CHEMICAL ENGINEERING TRANSACTIONS Volume 25, 2011
Editors Jiří Jaromír Klemeš, Petar Sabev Varbanov, Hon Loong Lam
Copyright © 2011, AIDIC Servizi S.r.l., ISBN 978-88-95608-16-7 ISSN 1974-9791
DOI: 10.3303/CET1125110

Design and Optimization of Total Site Energy Systems for Chemical Plants

Cheng-Liang Chen*, Chih-Yao Lin

Department of Chemical Engineering, National Taiwan University, No. 1, Sec. 4,
Roosevelt Road, Taipei, 10617 Taiwan
CCL@ntu.edu.tw

Total site design technique is developed for the optimal synthesis of whole energy systems that consist of the heat recovery system and the steam power system. In the design of a total process system, heat exchange between a heat recovery network (HEN) and a steam distribution network (SDN) is available for obtaining the better energy utilization. Specifically, the heat flow distribution between total sites is considered to enhance the performance of whole systems. A systematic energy management is fulfilled with the proposed integrated SDN-HEN model, where the allocation of the energy flow is optimized. Case study is presented to demonstrate the feasibility and benefits of the proposed approach.

1. Introduction

Improving energy efficiency and reducing energy waste is one of the most important issues in recent years due to increasing prices of energy sources. Linking to a number of processes to supply most of the energy utilities, steam plants are highly interactive with chemical plants. Therefore, it is necessary to develop the total site integration technique to increase the efficiency and performance of energy systems.

There are important contributions that address problems in design of energy systems within the optimization framework. The design methodologies of utility systems are generally classified into two broad categories: the thermodynamic targets (Nishio et al., 1980; Chou et al., 1987) and the mathematical-model based on optimization technique (Papoulias and Grossmann, 1983a; Bruno et al., 1998; Aguilar et al., 2007; Chen and Lin, 2010). The total site design consideration can be stated as follows. Papoulias and Grossmann (1983b) addressed the design problem of total processing systems. Hackl et al. (2010) developed the targeting method of total site analysis. Fodor et al. (2010) studied the total site targeting accounting for individual process heat transfer characteristics. Kapil et al. (2010) proposed the method of exploitation of low-grade heat in site utility systems.

In this context, the objective of this work is to develop a general mathematical programming model for the design of total site energy systems. With the better performance of total systems, an integrated SDN-HEN model is proposed, which address the synthesis of a network and determination of operation conditions together for energy demands of chemical processes. The integrated SDN-HEN is accomplished by the combination of the SDN model and the HEN model (Yee and Grossmann, 1990),

Please cite this article as: Chen C.L. and Lin C.Y., 2011, Design and optimization of total site energy systems for chemical plants, Chemical Engineering Transactions, 25, 659-664
DOI: 10.3303/CET1125110

so that energy flow can be distributed in a good manner between steam system and chemical process sites. Illustrative example is provided to demonstrate the benefits of the proposed formulation.

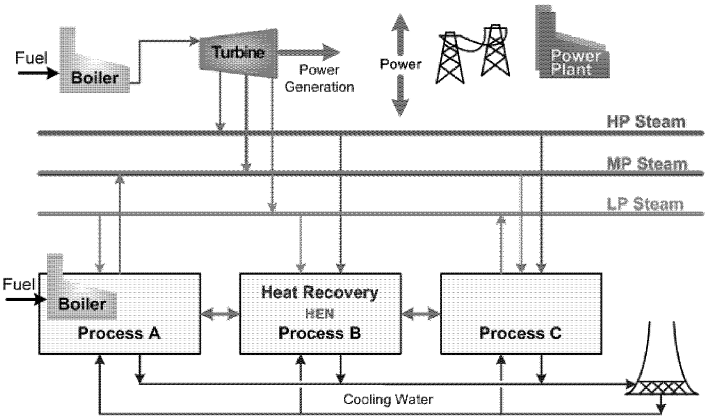

Figure 1: Typical structure of the total site utility system.

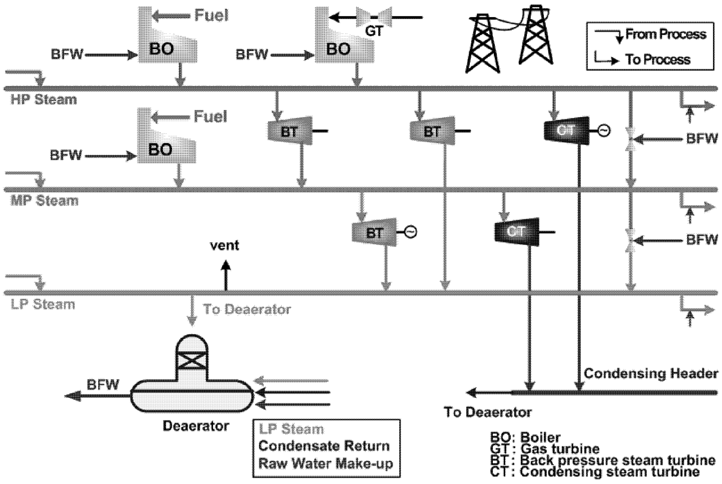

Figure 2: Generic structure of the steam distribution system.

