Material Selection Strategies for High-Pressure CO2 Systems: A Review

[1]Mandvi Rajak, [2]Mr. Deepak Solanki

[1]Department of Mechanical Engineering, Astral Institute of Technology & Research, Indore, (M.P.)

[2]Department of Mechanical Engineering, Astral Institute of Technology & Research, Indore, (M.P.)

Email mandvirajak.98@gmail.com

* Corresponding Author: Mandvi Rajak

Abstract: *This review paper explores the critical considerations and strategies for selecting materials in high-pressure CO2 (carbon dioxide) systems, which are widely used in various applications, including refrigeration, food processing, and carbon capture and storage. Material compatibility, pressure and temperature ratings, corrosion resistance, sealing materials, regulatory compliance, cost-effectiveness, and environmental impact are among the key factors discussed. The paper emphasizes the importance of expert consultation, material testing, and qualification to ensure the safe and efficient operation of high-pressure CO2 systems. Additionally, it provides insights into the unique properties of CO2 as a refrigerant and its implications for system design and performance.*

Keywords: *Material selection, high-pressure CO2 systems, corrosion resistance, pressure and temperature ratings, sealing materials, environmental impact, material compatibility, expert consultation, regulatory compliance.*

I. INTRODUCTION

As an environmentally friendly working fluid with superb thermo physical properties, CO2 has been readily applied in refrigeration and heat pump systems. Air cooled finned-tube condensers used in conventional refrigeration systems have also been greatly exploited in CO2 systems with cascade arrangements or all-CO2 Trans critical arrangements of which the CO2 heat exchangers operate as either condensers or gas coolers, depending on ambient conditions and 'head' pressure controls. Therefore, it is demonstrable that due to the low critical temperature and very high critical pressure of the CO2 fluid, a CO2 refrigeration system can periodically operate between high performance subcritical cycles and less efficient Trans critical cycles. However, this operating efficiency can be significantly improved through the use of an expansion turbine, a liquid-line/suction-line heat exchanger (llsl-hx), and more efficient system equipment such as a compressor, evaporator or gas cooler/condenser, as well as optimal controls of refrigerant high-side pressures. The feasibilities of such strategies can be substantiated through system experiment and modelling.

An experimental investigation was carried out on a two-stage CO2 Trans critical refrigeration system with external intercooling. In the test rig, air-cooled finned tube gas coolers with different structures and circuits were installed in the high pressure side. The test results showed that an optimal head pressure did exist to maximise the system COP which was necessarily controlled in actual operations. Alternatively, it would be beneficial for a direct staging CO2 Trans critical system such as the CO2 booster refrigeration system to be studied experimentally. To understand the performance of a CO2 air cooled gas cooler, a series of tests were conducted at different operating conditions using a purposely designed test facility. The effects of air and refrigerant side flow parameters on the heat exchanger heat transfer and hydraulic behaviours were examined. In addition, the temperature profiles along the heat exchanger circuit pipes were measured. Further investigation, including a model development, will be implemented to predict these effects on the performance of the associated system. Apart from the overall performance investigations of the CO2 gas coolers, the in-tube cooling processes of CO2 supercritical flow were extensively tested and correlated, which is helpful for the model development of a CO2 gas cooler. A CO2 transcritical cycle in an air-condition system was developed by Lorentzen in 1989 [1]. Later on, a performance comparison between a CO2 transcritical cycle and a conventional subcritical cycle in an air conditioning system was carried. They found that the cooling COP of the system with the CO2 transcritical cycle was 50% less than that of the traditional subcritical cycle due to a larger throttling loss in the former cycle. Similar result was also obtained by Sarkar. Subsequently, more attentions have been paid to improve the performance of CO2 transcritical cycles by means of internal heat exchanger integrations, expansion processes with work recovery, multi-stage compressions and optimal controls of high-side operating pressures. It was noted that the cooling COP of a CO2 transcritical cycle could be increased by adding the internal heat exchanger. Performance of a CO2 transcritical cycle with internal heat exchanger could match that of conventional subcritical cycles but was only applicable at lower evaporating temperature of around 233 K. Alternatively, investigations were carried out aiming to explore the effects of different expanders on the performance of CO2 refrigeration cycles [2]. The performance of such a heat exchanger plays an important role in its associated system and is necessarily to be further improved. Subsequently, during the past decades, a great deal of experimental and theoretical analyses on finned-tube gas coolers have been carried out by researchers in order to understand the characteristics of fluid heat transfer and friction involved and thus optimise their performances. Distributed method to calculate CO2 temperature profile along refrigerant pipe flow direction of a CO2 finned-tube gas cooler. Developed tubeby-tube approach for simulating finned-tube air to refrigerant evaporator performance and calculating refrigerant thermodynamic properties. Similar method can also be applied into the modelling of CO_2 gas coolers. Geometric parameters are important factors influencing the performance of finned-tube gas coolers which have been investigated and optimised by using CFD modelling strategies. However, these researches above are mostly based on uniform airflow conditions, which deviate somehow in actual operations.

