

Optimizing Heat Transfer Performance in CO₂ Finned Tube Gas Coolers: A Comparative CFD Study of Design Variations

Rajendra Ahirwar¹, Sanjay Kumar Singh², Ravishanker V. Choudri^{2*}

Abstract

Computational fluid dynamics (CFD) simulations and mathematical analysis are used in this study to examine the heat transfer efficiency of CO₂ finned tube gas coolers. To maximize heat transfer efficiency, CFD simulations were carried out on a variety of gas cooler designs with variable fin geometry, including offset strip fins, using the ANSYS Fluent program. Under the baseline design, there was a finned tube cooler measuring 610 mm in length, 50 mm in width, 0.13 mm in fin thickness, and 7.9 mm in outer tube diameter. The heat transfer rate for refrigerants varied from 1756.37 W for Design-1 to 2107.65 W for Design-4, according to simulation data. Attaining the maximum heat transfer rate, Design-4 outperformed the baseline by 20.29%. In Design-4, at a velocity of 1 m/s airflow, a temperature reduction of up to 65.8 K was measured across the finned surface. The study shows that because there were less temperature differentials, raising the airflow velocity from 1 m/s to 3 m/s usually reduced the heat transfer rate. Design-4 was the most efficient arrangement, with notable improvements in heat transfer efficiency and thermal performance. To assess the heat transfer efficiency of CO₂ finned tube gas coolers, we conducted a comparative CFD analysis in this work. We pay particular attention to the consequences of different design modifications. The goal of the research is to determine the best possible design arrangements that maximize heat transfer rates while lowering pressure drop and energy usage.

Keywords: CO₂ gas cooler, finned tube, heat transfer, computational fluid dynamics (CFD), ANSYS fluent program

INTRODUCTION

CO₂ has re-emerged as an eco-friendly and nature-derived cooling agent choice for cooling and heat pump systems owing to its excellent thermal properties and low global warming potential (GWP). These

systems function in either subcritical or transcritical cycles, with the choice contingent on the surrounding temperature conditions. However, high-temperature environments present specific challenges for this operation. In warm and humid environments, such as those in India, systems need to function within the transcritical cycle because CO₂ has a comparatively low critical temperature [1]. Therefore, heat is released within the supercritical region, preventing condensation in the gas cooler. The design and functionality of gas coolers are especially important in warmer climates because they have a significant impact on the overall effectiveness of the system. The geometric parameters of these coolers, which significantly affect their performance, were thoroughly examined

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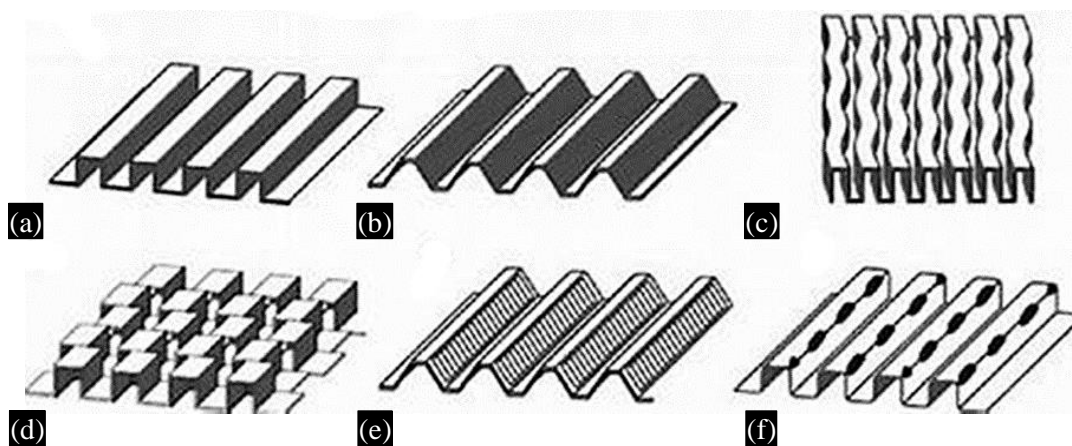
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Table 1. Specification of the modeled gas cooler.

Parameter	Value
<i>Dimensions</i>	
Width (W)	0.61 m
Height (H)	0.46 m
Depth (D)	0.05 m
Front area	0.281 m ²
<i>Fin specifications</i>	
Shape	Raised lance
Pitch	1.5 mm
Thickness	0.13 mm
<i>Tube specifications</i>	
Number of rows	3
Outside diameter	7.9 mm
Inside diameter	7.5 mm
Shape	Smooth

**Figure 1.** Distinctive plate-fin heat exchanger surface types.

and optimized using computational fluid dynamics (CFD) modeling. The specifications of the modeled gas cooler are listed in Table 1. However, it is important to note that most of these studies were based on uniform airflow conditions, which may differ from real-world scenarios [2].

Varieties of Plate-Fin Heat Exchanger Surfaces

Heat exchangers with plate fins commonly utilize extended surfaces to compensate for the lower heat transfer coefficient on the gas side. These extended surfaces were designed to enhance the heat transfer coefficients. To achieve this, fins with specialized geometries have been created, providing significantly higher heat transfer coefficients than extended plain surfaces [3, 4]. However, these specialized designs can sometimes lead to increased pressure drop. Several types of extended surfaces have been created, such as louvered, wavy offset, plain rectangular, and plain trapezoidal. Distinctive plate-fin heat exchanger surface types are shown in Figure 1. In our numerical and experimental studies, we focused on offset strip fin geometry.

- *Plain fins:* These flat untextured surfaces are commonly used for fluids with little to no fouling. They offer a straightforward design and are relatively easy to manufacture.
- *Perforated fins:* A pattern of evenly spaced holes was punched into the fin material to create the perforated fins. The fin material was then folded to create the flow channels. Featuring small holes, these fins promote increased turbulence in the fluid flow, which enhances heat transfer. They are particularly effective for fluids with moderate viscosities.

- *Louvered fins*: These fins have small cuts that create louvered patterns. The design increases the surface area and turbulence and improves the heat transfer rates. They are well-suited for air-to-liquid heat exchange. High Reynolds number values cause the fluid to flow along the direction of the louvers, resulting in a boundary layer flow, whereas low Reynolds numbers cause the stream to flow parallel to the axial direction (duct flow).
- *Wavy fins*: Wavy fins are shaped like plain fins in the cross-section, but they are curved in the direction in which the fluid flows. Upon crossing the concave, wavy surface, and fluid, the resulting wave-like structures in the wavy fins create a complicated flow field and effective interruptions that eventually culminate in the formation of a vortex. With a corrugated shape, these fins create a more turbulent flow, enhancing heat transfer. The wavy design is beneficial for applications with high heat transfer requirements.
- *Offset strip fins*: Comprising of lanced strips offset from each other, these fins disrupt the flow, significantly increasing the heat transfer coefficient. This design is effective for compact heat exchangers.
- *Pin fins*: These consist of small pins that extend from the plate surface, expanding the area covered and heat transfer. They are ideal for high-temperature and high-pressure applications [5].

