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Analysis of Industrial Air-Cooled Radiators and Research on Performance Optimization Techniques

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Abstract:
With the increasing power density of industrial equipment, the heat flux density is also rising, making the heat dissipation issue of electronic components increasingly prominent. Currently, air-cooled radiators and liquid-cooled radiators are the main solutions for component heat dissipation. Unlike liquid-cooled radiators, air-cooled radiators have absolute advantages such as independent heat dissipation, low cost, easy installation, and maintenance-free operation. However, compared with liquid-cooled radiators, their insufficient heat dissipation capacity is a drawback, especially the high power and high heat components. This paper studies the types of profile radiators and heat pipe radiators, analyzes the principles and characteristics of flat-fin, corrugated-fin, louver-fin radiators. It explores performance improvement methods from material, structure and technology aspects. The research shows that selecting the appropriate type and comprehensive optimization can enhance performance, and air-cooled radiators will use disciplinary integration to develop towards high-performance and intelligent directions in the future. In order to solve the above problems, based on existing research, this article first analyzes in detail the common air-cooled radiators, including their structural characteristics, heat transfer principles, and performance comparisons. Next, explore performance improvement methods from the aspects of material innovation, structural optimization and intelligent assistance.

Keywords: Air-Cooled Radiator; Heat Pipe; Flat-Fin; Corrugated-Fin; Louver-Fin.

1. Introduction

Modern industrial equipment is becoming increasingly integrated and powerful, which means that the core components and chips of the equipment will generate more heat. In the fields of data centers, power electronics, and high-performance computing, these systems can maintain stable operation, extend service life, and improve overall efficiency by optimizing heat dissipation [1]. Although a considerable number of devices in the highly integrated data center field have recently replaced air-cooled radiators with liquid cooled ones to meet high-intensity heat dissipation requirements, air-cooled radiators still maintain a crucial position in the field of industrial equipment heat dissipation. Air-cooled radiators are widely used in industry. Compared with liquid cooling systems, they have lower costs. They are also easy to install and do not require complex maintenance work. But with the increasing demand for cooling performance in industry, we must research and improve air-cooled radiators. While leveraging the various advantages of air-cooled radiators, we must further enhance their heat dissipation performance to meet the stringent requirements of new equipment.

In China, the research and development of air-cooled radiators has gone through a long process. Scientists here have been working mainly on two fronts: developing new materials and improving designs. For example, they have tried using aluminum alloys to enhance the heat dissipation performance of radiators [2]. In terms of design, they continuously test new fin shapes to accelerate the heat transfer rate. Breakthroughs have also been made in product processing techniques. In recent years, in addition to traditional extruded profile air-cooled radiators, plug-in radiators and shovel-tooth radiators have been widely promoted and applied in new energy fields such as photovoltaics and wind power. For cases where radiators relying solely on aluminum or the same fins cannot achieve the required heat dissipation performance, the heat dissipation effect is achieved by changing the fin shape or adding heat pipes on the component mounting surface. Looking at the radiators used in photovoltaic inverters, for 50KW low-power modules, most can solve the heat dissipation problem with aluminum shovel-tooth radiators or plug-in radiators. However, for 220KW-400KW high-power string-type photovoltaic inverters, the form of shovel-tooth radiators combined with heat pipes is required to meet the heat dissipation requirements of the components.

Overseas, research progress is equally rapid. Scientists in developed countries often focus on incorporating new technologies into radiator designs. For example, microchannel heat pipe radiators have become one of the most promising cooling technologies, attracting extensive research due to their excellent heat transfer performance [3]. Just recently, a research team from the University of Tokyo in Japan also invented a new type of microchannel radiator. They found that the shape of microchannels and the distribution of coolant in the system have a significant impact on thermal performance and fluid dynamics. By ensuring continuous flow of water and steam, the team achieved a coefficient of performance (COP) of up to 100000, which is 7 times higher than traditional solutions in terms of thermal conductivity efficiency. While retaining various advantages, further improving heat dissipation efficiency to meet the heating needs of high-power chips. Different from domestic research, many interdisciplinary studies integrate knowledge from fields such as fluid dynamics, materials science, and electronic technology. This integration has promoted the advancement of heat dissipation technology in a unique way.

