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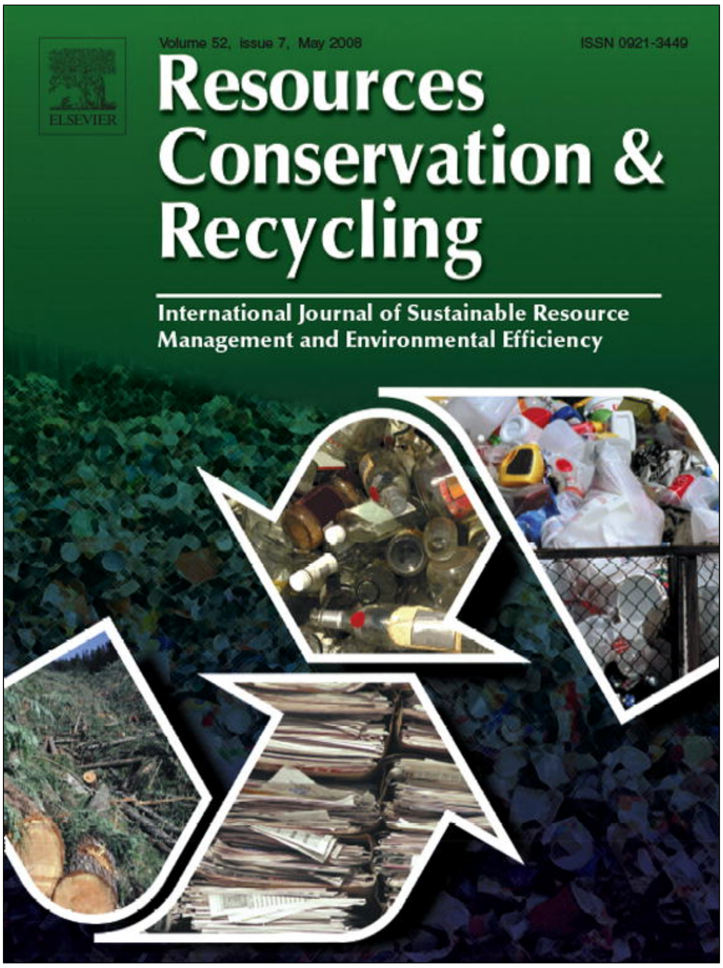

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Minimum energy consumption process synthesis for energy saving

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ABSTRACT

The paper presents a synthesis strategy for the chemical processes with energy saving. The concept of minimum energy consumption process (MECP) is proposed. Three characteristics of MECP are introduced, including thermodynamic minimum energy demand, energy consumption efficiency and integration degree. These characteristics are evaluated according to quantitative thermodynamic analysis and qualitative knowledge rules. The procedure of synthesis strategy is proposed to support the generation of MECP alternatives, which combine flowsheet integration and heat integration. The cases studies will focus on how integration degrees of a process affect the energy-saving results. The separation sequences of the hydrodealkylation of toluene (HDA) process and ethanol distillation process as case studies are used to illustrate.

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1. Introduction

The chemical process industries are energy intensive. In order to implement industrial sustainable development, energy issues are considered as one of the most important objectives in process design nowadays. There is no need to underline the necessity for reducing energy usage. Process system engineering plays an important role in such energy-saving task. Many methodologies and techniques have emerged such as process synthesis, pinch technology, mathematical programming and others.

Process synthesis has led to conceptual designs with lower energy demands at a desired economic performance. Heat integration techniques play significant roles in energy saving of industrial processes, while flowsheet integration plays a large part in determining actual energy efficiency early during process development. Considerable research efforts have been made to develop systematic methods. Examples include pinch technology, heuristics, and mathematic programming (Linnhoff, 1993; Grossmann et al., 1998; Biegler et al., 1997; Zhu and Vaideeswaran, 2000; Adonyi et al., 2003; Smith, 2005; Kemp, 2007). Halvorsen explored minimum energy requirements in complex distillation arrangements (Halvorsen, 2001). Grabowski and his co-workers determined minimum energy consumption of the novel process by simultaneously carrying out energy targeting and optimization of process (Grabowski et al., 2001). Using the approach based on heat integration pinch analysis a procedure is proposed for minimizing the compressor shaft work in the refrigeration system (Smith, 2005). Mascia et al. (2006) proposed the synthesis of partially thermally coupled and heat-integrated distillation systems applied to the light ends separation section of a crude distillation plant. This distillation system employs the thermal coupling and the heat-integration principles to significantly reduce the heat requirements compared with the traditional simple column train. Mixed integer non-linear programming based on the superstructure seems to be the most promising method, because the structure of a process and all the design and operating parameters can together be determined optimally and simultaneously. However, the complexities of practical problems still limit the use of superstructure optimization techniques (Pennington, 1999). The approach that has proven useful is to incorporate qualitative knowledge-based rules into the design of chemical processes (Douglas, 1988). The purpose of this work is to present the synthesis strategy for minimizing energy consumption by knowledge-based rules and thermodynamic analysis.

