Enhancing CO_2 heat pump efficiency for integrated DHW and cooling via solar assistance and thermal inertia

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Abstract

This article investigates an integrated architecture designed to optimize the efficiency of CO_2 cooling in regions with high solar irradiance and extreme ambient temperatures. The system utilizes solar hybrid panels (PVT) as the primary endothermic source, generating electrical energy injection into the main grid and simultaneously capturing thermal energy for domestic hot water (DHW) preheating. This thermal energy is processed by a secondary R290 circuit that generates a stable energy reserve within a glycol-water Integrated Thermal Buffer (ITB). The core of the proposed innovation lies in the active transfer of 10.8 kW of cooling power from the secondary circuit directly to the primary CO_2 rack via subcooling. Thermodynamic modelling, validated through Danfoss Coolselector®2, demonstrates that when the system reaches a critical ambient stress of 37 °C, the ITB intervention effectively lowers the gas cooler exit temperature to **30.65 °C.**
This shift allows the cycle to operate in a **stabilized high efficiency trans critical regime** at **77.93 bar**, achieving a global **COP of 2.42**. The energy balance confirms a **net energy profit of 2.99 kW**, as the 6.51 kW power reduction in primary compressors significantly outweighs the marginal consumption of the support circuit.
Furthermore, although this study focuses on a specific power configuration, the modular nature of the ITB architecture allows for various power combinations and scalable deployment across different industrial capacities. The results validate the system as a robust and water-free solution for the decarbonization of food retail, hospitality, and healthcare establishments.
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Keywords: CO_2 Refrigerant; Active Subcooling; Thermal Inertia; System Integration; Heat Pump; High Ambient Temperature; Food Retail; Energy Efficiency.

1. Introduction

The growing global urgency to decarbonize buildings and the cold chain requires the large-scale adoption of highly efficient Heating, Ventilation, and Air Conditioning (HVAC) systems, with a focus on low GWP refrigerants. In this context, CO_2 (R744) has established itself as a natural refrigerant of choice, not only for its zero environmental impact but also for its excellent heat transfer properties.

However, the application of CO_2 in high-temperature climates presents a significant challenge, particularly relevant in Southern European regions. When the ambient temperature exceeds the critical point (30.978ºC), the refrigeration system is forced to operate in the trans-critical regime. In this state, the absence of a condensation phase and the consequent high heat rejection pressures lead to a drastic and systemic drop in the efficiency of the Coefficient of Performance (COP). This technical dilemma has been the main barrier to the widespread adoption of CO_2 systems in refrigeration and heat pump applications in these markets. Traditional solutions to mitigate trans-critical inefficiency (such as parallel compression, the use of ejectors, or adiabatic cooling) tend to introduce mechanical complexity, increase initial investment costs, or create resource dependency (such as water consumption for evaporative cooling).

The present paper proposes and validates a new architecture to solve this challenge: the **Integrated Thermal Buffer (ITB) System**. This approach innovates by achieving optimization through **strategic energy integration** instead of mechanical complexity. The ITB System combines solar thermal and photovoltaic capture with a secondary heat pump circuit (R290) to generate a cold thermal inertia reserve, a process referred to as active subcooling.

The main objective of this work is to demonstrate, through rigorous thermodynamic simulation, that this architectural solution achieves a substantial increase in the system's global COP, improves operational resilience, and eliminates dependence on evaporative cooling. The subsequent sections detail the design of the

ITB System, present the thermodynamic analysis of the COP gain, and provide a comprehensive discussion on the strategic implications of this new architecture for the future of sustainable refrigeration and DHW systems.

2. Methods/Approach

2.1. Integrated System Architecture

The proposed solution, designated the **ITB System**, is a modular, dual-circuit architecture designed to optimize the energy balance in facilities requiring simultaneous cooling and heating (Fig. 1). The system is comprised of a compact central unit that interfaces with two primary thermodynamic subsystems:

- **Sustainability and Support Circuit (R290):** This circuit is powered by hybrid solar panels. It employs an R290 heat pump (14.3 kW heating capacity) to simultaneously DHW and, by thermodynamic consequence, cool the **Glycol Thermal Inertia Tank ($T_{inertia}$)**. The electrical energy (0.88kWp) generated by the PVT panels is sent to main grid.
- **Primary Refrigeration Circuit (CO_2 Booster):** This circuit is dedicated to critical cold production (52 kW – 12 kW lower temperature 40 kW high temperature) for food preservation. The system is designed to operate with a high-side pressure of 9457 kPa in peak conditions.

The central innovation lies in using the "waste cold" from the support circuit to actively sub-cool the CO_2 system, thereby enhancing its efficiency.

The dimensioning of the support circuit is rooted in the facility's demand for DHW. To ensure the required heating capacity (14.3 kW) is met, the system utilizes a high-efficiency R290 heat pump, which operates with a heating COP of 4.06. By the 1st Law of Thermodynamics, the production of this thermal energy implies a direct and inevitable consequence: the removal of cold energy from the secondary circuit.