Most people associate CO₂ with the respiration or combustion of fossil fuels, and an atmosphere's high concentration of CO₂ is one of the main causes of global warming. Natural sinks, such as forests, primarily regulate the amount of CO₂ in the atmosphere, but the growing trend of deforestation is increasing the amount of CO₂ in the atmosphere. Utilizing carbon capture methods to transfer CO₂ to storage areas, such as subterranean geological reservoirs, is another way to manage the concentration of CO₂ [6].

LITERATURE REVIEW

Zhou K. et al. (2020) [7]—Zhou et al. analyzed a radial inflow turbine for the supercritical CO₂ (S-CO₂) Brayton cycle using CFD and tip clearance analysis. Their design achieves 85.36% efficiency and produces 1.16 MW of power. The study confirms the accuracy of the design model with a 3.73% deviation from the simulation results and notes that increasing the tip clearance decreases the efficiency and power output.

Kim D.M. et al. (2021) [8]—Kim et al. investigated the use of cryogenic cooling (liquid nitrogen) in hard-turning processes and compared it with traditional methods. They found that cryogenic cooling significantly extended the tool life by 3-6 times and reduced both operational time and environmental impact, making it a more sustainable and cost-effective solution.

Tsamis K.M. et al. (2017) [9]—Tsamis et al. assessed various CO₂ refrigeration system configurations in retail food stores for efficiency and environmental impact. Their findings indicate that the CO₂ booster system with a gas bypass compressor offers the best energy savings, improving performance by up to 5.0% in warmer climates.

Liu B. et al. (2022) [10]—Liu et al. focused on the thermal and hydraulic performance of a printed circuit heat exchanger (PCHE) used as a precooler in a marine S-CO₂ Brayton cycle. Their CFD-based study revealed that traditional heat transfer correlations are inadequate, leading to a new correlation for designing precoolers.

Zheng L. et al. (2016) [11]—Zheng et al. presented a dynamic model for a two-stage transcritical CO₂ refrigeration cycle, examining how various disturbances affect the system's performance. Their results, which align well with the experimental data, suggest that adjusting the compressor speed and expansion valve settings can significantly enhance the system efficiency.

OBJECTIVE

- A mathematical analysis was performed to investigate the heat transfer coefficient and total heat transfer rate of the CO₂ finned tube.

- The main objective of the present work is to improve the heat transfer performance of the CO₂ fin tube gas cooler through mathematical and CFD analyses, considering various geometries and pitch variations of the CO₂ finned tube.
- To compare the results of CFD with mathematical analysis and provide recommendations for enhancing the design of CO₂ finned tube gas coolers to improve heat transfer.

METHODOLOGY

CFD Analysis

CFD is a specialized domain within fluid mechanics that employs numerical analysis and data structures for the systematic examination and resolution of fluid-flow-related predicaments. In this specific context, the finned tube gas chiller for CO₂ CFD analysis was conducted using ANSYS Fluent software. Input parameters, sourced from foundational papers, guide this analytical process [12, 13]. Computational analysis necessitates the implementation of governing equations, encompassing the continuity, momentum, energy, and K and ϵ equations. The distinct stages of analysis encompassed in (CFD) analysis are outlined below.

1. *Preprocessor*:
 - i. Creation of a computer-aided design (CAD) model
 - ii. Generation of meshing
 - iii. Define materials.
2. *Solution processor*: At this stage of the study, the computer controls commands and uses the finite element approach to solve the instantaneous equation [14].
3. *Postprocessor*: The general postprocessor is used to review the analytic results for the entire model [15].

CFD Analysis Algorithm

CAD Model of CO₂ Gas Cooler with Finned tube

In this study, a CAD model of a CO₂ finned tube gas cooler was created using the design module in the ANSYS Workbench. The gas cooler had a width of 50 mm, a length of 610 mm, and 0.13 mm in fin thickness. The tube features an outer diameter of 7.9 mm and an inner diameter of 7.5 mm. The configuration comprises three tube rows, as illustrated in Figure 2.

Meshing is a pivotal operation in the analysis of CFD, wherein the CAD geometry undergoes subdivision into numerous smaller entities referred to as a mesh. In the current study, the process resulted in the generation of 695,186 nodes and 343,512 elements, as depicted in Figure 3.

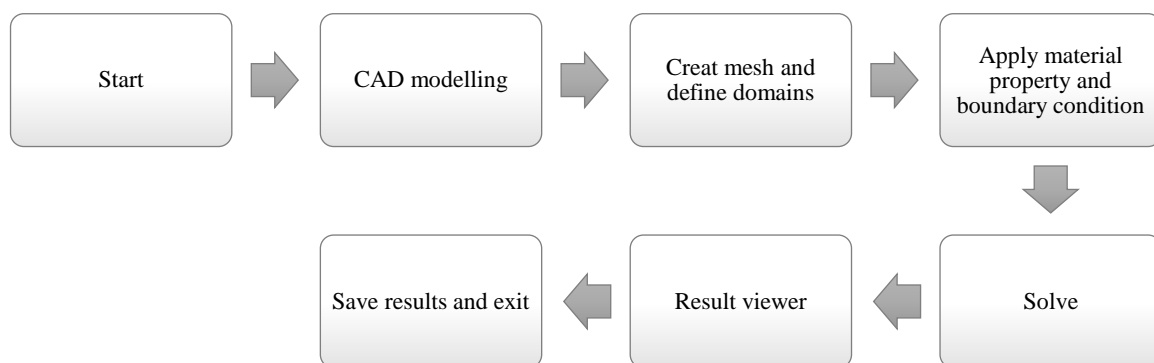


Figure 2. Algorithm used for computational fluid dynamics analysis.

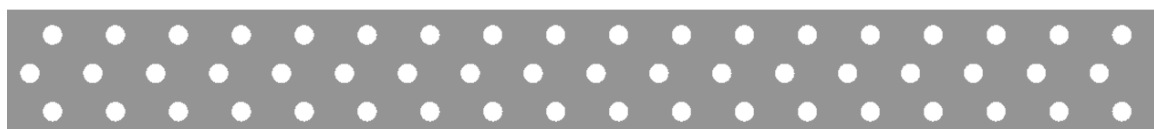


Figure 3. CAD Model of CO₂ finned tube gas cooler.