Section 2 describes the concept of MECP. The MECP consists of three characteristics for guiding the generation and screening of process alternatives. They are thermodynamic minimum energy demand, energy consumption efficiency and integration degree. They can be evaluated according to quantitative thermodynamic analysis and qualitative knowledge. Section 3 presents the framework of MECP synthesis and the suggested rules. In Section 4, case studies are presented.

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Nomenclature

E	practical energy consumption of the system (kJ)
e	energy (kJ)
G	Gibbs free energy (kJ/mol)
H	enthalpy of the system (kJ/kg)
Q	total heat transferred to the system (kJ)
S	entropy (kJ/kg °C)
T	temperature (°C)
W	work transferred to the system (kJ)

Greek symbols

η	energy efficiency

Subscripts

I	Into system
min	minimization
O	Out of system
R	Recovery

2. Minimum energy consumption process

2.1. Macrostructure of process energy flow

Most industrial processes involve heat transfer either from one process stream to another or from a utility stream to process stream. The target of energy saving is to is to maximize the process-to-process heat recovery and to minimize the utility (energy) requirements for an individual process or for a total site.

From the point of energy usage, the whole process can be divided into following parts: energy processing, energy utilization, energy recovery, and waste energy discharge. The relationship between them is shown as Fig. 1. This conceptual structure is called the macrostructure of process energy flow.

According to this macrostructure, the operation units are chosen and the corresponding inter-connection is made, then process alternatives are generated to evaluate and screen. The concept of MECP will be introduced to support such evaluation and screening. Such MECP inherently indicates a process of minimum energy consumption.

2.2. Characteristics of MECP

Three characteristics of MECP are thermodynamic minimum energy demand, energy consumption efficiency, and integration degree.

2.2.1. Thermodynamic minimum energy demand

The energy (heat and power) required for process system is provided from the surroundings. According to the First Law of Thermodynamics, heat transferred to the system (Q) equals enthalpy change of the system plus work transferred from the system (W) in the steady-state fluid system. The equation is expressed as:

$$Q = H_O - H_I + W \quad (1)$$

where H_O is the enthalpy out of system, and H_I is the enthalpy into system.

According to the Second Law of Thermodynamics

$$(S_O - S_I - Q/T) \geq 0 \quad (2)$$

where S_O is the entropy out of system, S_I the entropy into system, and T is the temperature.

Introducing Eq. (1) into the left-hand side of Eq. (2) results in

$$-W \geq (H_O - TS_O) - (H_I - TS_I) \quad (3)$$

Giving $G = H - TS$, Eq. (3) can be written as

$$-W \geq G_O - G_I \quad (4)$$

where G is Gibbs free energy.

The Eq. (4) denotes that the work transferred to the system is equal to or greater than Gibbs free energy change between the outlet streams and inlet streams of the system. $(-W_{min})$ can be given by

$$-W_{min} = G_O - G_I \quad (5)$$

$(-W_{min})$ is defined as the thermodynamic minimum energy demand. According to Eq. (5), the lowest limit of energy consumption of a system (e_I) is given in the context of thermodynamics:

$$e_I \geq -W_{min} \quad (6)$$

2.2.2. Energy consumption efficiency

The chemical process is energy intensive. It is important to underline the necessity for more efficient use of energy. In order to maintain the process operation, energy is required to perform the process driving force (e.g., pressure drop, temperature difference). Given the practical energy consumption E of a system, the energy consumption efficiency (η) can be defined as Eq. (7). To obtain the high efficiency, the minimum E is chosen.

