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Fluid-structure analysis and prediction of rectangle duct design: a case of air supply system

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Abstract

Since the fluid-structure analysis is widely applied to assess the fluid flow state of electromechanical products, the design of fluid-structure becomes crucial in improving product performance and efficiency. In this study, a numerical prediction method for fluid-structure parameters is proposed to evaluate and optimize the flow state and quality of the flow field in a rectangular duct system. The modular design concept is adopted in this research, where the overall flow of the duct is considered as the sum of local flow fields within the duct modules. By analyzing the structural parameters such as cross-section ratio, pipe length, and flow direction within each duct module, a numerical prediction model for flow based on fluid-structure parameters is developed using numerical fitting techniques. Experimental results show that the flow rate prediction accuracy for normal modules is within 10%, and the flow rate prediction accuracy for modules with irregular structures is within 15%. It validates that this numerical prediction method, based on the flow structure, is a reliable tool for assessing and optimizing the flow state and quality of the flow field in the entire rectangular piping system.

Keywords: Fluid-structure, rectangle duct, flow forecasts, air supply system

INTRODUCTION

In current engineering applications, the analysis of flow fields holds significant importance in assessing and enhancing the performance of electromechanical products. Particularly in air supply systems, the structural design of ducts directly influences the heat transfer efficiency, thereby impacting the overall system performance and energy efficiency. However, existing duct design methods suffer from various limitations, especially in optimizing airflow efficiency, often lacking systematic and quantitative analysis. This leads to inefficient design and difficulty in identifying improvement directions.

In the optimization of duct structures, scholars mainly improve the heat transfer efficiency by modifying the geometric shape and configuration of the ducts. Kumar *et al*. enhanced the efficiency of solar energy devices such as solar air heaters (SAHs) through duct structure design[1]. Karabulut *et al*. inserted rectangular baffles into ducts and extensively analyzed the effects of baffle angles and heights on heat transfer and pressure drop characteristics[2]. Wu *et al*. improved duct structures by adding guide vanes and conducted multi-objective optimization design of the vane profile to maximize the optimization effect of the guide vanes[3]. Cao *et al*. optimized the rectangular duct at the inlet of a hybrid power battery cooling system, which can reduce fan-induced noise while achieving the expected cooling effect[4].

Some scholars have employed different methods for structural optimization of pipelines. Morelli *et al*. conducted shape optimization of steam boiler hybrid ducts using surrogate-based optimization (SBO) and multi-objective genetic algorithm (MOGA)[5]. Hanan *et al*. proposed a comprehensive optimization design approach that combines response surface methodology and genetic algorithm to optimize existing pipeline characteristic data[6]. Czetany *et al*. presented a simple one-dimensional model to optimize the inlet and outlet of rectangular ducts, obtaining the optimal rectangular duct structure using nonlinear differential equations[7]. Alfaro-Ayala *et al*. utilized computational fluid dynamics (CFD) to study the transient behavior of small cooling cabinets and proposed three different models to compare and analyze the temperature and velocity distributions inside, validating the accuracy of CFD values with experimental data and proving that fitting temperature polynomials is a better approach[8]. Immonen *et al*. optimized a given baseline shape design using CFD and high-order polynomial response surface, determining the optimal path for a given S-shaped duct[9]. Wang *et al*. demonstrated the impact of storage capacity on the design of foundational transportation infrastructure, which can be applied to optimize the structure of large-scale CO_2 transportation pipelines[10].

Flow prediction is a crucial aspect of air supply system design. Regarding structure-based flow prediction methods, scholars have conducted the following research: Oyewola and Idowu utilized CFD to investigate the influence of Reynolds number (Re) on the flow state at the inlet section of battery thermal management systems (BTMS)[11]. Kodali and Idem proposed a numerical model to predict the relationship between flow rate and pressure distribution in a three-branch air duct system and the upstream static pressure[12]. They predicted the flow velocity through the initial branch pipe upstream using the secant method and simulated the flow through the remaining branch pipes using the Newton-Raphson method. Avcı *et al*. modeled and analyzed duct structures using CFD methods and employed artificial neural networks to predict the airflow state inside refrigerators, achieving a 7% improvement in refrigerator performance with the optimal structural design[13]. Tao *et al*. employed numerical simulation to model the initial duct shape and optimized regions with lower dynamic pressure by adding virtual forces to fluid elements[14]. Kong and Chong determined critical areas of maximum pressure drop by combining static equilibrium rectangular duct design methods with circular rectangular duct grids[15]. To enhance prediction accuracy, Ye *et al*. studied the accuracy of CFD modeling methods in predicting pipeline flow fields and analyzed the reasons for quantitative differences in model prediction results[16].

Modular design, as one of the green design methods, can shorten the product development and manufacturing cycle, increase product lines, improve product quality, and rapidly respond to market changes. Currently, modular design methods have been widely applied in various fields such as architecture and construction, manufacturing, robotics[17], software development, automotive industry[18], furniture design[19], and medical equipment[20]. However, there is relatively little research and application in the field of structural optimization of air supply systems. By applying the concept of modular design to the optimization process of ducts, the modeling process of air supply systems can be simplified, and the efficiency of duct structure design can be improved. You and Smith proposed a novel multi-objective green modular design method, which utilizes atomic theory and fuzzy clustering to establish modular structures, where each module can meet different design goals[21]. Zhang *et al.* introduced the concept of modularization for rectangular duct systems and obtained the optimal rectangular duct structure to enhance the uniformity of the flow field[22]. Ji *et al*. presented a dual-layer optimization model based on constrained genetic algorithm for joint decision-making in technical system modularization (TSM) and material reuse modularization (MRM), constructing a unified framework[23].

Due to the increasing application of rectangular duct structures, which exhibit excellent manufacturability, the internal duct systems of refrigerators are commonly designed as rectangular[24]. Based on existing research, the design of air supply efficiency in ducts is typically based on pre-designed structural schemes, and the air supply efficiency is verified through CFD simulations. However, this process suffers from inefficiency issues because every time there is a change in the structural scheme, it requires rebuilding the CFD model and conducting simulations. The direction of scheme modifications relies on the simulated results of air supply efficiency from CFD or the design experience of designers, lacking clear guidance. The influence patterns of duct structure parameters on air supply efficiency have not been clearly defined.

To overcome these limitations, a modular structural analysis method for rectangular ducts has been proposed, aiming to quantitatively study the numerical relationship between duct structural parameters and air supply efficiency. This method involves establishing a mapping function between duct structural parameters and outlet flow rate for specific research objects. Based on the established mapping function, it enables rapid validation of air supply system design schemes, thereby enhancing verification efficiency and shortening the product development cycle. This approach achieves rapid optimization of duct structural parameters with air supply efficiency as the design target, thereby optimizing air supply efficiency and reducing energy consumption. By revealing the mutual relationship between duct structural parameters and air supply efficiency based on the structure of the mapping function, it provides guidance for optimizing and improving air supply system structural schemes. This method reduces the number of experimental validations and physical prototype quantities for air supply system structural schemes, thereby lowering design and prototype manufacturing costs.

Especially in the application of mass-produced home appliance products, cost-effectiveness is an important consideration. Under the demand for multi-model design, modular design optimizes resource use by reducing the cost of air duct structural design and corresponding mold manufacturing. By standardizing and reusing modules, it reduces a variety of spare parts and mold costs, while also reducing material consumption. These measures not only help to reduce overall costs but also ensure effective air distribution efficiency, enhancing the overall performance and market competitiveness of the products.