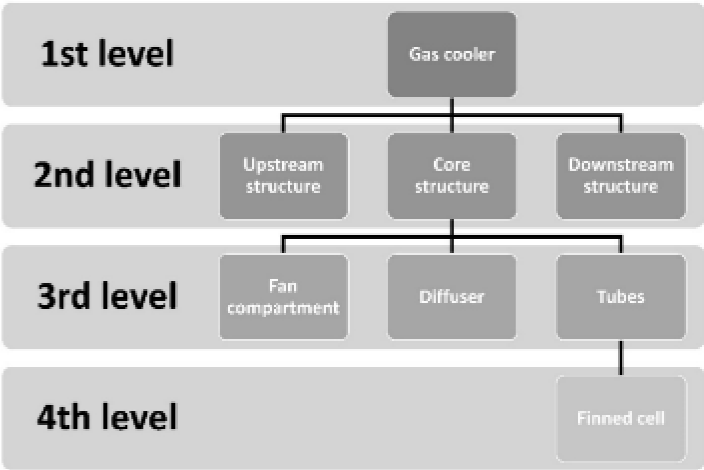

Figure 1 Schematic of Top-Down Numerical Model Development for Gas Cooler Performance Evaluation

A micro channel gas cooler (MCGC) operates in a Tran's critical CO_2 cycle at high pressure. The growing concern about environmental issues regarding the global warming potential (GWP) of these working fluids has led to some policy actions, such as the approval of the F-Gas Regulation [3] and the approval of the Kigali amendment to the Montreal Protocol, which aim to phase out their utilization soon. With the phasing out of hydro fluorocarbon (HFC) refrigerants following the provisions of the Montreal Protocol, CO_2 has gained considerable attention and wider acceptance as an alternative refrigerant for use in automotive air-conditioning systems. Unlike all the new fluorocarbon alternatives, CO_2 is widely available in large amounts in all regions of the world, behaves as an inert gas, and is thermally stable at higher temperatures. Additional toxicity testing is unnecessary because all the properties and characteristics of CO_2 are already well-recognized and fully documented. When using CO_2 as a refrigerant, the recycling or recovery of the refrigerant is not necessary either for environmental or economic reasons.

II PRINCIPLES AND MECHANICS OF CO2 GAS COOLERS

The review paper explores the fundamental operating principles and mechanical workings of CO_2 finned tube gas coolers. This part of the study highlights how these systems leverage the unique properties of carbon dioxide as a refrigerant to provide efficient cooling. The paper begins by explaining the basic thermodynamic cycle involved in CO_2 gas cooling, emphasizing the critical role of high-pressure operation due to CO_2's low critical temperature.