CAD Model of Design-2 for Finned Tube Gas Cooler with CO₂

In this study, a CAD model for Design-2 of a gas cooler with CO₂ fins was developed using the design module in ANSYS Workbench. The finned tube gas cooler had dimensions of 610 mm, width of 50 mm, and 0.13 mm for fin thickness. The tube exhibits 7.99 mm on the outside diameter and 0.8 mm on the inside 7.5 mm, augmented by the insertion of two rectangular ribs with dimensions of 0.75 mm × 1.5 mm. The configuration includes three tube rows, as illustrated in Figure 4.

The CO₂ gas cooler with the finned tube Design-2 meshing procedure breaks it up into a number of smaller units called meshes. In the current study, this operation resulted in the generation of 689,281 nodes and 386,708 elements, as depicted in Figure 5.

CAD Model of Design-3 for CO₂ Gas Cooler Finned Tube

The CAD model for Design-2 of the CO₂ finned tube gas cooler was developed in this study using the ANSYS Workbench design module. The gas cooler had a width of 50 mm, a length of 610 mm, and 0.13 mm in fin thickness. The tube had a 7.9 mm outside diameter and a 7.5 mm inner diameter. Additionally, two rectangular ribs, each measuring 0.75 mm by 1.5 mm, are inserted to enhance the design. The configuration includes three tube rows, as shown in Figure 6.

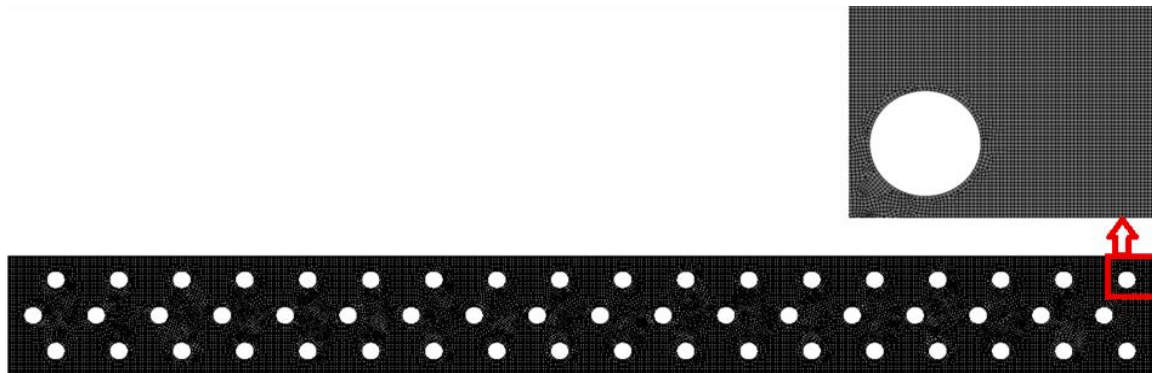


Figure 4. Finned tube mesh layout for CO₂ gas cooling.

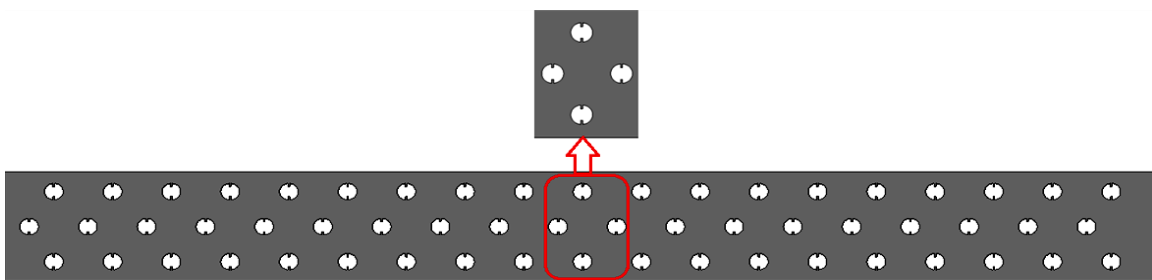


Figure 5. Design-2 CAD drawing of the CO₂ (carbon dioxide) gas cooler with finned tube.

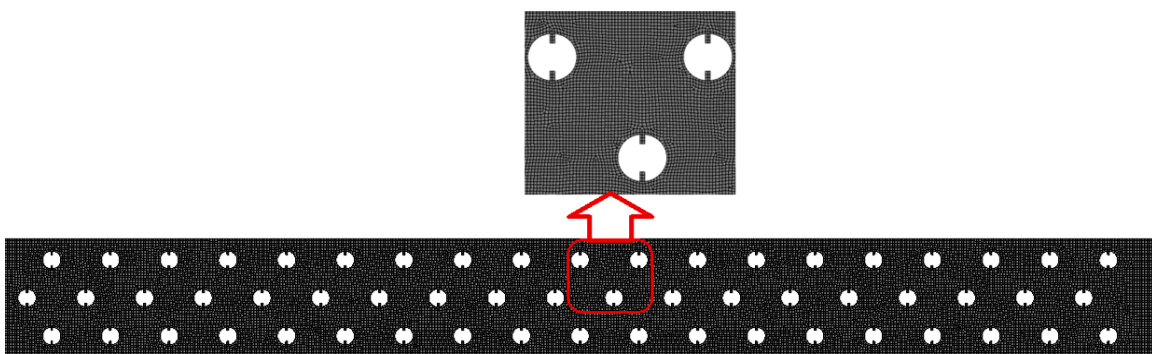


Figure 6. Design-2 meshing for CO₂ (carbon dioxide) finned tube gas cooler.

The meshing method divides the CO₂ (carbon dioxide) finned tube gas cooler Design-3 into several smaller units, called a mesh. In this study, this operation resulted in the generation of 623,386 nodes and 322,060 elements, as illustrated in Figure 7.

CAD Model of Design-4 for Finned Tube Gas Cooler with CO₂

In this study, the CAD model for Design-4, the finned tube gas chiller for CO₂, was generated using the design module of the ANSYS Workbench. The fin-equipped gas cooler measured 610 mm in length, 50 mm in breadth, and 0.13 mm a fin thickness. Design-3 meshing for CO₂ finned tube gas cooler is illustrated in Figure 8. The dimensions of the tube are 7.9 mm for the outer diameter and 7.5 mm for the inner diameter. It includes two rectangular ribs that measure 0.75 mm by 1.5 mm. The configuration includes three tube rows, as shown in Figure 9.

