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REVIEW

Structural design of aeroengine radiators: State of the art and perspectives

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Abstract Structural modularization, lightweight and functional integration are the urgent development directions for next generation high-performance aeroengines. Heat concentration during aeroengine operation would lead to local high temperature, which tremendously negative impacts on aeroengine structural life and performance. Therefore, the design and optimization of radiator structures are significant for the efficiency and reliability of aeroengine. The structural geometry design and layout optimization of radiators is promising to improve the heat dissipation efficiency and reduce aerodynamic loss. The purpose of this study is to investigate the state of the art and perspectives of aeroengine radiator structural design by a comprehensive literature review. The main contents involve the review on the structural design and layout optimization technologies of radiator structures, the analyses of the structural features, design theory and methods of existed radiator structures, the induction of the theory and method of different radiators structural optimization design, and the discussion on the application perspectives of advanced structures in aeroengine radiators, the report on the current challenges and development directions of the design of radiator structures, including smart materials, lattice structures, variable structures, advanced optimization theories and methods, heat dissipation methods and so forth. The efforts of this study are promising to support the high-performance and lightweight design of aeroengine structures besides radiators, and thermal management system.

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1. Introduction

The structure of the new generation of engines is developing towards compact, integrated and multi-functional. Thermal management system (TMS) plays a key role in dealing with excess heat of the engine, transferring excess heat from the engine radiator to the turbofan, but the existing thermal management system is difficult to adapt to the development trend and requirements of the aeroengine structure [1−3]. It is urgent to develop and design new heat dissipation structures [4−6] to improve the performance of heat dissipation structures and reduce aerodynamic losses. The primary function of the radiator is to dissipate the excess energy generated by the aircraft engine through conduction, convection, and radiation to maintain the temperature stability of the engine. The selection and structural design of aeroengine radiator (AR) must consider various factors such as engine power, aircraft speed, high-altitude flight, external environment temperature, geometric restrictions, and so forth, in order to ensure the normal operation of engines under various conditions.

The works on AR structure focus on two aspects of materials and structure design. The material choice and structural design directly affect radiators' service performance. The traditional radiators including plate-fin radiator, U-tube radiator, fin radiator and pin-fin radiator and so forth, usually adopt materials with high thermal conductivity, such as copper and aluminum alloy, to improve the heat transfer efficiency. The structures of radiators mainly include the optimization of the fins and the design of the hot flow channels, to expand the effective heat dissipation area. The next generation aeroengine requires multi-function integration and compact structure, so that it is difficult for the traditional thermal administrated system to meet the heat dissipation requirements. Recently, some critical research progress has been made in aeroengine thermal structures [7−12]. With the help of advanced numerical simulation and experimental techniques, scholars could accurately predict, evaluate and improve the radiator's performance by constantly optimizing the radiator material and structure [13−16]. However, it is still to further discuss some key challenges, such as how to efficiently develop the materials and advanced structures of radiators by weighting weight and strength, and heat dissipation and aerodynamic performance as well, to further improve the heat transfer efficiency of AR.

In what follows, Section 2 comprehensively reviews the structure and optimization design of different radiator, to provide reference and directions for developing aeroengine thermal management technology. In Section 3, the different types of heat dissipation structures are introduced to summarize their characteristics and application range. The theory and methods of heat dissipation and aerodynamic performance of radiators are described in Section 3. Section 4 discusses the ideas and methods of different heat sink optimization. In Section 5, the problems and challenges during radiator structure design are summarized. In respect of the faced problems and challenges, Section 6 gives the research direction of AR structural design. Some main conclusions and perspectives on this study are summarized in Section 7.

2. Types and design of radiator structures

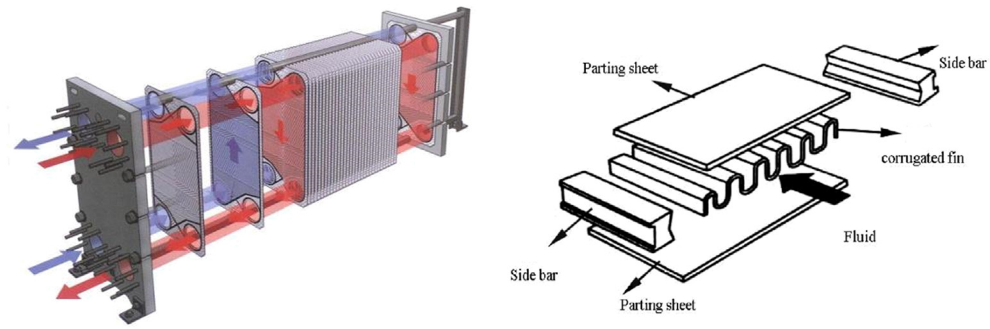
It is critical to select an appropriate radiator structure for efficient thermal management. This section mainly expounds on the types and application scenarios of heat sinks, and discusses the application scopes of various heat sinks with different structures in detail, and summarizes the merits and demerits of traditional heat dissipation structures as well.

2.1. Types of radiator structures

This section focuses on the types of radiator structures involving plate-fin radiator, U-tube radiator, fin & pin-fin radiator and the advanced structure radiator, and then discusses and compares their performance characteristics and development status.

2.1.1. Plate-fin radiator

Plate-fin radiator was firstly developed and manufactured by Marston Excelsior which is a British company. Plate-fin radiator as shown in Figure 1, mainly consists of fins, partitions, seals, deflectors and other parts [17]. The structures of plate-fin radiator use partitions and fins to divide flow channels into a mass of channels. Fin layout can significantly expand the heat transfer area to achieve excellent heat transfer efficiency [18,19]. Compared with other radiators, the presence of fins enables plate-fin radiators to have an extended secondary heat transfer surface. In the heat conduction process, the baffle carries out the primary heat conduction. In addition, heat will also be transferred along the height direction of fin surface, because the fin height is much greater than the thickness. In height direction, the fin length, width, height size, Reynolds number (*Re* number) and fin types significantly influence the overall heat transfer rate and choke of plate-fin radiator [20−22]. Najafi et al.



(a) The structure of plate-fin heat exchanger (b) The core structure of plate-fin heat exchanger

Figure 1 Plate-fin radiator [26].

[23] optimized the plate-fin heat exchanger based on the two objective functions of heat transfer rate and system cost, in respect of the optimization parameters, i.e., contacted length between cold side and hot sides in heat exchanger, fin frequency, fin length, fin thickness and fin number. Wang et al. [24] discussed the design and optimization methods of multi-flow plate-fin heat exchangers from the perspectives of the traditional design methods, hierarchical layout design theory and intelligent algorithm optimization. Li et al. [25] adopted a combination of numerical simulation and experiment to establish the plate beam calculation model of plate-fin heat exchanger based on heat transfer theory, and discussed the influence of structural parameters such as fin height, spacing, thickness and length on heat and mass transformer characteristics of the channels.

