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Calculation of the Rectification Column Network for the Criterion of the Minimum Exergy Loss

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The existing methods of calculation of the heat and power systems are based on the superstructure model. As it is commonly known, the term superstructure means a very complicated system which undergo simplification to the real and uncomplicated structure. The simplification of superstructure is performed according to the formulated objective function, where the decisive variables are mixed: integer and real. The existence of integer variables makes the serious disadvantage for the industrial application of the method because it is very difficult to find the extreme of the objective function even for the very simple system. For the complicated industrial systems it is a very big achievement to prepare the superstructure. However, for this case the simplification of the superstructure and searching for the extreme of the objective function is practically impossible.

Taking into account these obstacles, the author proposed the method of calculation of the rectification column network (RCN). The mathematical model is based on the idea of the ideal column model with multitude of reboilers and condensers. For this model the integer decisive variables doesn’t exist, thus it is possible to elaborate the reasonable results even for very complicated systems.

1. Introduction

The thermal separation of mixtures using a rectification column network (RCN) coupled with a heat sources (refrigeration system – for process below ambient temperature, combined heat and power system (CHP) - for process above ambient temperature) is an energy intensive process. To reduce energy consumption, the following measures can be applied:

- Optimisation of the sequence of separation of components (Smith, 2005),
- Use of side reboilers and condensers (Ullmann’s Encyclopedia, 1988),
- Selection of pressure levels in columns so that heat of condensation of their respective overhead vapours can be used in reboilers of other columns (King, 1980).

Pejpichestakul and Siemanond (2013) used Column Grand Composite Curves for heat integration of three distillation columns. Furthermore, advantage could be taken of a considerable energy-saving potential associated with the application of heat-integrated distillation columns (Iwakabe et al., 2004). Olujic et al. (2004) applied Pinch Analysis for design of heat-integrated distillation columns.

The present work is concerned with the design of energy-efficient separation systems comprising the RCN and a refrigeration subsystem (for process below ambient temperature) or CHP (for process above ambient temperature). The application of concepts and tools derived from Pinch Technology (PT) is proposed. In proposed model there is used the notion of ideal distillation column (with multitude of reboilers and condensers) and its profiles.

2. Mathematical model of an ideal distillation column

The procedure of heat integration of the RCN employs an ideal model of column (composed of infinite number of condensers and reboilers) and corresponding column profiles in the temperature – enthalpy diagram.

The model of an ideal column is based on the assumptions that at any point along the column there exists thermodynamic equilibrium between liquid and vapour.

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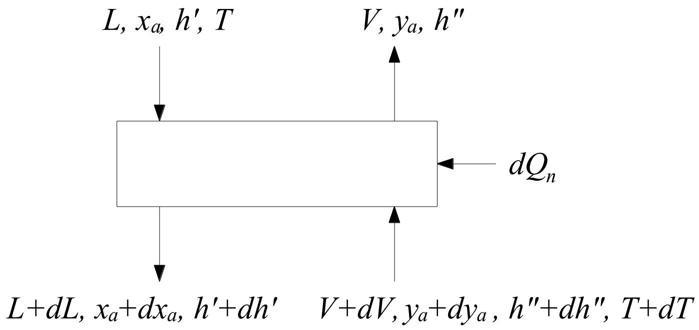

Figure 1: Inlets and outlets from an infinitesimal element of the column

The column profiles in the temperature – enthalpy diagram can be generated using differential equations of mass, energy and component balances.

The differential equation of the energy balance (Figure 1):

$$dQ_n = L \cdot dh' + h' \cdot dL - V \cdot dh'' - h'' \cdot dV \tag{1}$$

The differential equation of the mass balance (Figure 1):

$$dL = dV \tag{2}$$

The differential equation of mass balance for the *a-th* component (Figure 1):

$$L \cdot dx_a + x_a \cdot dL - V \cdot dy_a - y_a \cdot dV = 0 \tag{3}$$

The differential equation expressing thermodynamic equilibrium between liquid and vapour:

$$dy_a = k_a \cdot dx_a + x_a \cdot dk_a \tag{4}$$

By applying Eq(1÷4), the column profiles can be determined (Figure 2).

3. Procedure of thermal integration for the rectification column network

The separation system can be composed of three subsystems schematically shown in Figure 3 and Figure 4:

- Rectification column network,
- Heat exchanger network,
- Compression refrigerating cycle (for process below ambient temperature – Figure 3) or CHP system (for process above ambient temperature – Figure 4).