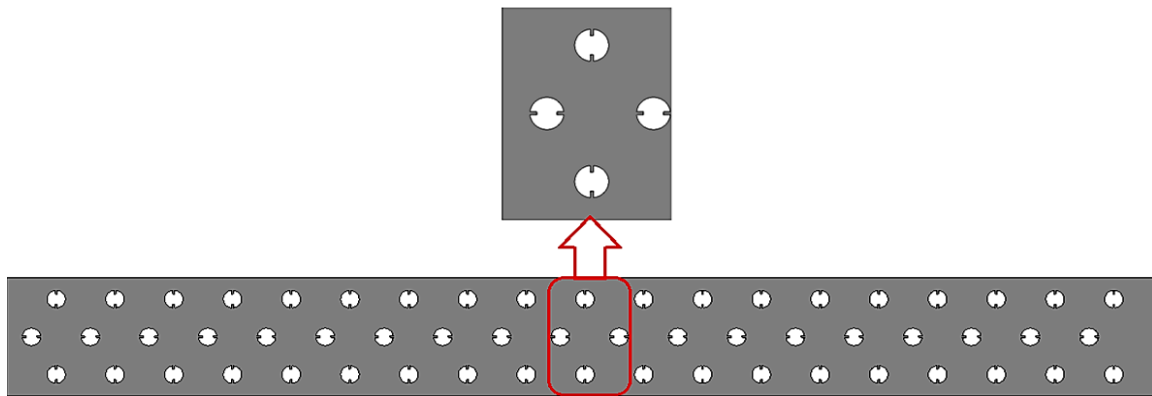


Figure 7. CAD model of the Design-3 CO₂ (carbon dioxide) finned tube gas cooler.

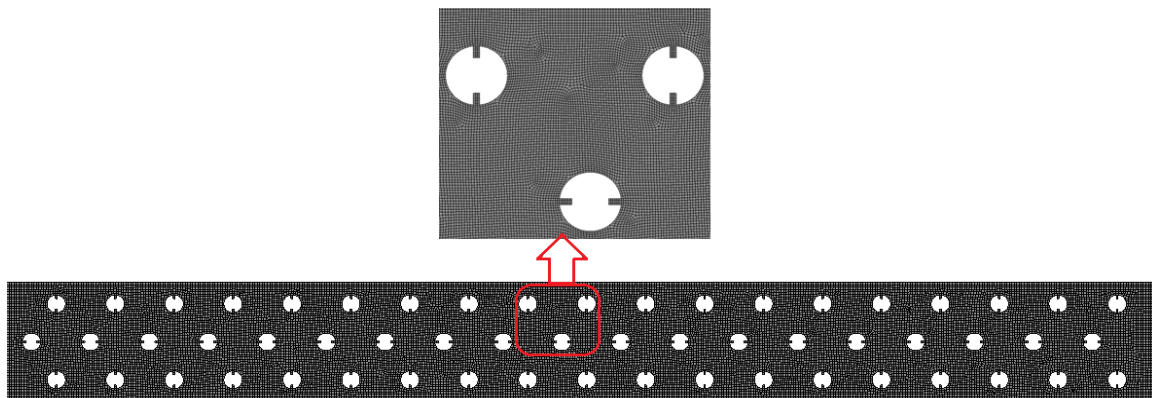


Figure 8. Design-3 meshing for CO₂ finned tube gas cooler.

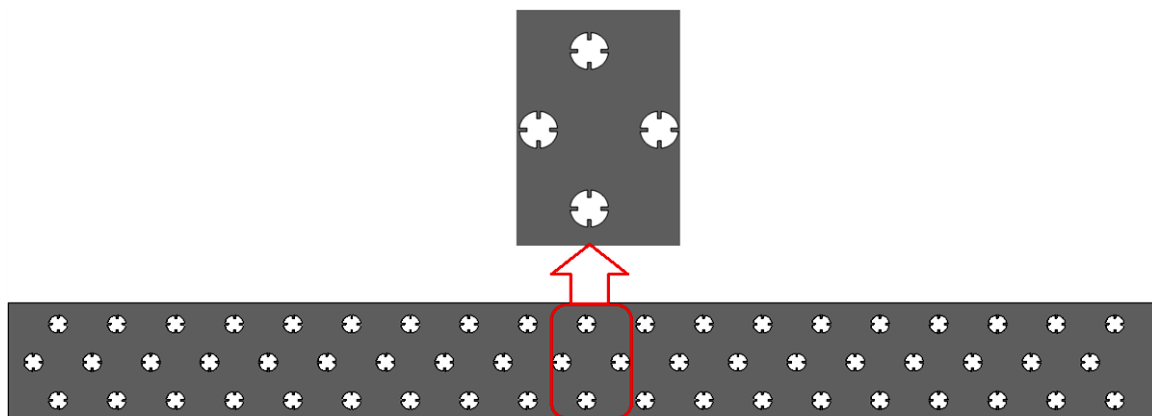


Figure 9. CAD model of Design-4 for a finned tube gas cooler on CO₂

The CO₂ finned tube gas cooler Design-4 meshing technique is divided into several smaller entities called meshes. In this study, this operation generated 689,713 nodes and 386,884 elements, as illustrated in Figure 10.

Properties of Liquid Carbon Dioxide

Liquid carbon dioxide is a form of liquid that results from the compression and cooling of gaseous carbon dioxide under high pressure. The temperature distribution at the central fin surface for parabolic airflow velocity at a speed of one meter per second [2] is shown in Figure 11. It does not naturally occur under standard atmospheric conditions; its existence is contingent on a pressure exceeding 5.2 bar and a temperature below 31.1°C (critical point temperature) but higher than (-56.6°C) (triple point temperature). At a 90-bar density of liquid carbon dioxide as shown in Table 2. Liquid carbon dioxide has various applications, including the decaffeination of coffee, extraction of virgin olive oil from olive paste, utilization in fire extinguishers, and as a coolant. It is transparent and odorless and possesses a density of 1101 kg/m³ when fully saturated at -37°C. The distribution of temperatures at the central fin surface for parabolic airflow velocity profiles at a speed of one meter per second is shown in Figure 12.