METHODS

Duct construction affects flow field

In most air supply systems, the air inlet of a rectangular duct is determined by the structure of the upstream room. The upstream room serves as a functional structure that provides high-quality air in terms of temperature, humidity, and other factors. Typically, the air inlet is equipped with a duct fan or pump to draw airflow from the upstream room, such as an evaporator room. Due to the energy consumption associated with duct fans and pumps, the number of air inlets is limited. On the other hand, the outlets of the rectangular ducts are positioned based on the specific requirements of the target room, such as the heat load of a refrigerator compartment. As a result, the structure of rectangular ducts serves as a connection between multiple inlets and multiple outlets in order to meet the varying flow requirements of each outlet. The shape and dimensions of the rectangular ducts can be adjusted to modify the flow rate profile at the outlets. This structural adjustment allows for flexibility in controlling the airflow distribution and achieving the desired performance in different target rooms.

Characterization of the study of the duct flow problem

The entire duct structure is indeed highly complex. Studying the entire duct pipeline, with its various types and numerous structural parameters, can be challenging. Additionally, the presence of multiple outlets in the duct pipeline makes it difficult to conduct specific studies on the flow rate of each outlet when considering the entire pipeline as the object of study. However, it is possible to analyze the duct pipeline by focusing on local sections. The fluid flow within the duct pipeline is unidirectional, with the front fluid domain influencing the back fluid domain while not being affected by it. This characteristic allows for analysis to start from the local sections, with the results of the front fluid domain serving as initial conditions for the study of subsequent sections. Moreover, certain parameters at a specific location can be considered as the accumulation of the fluid domain conditions from previous sections. This approach allows for a more manageable and systematic analysis of the flow and structure within the duct pipeline. By breaking down the study into smaller, interconnected parts, it becomes feasible to comprehensively understand and optimize the performance of the entire duct system.

In a rectangular duct, each outlet's flow condition is determined by the requirements of the entire air supply system. The airflow is driven by a duct fan, and the fan's operating speed is adjusted to meet these flow requirements. As the rotating velocity of the duct fan changes, the flow motion within the rectangular duct varies. However, due to the constraints imposed by the duct's structure on the flow direction, the predominant change in the flow motion is typically the variation in flow velocity. This variation in flow velocity directly affects the distribution of flow pressure within the rectangular duct. Furthermore, these changes in flow pressure also impact flow losses and other related variations. Considering the ease of measuring flow pressure, the variable distribution of flow pressure is often considered as an indicator of changes in the flow field throughout the entire rectangular duct. By analyzing the distribution of flow pressure, one can gain insights into the variations in the flow field and understand how the flow conditions are influenced by changes in the operating parameters of the duct fan.

Propose solutions

Indeed, the complexity and partial irregularity of the piping structure pose challenges for theoretical analysis and optimization of the structural parameters for the entire duct piping. Directly parameterizing the whole duct piping involves a large number and variety of parameters, which are coupled with each other. This complexity makes the structural optimization problem difficult to solve, and it becomes challenging to precisely optimize each structural parameter. To address these challenges, it is often necessary to adopt simplified models or divide the duct piping into smaller sections for analysis and optimization. This approach allows for a more manageable and systematic study of the flow and structure within the duct system. Additionally, advanced optimization techniques, such as numerical methods and computational simulations, can be employed to explore the design space and find optimal solutions within the given constraints. Furthermore, it is important to consider practical constraints, such as manufacturing limitations and cost-effectiveness, when optimizing the structural parameters of the duct piping. A balance must be struck between optimizing performance and ensuring feasibility in real-world applications.

In the concept of modular analysis in product design, the flow of information or functions is channeled through the input and output interfaces of each module. This allows the entire product to achieve comprehensive information processing or function operation. The design of each module can be independent of others, only needing to consider the specific functional requirements and input/output interface requirements of the current module. Moreover, for modules that are homogeneous in nature, the same set of design parameters can be used for their design. This simplifies the overall design process of the product, as it allows for standardized and reusable module designs. By modularizing the design, it becomes easier to modify or replace individual modules without affecting the entire product. This flexibility and ease of integration are key advantages of the modular approach in product design. Overall, modular analysis enables efficient and effective design by breaking down complex systems into manageable and interchangeable modules, simplifying the design process, and facilitating modular integration.

In line with the modular design concept, the overall flow within the duct can be understood as the sum of the local flow fields within each duct module. The cooling air moves through the inlet and outlet of each duct module as a material flow. The design of the entire duct system can be divided into the coupling design of these individual duct modules, where each part of the duct system corresponds to a different type of module. Modules of the same type can be designed with uniform structural parameters, while different types of modules may have varying structural parameters. The mapping function between the module structural parameters and the duct outlet flow rate is established by data fitting, and experimental verification of the final mapping function is sufficient. The specific modular analysis method is shown in Figure 1. This modular design approach provides significant convenience for the subsequent optimization process. It also facilitates the study of the numerical relationship between the structural parameters and the flow conditions at the outlet of the duct system. This design idea not only simplifies the design process but also enables a more efficient and cost-effective approach for subsequent product design of the same type. By leveraging the numerical relationship between the basic flow prediction and the structural parameters, designers can streamline the design process, enhance design efficiency, and reduce overall design costs.

Overall, the modular design concept allows for a more systematic and efficient approach to designing and optimizing the duct system. It enables a modular integration of the different components and simplifies the study of the relationship between structural parameters and flow conditions, leading to improved design efficiency and cost-effectiveness.

Pressure analysis inside the duct module

Flow pressure is the main factor affecting the changes in fluid mass flow rate, flow velocity, and other state parameters in pipeline structures. By analyzing the distribution of flow pressure along the pipeline, it is possible to understand how these changes influence the flow field and optimize the design accordingly. The fluid pressure situation in the duct module is demonstrated in Figure 2.

The total pressure P_{ti} in the duct module i is expressed as:

$$P_{ti} = P_{si} + P_{mi} \tag{1}$$

$$P_{mi} = \frac{1}{2}\rho v_i^2 \tag{2}$$

Where P_{ti}, P_{si}, and P_{mi} are the total pressure, static pressure and dynamic pressure of section I, respectively. The pressure drops from the $L_{(n-1)}$ to $L_{(n)}$ section of the rectangle duct are expressed as:

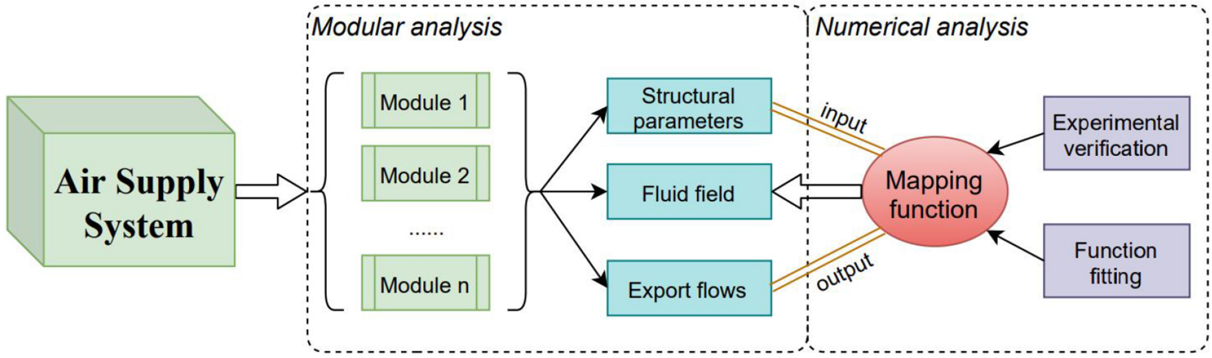

Figure 1. Methodology flow chart.

