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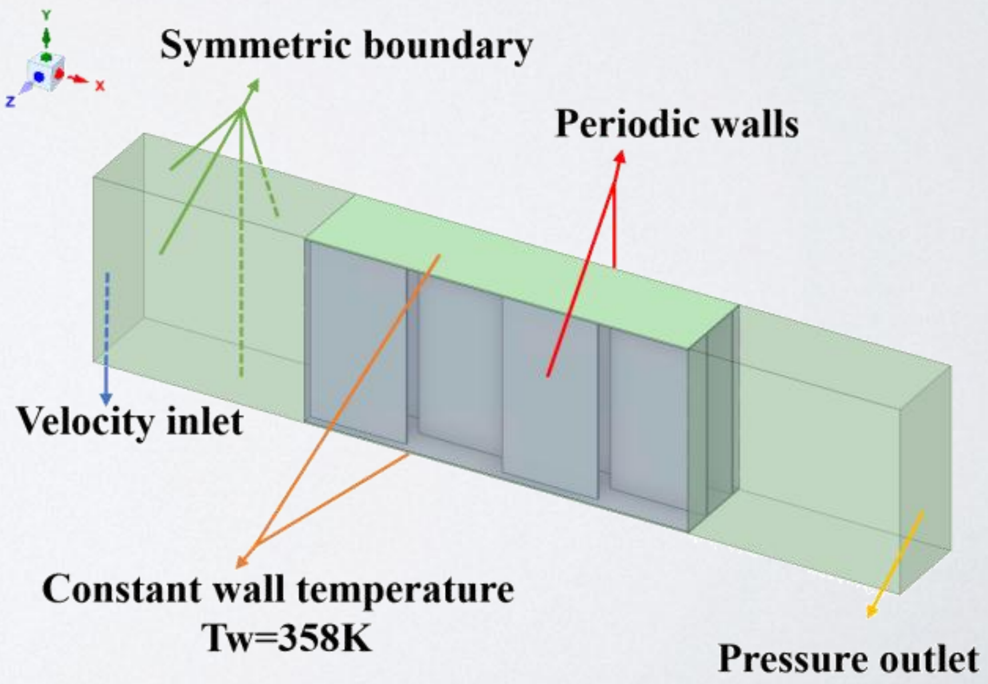
Performance analysis and optimization of staggered fin heat exchangers under varying altitudes using machine learning

Key words:

Staggered fins, High altitude, Machine learning, Improved NSGA-II algorithm



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Research Background and Core Challenges

High-altitude environment

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Deterioration of heat exchanger performance

- Altitude increase → Thinner air → Significant decline in heat transfer efficiency
- Staggered fins demonstrate better environmental adaptability

- Flow and heat transfer mechanisms inside fins remain poorly understood
- Traditional CFD simulations involve high computational costs and long cycles

Research Necessity:
Enhance operational reliability of special vehicles in complex plateau environments

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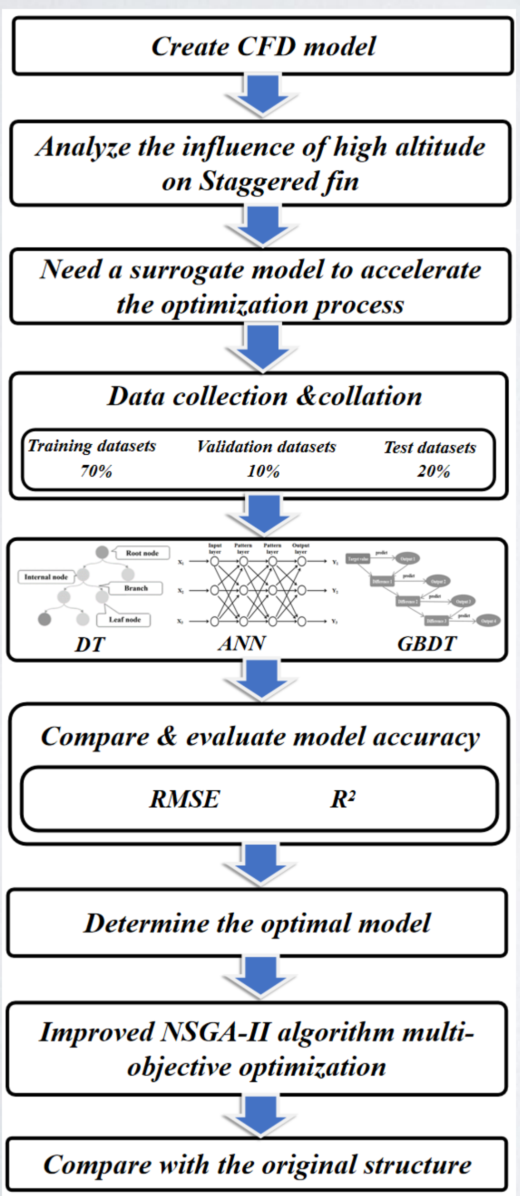
Research Methods and Technical Route

