

An Improved Calculation of the Thermodynamically Based Allocation of Cumulative Exergy Consumption in the Petroleum Distillation Process

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Abstract One of the most common problems arising from the application of exergy analysis is the allocation of cumulative exergy consumption (CExC) in the petroleum distillation process yielding several useful products. Based on the concept of exergy, an improved calculation of the minimum separation power of product (MSPP) in the petroleum distillation process is provided in this article. The calculation of MSPP can be derived from the concept of exergy. The related mathematical models are established. Finally, application of this method to a case study is given, and the results are compared with the ones using mass as an allocation parameter.

Keywords allocation, cumulative exergy consumption, minimum separation power of product, petroleum distillation process

1 INTRODUCTION

Many researchers and practicing engineers refer to exergy methods as powerful tools for industrial processes in terms of efficiency [1, 2], resource accounting [3, 4], yielding applications on process level [5, 6], sector level [7, 8], and national level [9, 10]. The analysis of cumulative exergy consumption (CExC) has been widely used to perform process energy thermodynamic evaluation [11], such as textile washing process [12], waste gas and solid waste treatment systems [13, 14]. Separation processes are frequently used in process industries. Particularly, multiple products are one of the central characteristics of separation processes. Just as energy and/or cost allocation in combined heat and power plants [15, 16] and in dual-purpose desalination systems [17], it is of significance to deal with the problem of the allocation of CExC in the separation processes.

For any allocation problem, an allocation parameter, such as mass, energy, exergy, number of moles, and so on, must be chosen in such a way that it describes the products and the possible process causation in the most appropriate manner. Now, there are two main methods to the allocation of CExC. One method is that the CExC is allocated proportionally to the exergy values of products. This method is also the most straightforward. However, this way of allocation turns out to be rather poor in many cases [11], since the industrial process is regarded as a black box [18, 19]. The other method is the allocation of the CExC on the basis of the CExC in the case of separate production of the by-products [11]. Nevertheless, the limitation to the use of this method is that there always has to be a distinction between the main product and the by-product and that separate production of the by-product is taking place, and sometimes, an alternative process must be selected.

The concept of the minimum separation power of the product stream (MSPP) has been applied to study the allocation of CExC in the multiple-product separation processes [20]. This method is not required to identify the distinction of the main product and the

by-product artificially, and moreover it allows for natural causality of allocation of CExC in terms of thermodynamics. However, it is necessary to know the specific compositions in each of the streams to the calculation of MSPP [20]. It is well known that the components of crude oil and its products are highly complex and their specific compositions are commonly unknown in the petroleum distillation process [21]. Based on the concept of exergy, an improved calculation of the MSPP is provided in this article, particularly suitable for allocation of CExC of the petroleum distillation process. Moreover, this method is also given another understanding of allocation principle.

2 THE IMPROVED CALCULATION OF THE MINIMUM SEPARATION POWER OF PRODUCT

A continuous separation process is considered as shown in Fig. 1 (enveloped in dashed line). The feeds (the molar flow rate is n_j^F) of l streams are separated into the products (the molar flow rate is n_k^P) of m streams. It is assumed that this separation process exchanges energy flow B (including heat and/or work) with the environment and that the chemical reaction cannot occur in the separation process.

Furthermore, it is assumed that a fictitious separation process is shown in Fig. 1 (enveloped in the solid line). A pseudo-product stream can be formed by the mixing of residual product streams from the m number of product streams except the k th product stream. That is to say, the k th product stream is separated from the feeds, and the residue of feeds is regarded as the pseudo-product stream. Thus, the minimum separation power of product (MSPP) of the k th stream is defined as the minimum separation power consumed in the fictitious separation process [20].

In the previous published report [20], the specific compositions in each of the streams must be known, and the calculation of MSPP is related to the constant temperature and the compositions in the product stream. Therefore, the previous calculation of MSPP cannot be applied to the allocation of CExC in the

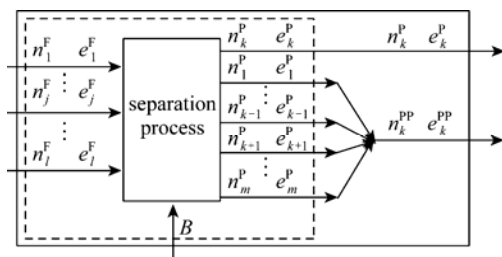


Figure 1 A separation process flow diagram

petroleum distillation process where there exist unknown compositions of product streams.

