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A novel method to improve the performance of heat exchanger——Temperature fields coordination of fluids

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Abstract **The methods to enhance the heat transfer in heat exchanger may be classified into two levels: one is to improve the heat transfer coefficient; the other is to upgrade the whole arrangement of the heat exchangers. For the second level, the performance of heat exchanger can be upgraded by increasing the coordination degree between the temperature fields of cold and hot fluids. When the temperature distributions are similar to each other, the temperature difference field (TDF) is more uniform, which means that the temperature fields are more coordinated with each other. For the cross-flow heat exchanger, rearrangement of the heat exchange surface area should improve the heat transfer effectiveness, which is even equal to that of the counter-flow heat exchanger when the surface area is reassigned optimally. For the multi-stream heat exchanger, the thermal performance is also dependent on the uniformity of the TDF, and the parallel-flow arrangement may achieve higher heat exchange effectiveness than the counter-flow arrangement, which indicates that the performance of heat exchanger depends on the coordination degree of temperature fields instead of the flow arrangement.**

Keywords: enhanced heat transfer, heat exchanger, field coordination.

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Heat exchangers are widely used in industries, and the improvement of their performances will raise the efficiency of energy utilization, and minimize the equipment. With the rapid growth of energy consumption in recent decades, improvement of heat exchanger becomes more important for energy conservation. Generally, to upgrade the thermal performance of heat exchangers, increasing the heat transfer coefficient is largely based on, and it is referred to as the technologies of the enhanced heat transfer. Because of the energy crisis occurred in the 70s last century, the technology of enhanced heat transfer achieved rapid development and the number of published papers in this field grew fast every year[1]. In the 1990s, however, the growth in enhanced heat transfer technology was slowed down, because some people thought that the technology had been termed “routine”[2], and the energy price was stable. Nevertheless Bergles[3] believed that the technology of enhanced heat transfer has been expanding its application fields, particularly, in the processing industry. Then the third generation of enhanced heat transfer technology is demanded, such as three dimension rib and compound enhancement technology. Guo[4] developed a new way to enhance the heat transfer by improving the coordination between velocity field and temperature field, which has been applied effectively in industry.

In fact, the effectiveness of heat exchanger can be improved from two levels. At the first one, heat transfer coefficient is increased by some enhanced devices such as rib, insertion, turbulence generator, etc. At the second, the heat exchanger effectiveness is improved under the same heat transfer coefficient. For instance, the flow arrangement will affect the thermal performance of heat exchangers. It is well known that the effectiveness of the counter-flow heat exchangers is higher than that of the parallel-flow heat exchangers for the given number of heat transfer unit. In this paper the concept of coordination between temperature fields of the hot and cold fluid in heat exchanger is presented to reveal the essence of thermal performance improvements at the second level. Based on this concept, some approaches can be developed to enhance the heat exchanger performance by means of improving the coordination between the temperature distribution of the cold and hot fluid.

1 Coordination of temperature fields

(ⅰ) Concept of coordination. Due to the energy exchange between the fluids with different temperatures in the heat exchanger, the fluid temperatures vary along the flow path and temperature fields of fluids are constructed. Guo[5] regarded the whole heat exchanger made up of many sub heat exchangers, in which the characteristic temperatures (the average temperature) of hot and cold fluid are t_h, t_c respectively. The local temperature difference θ in every sub heat exchanger forms a temperature difference field in the heat exchanger.

$$\theta(x,y,z) = t_h(x,y,z) - t_c(x,y,z). \quad (1)$$

It is well known that the effectiveness of heat exchanger does not only depend on the initial temperature difference of the hot and cold fluid and NTU, but also on the flow arrangements (counter-flow, parallel-flow, cross-flow). The characteristics of temperature difference field (TDF) between the cold and the hot fluid, are essentially considered to determine the thermal performance of heat exchanger. The temperatures of both the cold and hot fluids are the special function. The more similar functions these two functions have, the better the coordination between temperature fields of hot and cold fluid is, when the form of two function is the same and the difference between them is a constant. The temperature distributions of hot and cold fluid are

$$t_h(x,y,z) = A + f(x,y,z), \quad (2a)$$

$$t_c(x,y,z) = B + f(x,y,z), \tag{2b}$$

which means that the temperature difference does not vary with the position, that is, the TDF becomes uniform

$$\theta(x,y,z) = t_h(x,y,z) - t_c(x,y,z) = A - B = \text{Const.} \tag{2c}$$

For this case, the temperature fields of the hot and cold fluid are considered to be fully coordinated. Therefore, the uniformity degree of TDF indicates the degree of coordination between the two temperature fields.