2. Problem Statement

Given are a process stream data, mechanical power needs and electricity demands of process. The objective is to design a SDN of steam systems and a HEN of heat recovery system at minimum total annualized cost. In order to clearly illustrate the design idea, a typical structure of total site utility system is shown in Figure 1 (Klemeš et al., 1997).

Steam and power are generated from steam system and then is distributed into the processing sites. To enable the energy system with effective energy utilization, the integration between total sites are considered. Energy flow can be distributed to different processing sites and steam systems to enhance the performance of total site energy systems, which is known as an eco-industrial park. The generic structure of the SDN is shown in Figure 2. This structure consists of various equipments (boiler, gas turbine, steam turbine and deaerator) and depicts the distribution of steam of possible flow connections for all units. Figure 3 presents a superstructure for the synthesis of HEN (Yee and Grossmann, 1990), which allows for different possibilities and sequences for matching stream.

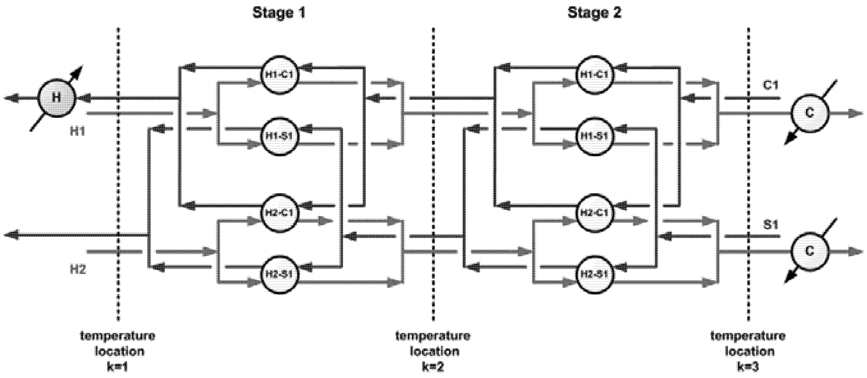

Figure 3: Superstructure of heat exchanger network.

3. Model Formulation

In the following equations, the subscript b is used to represent boiler, i is steam header, t is steam turbine, g is gas turbine, m is electric motor, h is hot process stream, c is cold process stream, and p is time period.

3.1 Steam system

Following equations are the mass and energy balances of steam system, which depicts the distribution of steam of possible flow connections for all units.

$$f^{\mathrm{fw}}_{bp} = \sum_{i\in I} f_{bip} + \sum_{i\in I} f^{\mathrm{bd}}_{bip} \qquad \forall b \in B, p \in P \tag{1}$$

$$f^{\mathrm{fw}}_{bp} H^{\mathrm{deaer}} + q_{bp} = \sum_{i\in I} f_{bip} h_{bip} + \sum_{i\in I} f^{\mathrm{bd}}_{bip} H^{\mathrm{sat,l}}_{i} \qquad \forall b \in B, p \in P \tag{2}$$

$$f^{\mathrm{w}}_{p} + \sum_{i\in I} f_{ip} + f^{\mathrm{C}}_{p} = \sum_{b\in B} f^{\mathrm{fw}}_{bp} + \sum_{i\in I} f^{\mathrm{ld}}_{ip} \qquad \forall p \in P \tag{3}$$

$$f^{\mathrm{w}}_{p} H^{\mathrm{w}}_{p} + \sum_{i\in I} f_{ip} h_{ip} + f^{\mathrm{C}}_{p} h^{\mathrm{C}}_{p} = (\sum_{b\in B} f^{\mathrm{fw}}_{bp} + \sum_{i\in I} f^{\mathrm{ld}}_{ip}) H^{\mathrm{deaer}} \qquad \forall p \in P \tag{4}$$

$$\begin{aligned}&\sum_{b\in B} f_{bip} + \sum_{\substack{i'\in I\\ i'<i}} \sum_{t\in T} f_{i'itp} + \sum_{\substack{i'\in I\\ i'<i}} f_{i'ip} + f_{ip}^{\mathrm{ld}} + f_{ip}^{\mathrm{ps}}\\ &= \sum_{\substack{i'\in I\\ i'>i}} \sum_{t\in T} f_{ii'tp} + \sum_{\substack{i'\in I\\ i'>i}} f_{ii'p} + f_{ip} + f_{ip}^{\mathrm{vent}} + f_{ip}^{\mathrm{pd}} \qquad \forall i \in I, p \in P \end{aligned} \tag{5}$$