According to the minimum separation work theory [22], the MSPP of the k th stream based on the concept of exergy, G_k , is given by

$$G_k = \sum_{j=1}^l n_j^F e_j^F - n_k^P e_k^P - n_k^{PP} e_k^{PP} \quad (1)$$

where n and e denote the molar flow rate and exergy, respectively, and n_k^{PP} is the molar flow rate of the pseudo-product corresponding to the k th product stream, calculated as

$$n_k^{PP} = \sum_{i=1}^{k-1} n_i^P + \sum_{i=k+1}^m n_i^P \quad (2)$$

or

$$n_k^{PP} = \sum_{j=1}^l n_j^F - n_k^P \quad (3)$$

Equation (1) can be changed into

$$G_k = \sum_{j=1}^l n_j^F (H_j^F - T_0 S_j^F) - n_k^P (H_k^P - T_0 S_k^P) - n_k^{PP} (H_k^{PP} - T_0 S_k^{PP}) \quad (4)$$

where H , S and T_0 denote enthalpy, entropy and ambient absolute temperature, respectively.

Thus, with respect to unknown compositions in the product stream, the calculation of MSPP is also obtained based on exergy. Obviously Eq. (1) is also suitable for known compositions, that is the previous calculation method [20], is a particular case of the presently proposed method.

3 THE MATHEMATICAL MODELS OF ALLOCATION OF CExC

3.1 The mathematical models of CExC of the petroleum distillation processes

Cumulative exergy consumption (CExC) is the sum of the exergy of all natural resources in all the steps of a production process. Detailed discussions of CExC theory are presented elsewhere [23].

According to the conservation law of CExC, the sum of increase of annual total CExC rate of the products in the considered separation process,

$\sum_{i=1}^m \Delta E_{C,i}^P$, can be determined from (with reference to

Fig. 1) [20]

$$\sum_{i=1}^m \Delta E_{C,i}^P = \sum E_C^{cr} + \sum E_C^{or} \quad (5)$$

where, $\sum E_C^{cr}$ is the sum of annual CExC rate of depreciation of constructing resources (kJ), and $\sum E_C^{or}$ is the sum of annual CExC rate of operating resources (kJ).

3.2 The allocation principle of the proposed method

The physical relationship of MSPP and $\sum_{i=1}^m \Delta E_{C,i}^P$

has been described in detail by Zhu and Feng [20]. Now, this relationship can also be understood as follows: the separate production of each of the product streams is taking place at the same operating conditions without a distinction between the main product and the by-product. This method is based on a formulation of an ideal point at which products are equivalent.

3.3 The establishment of mathematical models of allocation

The allocation coefficient based on the MSPP can be calculated as follows:

$$\alpha_k = \frac{G_k}{\sum_{i=1}^m G_k} \quad (6)$$

where α_k denotes the coefficient of allocation of the k th stream, $\sum_{i=1}^m G_k$ is the sum of the MSPP of each stream.

Combining Eqs. (5) and (6) gives

$$E_{A,k} = \frac{G_k}{\sum_{i=1}^m G_k} (\sum E_C^{cr} + \sum E_C^{or}) \quad (7)$$

where, $E_{A,k}$ is the value of allocation of annual total CExC rate to the k th product stream (kJ).

4 A NUMERICAL EXAMPLE

A numerical example for a four-product (or cuts) atmospheric petroleum distillation process is analyzed with the proposed method [24]. Fig. 2 shows schematically the process. The crude goes first to the crude furnace where it is partially vaporized, then to the atmospheric column. The stripping steam feeds to the bottom of the column. The column has a total condenser, two coupled side strippers, and three pump around circuits, and thus the crude is separated into four product streams.

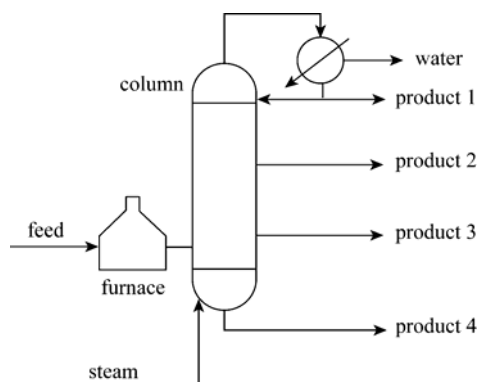


Figure 2 Schematic diagram of atmospheric petroleum distillation process

The operating conditions of this process are as follows:

(1) The crude stream is at 101.325 kPa and 250°C, and has a flow rate of 108.61 kg·s⁻¹.