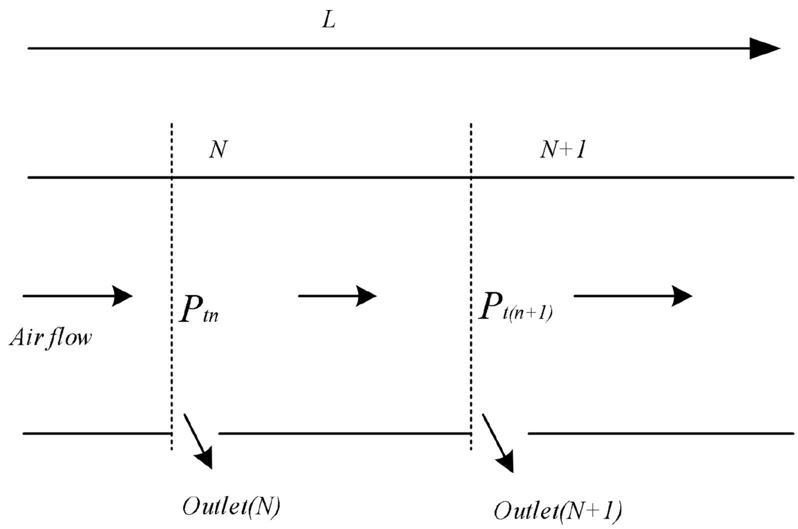

Figure 2. Flow field and related variations in duct module.

$$\Delta P|_{L_{N-1}}^{L_N} = P_{t(n-1)} - P_{tn} = P_{s1} - P_{sN} = \int_{L_{(n-1)}}^{L_n} \frac{\partial P}{\partial x} dx \tag{3}$$

Based on continuity equation, total pressure drop is described as the accumulation of pressure drops in each duct module, such as:

$$\sum \Delta P = \Delta P_1 + \Delta P_2 + \cdots + \Delta P_n = \Delta P|_{L_1}^{L_N} = P_{t1} - P_{tN} = P_{s1} - P_{sN} = \int_{L_1}^{L_N} \frac{\partial P}{\partial x} dx \tag{4}$$

Based on the previous statement, the entire duct structure can be viewed as a series-parallel combination of rectangular duct modules. The overall change in the flow field of the air supply system is considered as the cumulative effect of flow variations in each duct module [as expressed in Equation (4)]. In the design of the complete air duct piping system, the flow change characteristics of each rectangular air duct module are taken into account. This allows for the optimization and analysis of the structural form of the air duct piping and related structural parameters. The ultimate objective is to improve the flow performance and efficiency of the air supply system. By considering the flow variations in each duct module and their cumulative effects, designers can identify potential areas for improvement and optimize the design accordingly. This may involve adjusting the dimensions, layout, or other parameters of the duct modules to enhance flow efficiency and achieve better air supply performance. Through this iterative design process, the overall flow performance and air supply efficiency of the duct piping system can be improved, leading to a more effective and efficient air supply system. By optimizing the structural parameters based on the flow change characteristics, designers can achieve the desired goals of enhancing flow performance and improving air supply efficiency.

METHODOLOGY IMPLEMENTATION

Modularization of ducts and extraction of structural parameters

In this chapter, the study focuses on a common air-cooled refrigerator with built-in refrigerator air duct piping, which is available in Changhong Meiling Co., Ltd. To begin the analysis, the air duct piping is divided into modules. This modular approach allows for a more detailed examination of the structural parameters within each module. By studying the individual modules, it becomes easier to understand the overall performance and characteristics of the air duct system. The structural parameters of each module are carefully analyzed and studied. This includes parameters such as the dimensions, shape, materials, and other design elements that contribute to the functionality of each module. By investigating these parameters, researchers can gain insights into the relationship between the module's design and its performance within the air duct system.

The subsequent modular analysis, simulation, and verification experiments are conducted using this air duct as the carrier. This allows researchers to evaluate the performance of the individual modules and the overall air duct system. Through these experiments, the effectiveness of the modular design and the impact of different structural parameters can be assessed and optimized. Overall, this chapter focuses on dividing the air duct piping into modules and thoroughly analyzing the structural parameters of each module. This sets the foundation for subsequent experiments and simulations, which aim to improve the performance and efficiency of the air duct system.

In the analysis of the entire duct piping structure, it has been determined that the duct pipeline can be divided into modules based on its air outlet arrangement [Figure 3]. The duct modules were also categorized into different types.

The first type consists of modules with both inlet and outlet openings, along with air outlets. These modules include LC2, LC3, LC4, RC2, RC3, and RC4. The second type comprises modules with only inlet openings and air outlets. This category includes LC1, RC1, and BW. The third type consists of modules with only inlet and outlet openings. The module C2 falls into this category. The remaining duct modules, C1 and C3, can be considered analogous to the first category of duct modules, as they also have both inlet and outlet openings.

By categorizing the duct modules in this way, it becomes easier to analyze and study the structural parameters of each module individually. This modular approach allows for a more systematic understanding of the different types of modules and their specific characteristics within the duct piping structure.

In this study, the first type of duct module, which has the most complex structure, is chosen as the basic module. The structural parameters of this basic module are defined and used as the common structural parameters for all duct modules. By dividing the inlet and outlet by the direction of fluid flow in the duct, the wall of the duct is the air supply outlet, and the surface opposite to the air supply outlet is the bottom surface. Module structure parameters are as follows: a for the inlet area, b for the outlet area, c for the area

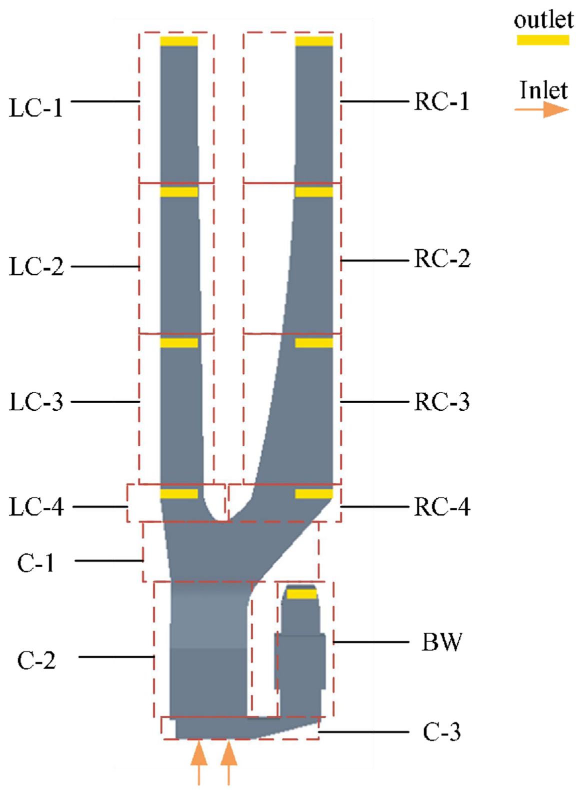

Figure 3. Duct module segmentation diagram.

of the air supply outlet, and l for the length of the air duct module. The exit angle x is the angle between the left and right sides of the duct module, and the inclination angle y is the angle between the vertical line of the air supply port section and the bottom surface (usually 90°, or 0° when the module has no air supply port). These structural parameters are shown in Figure 4, providing a visual representation of the different dimensions and angles that define the basic module and serve as common parameters for all the duct modules.