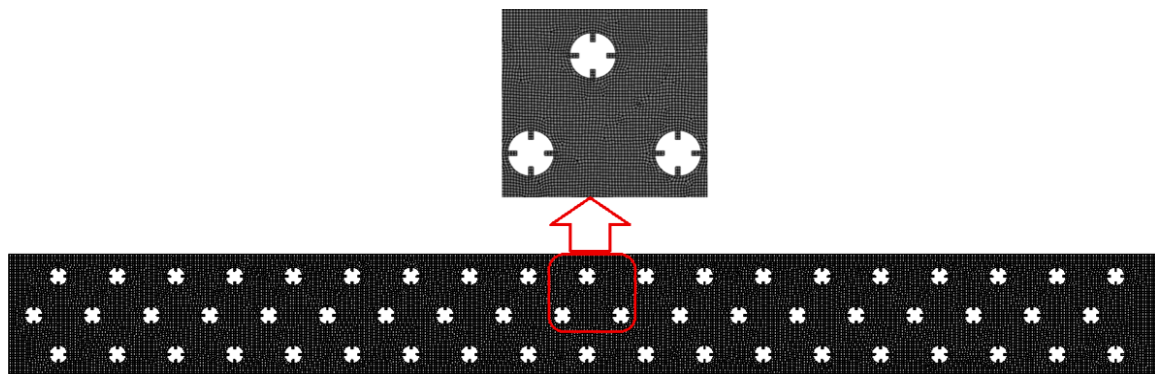


Figure 10. The meshing of Design-4 for CO₂ finned tube gas cooler.

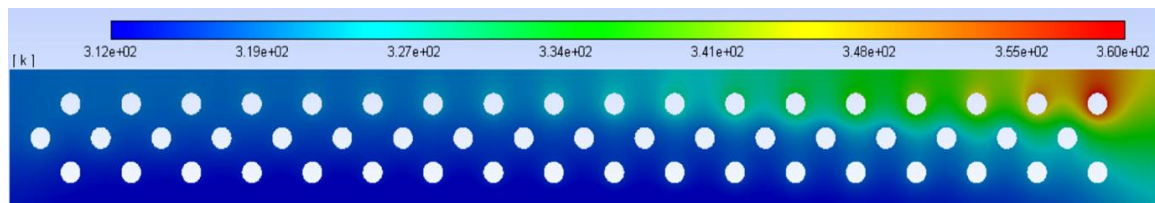


Figure 11. Distribution of temperatures at the central fin surface for parabolic airflow velocity profiles at a speed of one meter per second [2].

Table 2. At 90 bar density of liquid carbon dioxide.

Temperature T (°C)	Density ρ (kg/m ³)	Specific heat c_p (kJ/kg K)	Thermal conductivity k (W/m K)	Kinematic viscosity ν (10 ⁻⁶ m ² /s)	Prandtl's no. Pr
-50	1156	1.84	0.086	0.119	2.96
-40	1118	1.88	0.101	0.118	2.46
-30	1077	1.97	0.112	0.117	2.22
-20	1032	2.05	0.115	0.115	2.12
-10	983	2.18	0.110	0.113	2.20
0	927	2.47	0.105	0.108	2.38
10	860	3.14	0.097	0.101	2.80
20	773	5.0	0.087	0.091	4.10
30	598	36.4	0.070	0.080	28.7

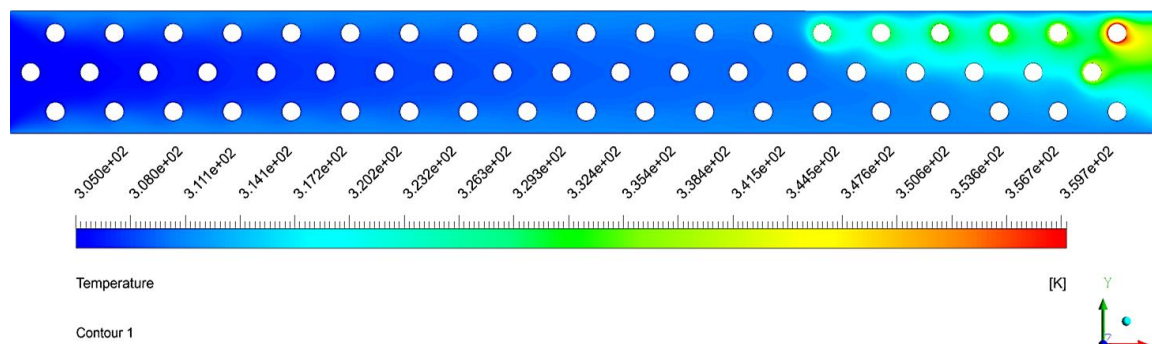


Figure 12. Distribution of temperatures at the central fin surface for parabolic airflow velocity profiles at a speed of one meter per second.

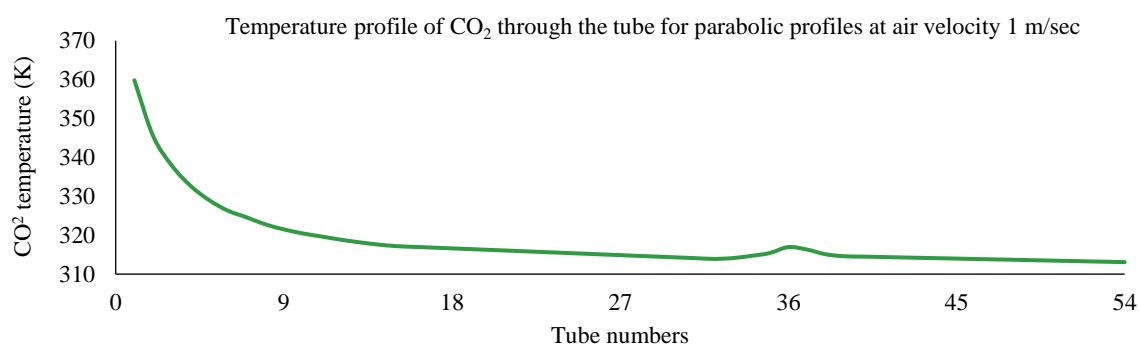


Figure 13. Temperature profile of CO₂ through the tube for parabolic profiles at air velocity 01 m/sec.

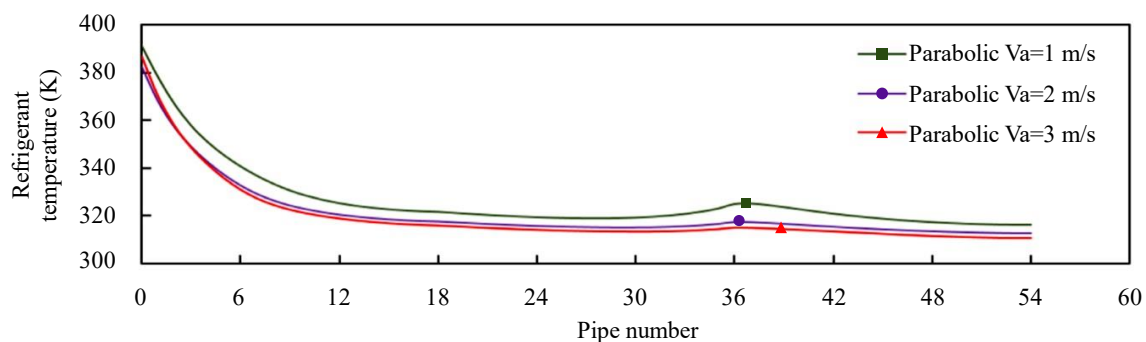


Figure 14. Temperature profile of CO₂ through the tube for parabolic profiles at air velocities 1, 2, and 3 m/sec [2].