2.1.2. U-tube radiator

U-tube heat exchanger was a tube-shape heat exchange system designed and developed by Motoren-und Turbinen-Union (MTU) LTD. The heat exchanger comprises collecting tubes and several U-tube heat exchangers, as shown in Figure 2. U-tube radiator is a regenerator that can fully use turbine high-temperature exhaust gas to increase the air temperature in high-pressure compressor to improve combustion efficiency. Liu et al. [27] compared and analyzed the influences of different U-tube bundle types, tube bundle declination angle, tube diameter, flow distribution, heat exchanger installation angle, intake mode and intake temperature on tube bundle flow and heat transfer. Kritikos et al. [28] employed the CFD technology for the numerical simulation on U-tube heat exchangers, which revealed that the calculated temperature distribution is consistent with the experiment. Albanakis et al. [29] performed the experiments on the double-U-tube regenerator of engine tail nozzle, to mainly study the influence of factors such as the inlet temperature of hot gas, inlet mass flow rate, inlet attack angle, and heat exchanger angle on heat exchange performance.

2.1.3. Fin & pin-fin radiator

As an integrated structure, finned heat sinks have been widely applied due to their stable performance and low manufacturing cost [30,31]. The structural shapes of typical finned radiators are shown in Figure 3, mainly including fin radiator, round pin-fin radiator, square pin-fin radiator. The bottom of the radiator is a substrate. The upper part is a parallel fin structure. The main heat exchange happens between the surface of the fin and the coolant. The structure and layout of the fin directly affect the cooling performance of radiator. The structure of pin-fin radiator is similar to the fin radiator [32,33], except that its fins adopt are a series of needle structures closely-arranged, rather than a rectangular sheet structure.

2.2. Advanced structural radiator

Due to the limitation of application range and optimization space, it is difficult for the traditional structural heat sink to meet the increasing demand for heat dissipation and performance [34−36]. Therefore, developing and designing advanced structural radiator has become an important research direction [37−39]. Zhang [34] designed a new type of flexible textile structure radiator to improve the application and performance analysis of the traditional pin-fin

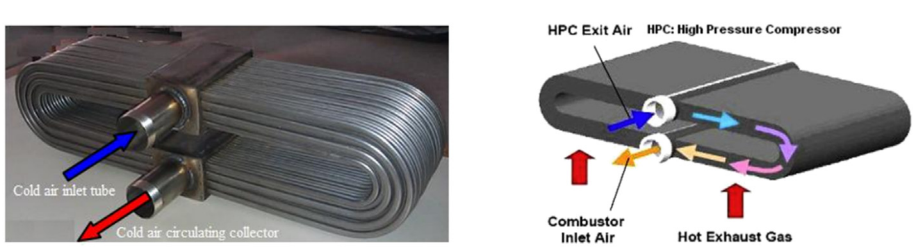
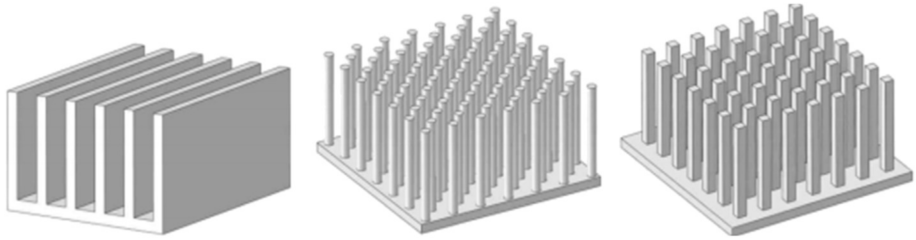


Figure 2 U-tube heat dissipation structure [27−29].



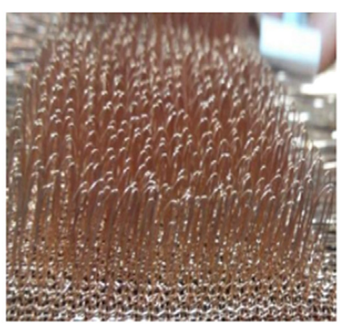
(a) Fin radiator (b) Round pin-fin radiator (c) Square pin-fin radiator

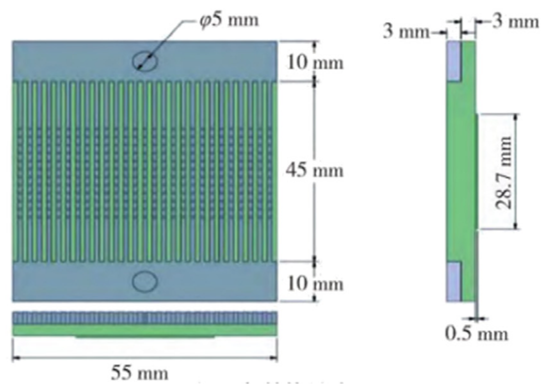
Figure 3 Type of fin & pin-fin radiator [30−33].

radiator by simulation methods. Zeng [35] proposed a porous wall microchannel structure aiming at the problems of small heat transfer area, low heat transfer performance, and boiling hysteresis in the traditional smooth micro-channels. Zheng [36] applied advanced finned structures to design three kinds of heat sinks involving straight fins, curved fins and spaced-type fins, and studied the influence of coupling changes between the three fin structures and the number of fins on the heat dissipation performance of controller. The height and thickness of fins were optimized in line with the optimal scheme. Lattice, honeycomb, corrugated and other advanced structures are employed to heat dissipation structure. The structures of several advanced structural heat sinks are shown in Figure 4.

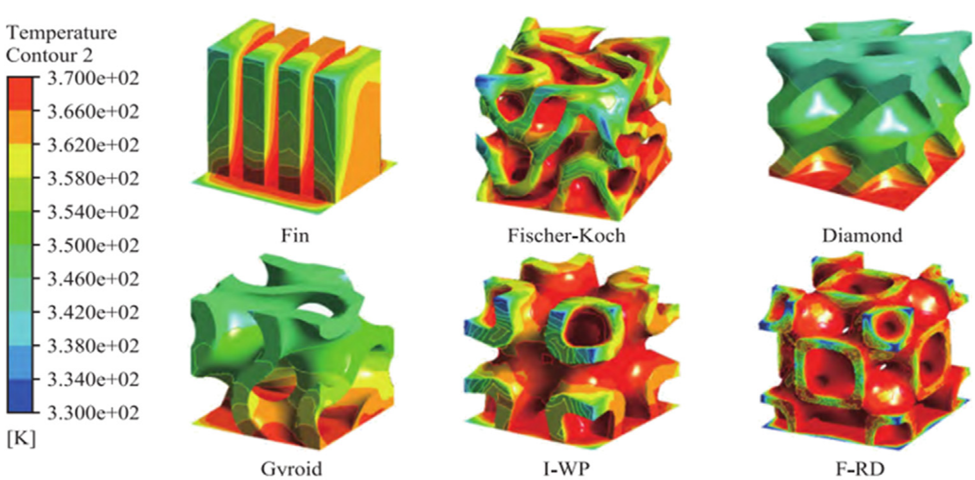
2.3. *Structural design of aeroengine integrated radiator*

The compact structure and integrated design of aeroengines have high requirements for the size and performance of heat dissipation structures. Regarding the characteristics of the existing heat dissipation structures, as shown in Table 1, the AR of fuel oil is mainly aimed at the excessively high temperature of the fuel, and the fuel temperature cannot be





(a) Woven fabric radiator [34] (b) Advanced micro-channel radiator [35]



(c) Solid temperature distribution of different heat dissipation structures [37]

Figure 4 Advanced structural heat sinks.