$$\eta = \frac{-W_{min}}{E} \quad (7)$$

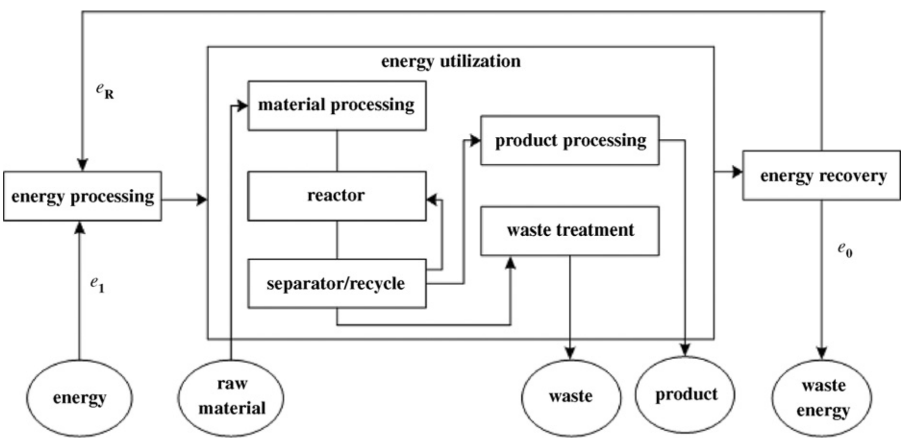

Fig. 1. The macrostructure of process energy flow.

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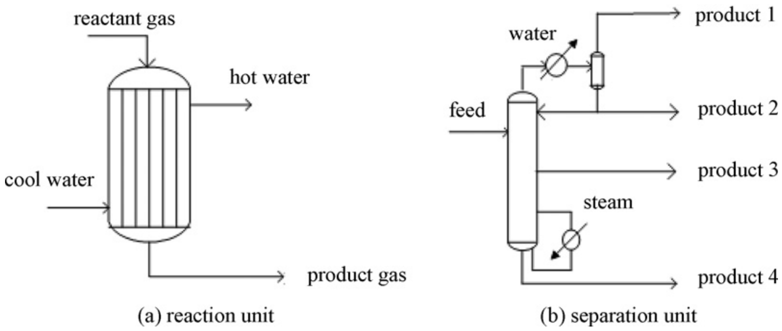


Fig. 2. Examples of integration degree for operation unit.

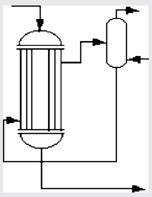
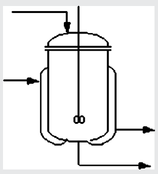
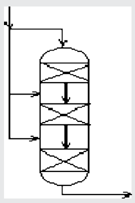
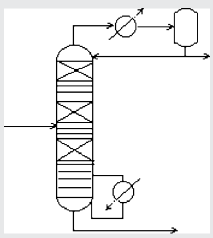
2.2.3. Integration degree

The concepts of task and integration degree are introduced in this sub-section. Achieving a task refers to finishing a specific operation. For example, a reaction process is a task; streams' passing a heat exchanger also is a task. The number of tasks achieved is defined as the integration degree of the operation unit.

Fig. 2(a) shows that the integration degree of the reaction unit is 2. The corresponding tasks are reaction operation and heat exchange operation. That is, the reactant gas is changed to the product gas, and the reaction heat is taken away by the cool water. Fig. 2(b) shows that the integration degree of one separation unit is 4. The corresponding tasks include two separators and two heat exchange operations. In Fig. 2(b), the feed to the column is split into several products. The top product goes to a decanter that separates two layers 'product 1' and 'product 2'. The heat exchange operations are the cooling water to condense the overhead vapor and the steam to heat the reboiler.

As mentioned above, these characteristics are three qualitative design knowledge-based rules: (1) from the viewpoint of thermodynamics, MECP has the lower minimum energy demand. The practical energy consumption approaches the minimum energy demand ($-W_{min}$), (2) from the viewpoint of kinetics, MECP has high energy efficiency. High efficiency under low driving force is preferred, (3) from the viewpoint of system engineering, MECP has high integration degree in the context of intensification. High integration degree can decrease irreversibility of the system. The

Table 1
The integration degree of reactor units

No.	Degree	Unit configuration	note
1	3		(1) Gas–solid reactor (2) Heat exchange in catalyst bed
2	2		(1) Continuous stirred-tank reactor (2) Heat-exchanging between the jacket and reactor
3	3		Multi-stage reactor
4	5		Reactive distillation

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common integration degree for the operation units are described and listed in Section 3.