Using these defined structural parameters, researchers can analyze and optimize the performance of each duct module and the overall air duct system. This approach helps ensure consistency and comparability among the different modules, enabling a systematic evaluation of their impact on airflow characteristics and system efficiency.

Parameters related to outlet flow

In this study, the duct module is set as the structural unit, and its flow field is only influenced by the flow at inlet and outlet. Considering the flow field in each duct module as the independent field, it is necessary to discuss the mapping relationship between the flow variations and structural parameters. According to the principles of fluid dynamics, the relationship between flow loss and pipe structural parameters is expressed as mathematical equations. Among them, the nomenclature used in this study is summarized in Table 1. The flow loss in the duct includes the along-line loss h_f and local pressure loss h_j, which is expressed as:

$$h_w = \sum h_f + \sum h_j \tag{5}$$

Table 1. Nomenclature

h_f	Along-line loss	L_0	Total length of air duct structure (m)
h_j	Local pressure loss	p	Pressure
g	Gravity (m/s^2)	ρ	Fluid density
Re	Reynolds number	P_t	Total pressure
l	Length of the air duct (m)	P_s	Static pressure
v	Velocity in the duct (m/s)	P_m	Dynamic pressure
τ	Kinematic viscosity of the fluid	K	Thermal conductivity
ς	Along-travel loss factor	A	Cross-section of the air duct (m^2)
d	Hydraulic diameter of the air duct (m)	L_i	Pathway from outlet i to terminal outlet (m)
φ	Angle between outlet and pipeline	θ	Inclination angle of duct side
a	Length of the air duct (m)	Q	Mass flow rate
b	Width of the air duct (m)		

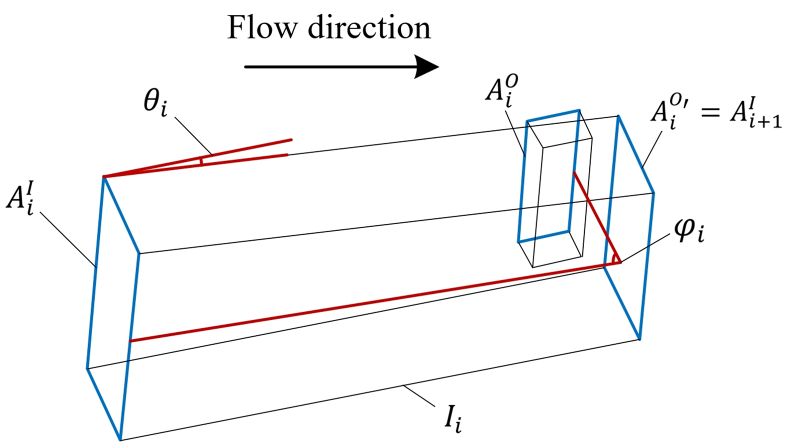

Figure 4. Structural parameters of the duct module.

Due to airflow in the duct (Re < 2,300), the flow is laminar, and the along-line loss h_f is:

$$h_f = \frac{64}{Re}\frac{l}{d}\frac{v^2}{2g} \tag{6}$$

Where $Re = vd/\tau$ is the Reynolds number; l is the length of the rectangle duct; v is the velocity of flow; τ is the dynamic viscosity of the fluid; $d = 2ab/(a + b)$ is the hydraulic diameter of the rectangle duct, a is the length of the rectangle duct and b is the width of the rectangle duct; g is the acceleration of gravity. The local pressure loss in the duct, caused by the bending, expansion and reduction structure of the rectangle duct, is expressed as:

$$h_j = \zeta\frac{v^2}{2g} \tag{7}$$

Where ζ is the along-travel loss factor and determined by the Colebrook equation. The local pressure loss coefficient is mostly related to the structure, informed by the study of Liu[25], local pressure loss coefficient is only related to the inlet and outlet section and angle of the rectangle duct, and it is expressed as:

$$\zeta = f(\theta, \frac{d}{D}, \frac{l}{L_0}) \tag{8}$$

Where l is the length of the air duct and L_0 is the total length of air duct structure. Besides, considering the relationship between flow loss and mass flow rate, the pressure drop is denoted as:

$$p = \frac{\zeta\rho}{2(ab)^2}Q^2 + \frac{(a+b)^2\rho\tau l}{4(ab)^3}Q \tag{9}$$

For module i of the duct piping, the portion of the pressure drop affected by the along-travel loss h_f is P_{hf} and the portion of the pressure drop affected by the local pressure loss h_j is P_{hj}:

$$P_{hf} = \Sigma\left[\frac{(a_i+b_i)^2\rho\tau l_i Q}{4(a_i b_i)^3}\right], i = 1,2,3...$$
$$P_{hj} = \Sigma[\zeta_i \frac{\rho Q^2}{2(a_i b_i)^2}], i = 1,2,3... \tag{10}$$

Therefore, the function of mass flow rate is proposed with the structural parameters of the rectangle duct, as:

$$\left\{\sum_{i=1}^{n}\left[\zeta_i \frac{\rho(Q_i^I)^2}{2(a_i b_i)^2}\right] - \frac{\zeta\rho\Delta Q^2}{2(a_0 b_0)^2}\right\} + \left\{\sum_j^n\left[\frac{(a_j+b_j)^2\rho\tau l_j Q_j^I}{4(a_j b_j)^3}\right] - \frac{(a_0+b_0)^2\rho\tau L\Delta Q}{4(a_0 b_0)^3}\right\} = 0 \tag{11}$$

And the mass flow rate in a rectangle duct is expressed as:

$$\Delta Q = |\ Q_k^O - Q_{all}^I| \tag{12}$$

Where $Q^I{}_{all}$ is the inlet mass flow rate, and Q_k^O is the mass flow rate of the k_{th} outlet in rectangle duct. The outlet flow Q^O is related to structural parameters D, inlet flow information Q^I and energy parameters E, while the energy parameters E are related to flow loss h_w , pressure drop p, length of the air duct l, velocity in the duct outlet and inlet v. The relationship is as follows:

$$Q^O = f_1(D, Q^I, E) = f_1(D, Q^I, E(h_w, p, l, v)) \tag{13}$$

From Equation (11), it can be concluded that:

$$E_1(h_w, p, l, v) = E_1(h_{w0} + \Delta h, p_0 + \Delta p, l, v) = E_2(h_{w0}, p_0, l, v) \tag{14}$$

And the length of the air duct l belongs to the structural parameters D, the velocity in the duct outlet and inlet v can be derived from the inlet flow information Q^I. So, the relationship of outlet flow Q^O is:

$$Q^O = f_1(D, Q^I, E(h_{w0}, p_0, D, Q^I)) = f_2(D, Q^I) \tag{15}$$

Among them, the structural parameters of duct module i (D_i) mainly include distance from air outlet to the end of pipeline (L_i), air duct inlet area (A_i^O), air duct outlet area (A_i^I), inclination angle of duct side (θ_i) and angle between outlet and pipeline (φ_i). Therefore, the form of structural parameters is as follows:

$$Q_i^O = f_2(D_i, Q_i^I) = f(L_i, A_i^O, A_i^I, \theta_i, \varphi_i, Q_i^I) \tag{16}$$

In conclusion, based on the relationship between the flow field and structural parameters in the duct module, the flow variations (flow loss and volume of flow) are expressed as the function of structural parameters (cross-section, duct length and flow direction). Moreover, comparing the existing equations from the traditional circular duct, it is necessary to discuss this mapping function in rectangle duct, as one evaluation tool with better accuracy.