(ii) Field coordination number. The temperature fields in heat exchanger are generally complicated so that it is necessary to define a parameter to describe quantitatively the coordination degree between two temperature fields. A uniformity factor of TDF Φ is defined for cross-flow heat exchanger[6], which is regarded as the composition of $i \times j$ sub heat exchangers. When the fluid of the larger heat capacity rate is mixed, and the fluid of the smaller heat capacity rate is unmixed, the uniformity factor of TDF is

$$\Phi = 2\sqrt{\frac{1-\exp[-(1-\exp(-N_{tu}))C_r]}{C_r N_{tu}[1+\exp(-N_{tu})][1+\exp(1-\exp(-N_{tu})C_r)]}}; \tag{3a}$$

When the fluid of the smaller heat capacity rate is mixed, and the fluid of the larger heat capacity rate is unmixed, the uniformity factor of TDF is

$$\Phi = 2\frac{1-\exp(-(1-\exp(-C_r N_{tu}))/C_r)}{\sqrt{N_{tu}[1+\exp(-C_r N_{tu})]\times[1-\exp(-2(1-\exp(-C_r N_{tu}))/C_r)]}}, \tag{3b}$$

where $C_r = C_{min}/C_{max}$ is the ratio of heat capacity rate, N_{tu} is the number of transfer unit.

Because the uniformity factor of TDF indicates the degree of coordination between the two temperature fields, it is called as field coordination number.

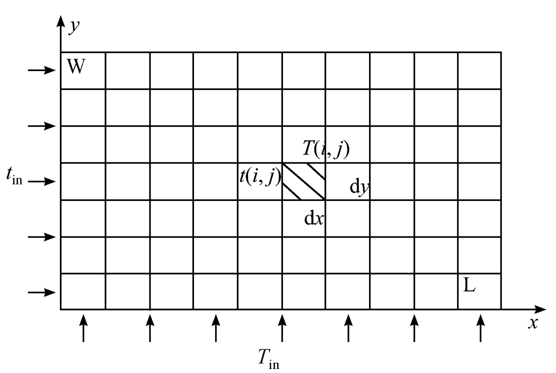

Fig. 1. Cross-flow heat exchanger.

(iii) Principle of coordinated enhancement for heat exchanger. As the simple flow arrangements, the counter-flow, parallel-flow and cross-flow heat exchangers can be ranked precisely by their thermal performances. However, many more complicated flow arrangements are adopted in industry because of the practical factors. It is difficult to quantitatively compare their thermal performance. However, the concept of coordination of temperature fields provided a quantificational criterion for the thermal performance evaluation. Fig. 2 shows the relationship between heat exchanger effectiveness ε and field coordination number Φ for heat exchangers with nine different flow arrangements, in which the effectiveness increases with increasing field coordination number. Therefore, the field coordination principle in heat exchanger can be stated as: the more coordinated the temperature fields of the cold and hot fluid are, the better thermal performance the heat exchanger has.

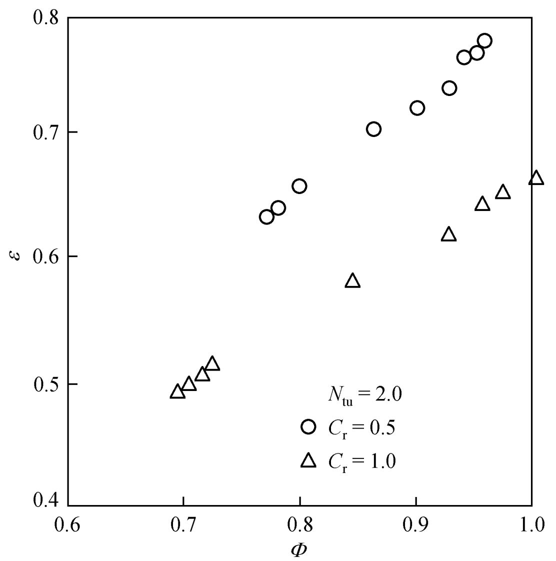

Fig. 2. Relationship between N_{tu} and ε.

3 Application of field coordination principle in heat exchanger

In general, when the thermal performance of heat exchanger is improved by increasing heat transfer coefficient, more pumping power is demanded. Nevertheless, the improvement of temperature of field coordination and the consequent increase of heat exchanger effectiveness is of no cost of additional pumping power. Therefore, this method is more effective in practical applications.

