Journal of Electronic Research and Application, 2025, Volume 9, Issue 7
http://ojs.bbwpublisher.com/index.php/JERA
ISSN Online: 2208-3510
ISSN Print: 2208-3502

Optimization Strategy of Heat Pump Product Structure from the Perspective of Mechanical Design

Zhipeng Liu*

Guangzhou 510000, Guangdong, China

**Author to whom correspondence should be addressed.*

Abstract: Mechanical design is of great significance to the structural optimization of heat pump products. The key components of the heat pump cooperate to realize heating or cooling based on the reverse Carnot cycle. Its structural optimization involves material mechanical properties, tolerance fit, dynamic load analysis, etc. Through the integration of topology and parametric design, heat transfer interface optimization and other methods, the structural strength, heat transfer efficiency, reliability and other factors are comprehensively considered, and the optimization is realized through experiments and monitoring, which provides support for the industrial application of heat pump.

Keywords: Heat pump products; Mechanical design; Structural optimization

Online publication: December 31, 2025

1. Introduction

With the release of the "Action Plan for Improving Energy Efficiency of Heat Pump Systems (2021–2023)" in 2021, the importance of optimizing the structure of heat pump products and improving the energy efficiency of heat pump systems has become increasingly prominent. The heat pump system is composed of multiple key components working together to achieve heat transfer based on the reverse Carnot cycle. In its structural design, material mechanics properties, tolerance fit, dynamic load analysis, etc. are all key points. By integrating topology optimization and parametric design methods, optimization is carried out from multiple aspects such as heat transfer interface, channel structure, and vibration suppression. At the same time, research is being conducted on new compressor bracket experiments, modular design energy efficiency testing of heat exchangers, etc., balancing structural strength and heat transfer efficiency, defining optimization domains under reliability constraints, using genetic algorithms, neural network prediction models, etc. to achieve multi parameter collaborative optimization and energy efficiency prediction, and providing support for optimization through full lifecycle cost assessment and long-term performance monitoring of actual operating conditions, promoting heat pump products to meet market demand.

2. Theoretical basis for structure and mechanical design of heat pump products

2.1. Structure composition and working principle of heat pump system

The heat pump system mainly consists of key components such as compressor, heat exchanger (evaporator and condenser), and expansion valve. As the core of a heat pump, the compressor compresses low-temperature and low-pressure gaseous refrigerant into high-temperature and high-pressure gaseous refrigerant, enhancing the energy of the refrigerant. The evaporator is located on the low-temperature heat source side, absorbing external heat to transform the refrigerant from liquid to gas. The condenser is located on the high-temperature heat source side, where the high-temperature and high-pressure gaseous refrigerant releases heat and condenses into a liquid state. Expansion valves can regulate the flow rate of refrigerant, transforming it from high-pressure liquid to low-pressure liquid, preparing for the heat absorption process of the evaporator. These components work together, based on the principle of reverse Carnot cycle, to transfer heat from low-temperature environment to high-temperature environment, thereby achieving the purpose of heating or cooling. The compressor provides power, the evaporator and condenser complete heat exchange, and the expansion valve controls the refrigerant circulation to ensure the efficient and stable operation of the heat pump system [1].

2.2. Technical requirements for mechanical design in heat pump structures

The mechanical properties of materials play a crucial role in the design of heat pump structures. The strength, stiffness, and toughness of different materials directly affect the ability of various components of the heat pump to withstand pressure, tension, and deformation. It is necessary to select materials reasonably based on the actual stress situation of the components to ensure that they do not undergo damage or excessive deformation during long-term operation [2]. The principle of tolerance fit is equally important. Accurate tolerance control can ensure good assembly relationships between components, reduce vibration and wear caused by improper fit, and improve overall stability and reliability. A tolerance that is too small increases manufacturing costs, while a tolerance that is too large affects performance. It is necessary to weigh and determine a reasonable tolerance range. In addition, dynamic load analysis is indispensable. During operation, heat pumps are subjected to various dynamic loads, such as the impact of compressor start and stop, fluid flow pulsation, etc. By accurately analyzing dynamic loads, optimizing structural design, and enhancing component fatigue resistance, the heat pump can operate reliably under complex working conditions.