Table 1 Comparison of different radiators.

Radiator types	Characteristics	Applicable scenes
Plate-fin radiator [17–26]	(1) High heat transfer efficiency (2) Large size	■ Large heat source structure volume ■ High demand on heat dissipation performance
U-tube radiator [27–29]	(1) High heat transfer efficiency (2) Large aerodynamic resistance	● High demand on heat dissipation performance ● Low demand on aerodynamic performance
Fin radiator [30–33]	(1) Low processing cost (2) High strength and low thermal resistance (3) Large lateral heat transfer area (4) Compact structure (5) Small size	◆ Suitable for small heat source radiator ◆ Shape restrictions by environment
Advanced structural radiator [34–39]	(1) High heat dissipation efficiency (2) Complex structure (3) Processing difficulty (4) High aerodynamic resistance	● Low load ● High demand on heat dissipation

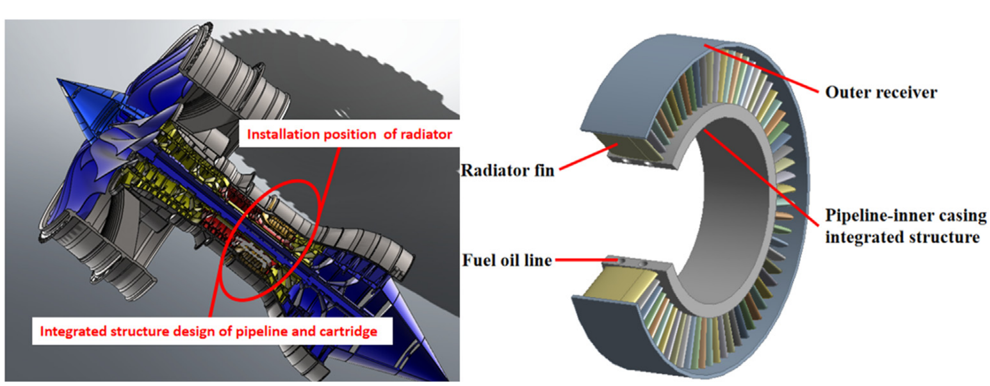
too low to ensure the combustion efficiency of the fuel. Therefore, the studied AR has fewer requirements for heat dissipation performance, and should be paid more attention to acquire low-pressure loss and high mechanical properties. In summary, it is appropriate to regard the fin radiator as the basis structure for the design and optimization of advanced structure. The design diagram of fin radiators is shown in Figure 5.

2.4. Radiator materials

The radiator materials mainly include copper, aluminum, and their alloy. Copper has good thermal conductivity and excellent machinability, while hold high the price and density of copper. The aluminum has the strengths of low density for the lightweight design of engine and good brazing performance. However, it is hard for mechanical property to satisfy engine harsh working environment [40–43]. In this case, advanced and intelligent materials were developed for AR [44–47]. Wu et al. [48] conducted an experimental investigation on five different heat sinks under two work conditions with and without phase-change materials (PCM) with regard to the constant heat load. Zhang et al. [49] studied the phase change heat transfer process by establishing the structural model of plate-fin phase change heat sink, and adopted the cascade phase change technology to optimize heat transfer performance and analyze the effects of the different combinations of PCMs, fin structure and different PCM volume ratios on heat transfer performance of phase change heat sink. Aris et al. [50] tried to make Vortex Generators (VG) by adopting innovative materials in tube-fin heat exchangers to achieve various changes in the tilting angle and improve heat transfer performance. Hao et al. [51] applied memory alloys to heat transfer in pool boiling. Vilarrubi et al. [52] designed a radiator structure by using bimetal and memory alloy, which can actively control heat transfer with temperature. The comparison between traditional materials and smart materials is shown in Table 2. Smart material has high application value. However, smart materials are not applied in practical engineering yet. It is necessary to further study on advanced materials and intelligent materials in the AR.

3. Analysis method for radiators performance

To optimize radiator, it is necessary to establish the relationship between the structural parameters and the thermal, aerodynamic and mechanical performance of



(a) Integrated structure of pipeline and cartridge (b) Radiator structure partial structure diagram

Figure 5 Radiator installation position and structure diagram.

Table 2 The features of different materials.

Materials	Traits
Copper [40,46]	● High thermal conductivity ● High material density ● High cost
Aluminum [41]	■ High thermal conductivity ■ Low density ■ Poor mechanical properties
Smart material [44,45]	◆ High thermal conductivity ◆ Excellent mechanical properties ◆ Adaptive performance tuning ability

radiator. In this section, thermal and aerodynamic performance are investigated to support the selection of appropriate optimal design methods.

3.1. *Thermal performance of radiators*

The relationship function between structural parameters and thermal performance for radiator is the basis of optimization design [53−55]. The relationship between geometric parameters and thermal performance may be expressed by one mathematical model through theoretical analysis and numerical simulation [56,57]. Yu et al. [58] explored a high-power light-emitting diode (LED) pin-fin radiator and discussed the influence of different substrate thickness, pin-fin height, pin-fin spacing and heat convection direction on the heat dissipation performance of the developed LED chips. It is demonstrated that the developed pin-fin radiator can be economically manufactured and reasonably designed, and has good heat dissipation effect as well. Chávez-Modena [59] et al., proposed an optimization method for the shape and distribution of fin under heat conjugate problem surface. Ocøoń et al. [60] optimized the shape of manifold subject to high temperature fin and tube heat exchanger manifold. Zhang et al. [61] investigated the influence of structural parameters on heat dissipation performance and performed the structural optimization of multi-channel water-cooled radiator subject to power loss and thermal resistance of insulated-gate bipolar transistor (IGBT) unit based on finite element (FE) simulation under multi-physical field coupling. Zhang et al. [62] studied the influence of geometrical parameters on the heat transformation of finned radiator to improve heat dissipation efficiency. Leon et al. [63] focused on the influence of aerodynamic transformation on the heat dissipation and flow performance of finned radiators. Wirtz et al. [64] studied the influence of the air flow bypass between fins on the heat dissipation characteristics of finned radiators. Li et al. [65] designed a new compact cross-flow air-air heat exchanger using the logarithmic mean temperature difference (LMTD) method, to experimentally study the performance of the structure in heat dissipation and flow feature. The designed heat exchanger is only 2.04 kg and capable of cooling high temperature air from high-pressure compressor in a limited space, in which the cooling air is from the bypass duct.

