.31994	1141.5
12	169.050	117.220	85.606	89.174	52.070	22.224	0.99432	1150.6
13	221.101	147.201	89.174	95.590	87.473	38.060	0.62153	2069.2
14	147.201	65.560	13.009	13.246	86.996	85.720	0.30654	2285.9
15	109.340	69.440	13.246	13.304	74.344	42.860	0.17781	566.6
16	198.376	131.237	91.340	133.665	51.308	128.580	1.15000	7586.7
17	335.400	109.340	91.340	109.248	82.246	207.690	0.18792	3210.1
18	174.731	139.686	121.457	123.852	31.809	207.690	0.12996	858.6
19	139.686	65.560	13.304	13.492	83.862	138.460	0.15640	1816.1
20	206.228	141.852	123.852	156.444	31.243	1384.600	0.27010	11684.2
21	178.700	174.444	156.444	157.270	19.665	27.692	0.54395	296.2
22	212.680	169.050	151.050	153.093	34.741	83.076	0.33560	968.6
23	240.070	171.093	153.093	156.731	42.634	41.538	0.97373	1724.4
24	253.200	206.228	162.390	180.376	57.110	1038.450	0.14375	8525.4
25	222.747	210.900	13.978	14.194	202.682	66.660	0.15433	2085.1
26	293.700	198.376	180.376	203.101	44.923	299.970	0.79934	10771.6
27	248.975	221.101	203.101	204.747	29.175	233.310	0.11466	780.5
28	290.380	222.747	204.747	229.860	35.065	1020.000	0.33281	11903.4
29	364.260	248.975	229.860	236.670	57.142	240.000	0.23538	3228.0
30	1500.000	912.546	236.670	351.930	891.221	180.000	0.34056	54633.2
31	141.852	116.050	13.492	13.978	114.751	60.000	0.68018	4683.1

In this case study, three typical optimization approaches are used to solve the retrofit problem. They are heuristic rule approach (Wang et al., 2012a), SA optimization approach (Wang et al., 2012b), and MILP-based iterative approach (Pan et al., 2012). Intensified technique is implemented to directly increase the overall heat transfer coefficients of enhanced exchangers. It is assumed that the maximum intensified coefficient of each exchanger is two times of its original value. The optimal solutions based on the three optimization approaches are shown in Table 3.

As presented in Table 3, heat transfer coefficients increase in the intensified exchangers, all exchangers remain unchanged area, and the optimal solution based on the MILP-based approach requires less computing time and give the best solution. It is noted that the MILP-based method can quickly find the most appropriate heat exchangers for intensification.

Table 3: Optimal solutions based on the three optimization approaches

Optimization approaches		Intensified exchangers (U: kW/m^2·°C)	Energy saving (kW)	Computing time
Heuristic rule approach (Wang et al., 2012a)		EX20 (0.348), EX24 (0.155), EX26 (1.2), EX28 (0.448)	1904.2	
SA optimization approach (Wang et al., 2012b)	Duty-based	EX4 (0.407), EX20 (0.3), EX23 (1.444), EX28 (0.413)	1118.6	2~3 h
	Partial area-based	EX4 (0.367), EX6 (0.211), EX12 (1.092), EX18 (0.151), EX28 (0.407)	929.0	22~24 h
	Area-based	EX20 (0.397), EX24 (0.195), EX26 (0.878), EX28 (0.425), EX29 (0.336)	2114.0	22~24 h
MILP-based iterative approach (Pan et al., 2012)		EX20 (0.385), EX24 (0.192), EX26 (0.851), EX28 (0.442), EX29 (0.35)	2161.4	< 1 min

4. Conclusions

Many conventional optimization approaches have been widely studied for retrofitting HENs with heat transfer intensification. However, most of the reported methods are still in the research stage and far from being used in industrial application. In this paper, the existing typical optimization approaches are compared and used to solve an industrial scale problem. The MILP-based iterative approach has been demonstrated to be more efficient for the bottlenecking of HENs with the systematic application of intensified heat transfer compared with the heuristic rule approach and SA optimization approach.

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