3. Optimization method for heat pump structure driven by mechanical design

3.1 Integrated topology optimization and parametric design methods

The integration of topology optimization and parametric design methods is of great significance in the structural optimization of heat pumps driven by mechanical design. Topology optimization can find the optimal distribution form of materials within a given design space based on mechanical, thermal, and other performance requirements, in order to maximize structural performance. For example, determining the optimal material layout for key components of heat pumps such as compressor casings can reduce weight while meeting strength and other conditions [3]. The parametric design method can establish a relationship model between structural parameters and performance, and use 3D modeling software to perform parameter driven optimization design on heat pump flow channels and other structures. By changing relevant parameters such as the diameter, length, and curvature of the flow channel, different schemes can be quickly generated, and combined with finite element simulation technology, the impact of each scheme on the performance of the heat pump can be analyzed to select the best scheme, optimize the flow channel, and improve the overall performance of the heat pump.

3.2. Optimization strategy for mechanical structure of heat transfer interface

In terms of optimizing the mechanical structure of the heat transfer interface, the adjustment of the geometric parameters of the fins has a significant quantitative impact on the heat transfer efficiency. By carefully changing the shape, spacing, height, and other parameters of the fins, the heat transfer effect can be effectively improved. For example, appropriate fin spacing can avoid airflow blockage, enhance convective heat transfer between air and heat transfer medium, and thus improve heat transfer efficiency [4]. Meanwhile, the improvement of the sealing structure has a significant impact on enhancing the energy efficiency of the system. The optimized sealing structure can reduce the leakage of working fluid in the system, lower energy loss, and ensure the stable and efficient operation of the heat pump system. For example, by using new sealing materials and sealing forms, the sealing performance can be improved to maintain a good pressure environment during the operation of the system, thereby improving the overall energy efficiency of the system and optimizing the heat pump product from the perspective of the mechanical structure of the heat transfer interface.

4. The impact mechanism of structural optimization on thermal energy management

4.1. Coupling analysis of mechanical structure and thermodynamic performance

4.1.1. The influence of channel structure on the flow characteristics of working fluid

In heat pump products, the channel structure has a significant impact on the flow characteristics of the working fluid. Different pipe diameter ratios and bending radii can alter the flow velocity distribution and pressure loss of the working fluid [5]. A smaller diameter ratio may lead to an increase in the flow rate of the working fluid, but at the same time, it will also increase pressure loss, which will affect the efficiency of heat transfer. If the diameter ratio is too large, although the pressure loss may decrease, the flow rate of the working fluid slows down, which is not conducive to the rapid transfer of heat. In terms of bending radius, a smaller bending radius will cause a drastic change in the flow direction of the working fluid, generate more local resistance, increase pressure loss, and may lead to uneven flow velocity distribution, affecting the effectiveness of thermal energy management. On the contrary, a larger bending radius can make the flow of the working fluid smoother, reduce pressure loss, and make the flow velocity distribution more uniform, which is conducive to efficient transfer and management of thermal energy. By quantitatively evaluating these factors through CFD simulation, we can gain a deeper understanding of the influence of channel structure on the flow characteristics of the working fluid, providing a basis for optimizing the structure of heat pump products.

4.1.2. Improvement of thermal stability by vibration suppression structure

In heat pump products, vibration suppression structures play a crucial role in improving thermal stability. From the coupling analysis of mechanical structure and thermodynamic performance, vibration can cause displacement and friction of internal components of the heat pump, thereby affecting heat transfer and system operation stability, leading to temperature fluctuations [6]. A well-designed vibration suppression structure can effectively reduce the amplitude of vibration. For example, by installing damping devices at critical locations, vibration energy can be consumed, component looseness and displacement caused by vibration can be reduced, and the stability of the internal heat transfer channels of the system can be maintained. This makes heat transfer smoother, avoiding local overheating or undercooling, thereby reducing the fluctuation range of system operating temperature, improving thermal stability, ensuring efficient and stable operation of heat pump products, and achieving more accurate thermal energy management.