The thermo syphon principle is a natural refrigeration cycle that can be used in CO_2 secondary refrigeration systems. In this type of system, the refrigerant CO_2 can be used to cool a secondary fluid, such as glycol, or be circulated through a cooling loop to cool various applications such as refrigeration circuits, process equipment or air conditioning units. The thermo syphon principle relies on the natural circulation of the refrigerant and the secondary fluid due to the differences in temperature and density. In a CO_2 secondary system, the thermo syphon loop typically consists of a vertical pipe connected to a heat exchanger, which is in turn connected to a horizontal pipe. As the refrigerant CO_2 absorbs heat from the secondary fluid in the heat exchanger, it vaporizes and becomes less dense. This causes the vaporized CO_2 to rise up the vertical pipe and enter the horizontal pipe, where it then releases heat and condenses back into a liquid. The liquid CO_2 then flows back down the vertical pipe to the heat exchanger, where the cycle begins again. The thermo syphon principle is a simple and reliable way to circulate refrigerant and secondary fluid without the need for pumps or other mechanical components. However, it requires careful design and sizing to ensure proper flow rates and heat transfer, as well as proper insulation to prevent heat loss and maintain system efficiency.

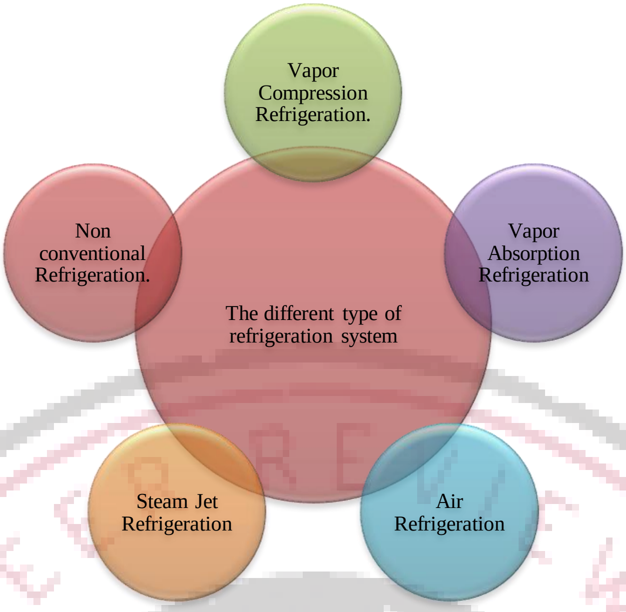

Figure 2 CO2 Gas cooler type of refrigeration system

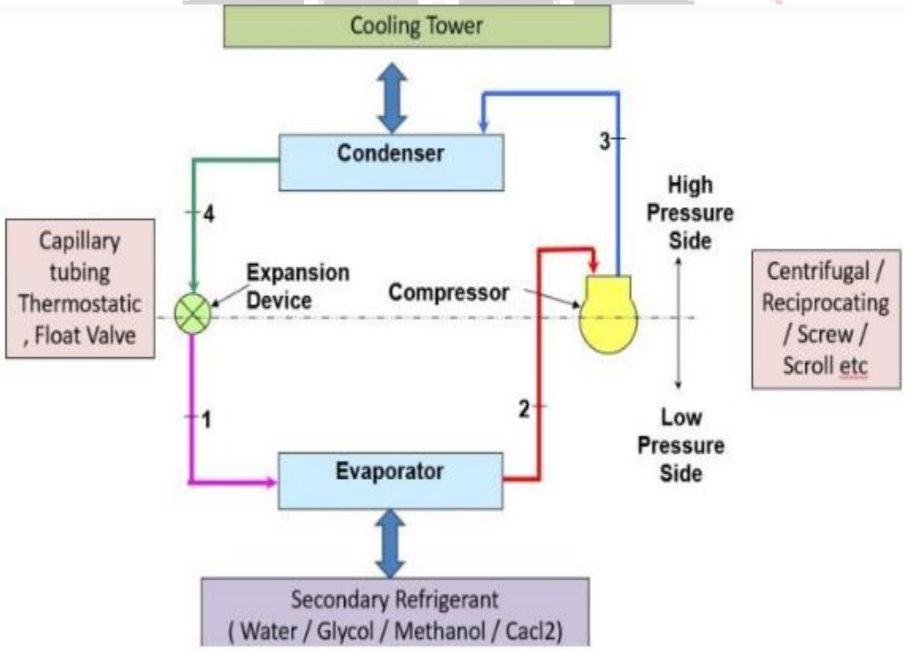

Figure 3 Schematic of a Standard Refrigeration System

- **CO2 as a Refrigerant:** The paper discusses the advantages of using CO2, such as its non-toxicity, non-flammability, and lower global warming potential compared to traditional refrigerants.
- **High-Pressure Operations:** It elaborates on the necessity for CO2 systems to operate at higher pressures, which presents both design challenges and opportunities for efficiency gains.
- **Heat Transfer Mechanisms:** The mechanics of heat transfer in finned tube designs are detailed, explaining how CO2's properties affect the heat exchange process.
- **Finned Tube Design:** The paper dives into the design specifics of finned tubes in CO2 coolers, outlining how they enhance heat dissipation and improve overall system performance.
- **System Components and Functionality:** An overview of the key components, like compressors, condensers, and expansion devices, and their functionality within the CO2 cooling cycle is provided.

The paper offers a comprehensive insight into the principles and mechanics underlying CO2 gas coolers. It not only explains the theoretical aspects but also connects these principles to practical design considerations, enhancing the reader's understanding of the efficient and environmentally friendly operation of CO2 finned tube gas coolers.

III. LITERATURE REVIEW

