Analysis of Local Thermohydraulic Synergistic Performance of H-Type Finned Tubes

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Introduction

As a typical compact heat transfer element, H-type finned tubes are widely used in industrial waste heat recovery due to their simple structure and excellent ash deposition resistance. However, conventional H-type fins face an inherent contradiction between heat transfer enhancement and flow resistance, and the synergy between the velocity field and the temperature field on the fin surface is suboptimal, which limits the improvement of overall performance. To address this issue, from the perspective of "field–lumped parameter and their interaction", this paper establishes an analytical method for the local thermal-hydraulic synergy performance of H-type finned tubes based on the analysis of the field synergy principle by Xin et al. [1]. It reveals the synergy mechanism between the velocity field and the temperature gradient field on the H-type fin surface, establishes a quantitative relationship between field parameters and macroscopic comprehensive performance, and proposes a design strategy of reducing negative-effect regions while expanding positive-effect regions, thereby coupling heat transfer enhancement with flow-guided drag reduction, in order to overcome the limitations of conventional fins in the coupled design of heat transfer, flow resistance, and ash deposition resistance. This study provides a scientific methodological framework for revealing the coupling mechanism between heat transfer surface structure and flow characteristics, enabling the evaluation and optimization of local thermal-hydraulic synergy performance, and developing novel heat transfer structures, representing an important exploration for the further development of convective heat transfer enhancement theory.