In sum, the presented works mainly focus on the relationship between radiator structure and radiator performance parameters [66,67], rather than the relationship between the structure and the heat dissipation of thermal mass, which is conducive to the demand-oriented structural optimization design. Therefore, it is urgent to establish an accurate relationship between thermal mass and structural parameters to achieve a high-performance and lightweight radiator.

3.2. *Aerodynamic performance of radiators*

High heat dissipation performance is the constant demand of ARs. It is necessary to study aerodynamic parameters to

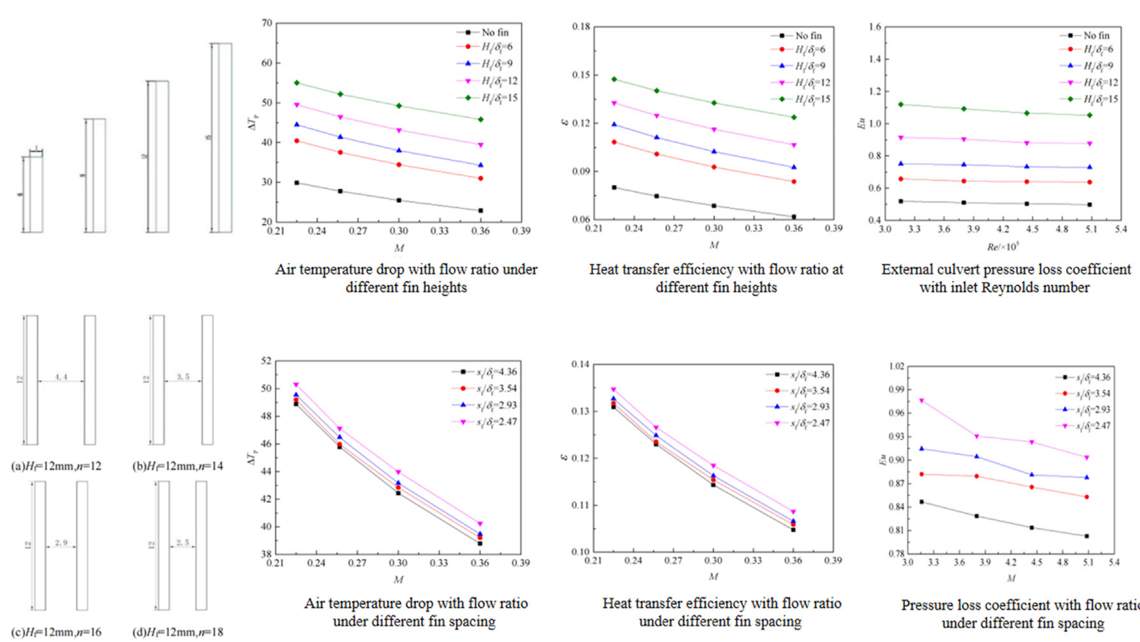


Figure 6 Influence curves of structural parameters on radiator performance [73].

ensure the efficient and healthy operation of aeroengine. Xu et al. [68] proposed a performance calculation method based on heat transfer unit (HTU) simulation, to calculate heat transfer capacity and air-side pressure drop of annular radiator. Doo et al. [69] performed three-dimensional numerical simulations of a series of parameter variations of an anti-phase secondary corrugation on a cross-corrugated heat exchanger. Villafañe et al. [70] studied the bypass flow of turbofans under complex transonic conditions, and evaluated the flow changes caused by two different fin heat exchanger designs and conducted experiments in a ground test facility. Ilori et al. [71] investigated the thermal and pressure drop performance of a compact Tube Heat Exchanger (T-HEX) under oscillatory flow conditions using experimental and numerical methods. Shah and London [72] studied the related characteristics of air flow between parallel fins of a finned radiator. Lei [73] used numerical simulation and experiments to study the structural performance of the dual-working medium air-fuel heat sink in outer bypass. The influence curve between the structural parameters of heat dissipation and performance parameters is shown in Figure 6. In the process of establishing the relationship function, the advantages and disadvantages of numerical simulation method and test method, are listed in Table 3.

Currently, test and simulation are two main methods to investigate aerodynamic parameters. The function between structural parameters and aerodynamic parameters is commonly modeled by these two methods [69−73]. For finned radiator, theoretical pressure drop formula mainly focuses on the deduction of air-side pressure drop of regular non-curvature finned structure. However, there are few reports on the deduction of air-side pressure drop of irregular curvature fins. Therefore, it is urgent to give the deduction theory of air-side pressure drop of irregular curvature fins to reduce the limitation of fin structure design.

4. Theory and methods for radiators optimization design

To enhance the heat dissipation and service performance of radiators, it is crucial to optimize the structures and layout of radiators. Different optimization workflows of radiator should be selected based on the application environment, including performance-oriented optimization method which means optimization for a single performance of radiator, and integrated thermal-aerodynamic performance optimization method which indicates muti-objects optimization of heat dissipation efficiency and aerodynamic performance. The optimization and design methods of radiators are introduced in this section.

4.1. *Optimization theory of heat dissipation structure*

In this subsection, thermal resistance optimization [74], convective heat transfer efficiency optimization [75] and surface treatment optimization [76] for radiators is discussed to improve the comprehensive performance of radiator structures.

4.1.1. *Optimization of thermal resistance*

Thermal resistance is defined as the ratio of the temperature difference between both ends of objects and the power of heat source as heat transmitted or happens the resistance encountered by heat in the path of heat flow [74,77,78]. Thermal resistance reflects the magnitude of the heat transfer capacity in medium. The total thermal resistance [74−76] R_{eq} of a conventional radiator is expressed as

$$R_{eq} = (T_i - T_a)\Big/P_c = \frac{T_i - T_b}{P_c} + \frac{T_b - T_s}{P_c} + \frac{T_s - T_f}{P_c} + \frac{T_f - T_a}{P_c} = R_i + R_b + R_{conv} + R_f \quad (1)$$

in which T_f represents the average temperature of fluid at radiator outlet; T_s is the average temperature of radiator fins; T_b indicates the average temperature of radiator base; R_i, R_b, R_{conv} and R_f are diffusion thermal resistance of heat source, contact thermal resistance of radiator base, fluid-solid convection thermal resistance and thermal resistance of fluid temperature rise, respectively; T_i represents the average temperature of heat source; T_a is the average temperature of the fluid at the end of the flow path; P_c is the power of the heat source.

The materials of radiator mainly involve aluminum alloy and copper alloy. It is required to increase thermal conductivity when diffusion thermal resistance is reduced. The diffusion thermal resistance has high heat flux density in the chip and is evident as the large ratio of fin length to thickness [75,76]. However, the thermal conductivity is finitely improved, while the increases of radiator substrate thickness and fin thickness are limited by space. Wiriyasart et al. [77] studied the heat transfer characteristics of cold

Table 3 Comparison of methods for establishing relational function.