Validation

The primary objective of this work is to optimize the heat transfer efficiency of CO₂ finned tube gas coolers using mathematical analysis and CFD applied to a range of gas cooler geometries. The temperature profile of CO₂ through the tube for parabolic profiles at an air velocity of 01 m/sec is shown in Figure 13. For the validation of the present work, a research paper was conducted, and CFD analysis was performed using a CAD model of the length and width of the gas cooler with a finned 610 mm × 50 mm with 0.13 mm fin thickness, and the outer and inner diameters of the tube were 7.9 mm and 7.5 mm with 1.5 mm with 03 rows of tubes. Following the completion of the CFD analysis, the results obtained were compared and validated against the existing literature. The temperature profile of CO₂ through the tube for parabolic profiles at air velocities of 1, 2, and 3 m/s [2] are shown in Figure 14.

From the contours in Figures 11 and 12 and graphical diagram, it was observed that the maximum temperature variation in the present work was 0.08%, and the minimum temperature variation was 0.335% compared with the base paper. The heat transfer rate of the refrigerant for different designs of

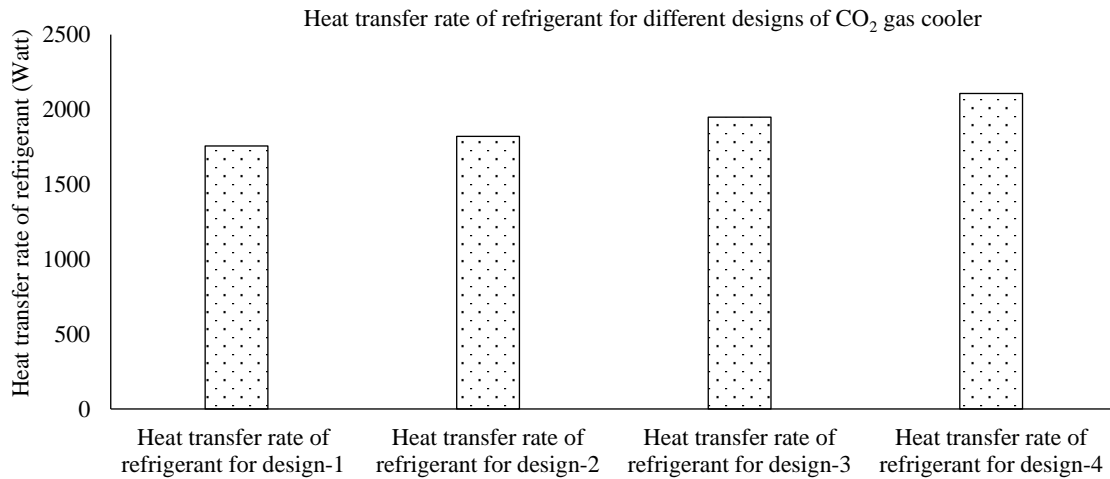


Figure 15. Heat transfer rate of refrigerant for different designs of CO₂ gas cooler.

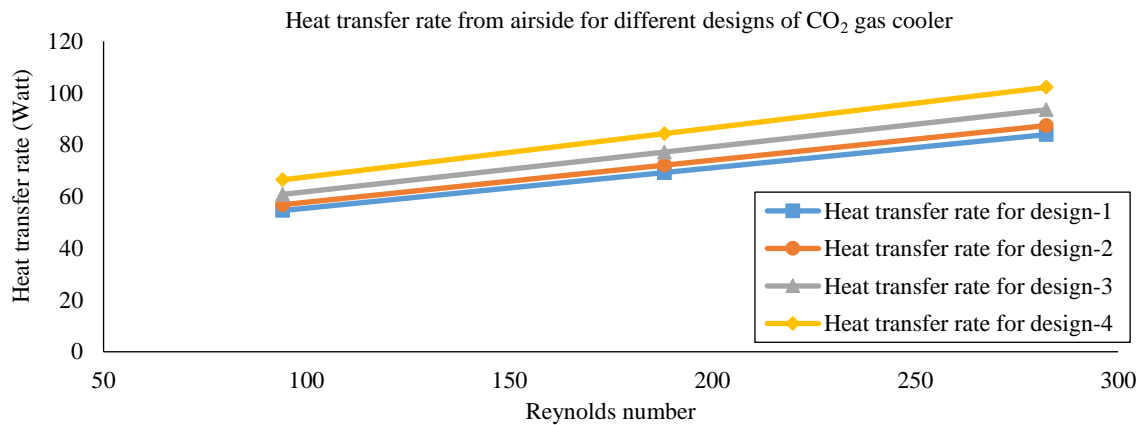


Figure 16. Heat transfer rate from airside for different designs of CO₂ gas cooler.

the CO₂ gas cooler is shown in Figure 15. All the results show very good agreement between the base paper and the present work; hence, further analysis for different designs of the CO₂ gas cooler with the same boundary conditions must be performed. The heat transfer rate from the airside for different CO₂ Gas Cooler designs is shown in Figure 16.

RESULT ANALYSIS

The heat transfer rate for refrigerant

$$Q_r = h_r A (T_r^{in} - T_r^{out})$$

Q_r = Heat transfer from refrigerant

\dot{m} = mass flow rate of the refrigerant

c_p = Specific heat of refrigerant

h_r = refrigerant heat transfer coefficient

A = Area of the refrigerant tube

T_r^{in} = Inlet temperature of refrigerant

T_r^{out} = Outlet temperature of refrigerant

$$Q_r = \dot{m} c_p (T_r^{in} - T_r^{out})$$

Refrigerant heat transfer rates for different designs are computed as follows:

- For Design-1: $Q_{r,Design-1} = 0.038 \times 840.37(360 - 305) = 1756.373 \text{ Watt}$
- For Design-2: $Q_{r,Design-2} = 0.038 \times 840.37(360 - 305) = 1820.241 \text{ Watt}$

- For Design-3: $Q_{r,Design-3} = 0.038 \times 840.37(360 - 305) = 1947.978 \text{ Watt}$
- For Design-4: $Q_{r,Design-4} = 0.038 \times 840.37(360 - 305) = 2107.648 \text{ Watt}$

The numerical analysis demonstrated a notable increase in the airside heat transfer coefficient. For example, with a uniform airflow profile, it increases from 47.71 W/m²•K to 73.37 W/m²•K when the Reynolds number decreases from 94.1 to 282.3. The temperature distribution for Design-1 at 1 m/s throughout the fin surface is shown in Figure 17.