The compressor shaftwork (Figure 3) or the consumption of primary energy (Figure 4) depends on the following factors:

- Order of separation of components in the column sequence,
- Pressure values in the individual columns,

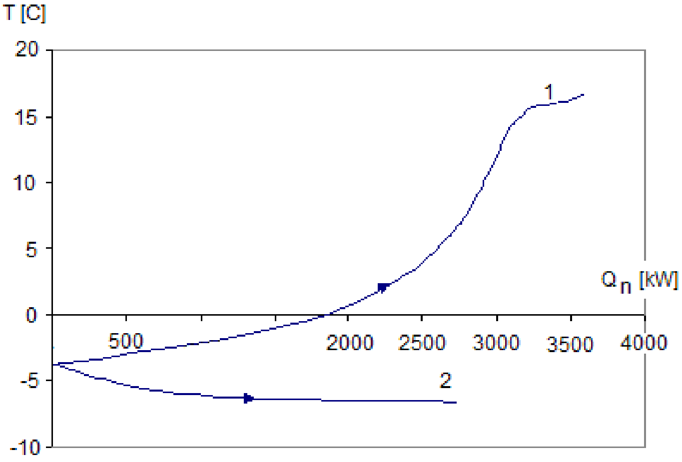

Figure 2: Example of column profiles; curve 1 - stripping section, curve 2 - rectifying section (Markowski, 2010)

- Number of temperature levels and the corresponding temperature values in reboilers and condensers,
- Number of temperature levels and the corresponding temperature values in utility system (refrigerant – Figure 3, steam – Figure 4),
- Structure of the heat exchanger network.

The procedure of minimum energy consumption is shown in Figure 5.

As the first step, the order of separation of components of the feed stream is determined according to criterion of minimum exergy loss. This makes it possible to identify the sequence of distillation columns.

Taking into account the minimum energy requirement for each individual separation element, the elements requiring low expenditure of energy are eliminated, thus the separation sequence is simplified.

Adjusting the values of decision variables (pressure levels in columns, number of condensers and reboilers in columns and their respective temperature levels) and taking into account established the separation sequence, it is possible to determine ideal column profiles. Obtained column profiles are used for generation the Composite Curves (CC) using PT method. These curves characterise the ideal separation process.

The ideal separation system operated at thermodynamic equilibrium is a purely theoretical concept as it would require an infinite number of trays as well as infinite numbers of reboilers and condensers.

Therefore CC curves are transformed basing on reduction to finite values, the numbers of reboilers and condensers. Transformed CC curves characterise the real separation process.

Thereafter the temperature levels of utility system are adjusted to minimize exergy loss. Described procedure is repeated until reaching the global minimum of exergy loss. Realisation of this procedure enables the selection of optimum process parameters (pressure, temperature and mass flow values). At the end of this procedure, the determination of process parameters make it possible to select the system structure using PT method.

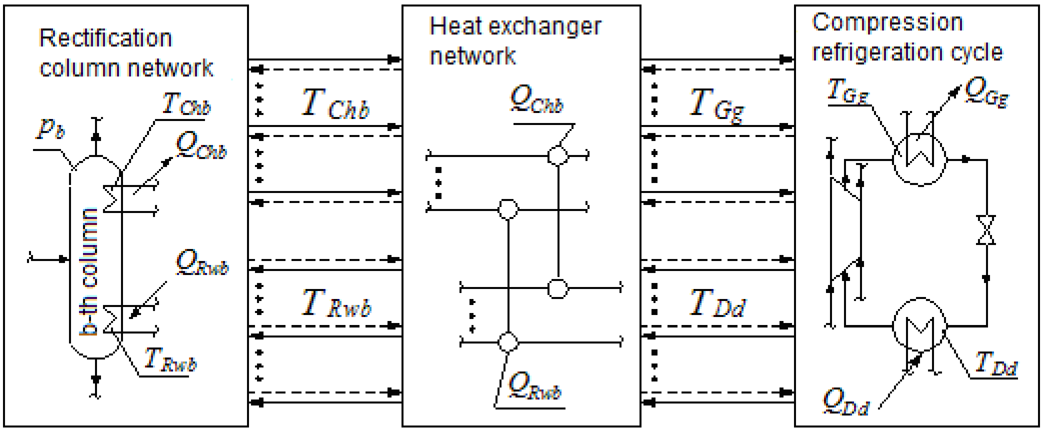

Figure 3: Scheme of interactions between subsystems for process below ambient temperature