To address these conflicts, this study establishes an efficient collaborative framework integrating numerical simulation, machine learning, and multi-objective optimization, balancing computational efficiency and accuracy.



High-fidelity numerical simulation

- A high-precision 3D CFD model is established and validated against classic experimental data, with an average error below 10%.
- Coupled effects of altitude (0–5000 m) on internal flow and heat transfer are systematically analyzed.

Machine learning surrogate model

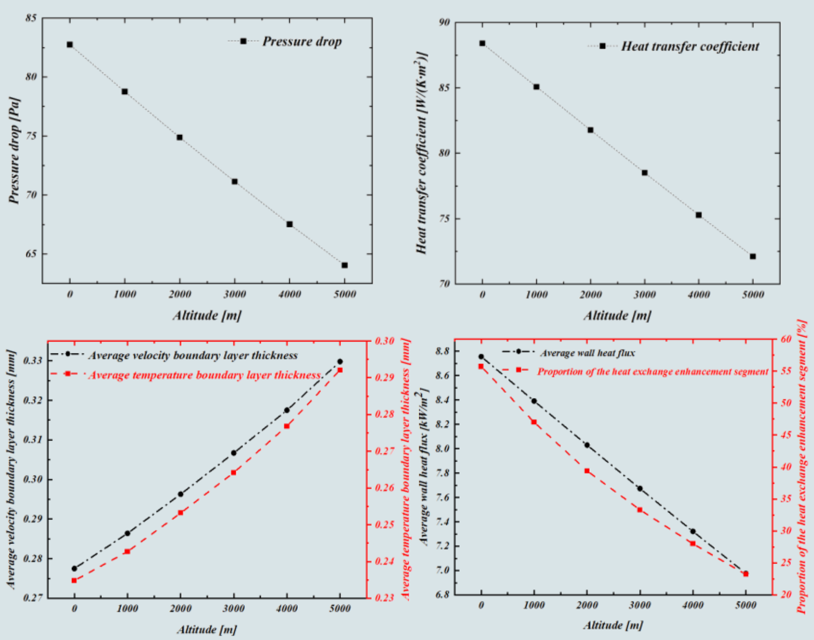
- A high-dimensional dataset of 180 cases is generated from CFD results.
- Three algorithms, DT, ANN and GBDT, are compared in performance.
- GBDT is selected as the optimal surrogate with $R^2 \approx 1.0$ for fast prediction.

Efficient multi-objective optimization

- The trained GBDT model is coupled with improved NSGA-II for optimization.
- Adaptive crossover and mutation are adopted to accelerate convergence.
- Two objectives are optimized to obtain the Pareto optimal solution set.