Haiyan Zhang et al. (2021) [4]: In a pioneering approach, a 100 KW class airfoil fin (AFF) Heat transfer-focused printed circuit heat exchangers, or PCHEs, were tested experimentally assessed as a cooler in a supercritical CO2 system. This investigation was complemented by numerical analysis to gain deeper insights into the flow and high-temperature transmission dynamics within the AFF channels. The results indicated a substantial improvement in hydraulic efficiency with the innovative AFF design, reducing pressure drop compared to zigzag channel PCHEs while maintaining heat transfer rates.

Manu Lata & Dileep Kumar Gupta (2021) [5]: evaluates the performance of a trans-critical CO2 refrigeration system in an Indian climate, comparing a conventional finned tube gas cooler with a modified version incorporating evaporative cooling. The modified system considerably increases the seasonal energy efficiency ratio (SEER) across various Indian cities, demonstrating SEER improvements of up to 28% in Ahmedabad, highlighting the potential of this enhancement strategy in high-ambient temperature environments.

X. Zhang & Y.T. Ge (2021) [6]: examines air-cooled CO2 fin-and-tube gas coolers, focusing on reducing reverse heat transfer resulting from longitudinal thermal conduction along the fins. Computational Fluid Dynamics (CFD) models for CO2 gas coolers with segmented fins show potential improvements in maximal and mean heating capacities by up to 22% and 10%, respectively. Customizing segmented fin integration based on specific tube circuit designs within the heat exchanger is essential.

Xia Song et al. (2021) [7]: addresses uneven temperature gradients in water-cooled CO2 gas coolers using a simulation model. It quantifies the mismatch coefficient and identifies two zones based on the water to CO2 mass flow ratio. A gas cooler design with segmental heating (SH) is introduced to amalgamate the advantages of both zones. The SH gas cooler shows improvements in heat transfer efficiency, CO2 exit temperature, hot water temperature, and the mismatch coefficient.

Antonio Rossetti et al. (2018) [8]: explores mismatched CO2 gas coolers with temperature glide discrepancies and introduces the concept of a gas cooler used for segmental heating (SH) to address these issues. An SH gas cooler improves heat transfer efficiency, lowers the CO2 exit temperature, raises hot water temperature, and diminishes the mismatch coefficient. SH gas coolers aim to merge the advantages of different zones within the heat exchanger.

Jianyong Wang et al. (2018) [9]: investigates cooling heat transfer characteristics in horizontal tubes of different diameters using supercritical CO2. Four turbulence models are validated against experimental data. Results indicate that heat transfer efficiency positively correlates with heat flux and tube diameter when the bulk temperature surpasses the pseudo-critical temperature, highlighting the impact of buoyancy effects on heat transfer performance.