(i) Cross-flow heat exchanger. For the heat exchanger with given flow arrangement, uniformity of TDF can be improved by adjusting the distribution of heat exchange surface area, and as a result the effectiveness of heat exchanger is increased. A cross-flow heat exchanger with fins divided into 16 segments is taken as an example shown in Fig. 3. Obviously, the temperature differences between hot and cold fluid in different segments differ from each other greatly. It means that the temperature fields are far away from the state of the complete coordination. For example, the temperature difference in segment 1 is the highest among all the 16 segments and the temperature difference in segment 2 is higher than those in segment 9 or 10. As a result, the temperature differences in left upper segments are larger than those in the right lower segments, and decreased along the diagonal. The heat exchanged in each segment can be calculated as:

$$Q_i(x, y) = CF_i K \Delta t_i, \tag{4a}$$

where F_i is the local surface area in segment i, K the heat transfer coefficient which can be considered as constant approximately, $\Delta t_i(x, y)$ is the local characteristic temperature difference in segment i, C is a constant which depends on the structure of the heat exchanger. Obviously, the transferred heat per unit area is

$$Q_i / F_i = CK\Delta t_i(x, y). \tag{4b}$$

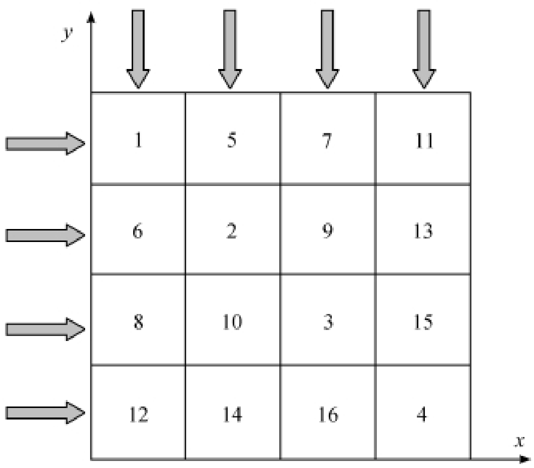

Fig. 3. Cross-flow heat exchanger.

Since both K and C are constants, the transferred heat per unit area is in direct proportion to the local characteristic temperature difference. Consequently, the transferred heat per unit area in segment 1 is the largest, that is, the heat transfer is the most effective. Likewise, the heat transfer efficiencies are more effective in left upper segments than those in the right lower segments. Hence, it is not reasonable to distribute heat exchange surface area equally. Instead, more area should be distributed in left upper segments, especially in segment 1. The adjustment of heat exchange surface area was investigated in analytical and numerical methods for the fixed total surface area[6]. The optimal distribution of the surface area is characterized by the most uniform TDF, i.e. the highest coordination degree. Fig. 4 shows the relationship of uniformity of TDF Φ to the heat exchanger effectiveness ε for the heat capacity rate ratio C_r=1. Parameter r at Y-coordinate is the percentage of increased heat exchanger effectiveness. The heat exchanger effectiveness is found to increase in direct proportion to the field coordination number Φ as long as the surface area is optimally distributed, the field coordination number is equal to unity and consequently the effectiveness of the cross flow heat exchanger can reach that of the counter flow heat exchanger.

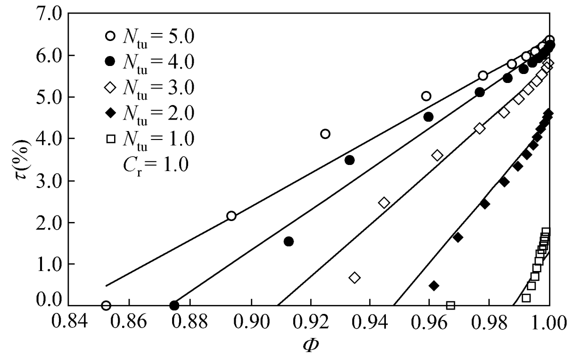

Fig. 4. Effectiveness for the redistribution of heat transfer area in cross-flow heat exchangers.

(ii) Multi-stream heat exchanger. There are more than two streams in the multi-stream heat exchanger as shown in Fig. 5 so that at least one of the streams exchanges energy with other two streams with the flow arrangement of either counter-flow or parallel-flow. It should be noted that the logarithmic mean temperature difference is no longer valid to evaluate the thermal performance of heat exchanger, and the influence of flow arrangement on the heat exchanger performance should be reconsidered. A triple-stream heat exchanger is studied as an example when the inlet temperatures:

$$T_{1in}\text{=300 K}, T_{2in}\text{=230 K}, T_{3in}\text{=180 K},$$

and the heat capacity rate:

$$\dot{M}C_1 = 2, \quad \dot{M}C_2 = 8, \quad \dot{M}C_3 = 8.$$

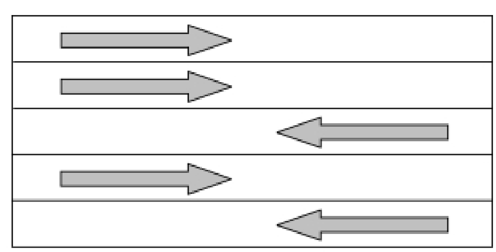

Fig. 5. Schematics of multi-stream heat exchanger.

