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A new design framework for air-cooled condensing unit#

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ABSTRACT

For energy efficient design, the widely used V-shaped air-cooled condensing units are not proper for the Installation space with height restrictions. This paper proposes a comprehensive design framework for air-cooled condensing unit, comprising structural design, CFD simulation, system modeling, and prototype test. A case study on an air cooler confirms the effectiveness of the design framework. The implementation of a blow-through configuration for air-cooled condensing unit enhances air flow rate, achieves dynamic pressure recovery, and optimizes component installation.

Keywords: air-cooled condensing unit, design framework, CFD, system modeling, prototype test

NONMENCLATURE

Abbreviations	
CDU	Condensing unit
CFD	Computational fluid dynamics
COP_c	Coefficient of cooling performance
Symbols	
Q_c	Cooling capacity, kW
W	Power consumption, kW

1. INTRODUCTION

Air-cooled condensing unit (CDU) is widely used in air conditioning, refrigeration, and thermal power industries due to its stability, reliability, and ease of installation and maintenance [1]. An air-cooled CDU typically consists of finned-tube condenser coils and condenser fans, with the most common configuration being V-shaped (Fig. 1a). This V-shaped design increases the heat exchange area. However, it often causes uneven air flow through the coils in practical applications [2]. Lee et al. [3] conducted a computational fluid dynamics (CFD) simulation to study various V-shaped configurations with variant fin configuration and variant row configuration. The optimal configuration increased the average air velocity and overall heat transfer rate by 10.3% and 5.3%, respectively. Despite these benefits, adopting a V-shaped configuration is challenging when the design height of the CDU is constrained. Meyer and Kroger [4] noted that when the V-shaped layout angle θ is less than 30°, the airside pressure drop increases significantly, leading to a reduction in air flow and uneven air intake, thereby impairing condensation heat dissipation.

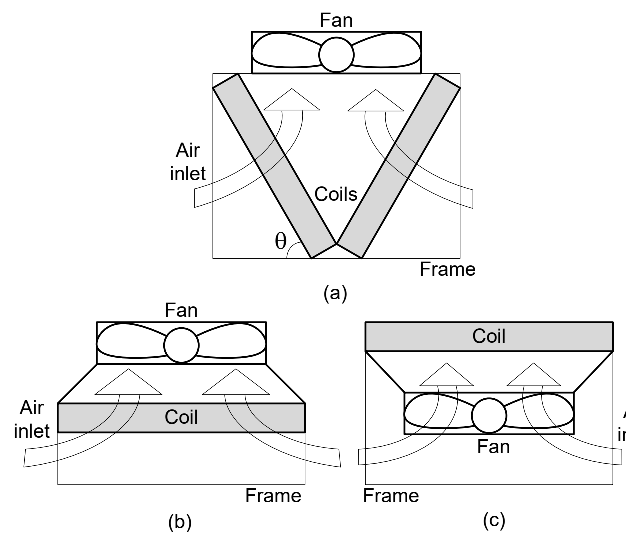

Fig. 1 (a) Traditional V-shaped, (b) draw-through, and (c) blow-through configurations for CDU.

To address the aforementioned issues, placing the condenser horizontally is a more effective approach. In this setup, the fan can be positioned either above the condenser for a draw-through configuration (Fig. 1b) or below the condenser for a blow-through configuration (Fig. 1c). The comparison of two configurations is presented in Table 1. While the blow-through configuration can enhance the air flow rate, it is rarely employed in practical applications. This paper proposes a design framework for CDU. Using the design of an industrial air cooler as a case study, feasibility of the blow-through configuration is evaluated, providing a crucial theoretical foundation for CDU design in engineering applications.

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Table 1 Comparison between blow-through and draw-through configurations for CDU.

Configuration	Draw-through	Blow-through
Features	1) At the fan inlet, the air temperature is high and the density is low. 2) The exhaust air velocity is high with minimal backflow effect, but this results in dynamic pressure loss. 3) Additionally, the air velocity at the condenser inlet is uneven.	1) At the fan inlet, the air temperature is low and the density is high. 2) Partial dynamic pressure recovery is achieved, resulting in a larger air flow rate. 3) However, the exhaust air velocity is low, potentially causing backflow, and the air velocity at the condenser inlet is more uneven compared to the draw-through configuration.