3. Synthesis strategy of the MECP

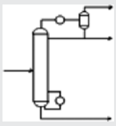
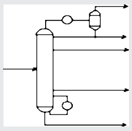
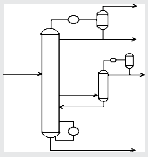
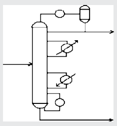
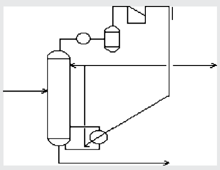
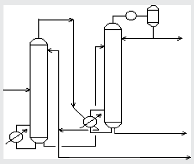
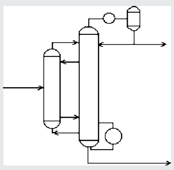
When we design a MECP, screening the benchmark process that has the lowest thermodynamic minimum energy demand is the first and important step. For example, there are many alternative processes to produce butadiene, such as (a) butane dehydrogenation, (b) additive process of ethane and ethylene, (c) catalytic conversion of ethanol, and (d) extractive distillation from C_4 cut. The thermodynamic minimum energy demand of each process differs greatly. Among them, that of the extractive distillation from C_4 cut is the lowest. We choose process (d) as the benchmark process.

After the benchmark process is chosen, constructing high integration degree process is the next step. High integration degree is preferred, because it could avoid some redundant computation and complicated modeling to obtain the optimal process, for example, using mixing integer non-linear programming. There are some knowledge rules on how to construct a high integration degree process based on benchmark process. Integration degrees about some reactor units are given in Table 1; Table 2 shows the integration degree of some separation processes.

From the above discussion, the procedure of MECP synthesis strategy is as following:

(1) To evaluate and screen the benchmark process based on thermodynamic insights. The benchmark process is determined according to minimum energy demand.
(2) To generate a process alternative set of high integration degree. Flowsheet integration is carried out based on proposed rules. Integration degree for every flowsheet is calculated. The process alternative set of high integration degree is generated. Process alternatives are simulated using a process simulator. The feasible alternatives are selected. Then the parameter optimization for feasible processes is carried out.

Table 2
Some integration degree of separation process

No.	Degree	Configuration	Note
1	4		(1) Standard column (2) Overhead: gaseous phase (3) Three products
2	5		(1) Distillation with side stripper (2) Four products
3	6		(1) Distillation with a side rectifier (2) Four products
4	6		(1) Pump-around distillation (2) Heat recovery
5	5		(1) Heat pump distillation (2) Saving heating reagents
6	6		Dual-effect distillation
7	5		Thermally coupled distillation

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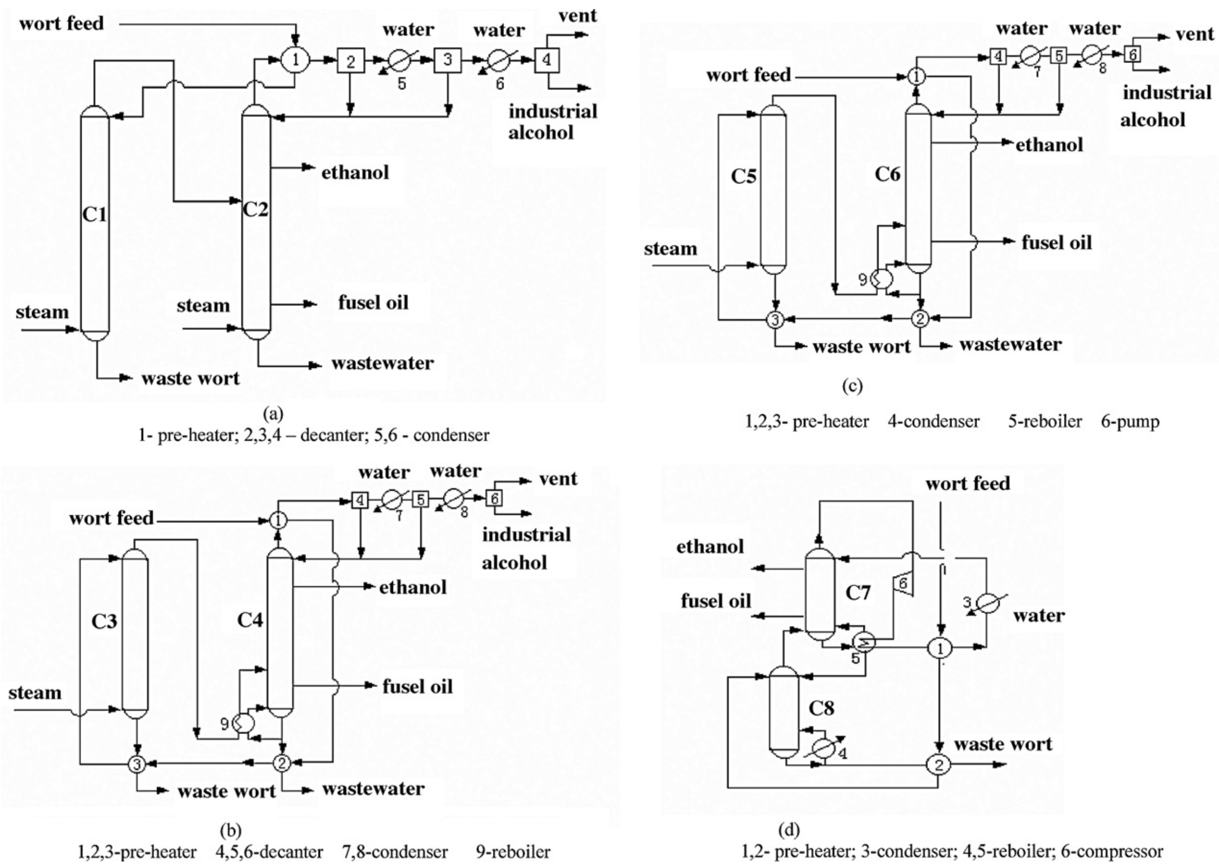

