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Automated Targeting Approach for Synthesis of Heat Exchanger Network (HEN) with Trigeneration System

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Abstract

In this work, a novel systematic approach for the synthesis of heat exchanger network (HEN) with trigeneration system via multiple cascades automated targeting (MCAT) is presented. The optimisation objective is to locate the minimum total operating cost (*TOC*) of the system. The minimum hot and cold utilities of the HEN, allocation of utilities and potential power generation as well as the type of fuel can be determined via proposed approach. A case study of formic acid processing plant is solved to illustrate proposed approach.

Keywords: Trigeneration system; automated targeting; multiple-cascades; optimisation; heat exchanger network

1. Introduction

Automated targeting approach was initially developed to synthesise mass exchange network (MEN) [1]. It was then extended in the synthesis of resource conservation network [2, 3] and integrated biorefineries [4, 5]. Multiple-cascade automated targeting (MCAT) was then proposed to synthesise an integrated biorefinery with the consideration of multiple process parameters [5]. In this work, MCAT is extended to synthesise heat exchanger network (HEN) with trigeneration system that produces three different forms of energies (power, heat and cooling) simultaneously from a single primary energy source which has not been considered in previous works. A case study of formic acid processing plant is solved to illustrate proposed approach.

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2. Problem Statement

The problem statement of synthesising HEN with trigeneration system is stated as follows: Given a set of fuel source $h \in H$, which can be combusted in a boiler to produce steams sources $i \in I$. The produced steams are then fed into different steam headers $k \in K$. The pressure of steam can be reduced via steam turbines to satisfy the process sinks $j \in J$ which are steams required in the process plant. Note that the waste steam which produces from the lowest steam header can be utilised in absorption chiller (AC) to produce chilled water. Besides, a set of hot and cold streams $g \in G$ with shifted inlet (T_g^{in}) and outlet (T_g^{out}) temperature based on the minimum temperature difference (ΔT_{min}), and respective heat capacity flowrate, CP_g are extracted to construct heat cascade for heat integration. These shifted inlet and outlet temperatures are identified as source (T_x^{in}) and sink (T_y^{out}) temperatures, respectively. In addition, the respective heat capacity flowrate are given as CP_x^{in} and CP_y^{out}. The main objective of this work is to minimise total operating cost (*TOC*) of HEN with trigeneration system.

3. Multiple Cascade Automated Targeting (MCAT)

In this work, steam, power, heat and utility cascades are developed via MCAT. Steam header is first arranged in descending order based on the specific enthalpy levels, and then steam cascade is performed. In this cascade, steam flowrate that fed into each steam header and supplied to process sink is determined via Equation (1).

$$\delta_k = \delta_{k-1} + \left(\textstyle\sum_{i \in I} F_{SRi} - \sum_{j \in J} F_{SKj}\right)_k \qquad \forall k \qquad (1)$$

where δ_k is net steam flowrate of each steam header k, F_{SRi} and F_{SKi} are steam flowrates of source and sink. Note that waste steam which can be utilised in AC is generated at the lowest level ($k = n$) and given flowrate as δ_n. To determine the refrigeration power of the chiller, Equation (2) is included in the model.

$$Q_{cw} = COP\ (\delta_n \times H_{ws}) \qquad (2)$$

where *COP* is the coefficient of performance of the chiller and H_{ws} is enthalpy of waste steam.

To determine the extractable power of the system, power cascade is performed. The extractable power, Q_k of each level of k is determined by multiplying the net steam flowrate at k level (δ_k) with the difference between two adjacent specific enthalpy levels ($H_k - H_{k+1}$) as well as efficiency of turbine in level k, η_k as shown in Equation (3). In addition, the residual power ε_k of level k is given in Equation (4).

$$Q_k = \delta_k (H_k - H_{k+1}) \eta_k \qquad \forall k \qquad (3)$$

$$\varepsilon_k = \varepsilon_{k-1} + Q_k \qquad \forall k \qquad (4)$$

where H_k is the enthalpy of steam in header k. Based on the power cascade, the total extractable power from the entire system ($Q_t = \varepsilon_n$) can be determined at the lowest level ($k = n$).

To determine the maximum heat recovery within HEN, heat and utility cascades are constructed. In heat cascade, the source temperature, T_x^{in} and sink temperature, T_y^{out} are arranged in descending order with respective heat capacity flowrate, CP_x^{in} and CP_y^{out}. The arranged temperatures in heat cascade level

p are given as T_p. Next, heat cascade is performed and the net heat flowrate for each level p, γ_p is determined via Equation (5).

$$\gamma_p = \gamma_{p-1} + (\textstyle\sum_{x \in X} CP_x^{\text{in}} - \sum_{y \in Y} CP_y^{\text{out}})_p \qquad \forall p \tag{5}$$

For utility cascade, the residual utility α_p of each level p is determined by multiplying γ_p with difference between two adjacent temperature levels ($T_p - T_{p+1}$) as shown in Equation (6). Based on Bandyopadhyay and Sahu [6], the hot and cold utility targets ($Q_{\text{H}}^{\text{min}}$ and $Q_{\text{C}}^{\text{min}}$) can be determined in the first level, $p = 1$ and the last level, $p = n$ of the utility cascade, respectively.