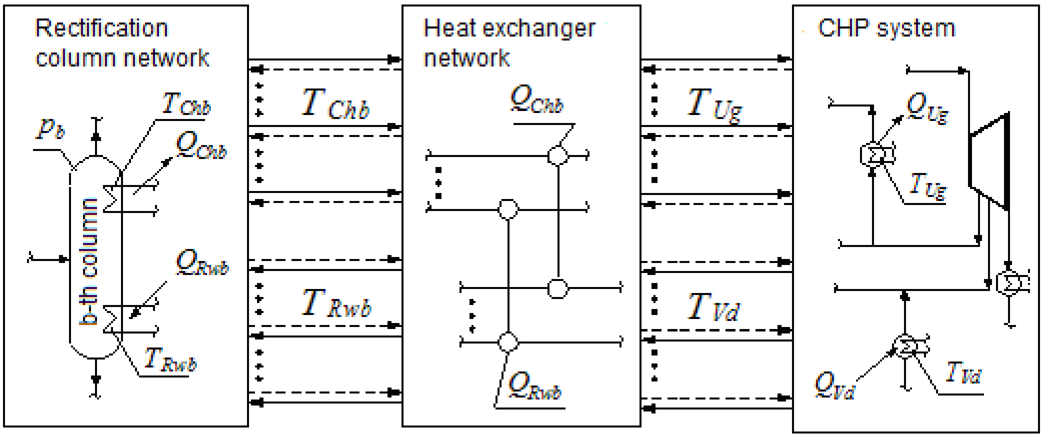

Figure 4: Scheme of interactions between subsystems for process above ambient temperature

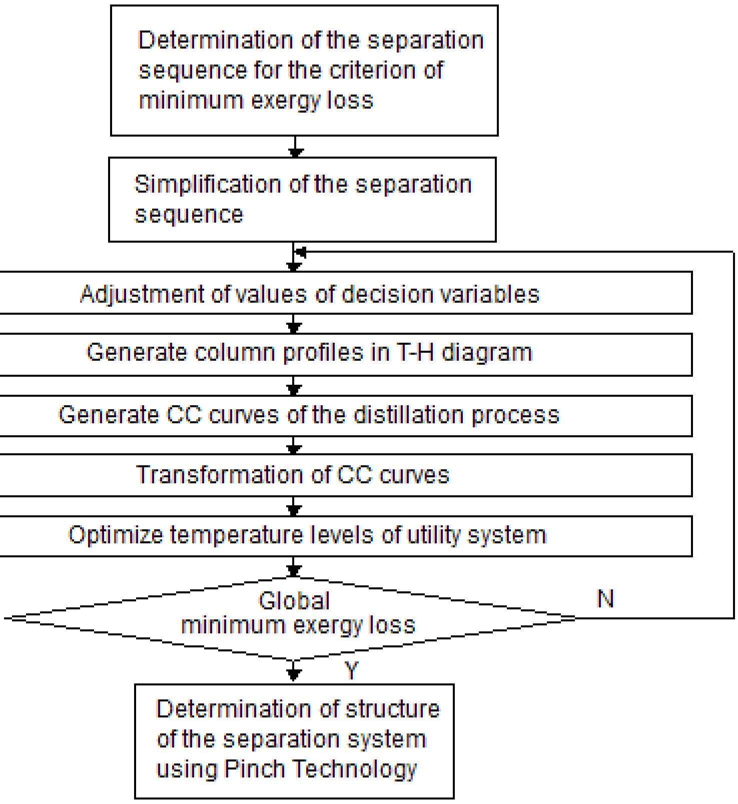

Figure 5: The heat integration procedure of the thermal separation system

4. Objective function

Instead of directly dealing with primary energy consumption (for process above ambient temperature – CHP) or compressor shaftwork consumption (for process below ambient temperature - refrigeration system), one can consider the objective function described by the following formulae:

- for separation process above ambient temperature

$$FHK = \sum_{g=1}^{t} Q_{Ug}\left(1-\frac{T_a}{T_{Ug}}\right) - \sum_{d=1}^{m} Q_{Vd}\left(1-\frac{T_a}{T_{Vd}}\right) \qquad (5)$$

- for separation process below ambient temperature

$$FCK = \sum_{d=1}^{m} Q_{Dd}\left(\frac{T_a}{T_{Dd}}-1\right) - \sum_{g=1}^{t} Q_{Gg}\left(\frac{T_a}{T_{Gg}}-1\right) \qquad (6)$$