2. Core Explanation and Forward-Looking Technology of Industrial Air-Cooled Radiators

2.1 Types of Air - Cooled Radiators

2.1.1 Profile radiators - flat-fin radiators

The structure of flat - fin radiators is as follows. They are composed of a base plate and parallel flat fins. The base plate, typically crafted from high - conductivity materials like aluminum or copper, serves as the primary heat collector from components. The rectangular fins arrange side by side vary in size, length, width, thickness, and spacing. All of them directly impact cooling performance.

As for the principle, the core function of flat-fin radiators is to maximize heat-dissipation area. When air passes over the fins, heat transfers from the hot surface to the cooler air via convection. This process adheres to Newton's law of cooling, where the heat-transfer rate depends on the temperature difference, heat - transfer coefficient, and surface area. In fact, a larger fin surface area allows for more contact with the air, enhancing heat removal. However, if the surface area is too large, it can cause air resistance to increase, leading fans to consume more energy and potentially causing noise issues.

Here are advantages and disadvantages. These radiators have the characteristics of simplicity, affordability, and ease of maintenance. Their straightforward design reduces manufacturing costs and simplifies repairs. However, their flat fin structure creates smooth airflow. It limits turbulence and heat-transfer efficiency. So flat-fin radiators often struggle to meet high-power cooling needs.

2.1.2 Profile radiators - corrugated-fin radiators

Corrugated-fin radiators are structurally more complex

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than flat-fin types. Their fins feature a wavy, corrugated design, with key parameters like amplitude, wavelength, and height directly impacting heat-transfer performance. These geometric variables not only expand the surface area for heat exchange but also alter airflow dynamics. For example, an equilateral triangular design that maximizes both surface exposure and structural feasibility can be created by a 60° corrugation angle, which can double the effective surface area when compared to flat fins of the same base dimensions [4].

About principle, the corrugated structure can enhance air turbulence. When air flows through the corrugated fins, the corrugated structure changes the air flow state, resulting in increased turbulence of the air and breaking the laminar boundary layer on the fins' surface. It improves the contact between the air and the fin surface, thereby improving the heat transfer coefficient and enhancing the efficiency of heat-dissipation.

These radiators have two key benefits, enhanced heat-dissipation and higher space efficiency. They are suitable for compact industrial setups. However, their complex geometric structure is a hassle. They require double the material of the flat fins which will double the cost per fin and take far longer to fabricate. For instance, to make the corrugated fins, four 3'x3' sheets will be bent 36 times (every 2 inches) each to make the corrugations taking an estimated 10 minutes per sheet and then cut taking 40 minutes for a total estimated fabrication time of 80 minutes. Additionally, the corrugated structure increases airflow resistance. It often necessitates more powerful fans that may raise energy consumption and noise levels.

2.1.3 Profile radiators - louver-fin radiators

Louver-fin radiators are defined by their distinctive louver-shaped fins. The key structural parameters include the louver angle, length, and opening size. For instance, a typical automotive radiator design employs a louver angle (La) of 28°, a louver pitch (Lp) of 0.0012 m, and a louver length (Ld) of 0.0366 m [5]. This configuration uses louvers as guide blades, which can guide the airflow to be more evenly distributed on fins' surface. In addition, the louvers' precise geometry, such as their angled orientation and spacing, has a direct impact on both heat transfer efficiency and airflow dynamics.

This principle is different from the last two. The louver structure enhances heat exchange by expanding the heat-transfer area and disrupting airflow boundary layers. The louvers guide the air to flow along a specific path. They make the contact between the air and the fins' surface more consistent, which breaks the laminar flow and increases turbulence. This turbulence effectively boosts the heat transfer coefficient [5].

Now I will introduce about advantages and disadvantages. These radiators perform well in high-power heat dissipation and have strong resistance to dust clogging. So they are suitable for harsh industrial environments. However, the louvered design causes a significant increase in airflow resistance. The pressure drop also increases with the increase in air through radiator. In addition, due to the complex structure between the louver fins, air flow can be reduced in certain areas, which can lead to uneven heat transfer locally and affect overall efficiency.