Finned Tube Gas Cooler CFD Study Using CO₂ for Design-1

After the CFD analysis of the carbon dioxide gas cooler with a finned tube initial design of -1 at 1 m/s was completed, the temperature distribution over the finned surface as a whole was investigated. The temperature distribution for Design-2 at 1 m/s throughout the fin surface is shown in Figure 18. The analysis showed that the gas cooler entrance tube had a maximum temperature of 359.7 K, whereas the exit end of the finned surface had a minimum temperature of 305 K. The total temperature drop, as depicted in, amounted to 54.7 K.

Following the completion of the CFD analysis for Design-1 of the carbon dioxide gas cooler with a finned tube at 1 m/s, an assessment of the temperature distribution across the entire finned surface was conducted. The analysis showed that the entrance tube of the gas cooler had a maximum temperature of 359.7 K, whereas the exit end of the finned surface had a minimum temperature of 306.8 K. The total temperature drop, as depicted in Figure 16, amounted to 52.9 K.

Analysis of Gas Cooler Using CO₂ Finned Tube Using Computational Fluid Dynamics for Design-2

After the CO₂ finned tube gas cooler Design-2 CFD study was completed at 1 m/s, temperature distribution over the finned surface was investigated. The analysis showed that the gas cooler's intake tube had a maximum temperature of 359.5 K, whereas the finned surface's exit end had a minimum temperature of 303 K. The total temperature drop depicted in Figure 16 amounted to 56.5 K.

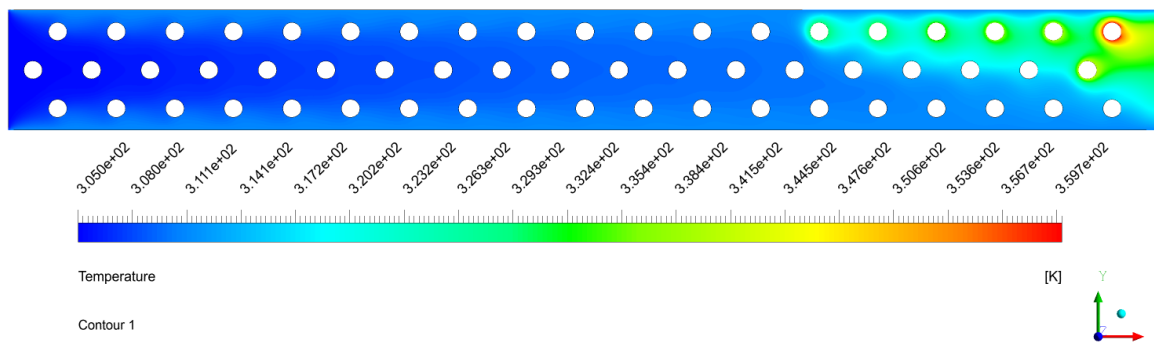


Figure 17. Temperature distribution for Design-1 at 1 m/sec throughout the whole fin surface.

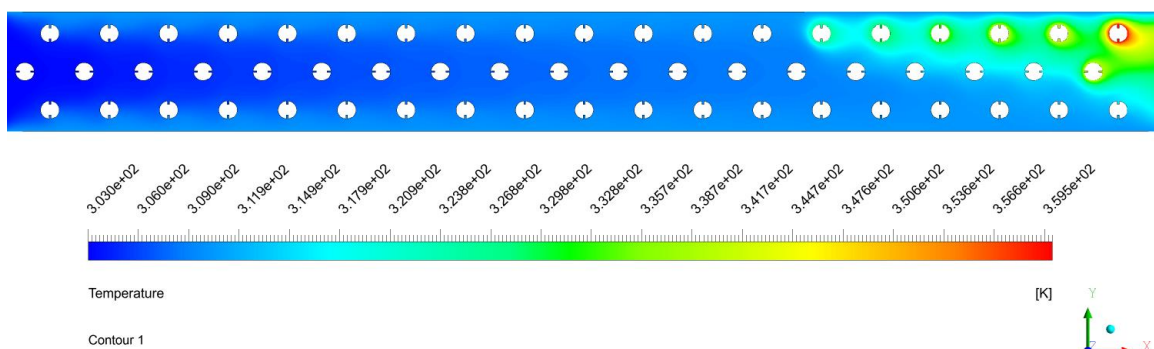


Figure 18. Temperature distribution for Design-2 at 1 m/sec throughout the whole fin surface.

After the CO₂ finned tube gas cooler Design-2 CFD study was completed at 1 m/s, the temperature distribution over the finned surface was evaluated. The analysis showed that the gas cooler's intake tube had a maximum temperature of 359.5 K, whereas the finned surface's exit end had a minimum temperature of 304.6 K. The total temperature drop, as shown in Figure 16, amounted to 54.9 K.

Evaluation of a Finned Tube Gas Cooler Using CFD and CO₂ for Design-3

After the Carbon dioxide gas cooler with finned tube Design-3 CFD study was completed at 1 m/s, the temperature distribution over the finned surface was investigated. The analysis showed that the gas cooler entrance tube had a maximum temperature of 359.7 K, whereas the exit end of the finned surface had a minimum temperature of 299 K. The total temperature drop, depicted in Figure 16, amounted to 60.7 K. Distribution of the temperature distribution across the entire fin surface for Design-3 at 1 m/s is shown in Figure 19.

A thorough assessment of the temperature distribution across the whole finned surface was conducted following the CFD study for the Design-3 carbon dioxide gas cooler with a finned tube at 1 m/s. The investigation found that the entrance tube of the gas cooler had a peak temperature of 359.7 K, while the exit end of the finned surface had the lowest temperature of 302.3 K. Comparison of the temperature distribution across the Entire Fin Surface for Various Designs is shown in Table 3. As illustrated in Figure 16 measured 57.4 K.