Method	Merits	Demerits
Numerical simulation method [71−73]	■ Low computational cost ■ High computational efficiency	■ Applicability and accuracy of the established relationship function need to be verified
Test method [70]	● High accuracy ● High engineering applicability	● High test cost ● Limited experimental samples ● Large randomness

plate radiators with rectangular, circular and conical fins on heated surface and effectively reduced the thermal resistance by optimizing the geometrical shapes. Kim et al. [78] optimized a plate-fin radiator with fin thickness varying perpendicular to the direction of fluid flow based on Volume Averaging Theory (VAT), to reduce the thermal resistance of the radiator. Alnaimat et al. [79] investigated the thermal performance of square fin heat sinks under different heat flow density and Reynolds numbers in respect of thermal resistance. It is demonstrated fron this study that the effect of fluid velocity on thermal resistance is significant compared to fin sizes. Huang et al. [80] adopted multi-objective genetic algorithm (NSGA-II) to comprehensively optimize the two optimization objectives of fin surface heat transfer coefficient and fin surface efficiency of the whole radiator, which are two main parameters affecting the heat dissipation of radiator, to effectively reduce thermal resistance. Heat pipes and vapor chamber embedded at the bottom of heat sink is promising to effectively reduce diffusion thermal resistance and optimize heat dissipation.

4.1.2. Optimization of convective heat transfer efficiency

Newton's Law of Cooling [81] is employed to calculate the heat dissipation efficiency of fins and air as the theoretical heat dissipation efficiency of radiators, i.e.,

$$Q = \lambda(T_w - T_0)A \tag{2}$$

where Q is the heat dissipation; T_w denotes the surface temperature of cooling surface; T_0 indicates ambient temperature; A expresses the area of cooling surface; λ is the comprehensive heat transfer coefficient; λ is determined according to surface shape, configuration characteristics and $(T_w - T_0)$ size as well as the magnitude of fluid velocity.

In light of the cooling law, it is obvious that heat transfer is directly enhanced by increasing convective heat transfer area. However, increasing heat transfer area usually require larger size of radiator, which goes against the trend of increasing compact aeroengine structures. Besides, the increasing sizes of radiators will enlarge the cost of structural processing and weight, and thus increase the fuel consumption and limit the performance enhancement of aeroengine. When the longitudinal channel space of outer bypass is given, system wind resistance which indicates the pressure drop of outer bypass air through the radiator, is considered with the increasing heat dissipation area. The increasing heat dissipation area of fine radiator increases the wind resistance which affects the internal air flow and reduces the convective heat transfer coefficients.

4.1.3. Optimization of radiator surface treatment

After the geometric design of radiators, surface treatment method significantly affects heat transfer effect [82–84]. During temperature range under operation, the intensity of radiative heat transfer is proportional to the infrared emissivity of radiator. For radiation heat transfer, surface treatment should be designed. For indoor situation, it is necessary to consider the operation temperature of radiator to improve the surface infrared emissivity. For radiators exposed to sunlight, it is necessary to increase the surface infrared emissivity and reduce the surface visible light emissivity [83]. In the investigations on the optimization of radiator surface treatment, the basic optimization methods of radiators are listed in Table 4.

4.2. Optimization method for heat dissipation structures

Methods of radiator structure design mainly include topology optimization [85–88] and intelligent algorithm optimization design [89,90]. This section reviews and summarizes the theory and flowchart of optimization design of radiators.

4.2.1. Topology optimization of radiator structures

By combing FE simulation and artificial intelligence technologies, the optimization design of heat dissipation

Table 4 Comparison of radiator optimization methods.

Methods	Optimization schemes	Scope of application
Thermal conduction [74–80]	● Use materials with high thermal conductivity ● Use heating components of heat pipes and vapor chambers to reduce diffusion thermal resistance ● Radiator parameters of tooth thickness and substrate thickness, affecting diffusion thermal resistance	● High heat-density flow environment
Convective heat transfer [81]	● Change shape parameters such as number of teeth, tooth height, substrate thickness and so forth, to achieve the optimal values of heat transfer area and flow resistance ● Improve the intensity of heat exchange by designing shape, broken, wrong and oblique teeth to match system air duct and utilizing the internal space of product	● High aerodynamic performance requirements ● Small channel space
Radiation heat transfer [82–84]	● Increase the surface infrared emissivity and decrease the surface visible emissivity. ● Use of composite coatings (e.g., graphene), metal coatings, etc.	● Need surface treatment after geometric structure optimization for radiators

structures is conducted respecting different performance requirements. Topology optimization mainly includes variable density method [91], level set method [92], and so on. The optimization model of topology optimization [85,86] is expressed as

$$\begin{cases} find: \rho_i, i=1,2,3,\ldots,n \\ \min f(x)=a_1 C_s(\rho)+a_2 C_t(\rho)+\ldots+a_n C_j(\rho) \\ s.t. K^s(\rho)U=F^s, \\ K^t(\rho)T=F^t, \\ \ldots \\ K^i(\rho)I=F^i \end{cases} \quad (3)$$

where design variable ρ_i is the material volume fraction corresponding to the ith element; n denotes the total number of elements for the discrete design domain; a_1 is the weight factors of structural performance, a_2 presents the weight factors of cooling performance and a_n indicates the weight factors of other design requirements; $C_s(\rho)$ is the objective functions of structural performance, $C_t(\rho)$ is the objective functions of heat dissipation performance and $C_j(\rho)$ indicates the objective functions of other performance; $K^s(\rho)$ and $K^t(\rho)$ respectively indicates the overall stiffness matrix and the overall thermal conduction matrix, $K^i(\rho)$ presents the over matrix of other performance; U, T and I are the vectors of node displacement, node temperature and other performance parameter, respectively; F^s, F^t, F^i are the vectors of node force load, node temperature load and other node load, respectively.

Variable density method and level set method are two common topology methods. The results of level set method have clear boundaries and can be directly used for manufacturing, but the optimization accuracy and efficiency of level set method are low. The variable density method originates from the homogenization method with reduced design variables, which has high precision and high efficiency. Compared with the horizontal set method, topological optimization boundary of variable density method is unclear and cannot be directly used for manufacturing. To further improve optimization results, it is necessary to perform the multi-scale topological optimization of macrostructure and microstructure for structures considering intelligent algorithm [93–96]. The main process of topology optimization is shown in Figure 7.

Chen [97] analyzed the conjugate heat transfer process based on FE method, and established a multi-objective topology optimization model to carried out the topology optimization design and numerical simulation analysis of heat dissipation problems from different heat source forms and different dimensions. Zhang [98] used topology optimization technology with flexible design and strong targeting to design the micro-channel radiator to improve the potentials of radiator performance through parameter optimization. Pei et al. [99] designed radiator structure with advanced electronic components by variable density topological optimization method, to the optimal flow path under constant temperature boundary condition. Zhu [100] applied the topology optimization design method to the structural design of micro-channel radiator and establish a multi-objective topology optimization model, for the topology optimization design and numerical simulation analysis of heat dissipation problems with different inlet and outlet modes and different inlet condition. Kobayashi et al. [101] employed a single design variable to solve two fluids and solid wall between the fluids, to prevent the mixing of the two fluids and achieve the maximum heat transfer rate under fixed pressure loss. Liu et al. [102] conducted the topological optimization of finned tube heat exchanger structure with zonal fin, to obtain a novel streamlined fin. Compared with the traditional structures, the heat transfer performance of novel structure is increased by 22.64%–28.04%. Meanwhile, the topology optimization of spiral wound tube heat exchanger (two-fluid) is realized by coupling MMA variable density method and FE framework to represent two kinds of fluid in one topology design variable. Topology optimization results of radiators with different structures are shown in Figure 8.