2. DESCRIPTION OF DESIGN FRAMEWORK

The design framework for CDU comprises structural design, CFD simulation, system modeling, and prototype test (Fig. 2). Structural design evaluates the advantages and disadvantages of various configurations. CFD simulation analyzes the air flow to optimize system design and guide prototype manufacturing. System modeling compares the performance of different designs, while prototype test validates the system model and further assesses performance. The following sections will detail the design framework through a case study.

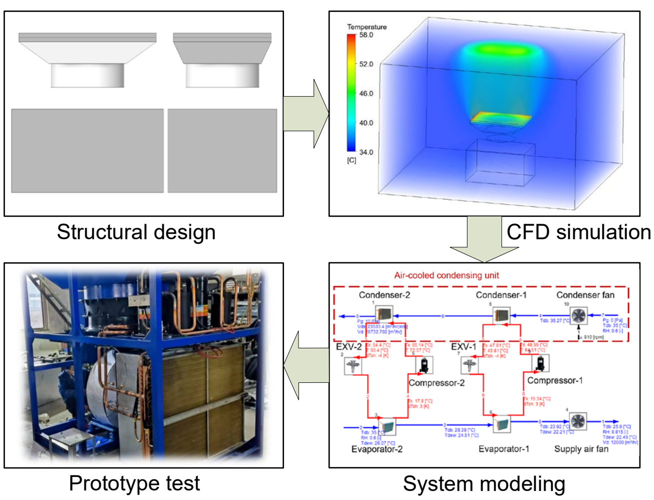

Fig. 2 Design framework for CDU.

3. CASE STUDY

3.1 Structural design

Based on the design framework, an industrial air cooler was designed and tested with the CDU placed on the top of the air cooler system. Due to height limitation, the CDU must achieve the required air flow rate through an optimal configuration to ensure the system's condensing temperature under extreme conditions does not exceed the compressor's operational limit. The possible configurations are illustrated in Fig. 3. Although the traditional V-shaped configuration increases the heat exchange area, it faces challenges with air entry at both ends of the coils, resulting in insufficient flow rate. The draw-through configuration has inferior air intake conditions and provides less flow rate compared to the blow-through configuration. Finally, the CDU adopts the blow-through configuration.

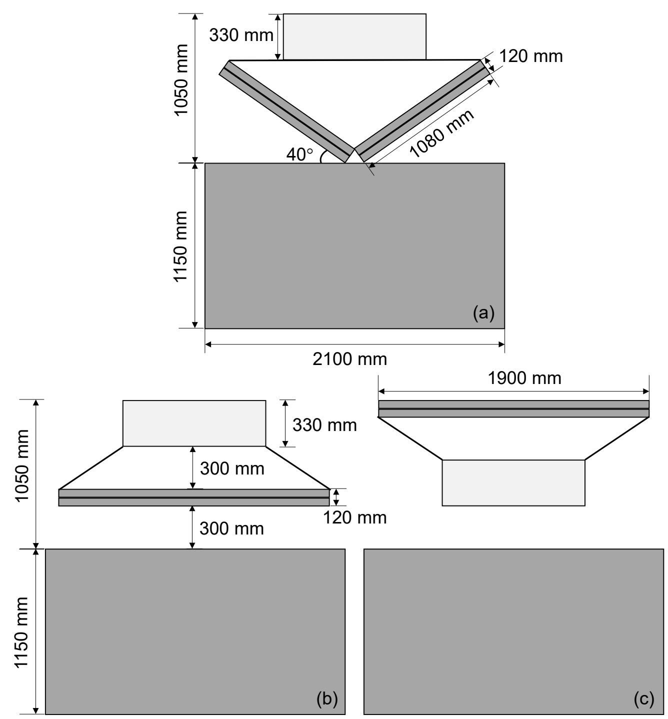

Fig. 3 (a) V-shaped, (b) draw-through, and (c) blow-through configurations for CDU in air cooler.