Model and method

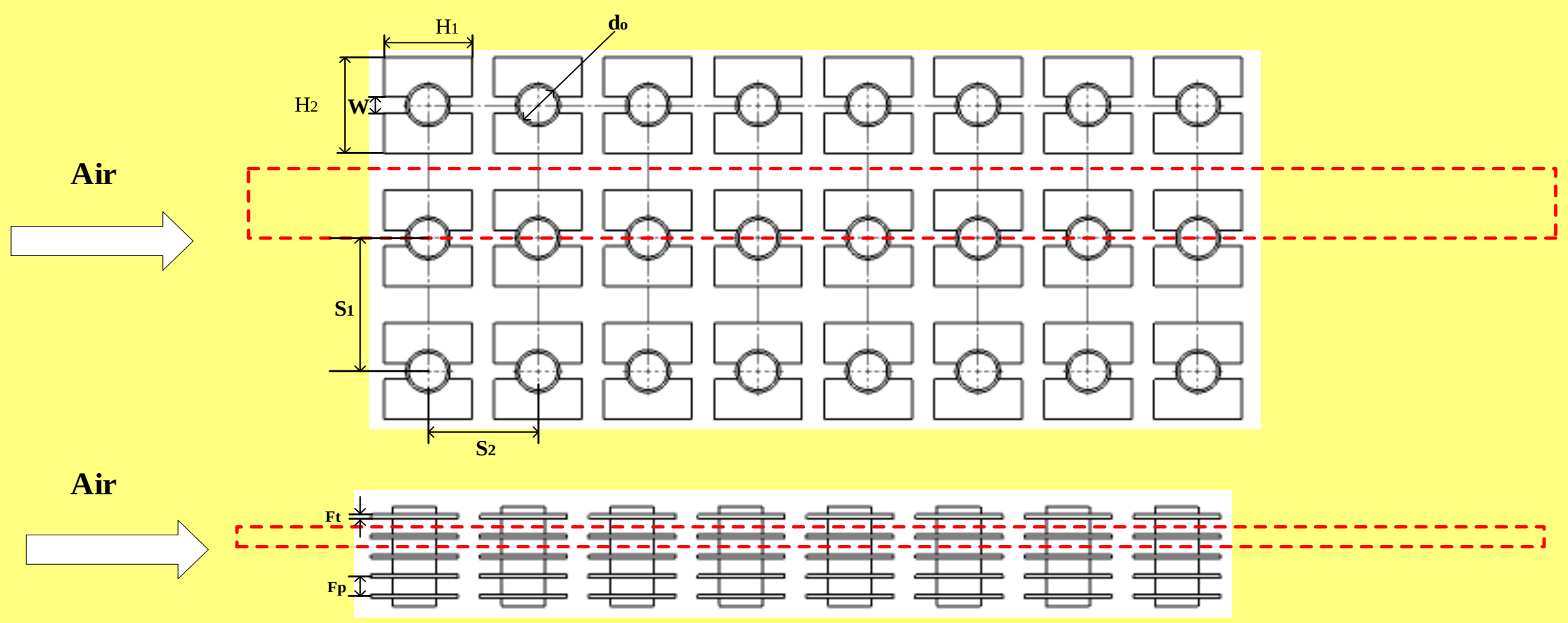

Fig. 1. Physical Model Diagram

Figure 1 shows the heat exchange tube bundle studied for the H-type fin. To simplify the calculation, the red area in the diagram is taken as the computational domain. In this paper, the RNG k-ε model and the finite volume method are used to solve the flow field outside the heat exchanger tube.

When the conductive thermal resistance of the tube wall and the internal thermal resistance are neglected, the pump power efficiency factor on the gas side can be derived based on the Q/Wp objective, given by:

$$\frac{Q}{W_p} = \eta_o \frac{j^3}{f\,Nu^2} \frac{2C_p d_o^2 \Delta t_m}{\nu^2} = F_{Q/W} \frac{2C_p d_o^2 \Delta t_m}{\nu^2} \tag{1}$$

where Nu is the equivalent Nusselt number, f is the equivalent heat transfer coefficient. j is the equivalent convective heat transfer coefficient.

Where the pump power efficiency factor for a single side is:

$$F_{Q/W} = \frac{\eta_o}{f} \frac{j^3}{Nu^2} \tag{2}$$

As the overall fin efficiency is a complex function of ho, it adversely impacts the straightforwardness of conventional heat exchanger performance assessment and design. Adopting the approach by Qin et al. [2] , this study advocates that the product of the overall fin efficiency and ho is the critical factor, thus proposing the equivalent convective heat transfer coefficient, *he*.

Based on this, the aforementioned single-side performance evaluation factor is simplified to:

$$F_{Q/W} = \frac{1}{f} \frac{j_e^{\,3}}{Nu_e^{\,2}} \tag{3}$$

Thermo-hydraulic synergy number：

$$\eta = \frac{k_{local} \cos\alpha}{f_{local}\,\mathrm{Re}^2} \tag{4}$$

where the four components of the criterion η are: k_{local} is the dimensionless temperature gradient, α is the synergy angle between the velocity vector and the temperature gradient vector, f_{local} is the local friction coefficient, and Re is the Reynolds number.