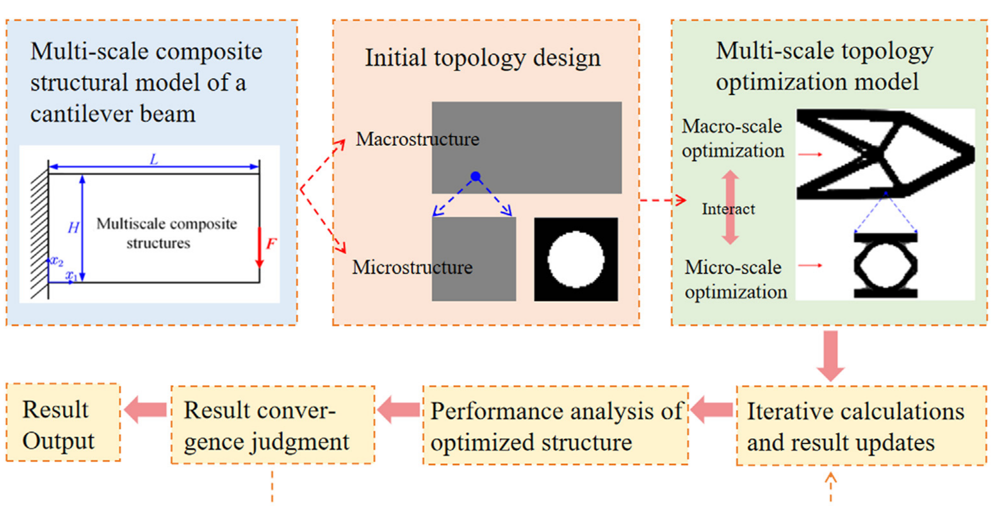
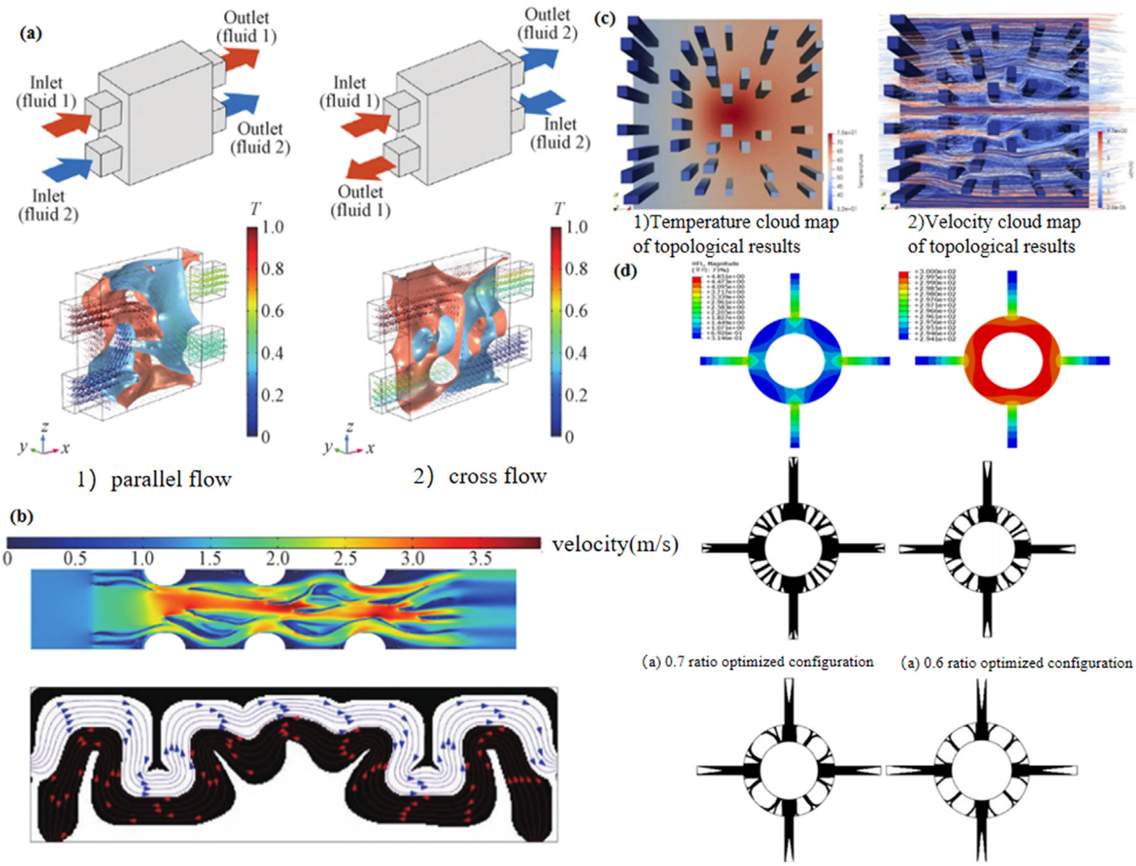


Figure 7 Flowchart of topology optimization [93].



(a) Topology optimization of dual-fluid heat exchangers; (b) Fin structure optimization with 2D heat exchanger;
(c) Topology optimization with ribbed pin radiator;
(d) Topology optimization of tubular ribbed heat dissipation structure

Figure 8 Topology optimization of radiator structures [97−100].

In topology optimization, the design variables are directly linked to optimization problems [101,102]. Topology optimization methods are suitable for high nonlinear structures, such as geometric nonlinear and material nonlinear problems. However, the optimization results are burry and cannot be directly applied and manufactured, and has the disadvantages of large computation loads and low optimization efficiency.

4.2.2. *Intelligent algorithm optimization*

To improve the optimization design and manufacturing efficiency, the scholars absorbed intelligent algorithm into the optimization design of radiators [103−105]. Intelligent algorithms often include the solution processes of establishing objective function, restricting boundary condition and surrogate modeling, which mainly comprise model-driven and data-driven optimization design. The flowchart of model-driven and data-driven optimization design is shown in Figures 9 and 10.