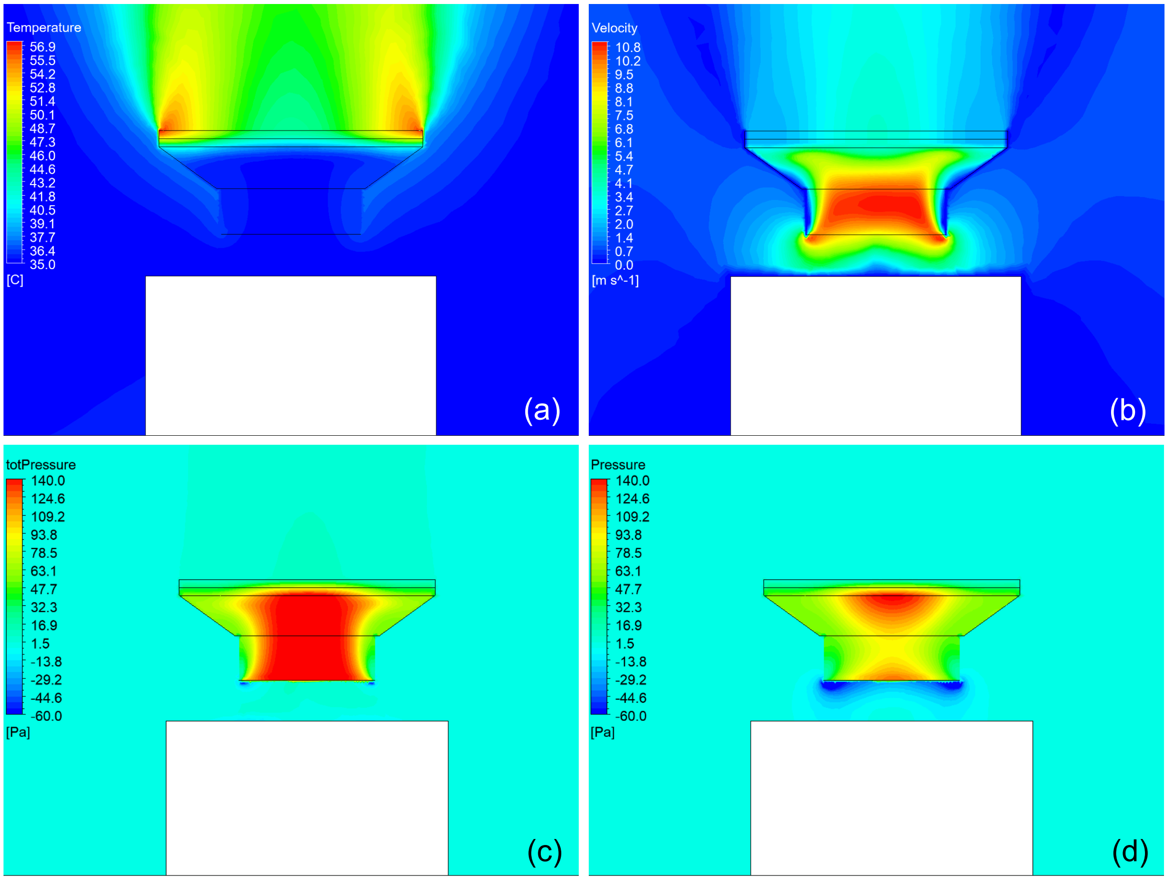

Fig. 4 (a) Temperature, (b) velocity, (c) total pressure, and (d) static pressure contours on central cross-sectional plane.

3.2 CFD simulation

Feasibility of the blow-through configuration for CDU requires further verification through CFD simulation. The simplified 3D model is shown in Fig. 3c, with the CDU featuring blow-through configuration at the top. The other components are placed at the bottom and are considered solid, allowing air to enter only from the sides. In the CFD simulation, the finned-tube condenser is regarded as a porous medium, with its pressure drop characteristic curve obtained using the air-side pressure drop correlations by Wang et al. [5]. Each condenser has a heat exchange capacity of 50 kW, treated as a uniform internal heat source in the model. The performance curve of the fan is provided by the manufacturer.

The CFD simulation results are shown in Fig. 4. The temperature contour (Fig. 4a) indicates a low air temperature at the condenser outlet, suggesting sufficient airflow rate. It also indicates an uneven air temperature distribution at the condenser outlet, suggesting uneven air velocity at the condenser inlet. This will serve as input for the subsequent system model to assess its impact on the condenser performance. Additionally, Fig. 4a reveals minor air backflow at the condenser outlet due to the low air flow rate at the outlet (2~4 m/s, Fig. 4b). The total pressure contour (Fig. 4c) shows the air pressure rise from the fan. The static pressure contour (Fig. 4d) more accurately reflects the pressure changes. A slight pressure drop occurs at the fan inlet due to sudden contraction, followed by a velocity increase as the air passes through the fan. When the high-speed air hits the condenser coil, the dynamic pressure of the centrally located air converts into static pressure, achieving dynamic pressure recovery. This increases the static pressure of the air, thereby enhancing the airflow rate.