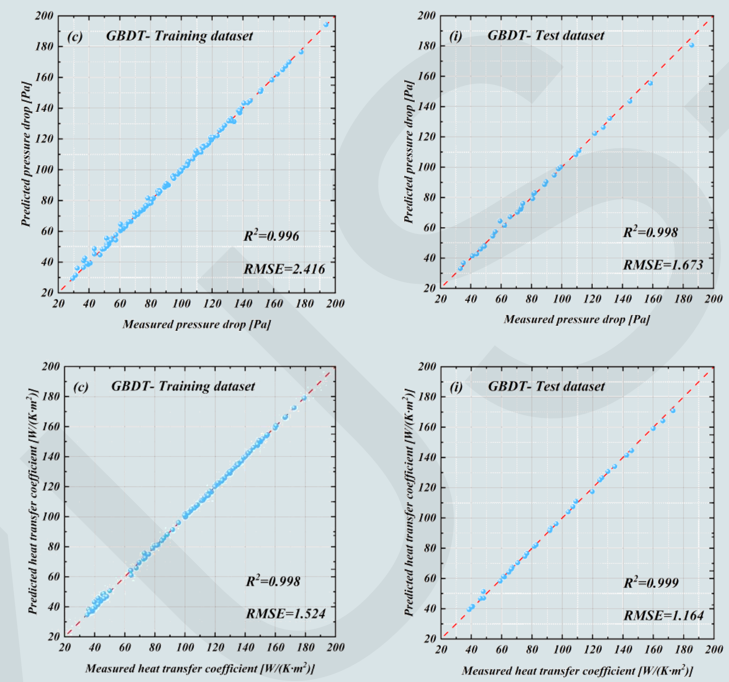
Core Findings and Optimization Results

Revealing the micro-mechanism of performance degradation



Increased altitude reduces air density, thickening boundary layers. At 5000m: velocity BL +**19%**, temperature BL +**24%**. This "insulation layer" causes degraded heat transfer.

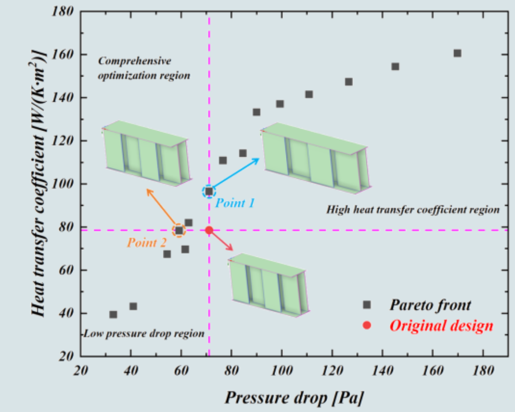
Superior performance of ML model

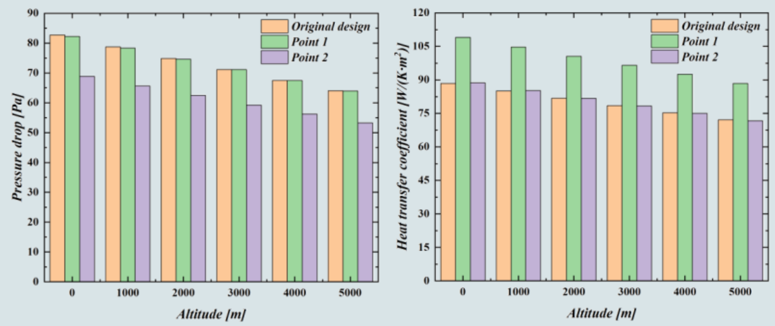


High-Precision Prediction Matches CFD results

$R^2 \approx 1.0$

Superior performance of ML model





Heat transfer coefficient increased:

+ 23%

Pressure drop reduced

- 17%

Conclusions and Outlook

1. Main conclusions

Mechanism revealed:

Clarified the internal mechanism of performance degradation due to boundary layer thickening.

Method innovation:

Successfully constructed a machine learning optimization framework, overcoming traditional CFD bottlenecks.

Significant results:

Achieved remarkable structural optimization, providing valuable design references.

2. Significance & value

Technological breakthrough:

Opened a new path for rapid, efficient design of high-altitude adaptive thermal equipment.

Application prospect:

Guides next-gen radiator R&D, enhancing vehicle reliability in complex environments.

3. Future outlook

Method expansion:

Extend the framework to other heat exchangers and complex multi-physics problems.

Model deepening:

Explore advanced deep learning models for more intelligent autonomous optimization.