Heat flows Q_{Ug}, Q_{Vd}, Q_{Dd} and Q_{Gg}, can be symbolically expressed as:

$$Q_{Ug} = f_g(T_{C11},...,T_{Chb},...,T_{Cue},T_{R11},...,T_{Rwb},...,T_{Rte},p_1,p_2,...,p_b,...,p_e,T_{U1},T_{U2},...,T_{Ug},...,T_{Ut}) \qquad (7)$$

$$Q_{Vd} = g_d(T_{C11},...,T_{Chb},...,T_{Cue},T_{R11},...,T_{Rwb},...,T_{Rte},p_1,p_2,...,p_b,...,p_e,T_{V1},T_{V2},...,T_{Vd},...,T_{Vm}) \qquad (8)$$

$$Q_{Dd} = f_d(T_{C11},...,T_{Chb},...,T_{Cue},T_{R11},...,T_{Rwb},...,T_{Rte},p_1,p_2,...,p_b,...,p_e,T_{D1},T_{D2},...,T_{Dd},...,T_{Dm}) \qquad (9)$$

$$Q_{Gg} = g_g(T_{C11},...,T_{Chb},...,T_{Cue},T_{R11},...,T_{Rwb},...,T_{Rte},p_1,p_2,...,p_b,...,p_e,T_{G1},T_{G2},...,T_{Gg},...,T_{Gt}) \qquad (10)$$

To minimise the energy consumption it is sufficient to minimise the objective functions, described by Eq.5 and Eq.6 formulae, where decision variables are: number of condensers and reboilers in columns and their respective temperature levels, pressure levels in columns, number of external heat sources and their respective temperature levels.

5. Example

There is considered separation of hydrocarbon mixture according to the following specification:

- Feed flowrate: 1,148 kmol/h
- Mole fraction of methane: 0.3
- Mole fraction of ethane: 0.1
- Mole fraction of ethene: 0.5
- Mole fraction of propene: 0.1.

Because the separation process is running below ambient temperature, the compression refrigeration plant is selected as the heat source. There are assumed three temperature levels at the cold source (three heat sinks) and one temperature level at the hot source.

The main features of the separation system are determined according to the procedure presented in Chapter 3. The structure of RCN is shown in Figure 6.