Results and discussion

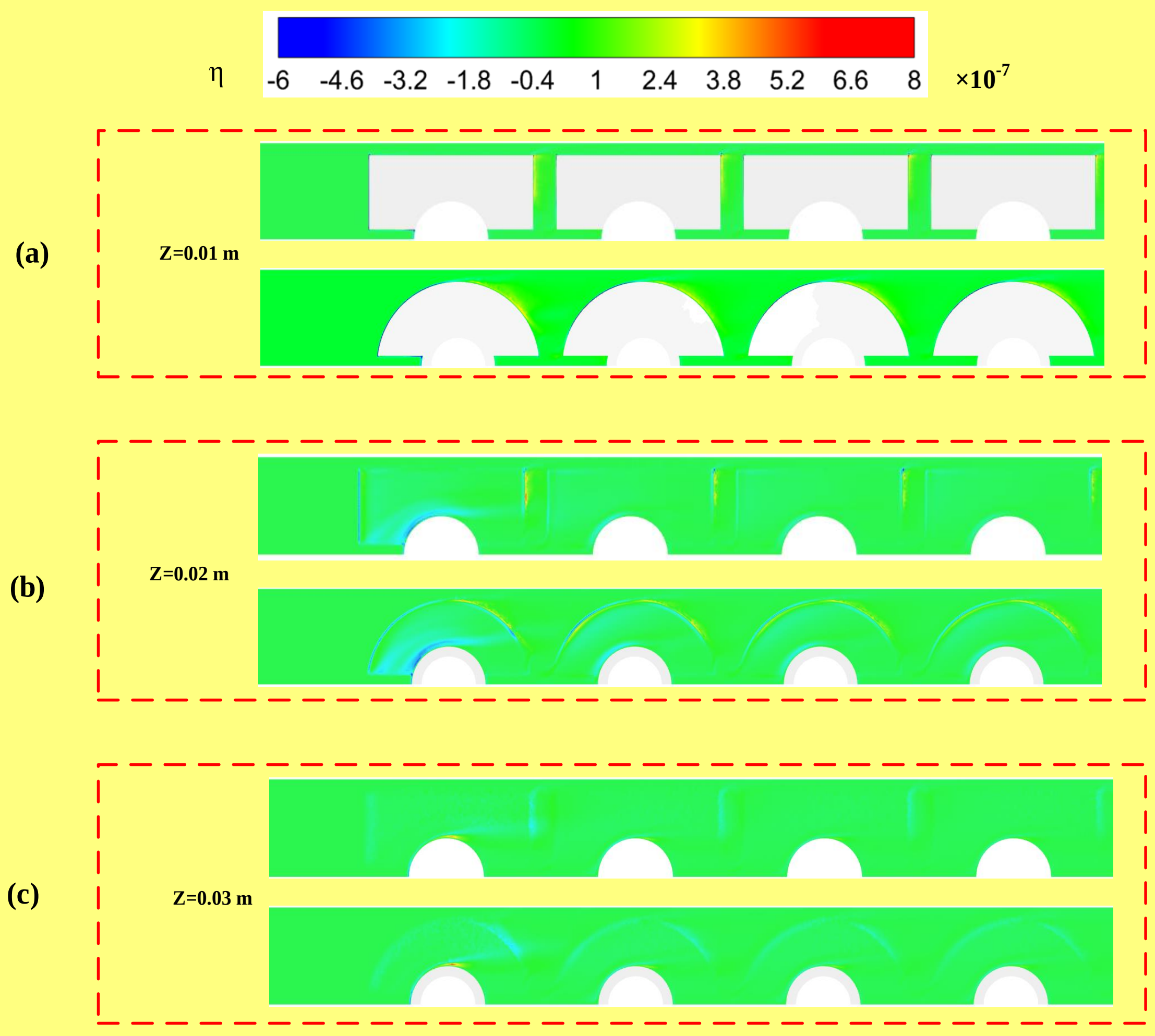

Fig. 2. Distribution Contours of the Thermo-hydraulic Synergy Number

Figure 2 shows the distribution contours of the thermo-hydraulic synergy number at the same Z-axis positions before and after optimization. Specifically, Figure 2(a) corresponds to the fin region (z = 0.01 m), where the positive effect zone is located at the windward front of the fin, and the negative effect zone is concentrated at the leeward end of the fin. After optimization using an arc-shaped structure, the extension of the leading-edge arc effectively enlarges the positive effect zone. Figure 2(b) corresponds to the region near the fin surface (z = 0.02 m), where a large positive effect zone appears on the windward side of the base tube. Following optimization, the area near the fin front is entirely covered by the positive effect zone with enhanced synergy intensity, while the negative effect zone near the fin end becomes more adjacent to the positive effect zone, resulting in weakened intensity. Figure 2(c) corresponds to the region away from the fin (z = 0.03 m), where the influence of the fin geometry diminishes, and the intensities of both positive and negative effects decrease. In this region, the negative effect zone is primarily observed near the flow separation point of the base tube.

