

Improving Energy Performance of Water Allocation Networks Through Appropriate Stream Merging*

FENG Xiao (冯霄)^{1,**}, LI Yucai (李育才)¹ and YU Xinjiang (余新江)²

¹ Department of Chemical Engineering, Xi'an Jiaotong University, Xi'an 710049, China

² Department of Petrochemical Engineering, Kalamay Vocational & Technical College, Dushanzi 833600, China

Abstract Water-using operations in the process industry have demands for water usually both on water quality and temperature, and the existing mathematical models of heat exchange networks cannot guarantee the energy performance of a water network optimal. In this paper, the effects of non-isothermal merging on energy performance of water allocation networks are analyzed, which include utility consumption, total heat exchange load, and number of heat exchange matches. Three principles are proposed to express the effects of non-isothermal merging on energy performance of water allocation networks. A rule of non-isothermal merging without increasing utility consumption is deduced. And an approach to improve energy performance of water allocation network is presented. A case study is given to demonstrate the method.

Keywords water allocation network, energy performance, non-isothermal merging

1 INTRODUCTION

Water and energy are widely used in process industries, and they play important roles in the sustainable development of the society. In the process industry, reduction of freshwater and energy consumption to meet the need of the economy and the environment is very important.

In 1980, Takama *et al.* [1] addressed an approach for optimal water allocation in a petroleum refinery based on a mathematical programming coupled with a superstructure of all possible reuse and regeneration opportunities. El-Halwagi and Manousiouthakis [2] defined the composite curve to denote mass exchange operations. Wang and Smith [3] introduced the concepts of “water pinch” and “limiting water profile”, which are further improved later [4–9]. Huang *et al.* [10] presented a mathematical programming solution of the combined problem of water allocation and treatment by solving a nonlinear problem. Savelski and Bagajewicz [11] developed necessary conditions for the optimal water/wastewater allocation-planning problem. Then, the same authors proposed a linear programming formulation of the problem based on the aforementioned necessary conditions [12]. The mathematical method is further developed [13–16].

Most water-using operations in the process industry have demands for water not only on water quality but also on temperature. In this case, water will be heated or cooled to a certain temperature before entering a process unit. Therefore, when synthesizing a water network, the energy performance of the network must be considered.

The influence of heat integration on the solution of the water network had been ignored for a long time. Savulescu and Smith [17] first raised this problem, and provided a method called “two dimensional grid diagram” to solve this problem. Bagajewicz *et al.* [18] later developed sequential mathematical models to solve this problem. But these two methods only can be

applied to single-contaminant systems. Zheng and Feng [19] developed a model which can be applied to a water using system with multiple contaminants.

Both of these mathematical models combine water allocation networks and heat-exchange networks. The mathematical model for heat-exchange network is from that proposed by Papoulias and Grossmann [20]. This model considers classical heat transfer only and does not take into account the possibility of heat exchanges through stream merging. Bagajewicz *et al.* [18] considered such merging in a case study, but no discussion was given on the influence of non-isothermal merging on the energy performance of water allocation networks, and on improving the energy performance of water allocation networks through appropriate stream merging.

In this article, the effects of non-isothermal merging on energy performance of water allocation networks are analyzed first. Then a rule of non-isothermal merging is proposed on the condition of not increasing utility consumption. And an approach to improve energy performance of water allocation network is presented.

2 THE TRADITIONAL METHOD FOR THE MINIMUM UTILITY CONSUMPTION

A case is used to explain why the traditional mathematical model for heat exchange network cannot guarantee the minimum utility consumption. Table 1

Table 1 Limiting process data of case 1

Process number	$C_{In,Max}$ /mg·L ⁻¹	$C_{Out,Max}$ /mg·L ⁻¹	Mass load of contaminant/mg·s ⁻¹	Temperature /°C
1	0	100	2000	60
2	0	50	2000	75
3	50	100	1000	71
4	75	150	3000	73
5	150	200	2000	90
6	100	200	2000	80

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** To whom correspondence should be addressed. E-mail: xfeng@mail.xjtu.edu.cn

gives the limiting water data and temperature for each water stream used in operations. The temperature of fresh water is 20°C, and the temperature of waste water is 30°C.