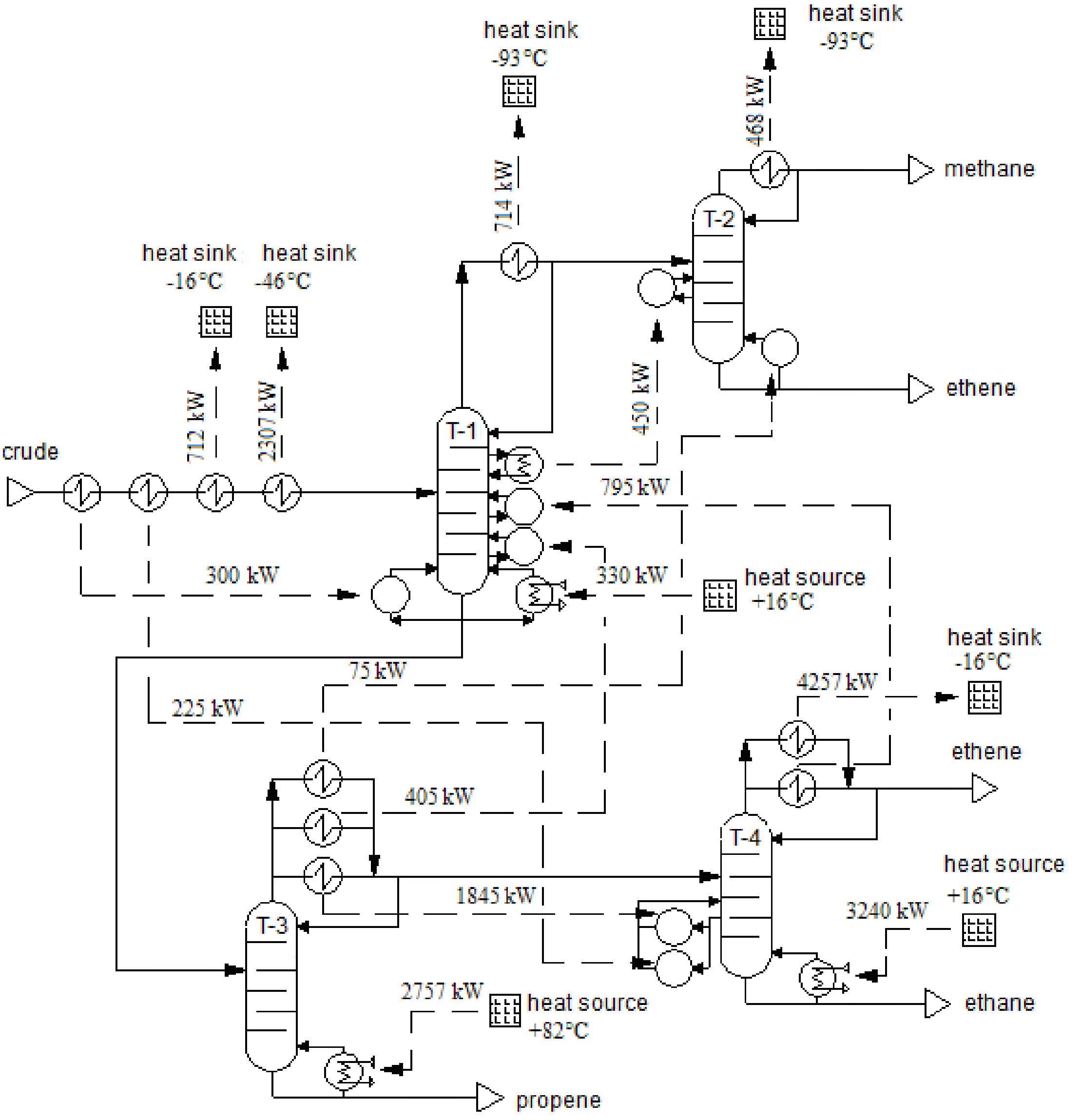

Figure 6: The structure of RCN coupled with the heat exchanger network and heat sources in the refrigerating cycle (Markowski, 2010)

6. Conclusions

Presented method of Heat Integration of a system comprising the rectification column network, heat exchanger network and heat source (refrigerating cycle or CHP) can be regarded as an engineering tool for industrial application. The results of example (Figure 6) illustrate the energy-saving potential of heat integrated RCN (there is 34 % reduction, in heat supplied to the refrigeration cycle, comparing with RCN without integration). For proposed model the integer decisive variables doesn't exists. Consequently the model of superstructure is eliminated and Heat Integration of the system comprising RCN is mathematically less complicated. Thus the industrial application of the proposed method makes it possible to obtain reasonable results even for complex separation systems.

Symbols

h' - molar enthalpy of liquid [J/mol]
h'' - molar enthalpy of vapour [J/mol]
H - enthalpy flow [W]
k_i - equilibrium constant of the *i-th* component [-]
L - flowrate of liquid [mol/s]
P_b - pressure in the *b-th* column [Pa]
Q_{Chb} - heat flow in the *h-th* condenser of the *b-th* column [W]
Q_{Dd}, - heat flow in the *d-th* low-temperature source of the refrigerating cycle [W]
Q_{Gg} - heat flow in the *g-th* high-temperature source of the refrigerating cycle [W]
Q_n - surplus or deficit of the heat flow [W]
Q_{Rwb} - heat flow in the *w-th* reboiler of the *b-th* column [W]
Q_{Ug}, - heat flow in the *g-th* temperature source of the CHP system [W]
Q_{Vd}, - heat flow in the *d-th* temperature source of the separation system producing steam [W]
T - temperature [°C]
T_a - ambient temperature [K]
T_{Chb} - temperature in the *h-th* condenser of the *b-th* column [K]
T_{Dd} - temperature of the *d-th* low-temperature of the refrigerating cycle [K]
T_{Gg} - temperature of the *g-th* high-temperature source of the refrigerating cycle [K]
T_{Rwb} - temperature in the *w-th* reboiler of the *b-th* column [K]
T_{Ug} - temperature of the *g-th* heat source in the CHP system [K]
T_{Vd} - temperature of the *d-th* heat source in the separation system [K]
V - flowrate of vapour [mol/s]
x_i - molar fraction of the *i-th* component in liquid [-]
y_i - molar fraction of the *i-th* component in vapour [-]

Indices

e - number of columns,
m - number of temperature levels for: low-temperature heat sources in the refrigerating cycle; steam obtained from the separation system,
t - number of temperature levels for: high-temperature heat sources in the refrigerating cycle; steam supplied from the CHP system,
u - number of condensers,
τ - number of reboilers,

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