Xu et al. [106] built a performance prediction model utilizing Slipcevie method and proposed one configuration optimization method by NSGA II-MOPSO (muti-objective particle swarm optimization) for shell-and-tube heat exchanger with disc-and-doughnut baffles of aero-engine. Hao et al. [107] used multi-objective genetic algorithm for the structure parameters of radiator involving channel number, channel width and height and inlet flow speed. Through many iterations to gain Pareto optimization solution and reduce heat resistance and pressure loss of series channel radiators, which provided the theoretical basis for optimizing series channel water cooling radiator. Song et al. [108] proposed a multi-objective optimization method for water cooling radiator under electromagnetic-heat-stress multi-physical field coupling environment on the premise of meeting surface pressure. Xie [109] established the optimization mathematical model of fin radiator with the consideration of manufacturing and space limitations, to get the sizes of fin radiator structure with the largest heat dissipating capacity. Xu et al. [110] proposed one performance analysis method by combining heat transfer unit (HTU) simulation and plate-and-fin heat exchanger (PFHX) performance calculation formulas, to propose a configuration optimization method of annular radiator. Liu et al. [111] developed a double-layer triangular microchannel radiator with a new thermal resistance network model. Taking thermal resistance and pressure drop as the optimization

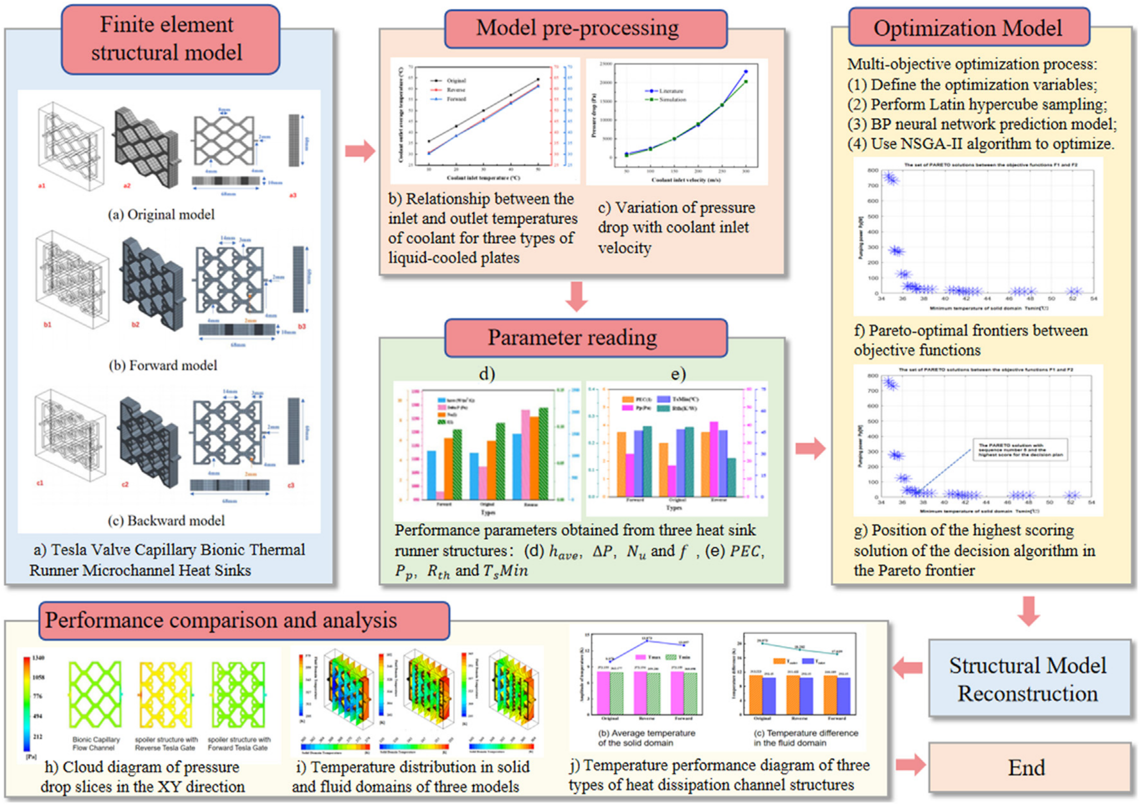


Figure 9 Model-driven intelligent algorithm optimization design [103].

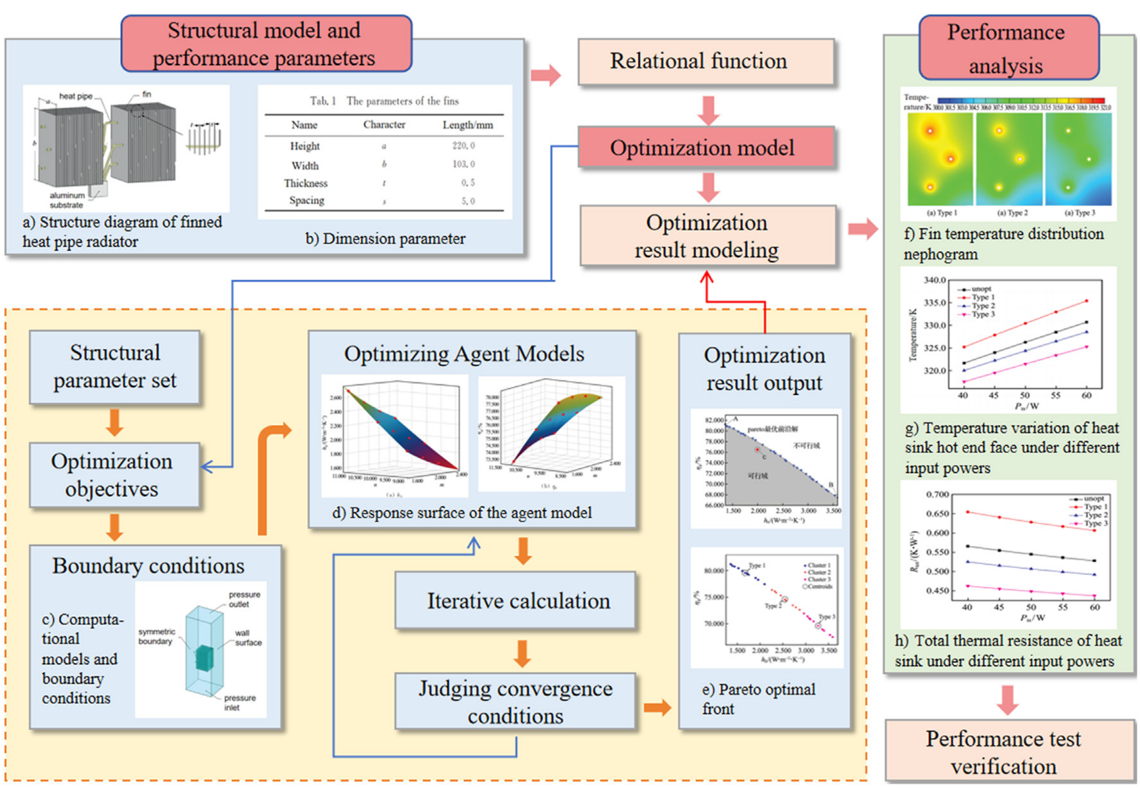


Figure 10 Data-driven intelligent algorithm optimization design [78].

objectives, the firefly algorithm based on Pareto optimal solution set is adopted to obtain the optimal structural parameters with thermal resistance of 0.284 (K/W) and pressure drop of 1386.89 Pa.