Using Zheng and Feng's model [19], first, the minimum freshwater consumption can be obtained as $60 \text{ kg}\cdot\text{s}^{-1}$. Then, take the minimum freshwater consumption of $60 \text{ kg}\cdot\text{s}^{-1}$ as a constraint, the minimum hot utility duty is obtained as 3024 kW, and the cold utility is 504 kW. The resultant water allocation network is shown in Fig. 1. In the figure, the number in a rectangle represents flow rate, and the number in a circle represents the stream number.

Observing Fig. 1 we can find that the temperature of stream 4 is from 75°C to 73°C, and the operation temperature of process 3 is 71°C. So, if we build a stream from process 3 to process 4, the temperature change of the stream is from 73°C to 71°C. Because the starting temperature of two streams is very close, so if they make a non-isothermal merging between the two streams, the utility consumption might be reduced. Trying to take minimum freshwater consumption $60 \text{ kg}\cdot\text{s}^{-1}$ and flow rate from process 3 to process 4 as $20 \text{ kg}\cdot\text{s}^{-1}$ as constraints, we can get water allocation networks 2 (Fig. 2). The streams in water allocation network 2 is shown in Table 2.

After stream 3 and stream 4 are merged, the resultant stream temperature becomes 73°C. Make heat

integration after the merging, we can find the minimum hot utility duty is 2856 kW, and the minimum cold utility duty is 336 kW, which is reduced by 168 kW compared with the targets from the mathematical model. Similarly, the total heat exchange load and the number of heat exchange matches can be expected to be different.

The mathematical model of heat-exchange networks which proposed by Papoulias and Grossmann [20] considers that streams can change their temperature only by heat-exchangers, and heat exchange will occur under a specific minimum approach temperature difference which is greater than zero. However, in water allocation networks, streams can change their temperatures through merging. Non-isothermal mixing is a kind of heat exchange process with the minimum approach temperature difference as zero. When two streams have a very small approach temperature difference, it is impossible that the two streams exchange heat through heat exchanger, but they can exchange heat through merging. If such situation happens, the effect is to reduce the minimum approach temperature difference, so using the traditional model for heat exchange network may not get the minimum utility duty at the given minimum approach temperature difference. This is the reason that in case 1, hot utility duty can be reduced through non-isothermal mixing. Similarly, because non-isothermal mixing does