(2) Column is modeled with 25 equilibrium stages, no reboiler, and a total condenser.

(3) Distillate product stream is at 19.36 kg·s⁻¹.

(4) Column and condenser both operate at a pressure of 101.325 kPa with no pressure drops.

(5) Open steam stream at 0.5 MPa and 300°C has a flow rate of 1.67 kg·s⁻¹ in the bottom.

(6) Furnace is simulated as a single-stage flash type.

(7) Furnace operates at a pressure of 101.325 kPa and a temperature of 360°C.

(8) Furnace outlet enters the atmospheric column on stage 21 of the column.

Aspen Plus process simulator is used for rigorous modeling of the process with the following postulations:

(1) The BK10 physical property option set (Braun K-10) is selected for evaluating vapor-liquid phase equilibrium, enthalpy, and density.

(2) The Steam Tables (STEAM-TA) and Method 2 are selected for the free-water phase properties and the water solubility, respectively.

(3) The atmospheric column and the crude furnace are simultaneously simulated with a single PetroFrac model.

Besides, bubble cap trays are considered for the column, and the model calculation is solved by the SCHUBERT method. More simulated operating conditions and detailed calculations of the annual total CExC of the petroleum distillation can be taken from published report [24].

4.1 Results of allocation

The values of G_k , α_k and $E_{A,k}$ can be gained according to Eqs. (1), (6) and (7), respectively, as shown in Table 1. For comparison, mass-based results are also performed in Table 2.

4.2 Discussion

From the results in Table 1, it is found that G_3 is

Table 1 Allocated results based on the MSPP

Streams	G/kW	α_k	$E_A \times 10^{-9}/\text{kJ}$
1	0.640	0.146	0.23
2	1.201	0.274	0.44
3	1.424	0.325	0.52
4	1.117	0.255	0.40
total	4.382	1.000	1.59

Table 2 Allocated results based on the mass of stream

Streams	$V/\text{kg}\cdot\text{s}^{-1}$	$\alpha_{k,m}$	$E_A \times 10^{-9}/\text{kJ}$
1	19.36	0.178	0.28
2	17.75	0.163	0.26
3	11.92	0.110	0.18
4	59.58	0.549	0.87
total	108.61	1.000	1.59

the biggest, and then G_2 and G_4 , and G_1 is the smallest. In general, a large driving force means large exergy consumption in irreversible process. This shows that the biggest ideal driving force is required to produce the stream 3 so that the biggest practical driving force, that is CExC is supplied accordingly. Thus, $E_{A,3}$ is the biggest, and then $E_{A,2}$ and $E_{A,4}$, and $E_{A,1}$ is the smallest. From a thermodynamic point of view, these results can reflect the physical, causal relationship of allocation of CExC in the petroleum distillation process [20].

Because all the products are similar, the mass of product stream is a frequently used allocation parameter in the petroleum distillation process [11]. Its results are different from those from MSPP method (Table 2). But this allocation method lacks physical causality, because the distillation process is regarded as a black box [19]. However, the MSPP-based results apparently make sense, and can meet the second law of thermodynamics.

5 CONCLUSIONS

In terms of unknown compositions in the petroleum distillation process, an improved calculation of MSPP can be derived from the concept of exergy in this article. This method is an extension of the thermodynamically based allocation of cumulative exergy consumption in the multiple product separation processes where the specific compositions in each of the streams are known. Although the two calculation procedures are both based on the minimum separation work theory, this method proposed is suitable for both known and unknown compositions of separation processes. The numerical example demonstrates that this method proposed has a wider use than ever. This method is of universal significance to the allocation of CExC of industrial processes.

NOMENCLATURE

B	energy flow, kW
E_A	value of allocation of annual total cumulative exergy rate, kJ

E_C	annual cumulative exergy rate, kJ
e	exergy, kJ·kmol ⁻¹
G	minimum separation power of product, kW
H	enthalpy, kJ·kmol ⁻¹
l	total number of feed streams
m	total number of product streams
n	molar flow rate, kmol·s ⁻¹
S	entropy, kJ·(kmol·K) ⁻¹
T_0	ambient absolute temperature, K
V	mass flow rate, kg·s ⁻¹
α	allocation coefficient

Superscripts

cr	constructing resource
F	feed
or	operating resource
P	product
PP	pseudo-product

Subscripts

i	index for product stream
j	index for feed stream
k	k th product stream

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