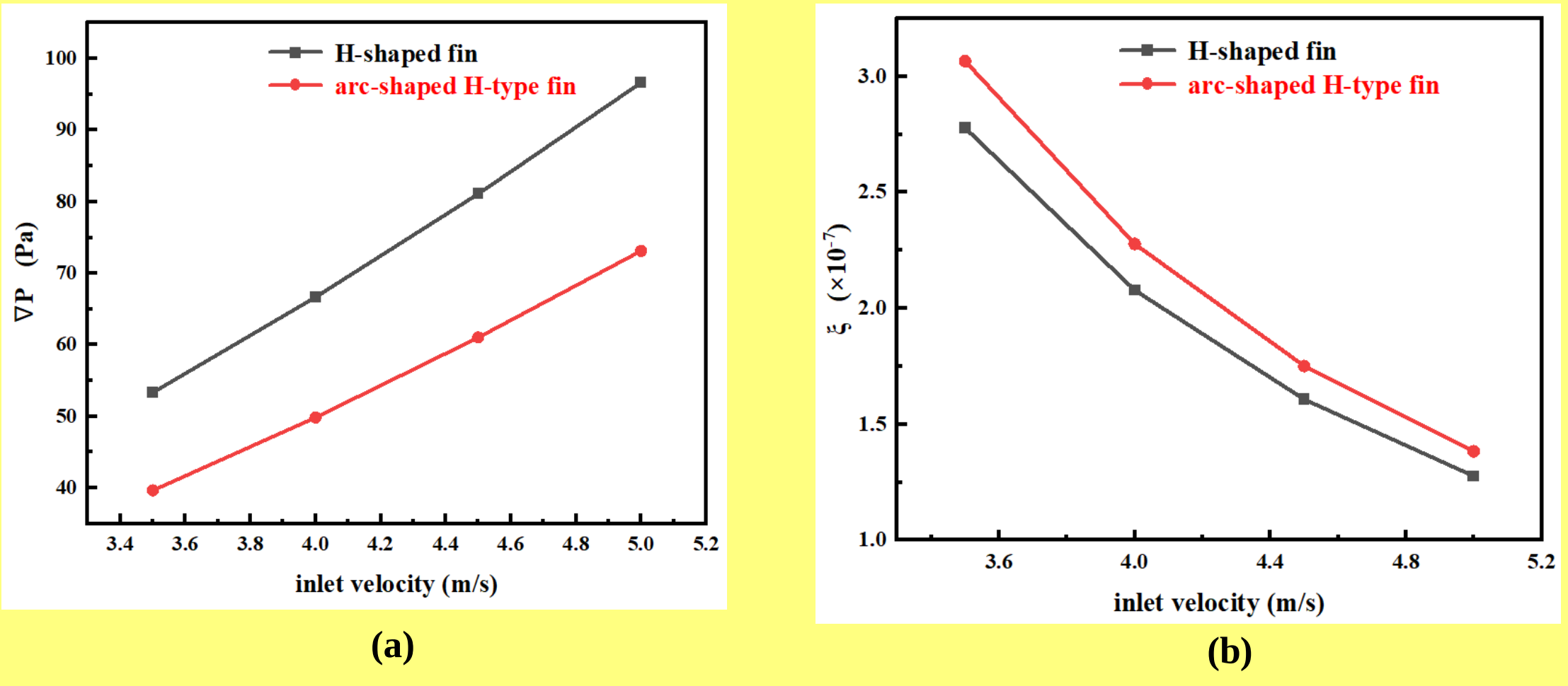

Fig. 3. H fin optimization: pressure drop and ξ comparison

As shown in Figure 3 (a), the pressure drop of both the H-type fin and the optimized arc-shaped H-type fin increases significantly, but the optimized fin reduces the pressure drop by about 25%. In Figure 3 (b), the comprehensive performance evaluation factor for both decreases sharply with increasing flow velocity, while the optimized fin improves the comprehensive performance by about 10%.

Conclusions

Based on the thermo-hydraulic synergy number η, this paper proposes a fin shape optimization strategy aimed at compressing the negative effect zone and expanding the positive effect zone, and conducts a numerical comparative study on the H-type fin and its arc-shaped optimized structure. The main conclusions are as follows:

(1) The positive effect zone is located on the windward side of the base tube and the leading edge of the fin, while the negative effect zone is concentrated at the leeward end of the fin and the separation point of the base tube.

(2) The arc-shaped structure extends the leading-edge curved surface, enlarging the positive effect zone, weakening the intensity of the negative effect zone, and making the boundary more compact.

(3) After optimization, the pressure drop is reduced by approximately 25%, and the comprehensive performance evaluation factor is increased by about 10%.

In summary, the performance diagnosis and shape optimization method guided by the local synergy number η can accurately identify the distribution characteristics of positive and negative effect zones, thereby achieving efficient and compact heat transfer surface improvement, providing a new technical pathway for the refined design of H-type finned tubes and other heat exchange components.

Acknowledgement

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References

[1] Xin, C.Y., et al., Local thermal-hydraulic synergy analysis of heat exchange tubes for convective heat transfer enhancement. International Communications in Heat and Mass Transfer, 2026. 175.

[2] Qin Lei, Lu Changxin, Xin Chengyun, et al. Analysis and Evaluation of Flow and Heat Transfer Performance of Integral Spiral Finned Tube Heat Exchanger [J]. Industrial Furnace, 2025, 47(05): 1-5.