Fig. 3. Ethanol distillation process (a) base case; (b) cocurrent alternative; (c) countercurrent alternative; (d) heat pump distillation (MECP alternative).

(3) To determine the final solution. The feasible processes are evaluated based on thermodynamic minimum energy demand, energy consumption efficiency, and integration degree. The optimal process is chosen. Heat integration is employed to achieve heat recovery of the optimal alternative.

4. Case studies

The ethanol distillation process and the separation sequence of HDA process are studied as cases. The base case study and detailed information were provided in the references (Douglas, 1988; Collura and Luyben, 1988; Wang, 2001).

4.1. *Case 1 ethanol distillation process*

In this case study, ethanol is produced by fermenting starch containing grain. Actual ethanol production has three steps: (1) feed preparation; (2) fermentation; (3) distillation. The fermented liquor is known as wort. Wort has a dry solid content of between 3 and 7% (w/w) and an ethanol concentration of between 6 and 10% (v/v). Ethanol is separated using the distillation step. Ethanol distillation process produces 95% (v/v) ethanol mixture as shown in Fig. 3(a) (Wang, 2001).

4.1.1. *Screen base case*

The two-column schema is the benchmark processes for the ethanol distillation process as showed in Fig. 3(a). Column 1 (C1) is the high-pressure column, and Column 2 (C2) is the atmospheric column; their integration degree are 2 and 3, respectively.

4.1.2. *Generate process alternatives*

Process alternatives are generated based on the flowsheet integration as shown in Fig. 3(b)–(d). Fig. 3(b), (c) and (d) represents cocurrent schema, countercurrent schema, and heat pump distillation, respectively.

4.1.3. *Calculate integration degree and energy consumption*

Process alternatives are simulated using Pro/II with PROVISION. The integration degree and energy consumption of every process flowsheet is calculated as shown in Table 3. C1 (2) represents the integration degree of Column 1 in Fig. 3(a).

From Table 3, alternative d is the best one of the four alternatives. The heat pump distillation is designated as the MECP. The integration degree of C7 and C8 are 4 and 3, respectively. The steam consumption for base case is 10,793 kg/h, and that of MECP alternative is 5500 kg/h. The MECP alternative consumes 49% less steam than the base case. The cooling water consumption for base case is 90 ton/h, and that of MECP alternative is 20 ton/h. The cooling

Table 3
Results for the alternatives

Alternative	Integration degree	Cooling water consumption (ton/h)	Steam consumption kg/h
a	C1 (2) C2 (3)	90	10,793
b	C3 (2) C4 (3)	51	6,620
c	C5 (2) C6 (3)	28	5,557
d	C7 (4) C8 (3)	20	5,500