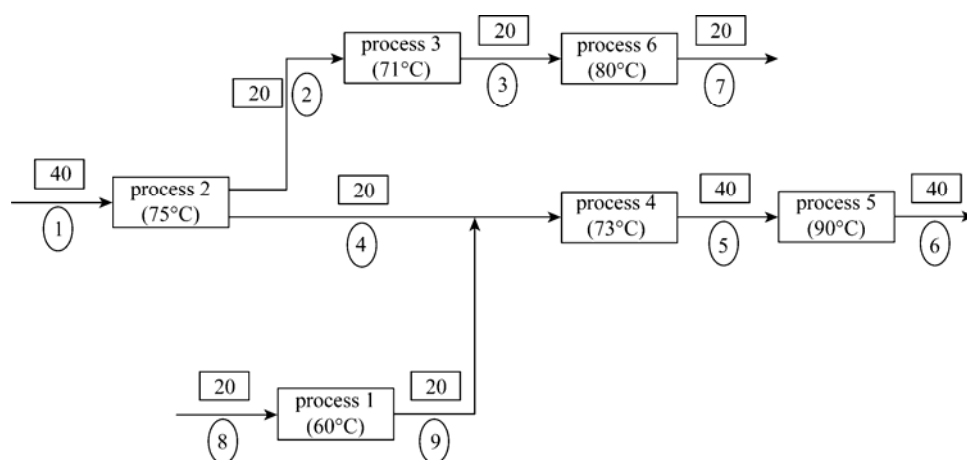


Figure 1 The water allocation network 1 obtained by Zheng and Feng's model

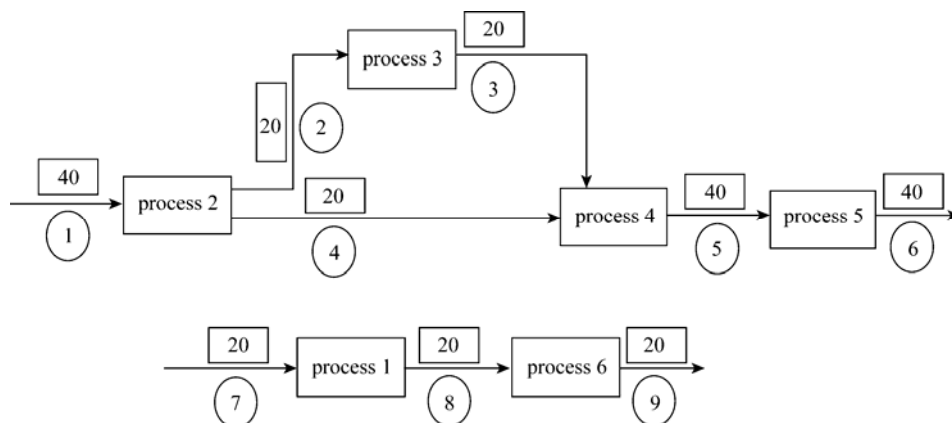


Figure 2 The water allocation network 2

Table 2 Streams in Fig. 2

Stream number	Supply temperature/°C	Target temperature/°C	Flow rate F /kg·s ⁻¹
1	20	75	40
2	75	71	20
3	71	73	20
4	75	73	20
5	73	90	40
6	90	30	40
7	20	60	20
8	60	80	20
9	80	30	20

not need heat exchanger, so the total heat exchange load and heat exchange match number may also be reduced.

3 THE PRINCIPLES OF NON-ISOTHERMAL MERGING

From the above case study, it can be seen that the non-isothermal merging of streams can have the following effects on energy performance of water allocation networks: (1) change utility consumption, (2) change total heat exchange load of the network, and (3) change the number of heat exchange match.

In case 1, non-isothermal merging improves the energy performance of the water allocation network. But not all non-isothermal merging can improve the energy performance. Further more, some non-isothermal merging increases the minimum utility duty and heat-exchange load. So, the effect of non-isothermal merging on energy performance of water allocation networks has to be addressed. Before the discussion, the following concepts are introduced or defined.

(1) Homogeneous streams: two streams that both need to be cooled or heated.

(2) Isomerism streams: two streams that one needs to be cooled while the other needs to be heated.

(3) Stream temperature difference: the temperature difference between the supply temperature and target temperature of a stream.

The effect of non-isothermal merging on energy performance of water allocation networks can be generalized as the following principles.

Principle 1: Non-isothermal merging between homogeneous streams cannot reduce the utility duty and the total heat exchange load of the network.

For non-isothermal merging between homogeneous streams, no heat exchange occurs between hot and cold streams as the heat exchange system expects. Therefore, utilities cannot be reduced. Further more, for non-isothermal merging between homogeneous streams will make the corresponding composite curve more smoothly, so that the hot composite curve and the cold composite curve will get closer than before, if such effect make somewhere exist lower temperature difference between the two curves than the pinch temperature difference, the utilities will increase.

Principle 2: If the non-isothermal merging be-

tween isomerism streams does not increase the utility duty, then the total heat exchange load of the network will be reduced.

Because the non-isothermal merging between isomerism streams can exchange heat between hot and cold streams without heat exchangers, the merged streams can be taken out from the hot and cold composite curves, so that the total heat loads of the two curves will reduce. If utility duties are not increase, the total heat exchange load of the network will be reduced.