4.2. Energy efficiency verification of typical optimization schemes

4.2.1. Experimental study on the structure of a new compressor bracket

Conduct experimental research on the new compressor bracket structure, mainly comparing the performance differences between traditional and optimized brackets in terms of vibration transmission rate and thermal deformation. In the experiment, the vibration transmission rate of two types of supports under different working conditions was accurately measured to evaluate their impact on the stability of compressor operation. The measurement of thermal deformation focuses on the deformation of the bracket in high-temperature environments, as this directly affects the efficiency of thermal energy transfer. Through experimental data, it can be found that the optimized bracket vibration transmission rate is significantly reduced, which helps to reduce energy loss caused by vibration and improve system stability [7]. At the same time, the amount of thermal deformation is effectively controlled, making the transfer of thermal energy more efficient and reducing heat transfer obstacles caused by structural deformation. From this, it can be seen that the optimization of the new compressor bracket structure has a positive impact on thermal energy management from both vibration and thermal deformation aspects, providing strong support for the energy efficiency improvement of heat pump products.

4.2.2. Energy efficiency testing of modular design of heat exchangers

In the optimization of heat pump product structure from the perspective of mechanical design, energy efficiency testing of modular design of heat exchangers is crucial. The detachable heat exchanger structure, as a typical optimization scheme, has a significant impact on system thermal energy management and energy efficiency. Through standard operating condition testing, the improvement effect of the design on the system COP value can be accurately verified. Moreover, simulate the standard operating conditions of the heat pump during testing, control key parameters such as ambient temperature, humidity, fluid flow rate, and temperature to ensure consistency and accuracy of the testing environment. Under this operating condition, compare the traditional heat exchanger with the modular designed detachable heat exchanger, analyze the cooling or heating capacity, input power and other data of the system, and calculate the COP value. Research has found that modular design can effectively improve the heat transfer efficiency of heat exchangers, thereby increasing the system COP value, optimizing thermal energy management, and providing strong energy efficiency basis for optimizing the structure of heat pump products [8].

5. Construction of multi-objective collaborative optimization strategy

5.1. Balance model between mechanical performance and thermal efficiency

5.1.1. Game analysis of structural strength and heat transfer efficiency

There is a complex game relationship between structural strength and heat transfer efficiency in the structural optimization of heat pump products from the perspective of mechanical design. The wall thickness parameter is a key factor affecting both. On one hand, increasing wall thickness can usually enhance structural strength and provide a solid guarantee for the stable operation of heat pumps, but it may increase thermal resistance due to the increase in materials, reduce heat transfer efficiency, and affect heat exchange efficiency. On the other hand, although reducing wall thickness is beneficial for heat transfer and improving heat transfer efficiency, it may weaken the structural strength and pose a risk of deformation or even damage to the product during operation. To achieve a reasonable balance between the two, it is necessary to conduct in-depth analysis of relevant parameters such as wall thickness, establish accurate mathematical models, and use optimization algorithms for multi-objective collaborative optimization, balancing the requirements of structural strength and heat transfer efficiency under different working conditions, in order to find the best design parameters, so that heat pump products can achieve efficient heat transfer and improve overall performance while having good mechanical performance [9].

5.1.2. Optimization domain definition under reliability constraints

In the structural optimization of heat pump products from the perspective of mechanical design, defining the optimization domain under reliability constraints is crucial. Reliability is the key to the stable operation of heat pumps, which constrains the optimization range of mechanical performance and thermal efficiency. From the perspective of mechanical performance, reliability indicators such as strength and stiffness of components under long-term complex working conditions should be considered. For example, the piston of a heat pump compressor needs to ensure that it does not break or deform excessively under high pressure and high-frequency motion [10]. In terms of thermal efficiency, it is necessary to balance the reliability of heat transfer and conversion, and avoid heat loss or reduced conversion efficiency due to unreasonable structure. By comprehensively evaluating various reliability factors related to mechanical performance and thermal efficiency, using mathematical models and simulation techniques, the region that meets reliability requirements and achieves balanced optimization of mechanical performance and thermal efficiency is defined. This optimization domain provides accurate range guidance for further improving mechanical performance and thermal efficiency while ensuring the reliable operation of heat pump products in the future.