$$\begin{aligned}&\sum_{b\in B} f_{bip} h_{bip} + \sum_{\substack{i'\in I\\ i'<i}} \sum_{t\in T} f_{i'itp} h_{i'itp} + \sum_{i'\in I} f_{i'ip} h_{i'p} + f_{ip}^{\mathrm{ld}} H^{\mathrm{deaer}} + f_{ip}^{\mathrm{ps}} H_{ip}^{\mathrm{ps}}\\ &= (\sum_{\substack{i'\in I\\ i'>i}} \sum_{t\in T} f_{ii'tp} + \sum_{\substack{i'\in I\\ i'>i}} f_{ii'p} + f_{ip} + f_{ip}^{\mathrm{vent}} + f_{ip}^{\mathrm{pd}}) h_{ip} \qquad \forall i \in I, p \in P \end{aligned} \tag{6}$$

$$\sum_{g\in GS} w_{gjp} + \sum_{t\in TS} w_{tjp} + \sum_{m\in M} w_{mjp} = w_{jp}^{\mathrm{dem,s}} \qquad \forall j \in J, \forall p \in P \tag{7}$$

$$\sum_{g\in GE} w_{gp} + \sum_{t\in TE} \sum_{i'\in I} \sum_{i\in I} w_{i'itp} + w_{p}^{\mathrm{imp,e}} = w_{p}^{\mathrm{dem,e}} + \sum_{m\in M} \sum_{j\in J} \frac{w_{mjp}}{\eta^{\mathrm{m}}} + w_{p}^{\mathrm{exp,e}} \qquad \forall p \in P \tag{8}$$

3.2 Heat recovery system

Equations (9) - (10) are the overall heat balances for each stream, which are used to ensure sufficient heating or cooling of each process stream. Equations (12) - (14) are the heat balances at each stage, which are used to determine the stage temperatures.

$$(T_{hp}^{\mathrm{in}} - T_{hp}^{\mathrm{out}}) F_{hp} = \sum_{c\in C} \sum_{k\in K} q_{hckp} + q_{hp}^{\mathrm{cu}} \qquad \forall h \in H, p \in P \tag{9}$$

$$(T_{cp}^{\mathrm{out}} - T_{cp}^{\mathrm{in}}) F_{cp} = \sum_{h\in H} \sum_{k\in K} q_{hckp} + q_{cp}^{\mathrm{hu}} \qquad \forall c \in C, p \in P \tag{10}$$

$$(h_{ip} - H^{\mathrm{deaer}}) f_{ip}^{\mathrm{ps}} = \sum_{h\in H} \sum_{k\in K} q_{hikp} \qquad \forall i \in I, p \in P \tag{11}$$

$$(t_{hkp} - t_{h,k+1,p}) F_{hp} = \sum_{c\in C} q_{hckp} \qquad \forall h \in H, k \in K, p \in P \tag{12}$$

$$(t_{ckp} - t_{c,k+1,p}) F_{cp} = \sum_{h\in H} q_{hckp} \qquad \forall c \in C, k \in K, p \in P \tag{13}$$

$$(h_{ikp} - h_{i,k+1,p}) f_{ip}^{\mathrm{ps}} = \sum_{h\in H} q_{hikp} \qquad \forall i \in I, k \in K, p \in P \tag{14}$$

3.3 Objective function

The objective function is given by the variable cost of equipment, while the operating cost is given by the fuel, water, cooling water and purchased electricity cost.

4. Case Study

Following case study is presented to illustrate the capabilities of integrated SDN-HEN model. These process stream data and power demands are presented in Table 1 and Table 2. The system is assumed to be operated continuously for 8600 h/y. Two types of fuels are used for the boilers. The price of fuel oil is 0.19 $/kg and its LHV is 45,000 kJ/kg. The price of natural gas is 0.22 $/kg and its LHV is 50244 kJ/kg. The prices of electricity and water is 0.08 $/kWh and 0.05 $/ton, respectively.

Table 1: Process stream data of case study

Stream type	FC (kW/℃)	T^{in}(℃)	T^{out}(℃)
H1	205	388	110
H2	152	210	60
C1	753	100	200
C2	377	140	255
C3	143	70	140

Table 2: Power demands of case study

Power demands	
Electricity demand	4.5 MW
Shaft work demand 1	2.0 MW
Shaft work demand 2	1.2 MW

Figures 4 and 5 show the resulting network structure of SDN and HEN, and the corresponding TAC is $16.07 M/y. As can be seen, the temperature levels are optimized, which are 388.7, 288.9 and 188.5 ℃ for high (50.9 bar), medium (19.1 bar) and low pressure (4.7 bar) steam headers, respectively. In this structure, a HP boiler, three back-pressure steam turbines are included. Shaft power demands 1 and 2 are satisfied with the HP-LP and the MP-LP back-pressure steam turbines, respectively. Electricity is generated with a HP-MP steam turbine. All of the electricity requirements are satisfied by the steam system (4,814 kW).