Function fitting

Data acquisition

In this study, the rectangular duct structure from the air inlet to each air outlet is divided into several duct modules. These modules are taken as samples to investigate the mapping relationship between the structural parameters of the duct modules and the flow field. The structural parameters of each module are measured and recorded, and are presented in Table 2.

After measuring and recording the structural parameters, the modularized duct piping system is simulated. The boundary conditions for the simulation are set as described in Table 3.

By simulating the modularized duct piping system with these boundary conditions, researchers can analyze the flow field and investigate how the structural parameters of the duct modules affect the flow characteristics. This analysis assists in understanding the relationship between the structural parameters and the flow field performance, and can guide the optimization of the duct module design for improved airflow efficiency within the system.

Parametric analysis

(1) The absolute value of the outlet flow rate is related to the inlet flow rate, while the structural parameters only affect the relative value of the outlet flow rate. Therefore, the relationship can be expressed as a fitting function: $Q_i^O/Q_i^I = f(x)$. The percentage of the outlet flow rate is a value greater than 0 and less than 1. In order to obtain a fitting function that reflects this percentage, we can take the inverse of the function $f(x)$, denoted as $Q_i^O/Q_i^I = [f(x)]^{-1}$, where $[f(x) > 1]$.

(2) The relative value of the inlet and outlet area can provide information about whether the ducting is expanding or contracting along the fluid flow direction. The parameters $A_i^{O'}/A_i^I$ and A_i^O/A_i^I can be used to indicate the impact of the duct module's shape on the percentage of flow at the outlet. Additionally, the diversion of the outlet flow also affects the flow distribution at the outlet. To account for this influence, the parameter $A_i^{O'}/(A_i^O + A_i^{O'})$ is used. This parameter represents the ratio of the effective outlet area to the total area at the outlet. It quantifies the extent of diversion or redirection of the flow at the outlet due to the module's design or geometry.

(3) Since the inlet flow rate of the back duct module is equal to the outlet flow rate of the front duct module, there is a relationship between the position of the duct module and the percentage of its outlet flow rate. The more forwardly positioned a duct module is, the smaller the percentage of its outlet flow rate compared to the inlet flow rate. This effect can be expressed by the parameter L_i/L_0.

(4) The shape factor θ can be used to indicate the difference between a straight duct module and an inclined duct module. The shape factor φ, on the other hand, can indicate the difference between a duct module with an air outlet and a duct module without an air outlet. In the standard duct module, both the shape factor θ and φ are 90°. To incorporate these shape factors into a fitting function, the cosine of θ ($cos\theta$) and the cosine of φ ($cos\varphi$) can be used. The $cos\theta$ and $cos\varphi$ parameters represent the influence of the respective shape factors

Table 2. Structural parameters of duct module

Modular	A_i^I (10^{-4} m^2)	A_i^O (10^{-4} m^2)	L_i (m)	L_i/L_0	θ_i	φ_i
LC-1	6.67	6.50	0	0	0.4	90
LC-2	7.09	6.50	0.20	0.217	0.9	90
LC-3	7.51	6.50	0.40	0.435	0.9	90
LC-4	10.19	6.50	0.60	0.652	23.8	90
RC-1	6.7	6.50	0	0	0.5	90
RC-2	8.95	6.50	0.20	0.217	5	90
RC-3	13.76	6.50	0.40	0.435	10.5	90
RC-4	15.54	6.50	0.60	0.652	11	90
C-1	21.34	15.54	0.64	0.696	3.2	41.69
C-2	27.45	0	0.73	0.793	14.2	0
C-3	30.90	16.74	0.90	0.978	0	75.72
BW	16.74	4.43	0	0	5.6	90

Table 3. Model setting in rectangle duct model

Parameters	Value
Duct structure	Rectangle duct
Region of refinement	Rectangle duct and fan
Type of fan	Axial
Rotation rate of duct fan	1,840 r/min
Inlet	Stagnation inlet
Outlet	Pressure-outlet
Back pressure of the outlet	0 MPa

on the flow characteristics.

(5) The fitting function used in the solid paper is expressed as: $Q_i^O/Q_i^I = [f(A_i^{O'}/A_i^I, A_i^O/A_i^I, A_i^{O'}/(A_i^O + A_i^{O'}), L_i/L_0, cos\theta, cos\varphi)]^{-1}$.

Determination of the fitting function

A number of polynomial functions can be obtained by combining the primary, quadratic and combined terms of the above parameters. According to the number of coefficients of the polynomial function, the corresponding number of duct module flow data is selected for substitution. The function obtained from the fitting is applied to the remaining data points for verification. The parameters of the fitting function are adjusted based on the verification results until satisfactory fitting accuracy is achieved. The final fitting function is as follows:

$$\xi_i = \frac{Q_i^o}{Q_i^I} = [K_1\frac{L_i}{L_0} + K_2\left(\frac{A_i^{o'}}{A_i^O + A_i^{O'}}\right)^2 + K_3\frac{cos\theta A_i^{o'}}{A_i^I} + K_4\frac{cos\varphi A_i^I}{A_i^O} + K_5 cos\varphi + 1]^{-1} \quad (17)$$

The mapping function is numerically fitted with the simulation results, and the values of each coefficient are obtained as: K_1 = 7.611; K_2 = 2.289; K_3 = -1.102; K_4 = 2.473; K_5 = -8.742. This function takes the form of $Q_i^O/Q_i^I = [f(x) + 1]^{-1}$, $[f(x) > 0]$. The terms corresponding to K_1, K_2 and K_3 are standard terms (applied to the duct module with air outlet), and the terms corresponding to K_4 and K_5 are non-standard terms (the duct module without air outlet). There are nine groups of standard items and three groups of non-standard items in the simulation data. Therefore, the fitting function based on this data can have at most eight standard terms and two non-standard terms. The number of polynomial terms is not as high as possible, and the

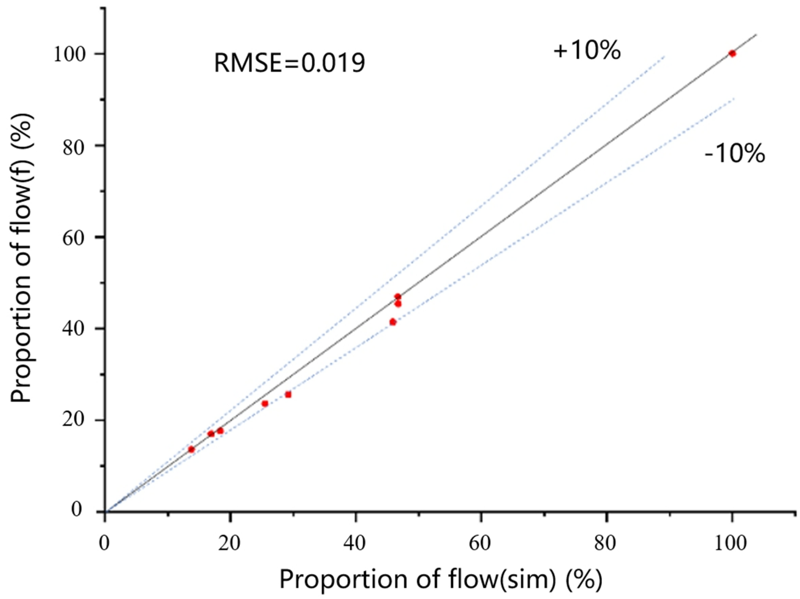

Figure 5. RMSE of mapping function. RMSE: Root mean square error.

appropriate terms should be chosen according to the actual mapping situation.