Rodrigo Llopis et al. (2018) [10]: focuses on subcooling techniques in CO2 refrigeration systems to enhance efficiency. It categorizes recent advancements into internal and external subcooling methods, offering insights into optimizing CO2 refrigeration systems through subcooling techniques. The review identifies potential research directions for further exploration in this field**.**

Saranmanduh Origin et al. (2018) [11]: The study emphasizes the role of longitudinal heat conduction in plate heat exchangers. It introduces heat transfer models that account for this process and demonstrates its impact on temperature distribution and flow stability within the exchanger. Longitudinal heat conduction significantly influences the overall performance of plate heat exchangers.

Siddhant Singh Yogesh et al. (2018) [12]: employs computational fluid dynamics to analyze the friction and heat transfer properties of elliptical tube finned tube heat exchangers. The study investigates how tube rotation and spring affect the Colburn coefficient, friction coefficient, and efficiency index, providing insights into energy efficiency improvements.

Xinying Cui et al. (2018) [13]: explores the thermal-hydraulic performance of innovative fin designs inspired by the NACA 0020 airfoil fin in printed circuit heat exchangers (PCHEs) using supercritical CO2 as the working fluid. Results indicate improved heat transfer coefficients and reduced pressure drop compared to the standard NACA 0020 airfoil fin in PCHEs. The study also emphasizes the role of fin arrangement and shape in enhancing thermal-hydraulic performance.

IV. MATERIAL SELECTION STRATEGIES FOR HIGH-PRESSURE CO2 SYSTEMS

Material selection for high-pressure CO2 (carbon dioxide) systems is a critical consideration to ensure the safe and efficient operation of such systems in various applications. High-pressure CO2 systems are commonly used in industries such as food and beverage processing, refrigeration, and carbon capture and storage. To make informed material choices for these systems, several strategies and factors should be taken into account:

Material Compatibility: The primary concern when selecting materials for high-pressure CO2 systems is their compatibility with CO2. Carbon dioxide can be corrosive under certain conditions, particularly in the presence of moisture. Materials must be chosen to withstand the potentially corrosive effects of CO2 to prevent system degradation and leaks.

Pressure and Temperature Ratings: Consider the operating pressure and temperature ranges of the CO2 system. Materials should have adequate pressure and temperature ratings to ensure the system's integrity and safety. This includes selecting materials that can withstand the high pressures associated with high-pressure CO2 systems.

Corrosion Resistance: Assess the resistance of materials to corrosion, both from the CO2 itself and any impurities or contaminants present in the CO2 stream. Stainless steel and corrosion-resistant alloys are often preferred for their resistance to corrosion.

Sealing and Gasket Materials: Select appropriate sealing and gasket materials that can maintain their integrity under high-pressure CO2 conditions. These materials should form reliable seals to prevent leaks.

Material Testing and Qualification: Conduct material testing and qualification to ensure that the chosen materials can perform under the expected conditions. This may involve exposure testing, stress testing, and evaluating material certificates.

Regulatory Compliance: Ensure that the chosen materials comply with relevant industry standards and regulations, such as those established by organizations like ASME (American Society of Mechanical Engineers) or API (American Petroleum Institute).

Cost Considerations: Evaluate the cost-effectiveness of materials. While high-performance materials may offer superior corrosion resistance, they can be more expensive. Consider the balance between performance and cost in your material selection strategy.

Material Availability: Check the availability of the selected materials in the quantities and forms needed for your specific application. Ensure a reliable supply chain for ongoing maintenance and repairs.

Environmental Impact: Consider the environmental impact of the materials you choose. Sustainable and environmentally friendly materials may align with your organization's values and sustainability goals.

Expert Consultation: Seek input and guidance from materials engineers and experts who specialize in high-pressure CO2 systems. Their knowledge and experience can be invaluable in making informed material choices.

Material selection strategies for high-pressure CO2 systems should prioritize material compatibility, pressure and temperature ratings, corrosion resistance, sealing materials, testing and qualification, regulatory compliance, cost-effectiveness, material availability, environmental impact, and expert consultation. Careful consideration of these factors will help ensure the reliability and safety of high-pressure CO2 systems in various applications.