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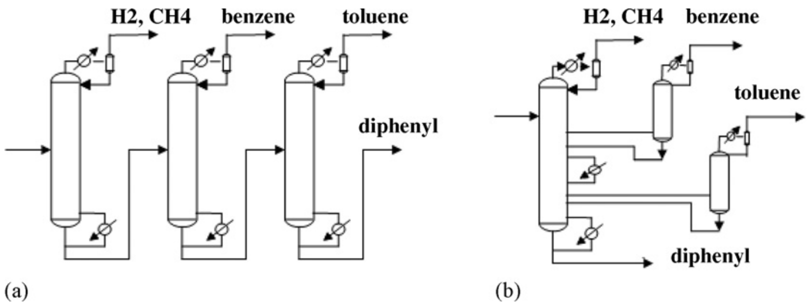

Fig. 4. HDA separation process (a) base case; (b) MECP alternative.

water consumption for base case is 3.5 times higher than that of the MECP alternative.

4.2. Case 2 HDA process

Fig. 4(a) shows the optimal separation sequence according to the conventional design method (Douglas, 1988). The integration level of the standard column in the base case is 4. Fig. 4(b) shows the integrated process. The integration level of integrated process is 11.

The thermodynamic minimum energy demand of this separation process is 5055 kWh. The energy consumption for base case is 17,410 kWh, and its energy consumption efficiency is 29.0%. The energy consumption of MECP is 16,730 kWh, and its energy consumption efficiency is 30.3%. The total energy consumption of MECP is 4.0% lower than that of the base case.

5. Conclusions

To achieve a more efficient process with low energy consumption, a systematic design tool is required for energy saving in process industries. This paper proposes the synthesis strategy for minimizing energy consumption through the integration of knowledge-based rules and thermodynamic analysis. Three characteristics of MECP are described, namely minimum energy demand based on thermodynamic insights, energy consumption efficiency, and integration degree. The framework of the synthesis strategy is proposed.

It is noted that the case studies could not support to illustrate the full framework of proposed synthesis strategy. Case studies of HDA process and ethanol distillation process are only used to illustrate the effect of integration degree. Although the process of higher integration degree saved more energy as the case studies showed, more future work should be done to prove and validate the proposed heuristic approach in the energy-saving process design.

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References

Adonyi R, Romero J, Puigjaner L, Friedler F. Incorporating heat integration in batch process scheduling. Applied Thermal Engineering 2003;23:1743–62.

Biegler LT, Grossmann IE, Westerberg AW. Systematic methods of chemical process design. New Jersey, USA: Prentice Hall PTR; 1997.

Collura, MA, Luyben, WL. Energy-saving distillation designs in ethanol production industrial and engineering chemical research 1988;27:1686–96.

Douglas JM. Conceptual design of chemical process. New York, USA: McGraw-Hill; 1988. p. 3–18.

Grabowski M, Klemes J, Urbaniec K, Vaccari G, Zhu FXX. Minimum energy consumption in sugar production by cooling crystallisation of concentrated raw juice. Applied Thermal Engineering 2001;21:1319–29.

Grossmann IE, Yeomans H, Kravanja Z. A rigorous disjunctive optimization model for simultaneous flow sheet optimization and heat integration. Computers & Chemical Engineering 1998;22:S157–64.

Halvorsen, IJ. Minimum Energy Requirements in Complex Distillation Arrangements. Dr. ing. Thesis, Norwegian University of Science and Technology (NTNU), Trondheim, Norway 2001.

Kemp IC. Pinch analysis and process integration: a user guide on process integration for the efficient use of energy. 2nd edition Oxford, UK: IChemE and Elsevier; 2007. p. 29–40.

Linnhoff B. Pinch analysis-a state-of-the-art overview. Transactions of the IChemE: part A 1993;71:503–52.

Mascia M, Ferrara F, Vacca A, Tola G, Errico M. Design of heat integrated distillation systems for a light ends separation plant. Applied Thermal Engineering 2006;27(7):1205–11.

Pennington DW. Chemical process design using heuristics in the context of pollution prevention. Clean Products and Processes 1999;1:170–9.

Smith R. Chemical Process Design and Integration. USA: John Wiley & Sons; 2005. p. 317–464.

Wang, Ai-Ci. Comparative analysis of energy saving for ethanol distillation. MSc dissertation, Qingdao University of Science and Technology, Qingdao, China (in Chinese, with English abstract) 2001.

Zhu FXX, Vaideeswaran L. Integration in analysis and optimization of energy systems. Applied Thermal Engineering 2000;20:1381–92.