Based on the comparison of simulation results with the mapping function shown in Figure 5, the root mean square error (RMSE) of the mapping function is reported to be 0.019. Since the error is less than 10%, it is considered to be within the acceptable error range. Consequently, it can be concluded that the mapping function proposed in the paper is reliable for calculating the flow distribution within rectangular duct modules.

EXPERIMENTAL VERIFICATION

Experimental setup

Still, the experimental equipment for studying flow variations in a rectangular duct is presented based on the laboratory devices at Changhong Meiling Co., Ltd. [Figure 6].

To ensure the validity of the simulation results, the appropriate parameters for the refrigeration system in the duct piping were set according to the simulation content. It was ensured that the inlet conditions of the duct piping matched the settings of the simulation. This experimental result can be used to verify the aforementioned simulation calculation method. The specific parameters related to the refrigeration system are shown in Table 4.

When the airflow in the entire air supply system is in a steady state, the velocity of flow at each outlet is measured. According to testing standard[26], the average velocity at each outlet is calculated using either the Process Average or Geometric Average Method. In this study, the average velocity is considered as the experimental result to determine the mass flow rate at each outlet.

Data comparison and analysis

Based on the modularization of the rectangle duct and the related parameters in the refrigeration system [Figure 3 and Table 2], the mass flow rate at each air outlet is calculated using Equation (17). By comparing these mass flow rate values obtained from simulations, experiments, and the function

Table 4. Testing parameters in refrigeration system

Experimental content	Parameter setting
Refrigerant	R600a
Compressor	Displacement 9.05 cm^3/r
Compressor's power	120 W
Axial fan	120 mm
Fan's power	1.5 W
Rotation rate	1,840 rpm
Evaporator	Straight fin

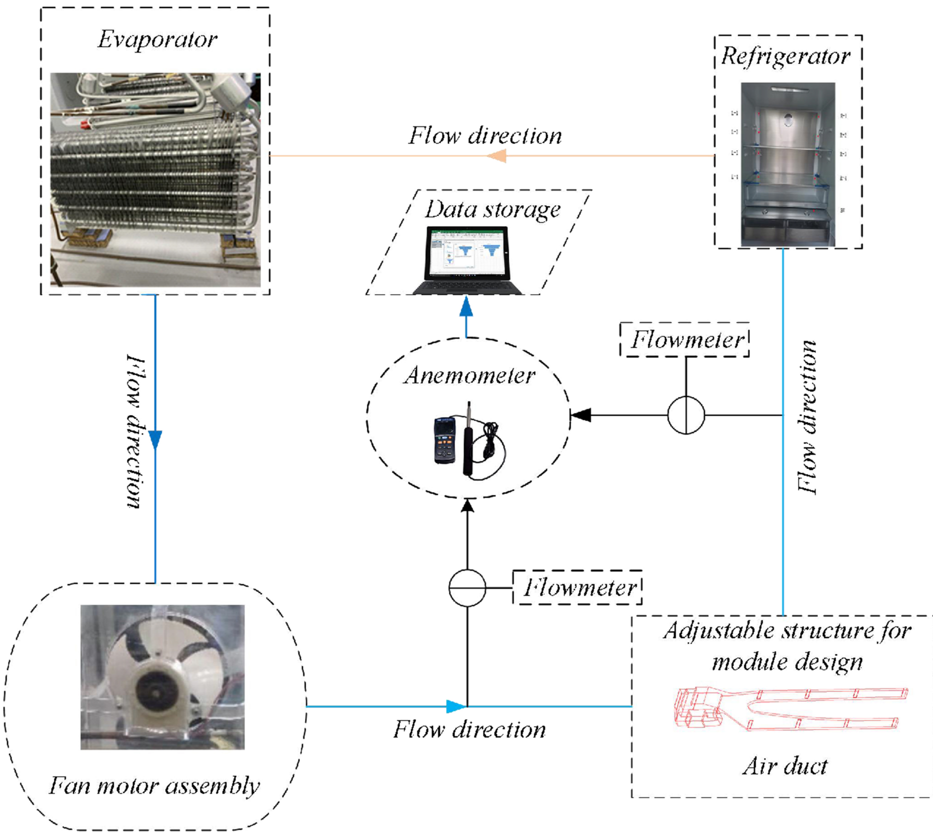

Figure 6. Experimental setting of flow variations in rectangle duct.

[Table 5 and Figure 7], it is observed that the experimental mass flow rate at each outlet is close to the values obtained from the simulation and the function. The average error between the experimental and simulation values is 5.448%, while the average error between the experimental and function values is 7.625%. Both average errors are less than 10%. The maximum error between the experimental and function values is 0.19 g/s for the mass flow rate of RC-3.

In the case of the duct system in this paper, the irregularity of the RC3 module's structure is relatively high, and the RC1 module follows the RC3 module. Therefore, the flow prediction results of the RC1 module and RC3 module under the mapping function have relatively large errors. As shown in Figure 7, the specific errors of the RC1 module and RC3 module are 14.12% and 15.7%, respectively. On the one hand, there are measurement errors inherent in the experiments themselves. On the other hand, the function fitting in the

Table 5. Numerical comparisons of functions, simulations and experiments

Modular	Mass flow rate (g/s)						Difference (%)	
	Function	Simulation	Experiment					
			Test 1	Test 2	Test 3	Average	F&E	S&E
LC-1	2.01	1.87	1.94	1.78	2.04	1.92	4.69	2.63
LC-2	1.67	1.64	1.74	1.32	1.68	1.58	5.70	3.94
LC-3	1.27	1.45	1.51	1.25	1.56	1.44	11.81	0.64
LC-4	1.01	1.01	0.93	0.74	0.98	0.88	14.77	14.30
RC-1	1.94	1.72	1.81	1.55	1.76	1.70	14.12	0.93
RC-2	1.37	1.46	1.45	1.17	1.53	1.38	0.72	5.58
RC-3	1.02	1.09	1.15	1.35	1.12	1.21	15.7	9.76
RC-4	0.93	0.96	0.82	0.75	0.97	0.85	9.41	13.06
C-1	5.26	5.23	5.23	4.82	5.38	5.14	2.33	1.75
C-2	-	-	-	-	-	-	-	-
C-3	1.77	1.79	1.82	1.52	1.84	1.73	2.31	3.67
BW	1.77	1.79	1.82	1.52	1.84	1.73	2.31	3.67

F&E: Function & Experiment; S&E: Simulation & Experiment.