$$\alpha_p = \alpha_{p-1} + \gamma_p\,(T_p - T_{p+1}) \qquad \forall p \tag{6}$$

To identify the allocation of hot and cold utilities in the heat cascade, both external hot and cold utilities demands are set as zero ($\alpha_1 = 0$ and $\alpha_n= 0$). Besides, the flowrate of very high pressure (VHP), high pressure (HP), medium pressure (MP) and low pressure (LP) steams are included as hot streams. In addition, the chilled water and cooling water flowrate (F^{CW} and F^{COW}) are included as cold streams. The optimisation objective of this work is to minimise total operating cost (*TOC*) of the trigeneration system:

$$TOC = F_h^{\text{FUEL}} \text{C}_h^{\text{FUEL}} - Q_t\,\text{C}^{\text{ELEC}} \tag{7}$$

where F_h^{FUEL} and C_h^{FUEL} are flowrate and unit cost of fuel h, respectively; C^{ELEC} is electricity tariff rate.

4. Case Study

To illustrate the proposed approach, a HEN with trigeneration system in a formic acid plant is solved. In this case study, liquid fuel oil (LFO), natural gas (NG), and briquettes (BQT) are considered as potential fuel sources in boiler to generate VHP steam with the flowrate of F^{VHP}. The inlet temperature and pressure of boiler's feed water are 100°C and 1.013 bar; the temperature and pressure of outlet steam are 300°C and 60 bar. Three turbines are utilised to reduce steam pressure; therefore, HP, MP and LP steams are generated. The flowrate of such steams are given as F^{HP}, F^{MP} and F^{LP}. In this work, the overall efficiency of all turbines is assumed to be 70 % (η = 0.7). Note that the waste steam which generated from the last turbine is supplied to AC for production of chilled water. In addition, the COP of the chiller is given in the range of 1.0 to 1.3; while, the flowrate of required chilled water for AC, F^{CWAC} in this plant is given as 8.09 kg/s. Besides, Q_{cw} and H_{ws} are given as 1,118 kW and 2,766.11 kJ/kg, respectively.

The proposed model is solved via LINGO, v.13.0 with Global Solver. Based on the optimised result, the minimum *TOC* is determined as USD 10.72 million. BQT is identified as the fuel source for boiler with the flowrate of 5.32 kg/s. Besides, 23.02 kg/s of VHP steam is converted to 0.23 kg/s MP and 22.38 kg/s LP. In addition, 8,000 kW of power (Q_t) and 0.40 kg/s of waste steam are generated from the system. On the other hand, F^{CW} and F^{COW} are determined as 40.06 kg/s and 11,441.26 kg/s, respectively.

5. Conclusion

A novel systematic approach for synthesis of HEN with trigeneration system is presented. The proposed approach is able to determine the minimum TOC of the trigeneration system. Besides, the allocation of utilities, minimum hot and cold utility targets, power generation and selection of fuel for steam generation are also can be determined. Note that the proposed approach can be applied in different industries that require different forms of energies (power, heat and cooling).

Table 1. Hot and cold streams data, unit cost of energy, steam and potential fuel properties

Stream	Sources		Sinks	
	T_x^{in} (°C)	CP_x^{in} (kW/°C)	T_y^{out} (°C)	CP_y^{out} (kW/°C)
1	60	1,060	55	1,060
2	55	7	10	7
3	52	33	10	33
4	32	1,350	30	1,350
5	115	51	30	51
6	145	1.7	30	1.7
7	25	$4.184F^{CWAC}$	11	$4.184F^{CWAC}$
8	265	$1{,}677F^{VHP}$	255	$1{,}677F^{VHP}$
9	200	$1{,}962F^{HP}$	190	$1{,}962F^{HP}$
10	170	$2{,}069F^{MP}$	160	$2{,}069F^{MP}$
11	152.9	$2{,}121F^{LP}$	142.9	$2{,}121F^{LP}$
12	100	2,900	102	2,900
13	65	13.3	125	13.3
14	100	193.3	115	193.3
15	155	671.4	162	671.4
16	30	$4.184F^{COW}$	40	$4.184F^{COW}$
17	9.4	$4.184F^{CW}$	17	$4.184F^{CW}$

Steam Properties			
Steam	Pressure (bar)	Enthalpy (kJ/kg)	Latent heat (kJ/kg)
VHP (F^{VHP})	44.8	1,120.56	1,677.00
HP (F^{HP})	13.8	827.06	1,962.40
MP (F^{MP})	6.9	694.65	2,069.00
LP (F^{LP})	4.5	623.3	2,121.00

Cost of Energy	
Types	Cost (USD)
Chilled water (CW)	4.0/GJ
Cooling water (COW)	0.020/m^3
Electricity/Power	0.076/kW·h

Fuel Source Price and Properties			
Fuel type	Price (USD/kg)	Eff. (%)	Heat Content (kJ/kg)
LFO	0.845	87	46,281.77
NG	0.227	90	37,681.20
BQT	0.070	75	14,250.00

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Biography

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