Intelligent algorithm is mainly applied to establish the relationship between optimization variables and optimization objectives and to acquire the optimal structural parameters by continuously iteration [15,112]. The optimization design with intelligent algorithm can efficiently deal with optimization problems and avoid local optimal solution problem. However, it is difficult to balance various performances due to the limited evaluation criteria.

5. Challenges of radiator structural design

In line with the above investigations and analysis, it is urgent to further design and optimize the AR due to the requirement of high performance and weight reduction. For this purpose, it is inevitable for AR design to face a series of challenges, which involving advanced materials and intelligent materials development, advanced structure design, radiator comprehensive performance evaluation and optimization theory, radiator multi-scale optimization design method, radiator surface treatment method, waste heat treatment methods and adaptive heat structure design. The specific challenges are summarized as follows:

- *Development and preparation of advanced materials or intelligent materials with high-performance and low-density to enhance radiator performance:* Currently, the available materials hardly satisfy the increasingly harsh working environment and advanced intelligent materials are immature to be widely applied in AR design [40−47]. For next generate aeroengine, the used advanced radiator materials require high heat-transfer coefficient, good uniform heat transfer performance and mechanical properties under high temperature conditions, and low density. Thus, it is obvious that the existing metal materials cannot meet the requirements, so that it is required to develop and prepare the advanced intelligent materials for practical engineering application.
- *Design and preparation of advanced structure, biomimetic structure and intelligent structure radiators:* The performance optimization potential for traditional radiator structure [17−33] is limited and cannot meet the future requirements of aeroengine. Besides, advanced structures such as lattice structure, bionic structure, honeycomb structure, and so forth, hold very difficult processing and unstable mechanical properties [34−37]. Moreover, the exaggerated layer density is unavoidable to increase the aerodynamic resistance of AR.
- *Limited performance evaluation criteria and optimization theory of aeroengine radiator:* Increasing surface area is frequently-used to improve the heat dissipation performance of radiators, but the increase of sizes will enlarge the aerodynamic resistance and weight of radiators [74−80]. In this case, it is difficult to weight the relationship among heat dissipation, flow loss, mechanical properties and lightweight for the optimization design of radiators. Although large number of works have been done, they are incapable to find the balance point among the key parameters. In addition, there is not a unified assessment system for the assessment of optimization results in academic field.
- *Multi-scale and multi-objective, high-efficient and accurate radiator optimization methods:* The FE method combined with intelligent algorithms have high calculation costs and low efficiency [103−110]. Therefore, the design of advanced structures for radiators lacks demand-oriented multi-scale optimization methods to adapt to the advanced heat dissipation.
- *Insufficient surface treatment methods of radiators under aeroengine extreme working conditions:* The surface treatment of radiator structure and material coating design lack research scheme to achieve high heat dissipation performance, low aerodynamic loss, lightweight and high reliability. It is crucial to fill the gap to meet the urgent needs of heat dissipation and stable performance of ARs in complex thermal environment.
- *Low energy utilization rate due to unsatisfactory waste heat treatment method of aeroengine:* The excess heat generated during aeroengine operation is often wasted by directly exhausting. The treatment method of waste heat causes a large amount of energy loss, which cannot meet the development trend of green aviation.
- *Lack of structure design and control methods of adaptive aeroengine radiator:* The structural design of radiators usually optimizes the structure and performance of the radiator under a single working condition, it is difficult to satisfy the demand for the change of boundary conditions during the whole flight.

6. Development directions of radiator structural design

In respect of the problems and challenges and the design requirements of next generation engine in high efficiency, high reliability, lightweight, adaptive and low cost, the further research directions of radiator structural design are summarized as follows:

- *Performance mechanism revelation of high-precision heat dissipation structures:* Most of the present researches in radiator structure design mainly focus on the relationship between structural parameters and structural heat dissipation to reveal the influence of heat dissipation area on heat dissipation efficiency [53−60]. To achieve accurate demand-oriented design of thermal structures, however, it is necessary to conduct the influence of structural parameters on heat dissipating capacity to achieve the demand-oriented design optimization of radiator structures.
- *Development and preparation of high-performance and lightweight heat dissipation structural materials:* By

combining advanced material genetic engineering technology and artificial intelligence (AI) algorithm, the multi-scale material design and performance screening in material composition, material component ratio and material structure is one important research direction for the demand-oriented material design and development of uniform heat transfer and high mechanical performance radiators with high temperature resistance, which is likely to improve the optimization potential of radiator performance.

- *Application of advanced structures such as lattice structures, bionic structures and smart structures to the design of radiator structures:* The improvement of the complexity of structures leads to the high requirements of heat dissipation and other performance, so that the applications of the traditional radiators are limited. Advanced structures have the features of high performance and lightweight, and contribute to the enhancement of heat dissipation efficiency [34−39]. However, advanced structures are difficultly processed and low stability, so that it is required to improve the applicability of advanced structures.
- *Proposition of comprehensive evaluation index and advanced optimization design theory:* The performance of AR involves heat dissipation efficiency, aerodynamic loss, mechanical properties, lightweight design, and so forth. It is contradictory among these performance parameters, so that it is significant to form a comprehensive evaluation index and balance their relationship to improve the overall performance of AR [62−73]. With the assist of AI technologies and surrogate models, comprehensive evaluation index and advanced optimization design theory are one important research direction of the structural design and performance optimization of radiators.
- *Waste heat utilization technology of excess heat to realize multi-way distribution and utilization:* Along with the emergence and rapid development of green aviation recently, secondary utilization of waste heat is regarded as one efficient measure to improve the utilization efficiency of fuel energy and reduce the energy loss of aeroengine.
- *Design and development of adaptive radiator structure:* because of the complex working conditions of aeroengine with large variation, stationary structures is insatiable for next generation engine structure design. variable structure [113−115] is an alternative for radiator design under different working conditions. Therefore, the design and development of variable structure is one of research directions on adaptive radiator to improve the thermal management system of aeroengine.

7. Conclusions

The aim of this paper is to comprehensively review literatures to present the state of the art and perspectives of aeroengine radiator structural design, which provide the techniques, methods, challenges and research directions to the high-performance and lightweight design of aeroengine structures besides radiators, and thermal management system. Firstly, it is reviewed to the theory and methods of structural design and optimization of different radiator involving existed radiator and advanced radiators with lattice structures, bionic structures, honeycomb structures, knitted structures and smart structures. Secondly, the advanced materials such as lattice material, memory alloy and phase-change material (PCM) are investigated. And then in respect of the analyses and inductions, the current challenges of advanced radiators design for next generation aeroengine are summarized. Lastly, the research direction and development perspectives of advanced radiators design for next generation aeroengine is presented with regard to advanced materials, advanced structures, artificial intelligence, waste heat utilization and green aviation. The efforts of this study offer open challenges and directions for researchers and scholars to explore the high performance and lightweight of advanced radiators, which conduce to the design of aeroengine heat radiation structures and the development of thermal management systems, for next generation aeroengines and aircrafts.

Data availability statement

The data used to support the findings of this study are included within the article.

Declaration of competing interest

The authors declare no conflict of interest in publication.

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