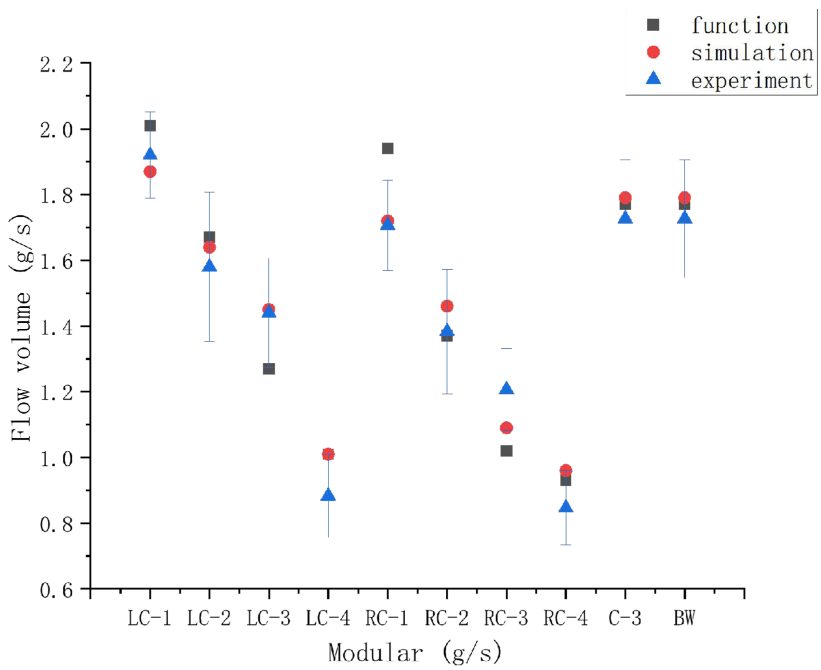

Figure 7. Comparison of simulated, experimental and function values.

paper is based on simulation results, which inherently contain errors compared to experiments. In the process of polynomial fitting for the mapping function, the more complex the polynomial pattern, the higher the accuracy of the fitting function, but the narrower the applicable range of this fitting function. In engineering practice, if the accuracy of the prediction method is acceptable, there will be a higher pursuit of the applicability of the fitting function. Therefore, under the premise of pursuing a broader applicable range (using as few structural parameters as possible for the fitting function), this method aims for a flow prediction accuracy within 15% for irregular structure modules and within 10% for normal modules, thereby preliminarily verifying the feasibility of this method.

Furthermore, using the equations [Equation (9)] that relate mass flow rate to pressure drop, the pressure drop in the rectangle duct is calculated based on the function values provided in Table 5. When comparing these calculated pressure drop values to the simulation values [Figure 8], it is observed that the average error is 4.64%. This indicates that the proposed function is feasible and effective in predicting the flow variations in the rectangle duct structure.

Based on the data obtained from the function, simulations, and experiments, it is observed that the flow rate is nonlinearly correlated with various factors such as the distance from the air outlet to the end of the pipeline (L_i), the area ratio in the rectangle duct ($A_i^{O'}/A_i^{O}$), the inclination angle of the duct side (θ_i), and the angle between the outlet and the pipeline (φ_i). The proposed function expresses this nonlinear mapping relationship. In the structural design of the rectangle duct, the flow rate and its related variations can be predicted using this prediction function. Therefore, the prediction function can serve as a valuable tool for evaluating the structural design of the entire rectangle duct in an air supply system. Additionally, when considering the operational requirements of the rectangle duct performance in an air supply system, such as the required air volume and its related variations, the proposed function can be used to obtain reasonable structural parameters that fulfill these operational requirements. These structural parameters can then serve as references for the detailed design of the entire air supply system. Therefore, the prediction function can also be utilized as a crucial data foundation for the structural design of the rectangle duct.

On this basis, the method was further utilized to optimize the pipeline design. By analyzing the impact of pipeline size on flow velocity and pressure loss, the optimal dimensions were determined, which not only ensured the even distribution of the refrigerant but also minimized energy consumption. The bends in the ductwork can cause local pressure losses, and the reduction of flow velocity and change in flow direction at these bends lead to significant energy loss. Moreover, the insulation of the pipeline structure has been enhanced, especially in applications such as air-cooled refrigerators, to reduce heat loss, stabilize airflow temperature, and improve cooling capacity and energy efficiency. These measures collectively contribute to a more effective and energy-saving air supply system, highlighting the significance of the predictive function of this method in guiding the design towards green energy solutions.

DISCUSSION AND APPLICATION OF FITTING FUNCTIONS

The mapping function of structural parameters reveals that the outlet flow ratio is influenced by multiple parameters. By analyzing the sensitivity of each structural parameter in this proposed mapping function, a structural optimization method for the refrigerator air duct can be established. This method can help optimize the design of the duct by identifying which parameters have the most significant impact on the outlet flow ratio and adjusting them accordingly.

Furthermore, the mapping function can also be applied as an evaluation method for existing duct structures. By inputting the parameters of the existing duct into the mapping function, it is possible to assess the flow efficiency of the duct system in an inter-cooled refrigerator. This evaluation can identify areas for improvement and guide efforts to enhance the flow efficiency of the duct system.

Parameter sensitivity analysis

In order to analyze the influence of the modularized parameters in the duct system, the sensitivity of each structural parameter is assessed based on the mapping relationship [Equation (17)]. Focusing on the structural parameters in the RC-2 duct module, the baseline values for these parameters are provided in Table 6.

Table 6. Sensitivity analysis initialization

Parameters	Content	Defaults
θ_i	Inclination angle of duct side	5
L_i	Pathway from outlet i to terminal outlet	0.2
A_i^I	Cross-section of inlet	8.95
A_i^O	Cross-section of duct outlet	6.5
$A_i^{O'}$	Cross-section of duct modular outlet	6.7
φ_i	Angle between outlet and pipeline	90

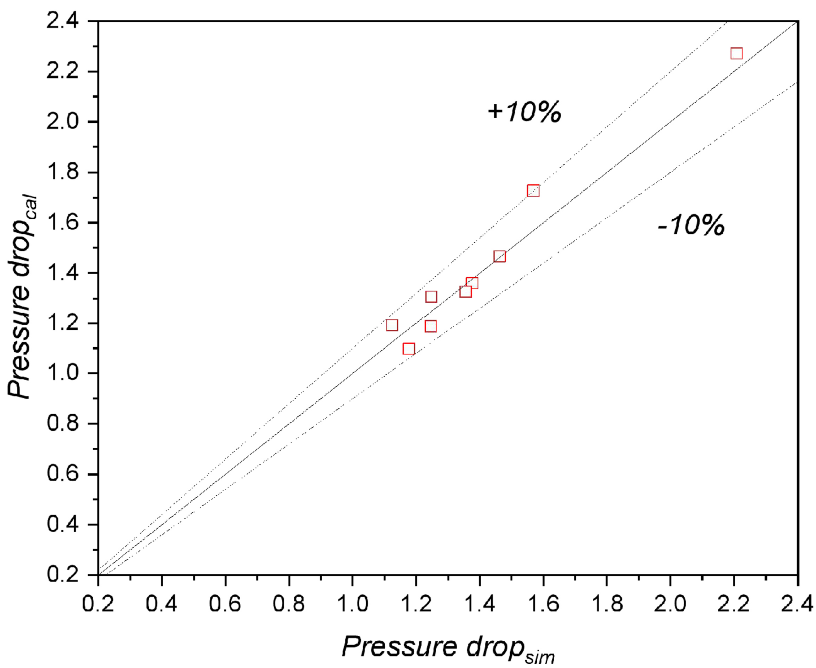

Figure 8. Comparison between calculation and numerical results for pressure drop.

Additionally, a 10% variation is applied to each structural parameter as a sensitive variable to compare the flow performance of the entire duct system. It is important to note that the parameter φ_i is directly determined by the location of the duct module and its value remains constant throughout the structural design process. Therefore, no sensitivity analysis is conducted for this parameter. The structure of the analysis is shown in Figure 9.

The influences of duct modular structural parameters are discussed based on the mapping function. The analysis reveals the following insights:

(1) Inclination angle of duct side (θ_i) is negatively correlated with the proportion of outlet flow. It shows that this negatively correlation is small, and flow variation (such as velocity, flow loss, *etc*.) changes little with variable direction of duct side. Thus, inclination angle of duct side (θ_i) is one insensitivity factor, which should be designed with other structural constrains than flow requirements.