Two types of flow arrangement are shown in Fig. 6(a) and Fig. 7(a), where stream (1) and stream (2) are arranged as counter-flow and parallel-flow respectively. Numerical results show that the heat of 134 J is exchanged between streams (1) and (2) for counter-flow arrangement but the heat of 143 J for parallel-flow arrangement. It seems unreasonable that the parallel-flow arrangement is better than the counter-flow arrangement in heat exchange for the same number of heat transfer unit (NTU). In fact, the opposite conclusion in textbooks and literatures for heat exchangers is conditional, that is, there is no heat source in the heat exchanger and no heat exchanged between the fluids and the circumstances. In multi-stream heat exchanger these conditions are not satisfied so that parallel-flow is not definitely better than counter-flow in heat exchange. Hence we should analysis the problem with the concept of temperature field coordination. The temperature distributions are shown in Figs. 6(b) and 7(b), where the TDF of counter-flow is far from uniform, that is, the coordination degree is low. On the contrary, the TDF of parallel-flow is much more uniform so that the higher thermal performance is achieved. This case shows that, under the complex conditions, the heat exchanged between two parallel-flow streams may be higher or lower than that between two counter-flow streams, and the coordination degree between the temperature fields of two streams determines the thermal performance of heat exchanger essentially.

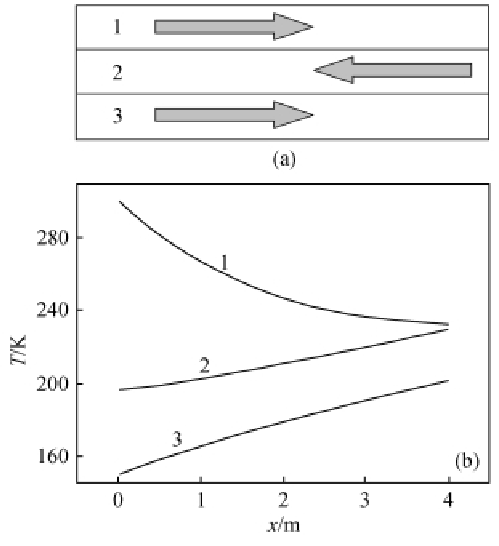

Fig. 6. Fluid temperature fileds for streams (1) and (2) being counter-flow arrangement.

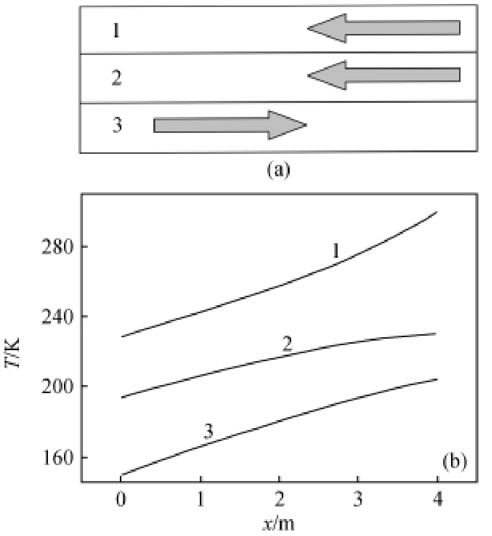

Fig. 7. Fluid temperature fileds for stream (1) and (2) being parallel-flow arrangement.

4 Conclusion

The thermal performance of heat exchanger can be increased at two levels. The first is to increase heat transfer coefficient. The second is to improve the coordination degree of the fluid temperature fields. The more similar the form of fluid temperature fields, that is, the more uniform the temperature difference fields of two streams, the better coordination the temperature fields of two streams. The better coordination of temperature fields leads to higher effectiveness of heat exchanger.

For cross-flow heat exchanger, its thermal performance can be upgraded in terms of redistribution of heat transfer surface based on the concept of improvement of temperature fields coordination. The effectiveness of cross-flow heat exchanger can reach that of the counter-flow heat exchanger when the heat transfer area is distributed optimally.

In multi-stream heat exchanger, the thermal performance of parallel-flow may be better than that of counter-flow under some conditions. It implies that, instead of the flow arrangement, the coordination degree of fluid temperature fields essentially determines the heat transfer performance of the heat exchanger.

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