V. CONCLUSION

Material selection for high-pressure CO2 systems is a complex and critical process that requires careful consideration of various factors. This review paper highlights the key strategies and factors to be taken into account, including material compatibility, pressure and temperature ratings, corrosion resistance, sealing materials, regulatory compliance, cost-effectiveness, and environmental impact. It emphasizes the importance of expert consultation, material testing, and qualification to ensure the safety and efficiency of high-pressure CO2 systems. Furthermore, the paper underscores the unique properties of CO2 as a refrigerant and its impact on system design and performance, providing valuable insights for engineers and researchers in the field.

REFERENCES

[1] Ge, Y. T., Tassou, S. A., Santosa, I. D., & Tsamos, K. (2015). Design optimisation of CO2 gas cooler/condenser in a refrigeration system. *Applied Energy*, *160*, 973-981.https://doi.org/10.1016/j.apenergy.2015.01.123

[2] Zhang, X., Ge, Y., & Sun, J. (2020). CFD performance analysis of finned-tube CO2 gas coolers with various inlet air flow patterns. *Energy and Built Environment*, *1*(3), 233-241.

[3] Maiorino, A.; Aprea, C.; Del Duca, M.G. A Flexible Top-Down Numerical Modeling of an Air-Cooled Finned-Tube CO_2 Trans-Critical Gas Cooler. *Energies* **2021**, *14*, 7607. https://doi.org/10.3390/en14227607

[4] Haiyan Zhang et al. (2021) "Experimental and numerical investigations of thermal-hydraulic characteristics in a novel airfoil fin heat exchanger"International Journal of Heat and Mass Transfer 175 (2021) 121333. https://doi.org/10.1016/j.ijheatmasstransfer.2021.121333.

[5] Manju Lata & Dileep Kumar Gupta (2021) "Simulation and performance evaluation of trans-critical CO2 refrigeration system with modified evaporative cooled finned tube gas cooler in Indian context" Applied Thermal Engineering 186 (2021) 116500 https://doi.org/10.1016/j.applthermaleng.2020.116500.

[6] X. Zhang & Y.T. Ge. (2021) "The effect of heat conduction through fins on the performance of finne d-tub e CO 2 supercritical gas coolers" International Journal of Heat and Mass Transfer 181 (2021) 121908. https://doi.org/10.1016/j.ijheatmasstransfer.2021.121908.

[7] Xia Song et al. (2021) "Improvement of heat transfer performance and unmatched characteristics of a water-cooled carbon dioxide gas cooler" Applied Thermal Engineering 197 (2021) 117326 https://doi.org/10.1016/j.applthermaleng.2021.117326.

[8] Antonio Rossetti et al. (2018) "Multi-Physics Simulation of Co2 Gas Coolers Using equivalence Modeling" International Journal of Refrigeration (2018), 10.1016/j.ijrefrig.2018.04.013.

[9] Jianyong Wang et al. (2018) "Numerical study on cooling heat transfer of turbulent supercritical CO2in large horizontal tubes" International Journal of Heat and Mass Transfer 126 (2018) 1002–1019https://doi.org/10.1016/j.ijheatmasstransfer.2018.06.070.

[10] Rodrigo Llopis et al. (2018) "Subcooling methods for CO2 refrigeration cycles. A Review." International Journal of Refrigeration (2018), doi: 10.1016/j.ijrefrig.2018.06.010.

[11] Saranmanduh Borjigin et al. (2018) "A Numerical Study of Small-Scale Longitudinal HeatConduction in Plate Heat Exchangers" Energies 2018, 11, 1727;10.3390/en11071727.

[12] Siddhant Singh Yogesh et al. (2018) "Heat transfer and pressure drop characteristics of inclined elliptical fintube heat exchanger of varying ellipticity ratio using CFD code" International Journal of Heat and Mass Transfer 119 (2018) 26–39https://doi.org/10.1016/j.ijheatmasstransfer.2017.11.094.

[13] Xinying Cui et al. (2018) "Numerical study on novel airfoil fins for printed circuit heat exchangerusing supercritical CO2" International Journal of Heat and Mass Transfer 121 (2018) 354–366https://doi.org/10.1016/j.ijheatmasstransfer.2018.01.015.