5.2. The application of intelligent algorithms in structural optimization

5.2.1. Parameter optimization driven by genetic algorithm

Genetic algorithm plays an important driving role in the multi-parameter collaborative optimization of compressor cavity structure in heat pump products. Based on the NSGA-II algorithm, key parameters such as the geometric dimensions and wall thickness of the cavity are encoded as genes. For instance, simulate the selection, crossover, and mutation operations in biological genetics, and continuously evolve these parameters. By selecting operations, individuals with high fitness are retained, that is, those parameter combinations that make the compressor performance better. Cross operation allows for information exchange between different parameter combinations to explore better solutions. Mutation operations increase population diversity and avoid falling into local optima. In each iteration, evaluate the impact of different parameter combinations on the structural performance of the compressor chamber, such as heat transfer efficiency, pressure loss, and other multi-objective functions. Ultimately, continuously evolve the population and ultimately find a set of parameters that can balance and optimize the compressor chamber structure across multiple performance indicators, thereby achieving optimization of the heat pump product structure from a mechanical design perspective.

5.2.2. Construction of neural network prediction model

The construction of neural network prediction models is crucial for structural optimization of heat pump products from a mechanical design perspective. Firstly, collect a large amount of system energy efficiency index data for different structural schemes of heat pump products, covering multidimensional information such as structural parameters and operating conditions. Next, preprocess these data, including data cleaning, normalization, etc., to improve data quality. Choose a suitable neural network architecture, such as multi-layer perceptron or convolutional neural network, and adjust it according to the structural characteristics of the heat pump product. By training the model, adjusting the network weights and biases to accurately map the relationship between structural schemes and energy efficiency indicators. During the training process, cross validation is used to avoid overfitting and improve the model's generalization ability. Eventually, a high-precision neural network prediction model was constructed to provide reliable energy efficiency index predictions for optimizing the structure of heat pump products and assist in subsequent optimization decisions.

5.3. Industrial application verification system

5.3.1. Whole life cycle cost assessment model

In the structural optimization of heat pump products from the perspective of mechanical design, the full lifecycle cost assessment model is crucial. This model takes into account multiple aspects such as manufacturing costs, maintenance expenses, and energy consumption expenditures. The manufacturing cost covers the costs of raw material procurement, component processing, and assembly, and its level directly affects the initial investment of the product. The maintenance cost involves daily maintenance, fault repair, and replacement of parts, reflecting the continuous investment during the use of the product. Energy consumption expenditure reflects the energy consumption cost during product operation and is closely related to product energy efficiency. By constructing a full lifecycle cost assessment model, the cost situation of heat pump products throughout their entire lifecycle can be analyzed as a whole, providing data support for multi-objective collaborative optimization strategies, helping to find the optimal balance between cost and performance, and promoting the economic feasibility and market competitiveness of heat pump products in industrial applications.

5.3.2. Long-term performance monitoring under actual working conditions

Long-term performance monitoring of heat pump products is crucial under actual operating conditions. Multiple sets of sensors need to be deployed in different types of industrial sites based on actual working conditions to comprehensively collect key parameters during the operation of heat pumps, such as temperature, pressure, flow rate, etc. Continuously monitor these parameters for a long time, analyze their trends over time, and determine whether the optimized structure remains stable during long-term operation. For example, observing the performance changes of compressors under long-term high-frequency operation, and the fluctuations in heat transfer efficiency of evaporators and condensers under different operating conditions. Through long-term monitoring data, we can gain a deep understanding of the durability and stability performance of optimized structures in actual working conditions, providing strong basis for further improvement and ensuring that heat pump products can operate stably and efficiently in industrial applications, meeting actual production needs.

6. Conclusion

Mechanical design is of great significance for optimizing the structure of heat pump products. In the optimization of heat pump structure, the key technical path of mechanical design summarized by the system provides clear guidance for optimization work. Intelligent design endows heat pump products with stronger performance and adaptability, while the application of new materials fundamentally improves product quality and efficiency. Both will become important driving forces for the future development of heat pump products. The construction direction of a full parameter optimization system based on digital twins is highly forward-looking. With the help of this technology, comprehensive and accurate optimization of heat pump products can be achieved, significantly improving product performance and market competitiveness. In the future, we should further explore the potential of mechanical design methods in optimizing the structure of heat pump products, strengthen intelligent design and the application of new materials, accelerate the construction of full parameter optimization systems based on digital twins, and promote the continuous advancement of heat pump product structure optimization to new heights, in order to meet the market's demand for efficient, energy-saving, and environmentally friendly heat pump products.

Disclosure statement

The author declares no conflict of interest.

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