5. Conclusion

A novel model has been developed to design the entire energy system. The model predicts the optimal system configuration and optimal conditions. By exploiting the total site energy integration technique, steam system and the total processing sites with performance consideration can be achieved simultaneously. For the further work, the proposed model can be applied to the industrial park for the design of a central utility system, and the optimal energy distribution between sites can be realized.

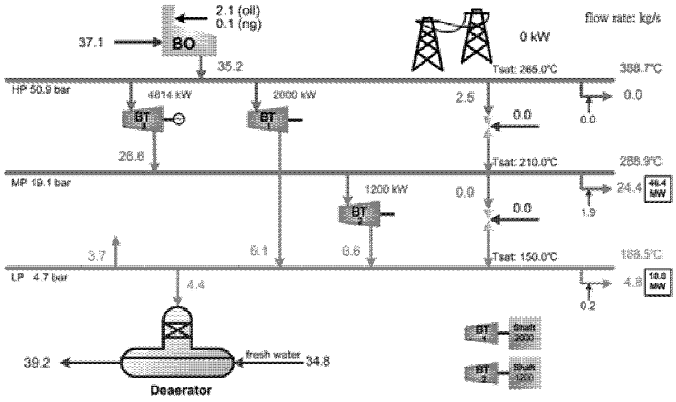

Figure 4: Optimal configuration of steam system.

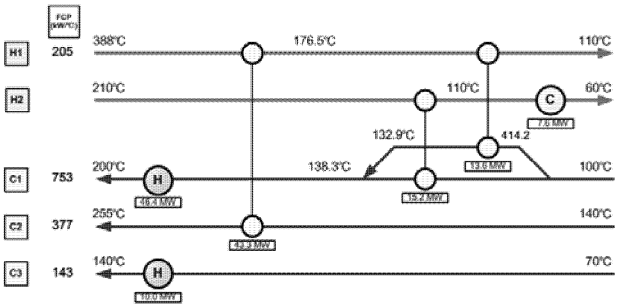

Figure 5: Optimal configuration of heat recovery network.

References

Aguilar O., Perry S.J., Kim J.-K. and Smith R., 2007, Design and optimization of flexible utility systems subject to variable conditions, Part 2: Methodology and Applications, Trans IChemE, 85, 1149-1168.

Bruno J.C., Fernandez F., Castells F. and Grossmann I.E., 1998, A rigorous MINLP model for the optimal synthesis and operation of utility plants, Trans IChemE, 76, 246-258.

Chen C.L. and Lin C.Y., 2010, A flexible structural and operational design of steam systems, Chemical Engineering Transactions, 21, 265-270.

Chou C.-C. and Shih Y.-S., 1987, A thermodynamic approach to the design and synthesis of plant utility systems, Ind. Eng. Chem. Res., 26, 1100-1108.

Fodor Z., Varbanov P.S. and Klemeš J.J., 2010, Total site targeting accounting for individual process heat transfer characteristics, Chemical Engineering Transactions, 21, 49-54.

Hackl R., Andersson E. and Harvey S., 2010, Targeting for energy efficiency and improved energy collaboration between different companies using total site analysis (TSA), Chemical Engineering Transactions, 21, 301-306.

Kapil A., Bulatov I., Kim J.-K. and Smith R., 2010, Exploitation of low-grade heat in site utility systems, Chemical Engineering Transactions, 21, 367-372.

Klemeš J., Dhole V. R., Raissi K., Perry S. J. and Puigjanerl L., 1997, Targeting and design methodology for reduction of fuel, power and CO_2 on total sites, Appl. Therm. Eng., 17, 993-1003.

Nishio M., Itoh J., Shiroko K. and Umeda T., 1980, A thermodynamic approach to steam power system design, Ind. Eng. Chem. Proc. Des. Dev., 19, 306-312.

Papoulias S.A. and Grossmann I.E., 1983a, A structural optimization approach in process synthesis Part I: Utility systems, Comput. Chem. Eng., 7, 695-706.

Papoulias S.A. and Grossmann I. E., 1983b, A structural optimization approach in process synthesis Part III: Total processing systems, Comput. Chem. Eng., 7, 723-734.

Yee T.F. and Grossmann I.E., 1990, Simultaneous optimization models for heat integration-II. Heat exchanger network synthesis, Comput. Chem. Eng., 14, 1165-1184.