2.1.4 Heat pipe radiators

In structure, heat pipe radiators consist of three core components: heat pipes, heat-dissipation fins and housing. The heat pipes are usually metal tubes made of copper or aluminum. There is a porous wick structure inside, such as sintered powder and mesh. In addition, the heat pipes will be filled with liquid like water, ammonia and so on. The heat-dissipation fins are always extruded aluminum sheets attached to the condenser end. They can further increase the heat - transfer area. Finally, the housing is a protective casing. It encloses the components and has airflow channels designed for forced or natural convection.

This principle is also different. The heat pipes operate on a phase-change heat transfer mechanism. Here's a step-by-step breakdown:

1. Evaporation Stage: When the evaporator end of the heat pipe is heated, the working fluid absorbs heat and turns into vapor.
2. Vapor Migration: The vapor rises toward the condenser end due to a pressure difference.
3. Condensation Stage: At the cooler condenser end, the vapor releases heat and turns back into the liquid.
4. Liquid Return: The porous wick structure uses capillary force to pull the liquid back to the evaporator and the cycle is completed.

If comparing advantages and disadvantages, the significant advantage of heat pipe radiators is the high heat-transfer efficiency. They can maintain uniform temperature over long distances. They are appropriate for situations where heat needs to be transported from small areas to distant locations, like centralized heat dissipation for electronic devices. But their manufacturing process is very complex, so the cost and maintenance difficulties are relatively high. In addition, the aging of the internal liquid will also affect the life of radiators.

2.2 Approaches to Improve the Performance of Air - Cooled Radiators

2.2.1 Material - related improvements

Application of New Heat - Dissipation Materials are increasingly focused on novel thermal management materials, such as metal-matrix composites and nanoporous materials. Firstly, the metal-matrix composites integrate high strength to metals with the excellent thermal conductivity of filler materials. This material can significantly improve the heat-dissipation performance of the radiator. For example, carbon nanotubes have a thermal conductivity of up to 6000W m-1 K-1[6], and when incorporated into metal matrices like magnesium or nickel, they can enhance the composite's thermal conductivity by up to 200% [6]. Secondly, Nanoporous materials are known for their unique pore structure. It also enhances their heat transfer performance. The nanoscale pores of this material significantly increase its specific surface area, thereby improving heat transfer efficiency. They have good thermal stability and environmental characteristics, so they have great prospects in the field of high-power electronic devices in the future

The surface treatment technology is like this. Optimizing the surface characteristics of thermal materials is another critical approach. These techniques include anodizing, electroplating and specialized thermal spraying. Anodizing is generally particularly effective for aluminum. It can form a durable oxide layer on the surface. Electroplating is the process of depositing a thin and highly thermally conductive metal coating onto the base materials. Thermal spraying can be used to apply heat-dissipation coatings with special properties. These three techniques can significantly improve corrosion resistance of heat - dissipation materials and surface emissivity.

2.2.2 Structural improvements

Optimizing the fin structure is an important way to improve the performance of air-cooled radiators. According to the research of Yardi and others, reducing the fin spacing from 28 mm to 20.5 mm can significantly improve the heat transfer efficiency. Finally, the optimal spacing range was determined to be between 20.5 mm and 16 mm (applicable to base plates of 110 mm x 107 mm) [7], because it can better increase the surface convection area. However, when the spacing is less than 16 millimeters, heat transfer will decrease, possibly due to increased air flow resistance. Using data simulation to demonstrate that at Δ T=15°C, 25°C and 60°C, a spacing of 20.5 mm (five-fin sample) can achieve the highest heat transfer efficiency [7].

Air-duct design improvement is equally critical. A reasonable air-duct design can guide the air flow, reduce the air resistance, and improve heat-dissipation efficiency. Material costs and energy losses are higher when ducts are oversized, and poor airflow and increased energy consumption due to higher fan power requirements are caused by undersized ducts. For air-cooled radiators, optimizing the position and shape of the air inlet and outlet, and adding the air deflectors can make the air flow more evenly cover the radiators' surface.