Principle 3: Only if the non-isothermal merging between two streams whose temperature differences are less than the minimum approach temperature difference of the network, the utility duty can be possibly reduced.

From the pinch technology it is known that to reduce the minimum utility duty at a certain pinch temperature difference, the only way is that a cold stream above the pinch is heated by a hot stream below the pinch, which can be realized by merging such two streams. This is to take use of the feature that merging isomerism streams like exchange heat at zero approach temperature difference.

4 THE RULE OF NON-ISOTHERMAL MERGING AND METHOD TO IMPROVE ENERGY PERFORMANCE

From the discussion above, it can be seen that some non-isothermal merging can reduce utility duty, but some others increase utility duty. So finding non-isothermal mergings that can improve the energy performance of water allocation networks is very important. Here, we present a rule targeting not increase utility duty.

Merging rule: In the temperature range defined by the highest temperature and the lowest temperature of the merged streams before merging, if the heat flux of each temperature interval is greater than the heat flux reduction caused by the merging, the non-isothermal merging will not increase the utility duty.

According to the pinch technology, to ensure utilities not to increase, heat flux of each temperature interval cannot be less than zero after the merging. That is, the heat flux of each temperature interval before the merging is greater than the heat flux reduction caused by the merging.

Based on the above theorems and the merging rule, an approach to improve energy performance of water allocation networks is presented. The approach includes the following steps.

Step 1 To find whether there are two streams that their stream temperature difference is less than the minimum approach temperature difference. If there are not, just consider to reduce the heat exchanger load and heat exchanger match number. As mentioned before, this is because two streams' non-isothermal merging cannot reduce the utility duty, if their stream temperature difference is greater than the minimum approach temperature difference.

Step 2 If there are two streams that their stream temperature difference is less than the minimum

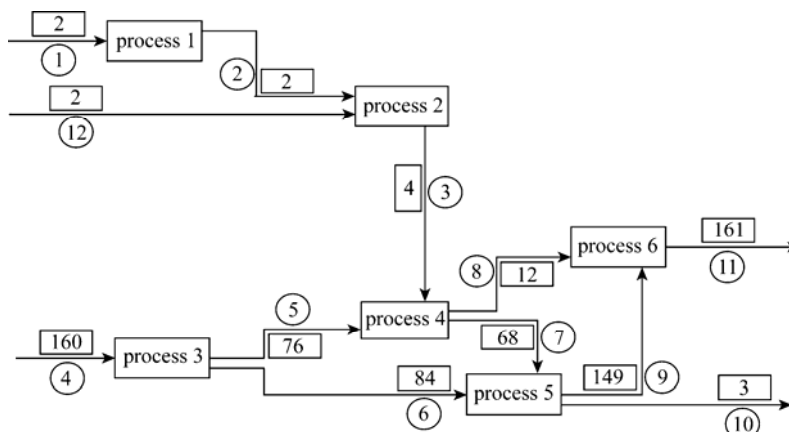


Figure 3 Water allocation network from the mathematical model

approach temperature difference, consider the non-isothermal merging. If the utility duty does not increase, mix them. Otherwise, give it up.

Step 3 Consider the non-isothermal merging between isomerism streams to reduce heat exchanger load. If the merging does not increase the utility duty, take it.

Step 4 Consider the non-isothermal merging between homogeneous streams to reduce heat exchanger match number. If the merging does not increase the utility duty, accept it.

5 CASE STUDY

Consider the case in Table 3. Using Zheng and Feng's model [19], first, the minimum freshwater consumption can be obtained as $164 \text{ kg}\cdot\text{s}^{-1}$. Then, take the minimum freshwater consumption $164 \text{ kg}\cdot\text{s}^{-1}$ as a constraint, the minimum hot utility duty obtained as 7459.2 kW. Take the minimum freshwater consumption and the minimum hot utility duty as constraints, the minimum total heat exchanger load of the network can be obtained as 61866 kW. Take all of the above results as constraints, the minimum heat exchanger number can be obtained as 15. The resultant water allocation network is shown in Fig. 3. The streams of water allocation network in Fig. 3 are shown in Table 4.