3.3 System modeling

To ensure that the air cooler can achieve the air supply target across a wide range of operating conditions, the air cooler is equipped with two vapor compression refrigeration systems, forming an efficient stepped pressure cycle [6]. The CDU employs non-uniform air inlet distribution to reflect the actual condenser performance. The system model is developed using the simulation software GREATLAB (Fig. 5) [7],

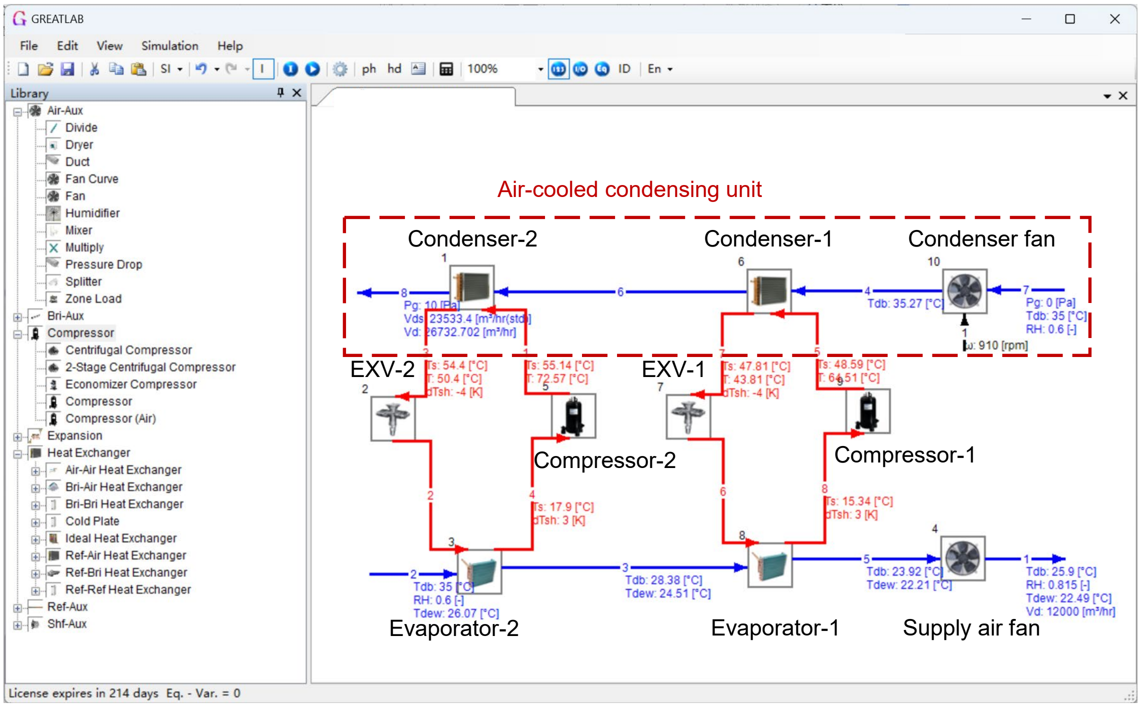

Fig. 5 Air cooler system model in GREATLAB.

whose accuracy has been widely validated through numerous case studies [8]. Detailed component models in the system can be found in previous work [9].

3.4 Prototype test

Based on CFD simulation and system modeling, this study further built a prototype of the air cooler for testing (Fig. 6). Due to the blow-through configuration at the top, the prototype components are compactly arranged, allowing ample space at the bottom for the condenser fan to draw in air. The prototype evaluated system state parameters under two operating conditions. The test results were compared with the system simulation outcomes. Both the air side parameters (Table 2) and the refrigerant side parameters (Fig. 7) were in good agreement, verifying the rationality of the system model.