Evaluating CO₂ Finned Tube Gas Cooler Through CFD for Design-4

Heat transmission was found to decrease as airflow increased from 1 meter per second to 3 meter per second, due to a reduced temperature differential. This was observed through a comparative analysis of the temperature distribution across the fin surface for the various designs. The CO₂ finned tube gas cooler's Design-4 showed the biggest temperature drop out of all of them, which suggests a more effective rate of heat transfer. It is also observed that Design-4 achieved a maximum temperature drop of 65.8 K. Comparing the heat transfer rates of refrigerants across Various Designs, as shown in Figure 20.

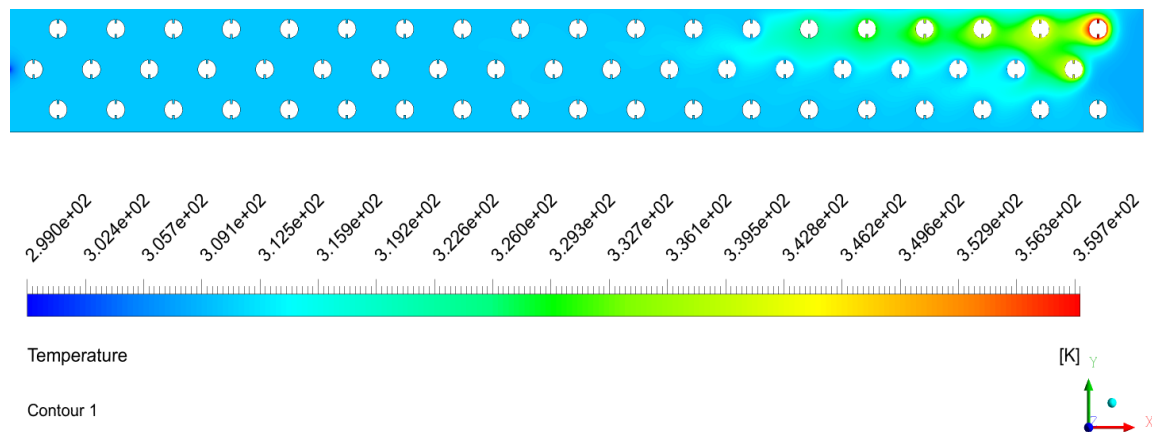


Figure 19. Distribution of temperature across the entire fin surface for Design-3 at 1 m/s.

Table 3. Comparison of temperature distribution across the entire fin surface for various designs.

Velocity	Design-1		Design-2		Design-3		Design-4	
	Max. temperature	Min. temperature	Max. temperature	Min. temperature	Max. temperature	Min. temperature	Max. temperature	min. temperature
At 1 m/sec	359.7	305	359.5	303	359.7	299	359.8	294
At 2 m/sec	359.7	306.8	359.5	304.6	359.7	302.3	359.8	298.3
At 3 m/sec	359.7	308.1	359.5	306.4	359.7	304.7	359.8	300

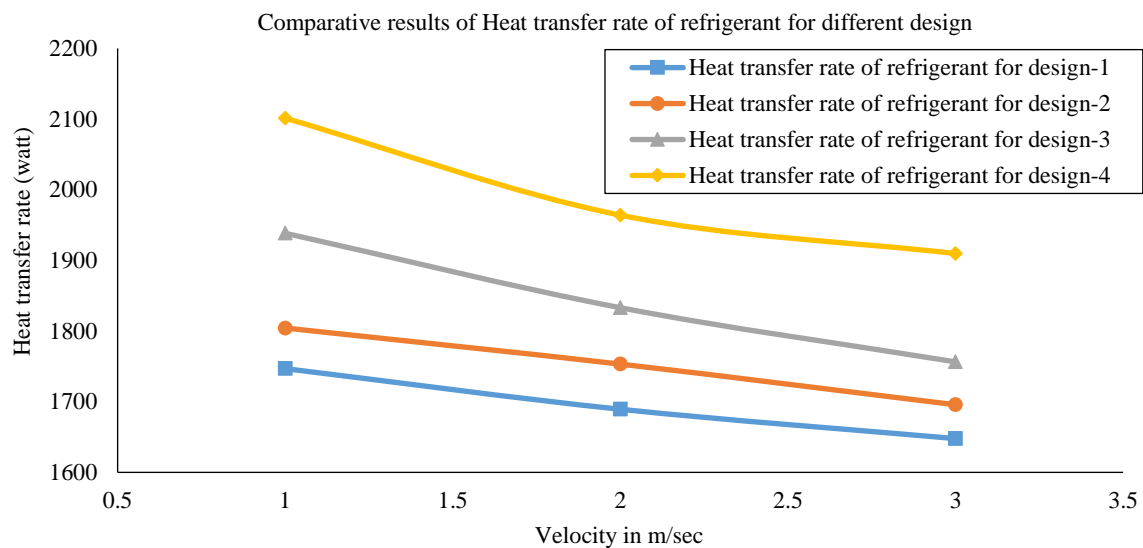


Figure 20. Comparing heat transfer rates of refrigerant across various designs.

Table 4 Improved CO₂ (carbon dioxide) finned tube gas cooler performance in different designs in comparison to the base design.

Velocity	Performance improvement of Design-2 as compared with base design	Performance improvement of Design-3 as compared with base design	Performance improvement of Design-4 as compared with base design
At 1 m/sec	3.29	9.97	19.29
At 2 m/sec	2.78	7.51	15.26
At 3 m/sec	1.91	5.59	14.89

A comparative analysis of the heat transfer rates for different designs showed that increasing the airflow from 1 m/s to 3 m/s resulted in a decrease in the heat transfer rate. The accompanying graph indicates that Design-4 of the CO₂ finned tube gas cooler achieved the highest heat transfer rate.

In Table 4. When the CO₂ finned tube gas cooler performance gains from various designs are compared to the base design, Design-4 provides the highest performance gain. This demonstrates a 20.29% improvement compared to Design-1. For Design-3, there is a 10.97% improvement over the base design, and Design-2 shows a 3.29% improvement over the base design.

CONCLUSION

The heat transfer efficiency of the CO₂ finned tube gas coolers was optimized using CFD and mathematical analysis. The heat transfer efficiency was shown to be significantly improved by examining several fin designs, such as offset strip fins, and introducing changes, such as rectangular ribs. Design-4 outperformed the other designs examined in terms of the thermal transfer rate and total performance increase, outperforming the base design by 20.29% at an airflow velocity of 1 m/s. The highest temperature drop, 65.8 K, was also observed for Design-4, demonstrating its greater thermal efficacy. The methodology and conclusions of the study were validated by the close alignment of the CFD results with the extant literature. The results highlight the significance of airflow control and fin geometry in improving the CO₂ gas cooler performance, providing insightful information for future design improvements and useful applications in warm regions.

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