Table 3 Limiting process data of case study

Process number	$C_{\text{In,Max}}/\text{mg}\cdot\text{L}^{-1}$	$C_{\text{Out,Max}}/\text{mg}\cdot\text{L}^{-1}$	Mass load of contaminant/ $\text{mg}\cdot\text{s}^{-1}$	Temperature/ $^{\circ}\text{C}$
1	5	20	40	117
2	10	25	60	112
3	0	25	4000	98
4	25	75	4000	102
5	50	100	8000	100
6	100	200	16400	108

According to the approach to improve energy performance of water allocation networks, first the non-isothermal merging between streams whose stream temperature difference is less than the minimum approach temperature difference is considered.

Table 4 Streams in Fig. 3

Stream number	Supply temperature/ $^{\circ}\text{C}$	Target temperature/ $^{\circ}\text{C}$	Flow rate $F/\text{kg}\cdot\text{s}^{-1}$
1	20	117	2
2	117	112	2
3	112	102	4
4	20	98	160
5	98	102	76
6	98	100	84
7	102	100	68
8	102	108	12
9	100	108	149
10	100	30	3
11	108	30	161
12	20	112	2

Streams 6 and 7 are such ones, and both streams flow to process 5. After non-isothermal merging, these two streams change to a stream from 99.8°C to 100°C whose flow rate is $152 \text{ kg}\cdot\text{s}^{-1}$. After heat integration, the minimum hot utility duty is 6888 kW, and the minimum cold utility duty is 0.

Then we consider the merging between other isomerism streams. Both streams 2 and 3 flow to process 2. But the supply temperature of stream 2 is 117°C , and that of stream 3 is 20°C . If there is a mix between streams 2 and 3, there must be heat transfer across the pinch point, which makes utility duty increase.

Then, we consider the non-isothermal merging between streams 3 and 5, both of which flow to process 4. Streams 3 and 5 can be merged into a stream from 98.7°C to 102°C , whose flow rate is $80 \text{ kg}\cdot\text{s}^{-1}$. After the merging, the heat integration gets that the minimum hot utility duty remains 6888 kW, while the minimum total heat exchanger load of the network reduced to 60555.6 kW.

Finally, a merging between homogeneous streams is considered, that is, the merging between streams 8 and 9. These two streams are merged to a stream from 100.15°C to 108°C whose flow rate is $161 \text{ kg}\cdot\text{s}^{-1}$. The merging does not reduce the minimum utility duty and minimum total heat exchanger load. However, it reduces the stream number.

Table 5 Comparison between results from Zheng and Feng's model and results from the method proposed in this article

	Minimum freshwater consumption/kg·s ⁻¹	Minimum hot utility duty/kW	Minimum total heat exchanger load/kW	Minimum heat exchanger number
Zheng and Feng's model	164	7459.2	61866	15
method proposed in this article	164	6888	60555.6	10

After all the above mergings, the minimum hot utility duty is reduced to 6888 kW, the minimum total heat exchanger load of the network is reduced to 60555.6 kW, and the minimum heat exchanger number is reduced to 10.

6 CONCLUSIONS

Non-isothermal merging between streams can affect energy performance and economic feature of water allocation networks by changing utility consumptions, the total heat exchange load of the network, and the number of heat exchange matches.

No heat exchange occurs for non-isothermal merging between homogeneous streams, so that utilities cannot be reduced. Such merging can reduce the number of streams, so that can be considered to reduce heat exchanger match number.

The effect of non-isothermal merging between isomerism streams is heat exchange. Only if the non-isothermal merging between two streams whose temperature differences are less than the minimum approach temperature difference of the network, the utility duty can be possibly reduced. Merging between isomerism streams with bigger temperature difference can be considered to reduce the heat exchanger load and heat exchanger match number.

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