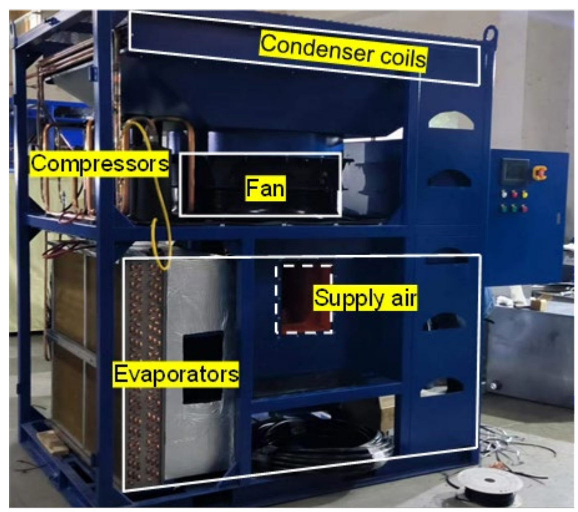

Fig. 6 Air cooler prototype.

Table 2 Simulated vs. experimental results.

Parameter	Condition 1 (26.4°C/62.3%)			Condition 2 (19.3°C/62.3%)		
	Experiment	Simulation	Error	Experiment	Simulation	Error
Supply air temperature, °C	15.6	15.3	–0.3°C	10.8	10.4	–0.4°C
Exhaust air temperature, °C	40.9	39.2	–1.7°C	29.4	29.9	0.5°C
Supply air flow rate, m^3/h	9742	9996	2.6%	9059	9524	5.1%
Exhaust flow rate, m^3/h	25763	26701	3.6%	-	-	-
Cooling capacity Q_c, kW	69.2	65.0	–6.1%	54.4	59.4	9.2%
$COP_c = Q_c/W_{total}$	2.64	2.49	–5.7%	2.26	2.51	11.0%

The prototype test confirmed that the system performance met the design requirements, with the blow-through configuration playing a pivotal role. It delivered enough air flow rate (≥ 25,000 m^3/h) for the CDU, exhibited excellent condenser performance, and maintained the condensing temperature within the expected range during system operation.

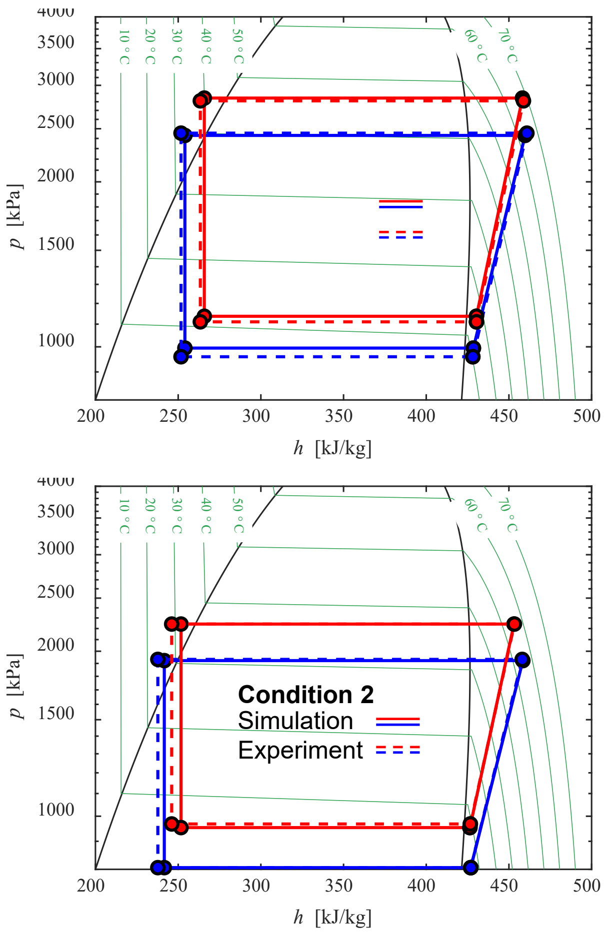

Fig. 7 Comparison of simulation and experiment in refrigerant parameters for conditions 1 and 2.

4. CONCLUSIONS

This paper proposes a comprehensive design framework for air-cooled CDU, illustrated through a detailed case study of an industrial air cooler. The design framework includes structural design, CFD simulation, system modeling and prototype test. The main conclusions are as follows:

The design framework for air-cooled CDU effectively guides system design, facilitates optimal configuration selection, and ensures reliable system operation. The case study affirms the superiority of the design framework, with the prototype demonstrating robust performance during operation. The condenser performance and the air flow rate are as expected.

The design framework validates the feasibility and benefits of the blow-through configuration for air-cooled condensing unit. This configuration enhances the air flow rate and achieves partial dynamic pressure recovery. Furthermore, adopting the blow-through configuration ensures lower air temperature and higher density at the fan inlet.

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