(2) Pathway from outlet *i* to terminal outlet (L_i) is negatively correlated with the proportion of outlet flow. It shows that this positively correlation is obvious, because of the increasing flow loss with shorter pathway of

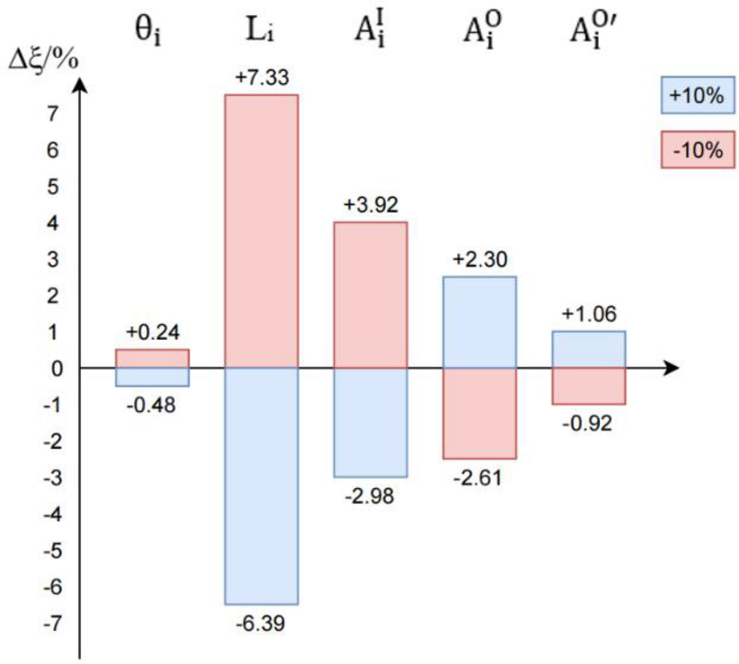

Figure 9. Sensitivity analysis of structural parameters.

rectangle duct. Thus, pathway from outlet i to terminal outlet (L_i) is one sensitivity factor to be considered in design of duct outlet.

(3) Cross-section of inlet (A_i^I) is negatively correlated with the proportion of outlet flow. It shows that this negatively correlation is also obvious, because the decreasing cross-section of inlet increases the velocity of flow in this duct structure. Thus, cross-section of inlet (A_i^I) is one sensitivity factor, which must be considered with flow requirements of duct outlet.

(4) Cross-section of duct outlet (A_i^O) is positively correlated with the proportion of outlet flow. It shows that this positively correlation is obvious, since the flow (Q^O) is directly determined by cross-section (A_i^O) at the same outlet. Thus, cross-section of duct outlet (A_i^O) is also one sensitive factor to be discussed with design requirements.

(5) Cross-section of duct modular outlet ($A_i^{O'}$) is positively correlated with the proportion of outlet flow. It shows that this positively correlation is small, since duct modular outlet is the intermediate structure in duct system, and it has little connection with the cross-section and velocity of flow at duct outlet. Thus, cross-section of duct modular outlet ($A_i^{O'}$) can be set as an insensitivity factor and designed as the cross-section of inlet (A^I_{i+1}) of connecting duct modular outlet.

Methods for predicting variation in duct flow

With the proposed equation of the fitted function [Equation (17)], it becomes possible to analyze the flow variations of a rectangle duct with a variable structure. This method of flow variation prediction involves three steps:

(1) Modularizing: In order to account for the influence of the rectangular air duct structure on the airflow volume, five dimensionless variables are defined. These variables include the length factor $X_1(L_i/L_0)$, the outlet area factor $X_2[A_i^{O'}/(A_i^{O} + A_i^{O'})]$, the inlet area factor $X_3(A_i^{O'}/A_i^{I})$, the pipe wall angle factor $X_4(cos\theta_i)$, and the outlet angle factor $X_5(cos\varphi_i)$. These variables serve as the calculation basis for each duct module as the initial design of the entire duct system consists of a series of duct modules with related structural parameters. Therefore, the performance of each duct module can be expressed as:

$$DM_i = [X_1, X_2, X_3, X_4, X_5] \tag{18}$$

(2) Predicting: In the duct system, the flow conditions at the inlets (Q_i^I) are considered as the input. The flow field of each duct module is then analyzed using Equation (20). By combining the flow variations of all the duct modules, the total flow variation in the system can be estimated as:

$$Q_i^o = Q_i^I \xi_i = \frac{Q_i^I}{K_1 X_1 + K_2 X_2{}^2 + K_3 X_3 X_4 + K_4 \dfrac{X_2 X_5}{X_3 - X_2 X_3} + K_5 X_5 + 1} \tag{19}$$

(3) Decision-making: In order to meet the flow requirements of each outlet in the air supply system, it is crucial to analyze the flow variations at each outlet. This data serves as a performance indicator to evaluate the structural design of the entire rectangular duct. Additionally, with the predicted results from the aforementioned functions, it is possible to identify and optimize the duct module that exhibits high flow loss and large volume. This optimization process aims to enhance the flow efficiency and overall structure of the duct system.

CONCLUSION

In this paper, a numerical prediction method is proposed to evaluate the flow variation in an air supply system by modularizing the rectangular duct structure. The following conclusions are drawn:

(1) Based on numerical testing of the rectangle duct in a refrigeration appliance, it is observed that the pressure-drop and flow variation are nonlinearly positively correlated with the inclination angle of the duct module side (θ) and cross-section (A), while they are nonlinearly negatively correlated with the duct length (l). Among these factors, the cross-section (A) is found to be the most influential. Additionally, a numerical expression of flow variation in the rectangle duct module is proposed.

(2) Experimental validation is conducted using a refrigeration appliance. The average error between the proposed function and the experimental data is found to be less than 10%, indicating that the numerical function and related method of flow variation are validated. In the future, this proposed method can be applied as a potential design tool to evaluate the performance of the entire rectangle duct and optimize the duct structure for air supply systems.

(3) The adoption of modular analysis and mapping function methods has facilitated the rapid optimization of duct structural parameters with air supply efficiency as the design target, thereby improving the rate of research and development and shortening the design cycle. However, its accuracy is somewhat lower compared to prototype experiments and whole-system CFD simulations of air supply systems. Additionally, the modular analysis method is highly suitable for relatively regular rectangular ducts, but real duct systems often comprise irregular duct structures, such as the C-1, C-2, C-3, and BW modules, in the case discussed in this paper. Faced with the optimization design of irregular duct structures, this method in the paper has limitations.

(4) This study has clarified the relationship between duct structural parameters and air distribution efficiency through mapping functions, achieving rapid optimization of duct structures. At the same time, the optimized ducts, due to improved flow characteristics, can reduce the working power of compressors and fans or shorten working hours while meeting the same air distribution requirements. The optimization method reduces the need for experimental validation, lowers design costs, and enhances air distribution efficiency. It not only reduces energy consumption but also responds to the demand for green energy and sustainable design.

(5) For future development, the proposed modular design method still requires continuous refinement and expansion. Faced with new forms of duct system modules, by further subdividing modules and using similar mapping functions, it can more effectively adapt to irregular pipe structures.

DECLARATIONS

Authors' contributions

Conceptualization, methodology, validation, system construction, original draft preparation: Fang D
Supervision, review and editing, formal analysis: Ke Q
Methodology, investigation: Sha J
Data curation, investigation: Cui P

Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Conflicts of interest

Cui P is affiliated with Changhong Meiling Co., Ltd., China, while the other authors have declared that they have no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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