2.2.3 Other improvements

We can think of some fan performance enhancement. Choosing the high-performance fans is crucial for air-cooled radiators. Fan parameters such as air volume, air pressure, rotation speed and noise all affect the heat-dissipation. New fan technologies like magnetic levitation fans have many advantages. For example, the magnetically levitated impeller has no contact with the stator, so the lifespan of the machine can be significantly improved (the failure rate within 10 years is less than 2.5%) [8]. Also, magnetic levitation fans technology can adapt well to harsh environments because they can operate between -10°C and 60°C and dust rarely enters [8]. In addition, they have very low power consumption (power consumption at 0 rpm is only 1.7W) [8].

Intelligent control technology can be utilized in air-cooled radiators to strike a balance between energy conservation and efficient heat dissipation. The fan rotation speed can be adjusted automatically based on the equipment temperature or the opening and closing of air-duct valves can be controlled. This technology not only ensures heat-dissipation efficiency, but also effectively suppresses ineffective energy consumption.

3. Conclusion

This paper shows different types of air-cooled radiators including profile radiators (flat-fin, corrugated-fin, louver-fin) and heat pipe radiators comprehensively. Each radiator has distinct structural characteristics, working principles, and advantages and disadvantages. In addition, the performance of air-cooled radiators has been improved through the exploration of effective methods on material, structure, and other aspects through research and experimentation. It is found that selecting the appropriate type can significantly improve its heat-dissipation performance. In the future, continual innovation and breakthroughs in interdisciplinary fields are crucial for improving air-cooled radiators' performance limits and adapting to increasingly complex application requirements. For example, materials science can develop intelligent and adaptable materials. These materials can actively change their thermal conductivity path and other physical properties based on temperature or force. At the same time, it is crucial to consider the sustainability of materials, energy consumption and emissions during the manufacturing process, and the recyclability of radiators at the end of their lifespan. Also, developers use artificial intelligence to drive topology optimization and design microchannel grid structures that maximize heat dissipation efficiency compared to traditional fins. And by controlling artificial intelligence, it is possible to achieve optimal global regulation of

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heat-dissipation efficiency, noise, and power consumption. Finally, these interdisciplinary fusion technologies are key to addressing the challenges such as heat-dissipation requirements and energy consumption reduction for future high-power density devices. They will not only promote the advancement of air-cooled cooling technology, but also provide solid support for equipment, thermal reliability, energy efficiency improvement in many important fields such as manufacturing and transportation and so on.

References

[1] Italia, R. An analysis of heat dissipation techniques in power electronics. Journal of Engineering and Applied Sciences Technology, 2023, 1–6.

[2] An, M., Sun, X., Chen, D., & Yang, N. Research progress of thermal transport in graphene-based thermal interfacial composite materials. Acta Physica Sinica, 2022, 71(16), 166501.

[3] Peng, M., Chen, L., Ji, W., & Tao, W. Numerical study on flow and heat transfer in a multi-jet microchannel heat sink. International Journal of Heat and Mass Transfer, 2020, 157, 119982.

[4] Ghandouri, I. E., Maakoul, A. E., Saadeddine, S., & Meziane, M. Thermal performance of a corrugated heat dissipation fin design: A natural convection numerical analysis. International Journal of Heat and Mass Transfer, 2021, 180, 121763.

[5] Dwivedi, V. D., & Rai, R. Design and Performance Analysis of Louvered Fin Automotive Radiator using CAE Tools. International Journal of Engineering Research And, 2015, 4(1).

[6] Bakshi, S. R., Lahiri, D., & Agarwal, A. Carbon nanotube reinforced metal matrix composites - a review. International Materials Reviews, 2010, 55(1), 41–64.

[7] Yardi, A., Karguppikar, A., Tanksale, G. & Sharma, K. Optimization of fin spacing by analyzing the heat transfer through rectangular fin array configurations (Natural convection). International Research Journal of Engineering and Technology, 2017, 4(9). 985-993.

[8] Jungmayr, G., Marth, E., Panholzer, M., Amrhein, W., Jeske, F., & Reisinger, M. Design of a highly reliable fan with magnetic bearings. Proceedings of the Institution of Mechanical Engineers Part I Journal of Systems and Control Engineering, 2015, 230(4), 361–369.