Thus, to generate the required heat, the R290 circuit must continuously extract 10.8 kW of cooling power from the cold side. This 10.8 kW is captured and stored in the **Glycol Thermal Inertia Tank**, thereby transforming a thermodynamic byproduct into a valuable, sustained resource. This energy then funds the optimization of the primary CO_2 cycle.

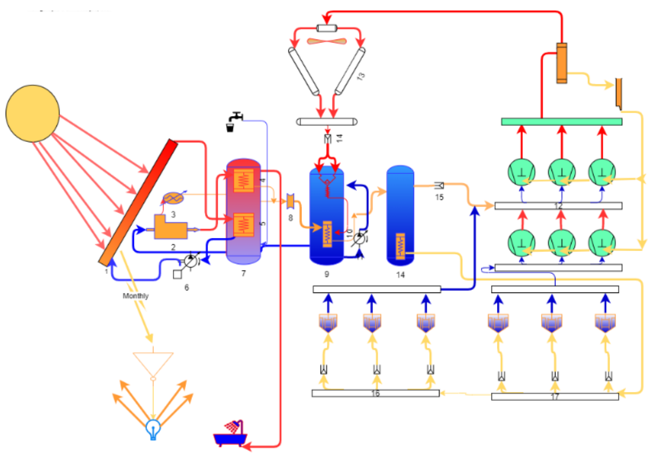

Figure 1. Scheme of operation of the installation

2.2. Thermodynamic Modelling and Approach

The primary objective of the modelling is to quantify the COP gain achieved by eliminating the highly inefficient trans-critical regime through active subcooling. The Engineering Equation Solver (EES) was used for rigorous thermodynamic analysis.

Due to the extreme variation in the heat capacity of R744 in the trans-critical region, simple methods like the LMTD are insufficient. The model uses the enthalpy (h) for precision, based on the following benchmark data derived from industry software at 35ºC ambient (Danfoss cool selector)

The simulation's baseline (the stress scenario) assumes the CO_2 exists the Gas Cooler at 37ºC and 9457 KPa, resulting in a COP of 1.84 Due to the non-linear properties of CO_2 in this region, the analysis uses enthalpy (h) to ensure precision.

2.2.1. The Trans-critical Problem and Benchmarking

Table 1. Operations Conditions 35 º C Ambient

Variable	Value	Units
Pressure at gas cooler outlet	9457	kPa
Mass flow at gas cooler outlet	0.391	kg/s
Temperature at gas cooler outlet Tin	37	ºC
Enthalpy at gas cooler outlet	-202.8	kJ/kg
COP	1.84	-

2.2.2. Modelling the Active Subcooling 10.8 kW Intervention: ($Q_{subcooling}$)

The system's efficiency gain is modelled by enforcing the energy balance on the subcooling heat exchanger. The available cooling power from the support circuit 10.8 kW dictates the temperature drop in CO_2.

The following equations represent the energy balance used for simulation:

Energy Balance Equation: The heat removed from the CO_2 must equal the maximum cooling power available from the support circuit:

$$Q_{subcooling} = \dot{m_{co2}} * (h_{in} - h_{out}) \quad \textit{[kW] EQ. 1}$$

- **Imposing the Limit:** We impose the maximum available power from the support system Subcooling 10.8 kW to calculate the achievable enthalpy drop and the new operating temperature

$$h_{out} = h_{in} - \left[\frac{Q_{subcooling}}{m_{co2}}\right] \quad \textit{[kJ/kg] EQ. 2}$$

- **Validate the temperature obtained:** After calculating the output enthalpy we remove the output temperature of the exchanger where the extra cooling power was activated. The temperature outlet whit the subcooling is T_{out}= 30.65 [ºC]

$$T_{out} = TEMPERATURE(R744; P = 9457; h = h_{out}) \quad \textit{[ºC] EQ. 3}$$

By working on the value of the available cooling power, we obtain a table in which we can verify the same input condition the effect on the output temperature, a useful interpretation to be able to decide in other types of needs, the values and direction to follow.

Table 2. Temperature outlet simulation for different Qsubcooling and same start conditions.

Run Nº	hi [kJ/kg]	ho [kJ/kg]	m_{co2} [kg/s]	PC Co_2[kPa]	Q_Sub. [kW]	Tin Co_2 [ºC]	Tout; Co_2 [ºC]
1	-202.8	-230.4	0.3911	9457	10.81	37	30.68
2	-202.8	-232.7	0.3911	9457	11.69	37	30.05
3	-202.8	-234.8	0.3911	9457	12.54	37	29.42
4	-202.8	-237	0.3911	9457	13.38	37	28.79
5	-202.8	-239.1	0.3911	9457	14.20	37	28.16
6	-202.8	-241.1	0.3911	9457	15	37	27.52
7	-202.8	-243.1	0.3911	9457	15.78	37	26.89
8	-202.8	-245.1	0.3911	9457	16.55	37	26.26
9	-202.8	-247	0.3911	9457	17.31	37	25.63
10	-202.8	-248.9	0.3911	9457	18.06	37	25

3. Results and Discussion

3.1. Analysis of Baseline Performance (Trans critical Benchmark)

The initial analysis established a performance benchmark under defined peak stress conditions. The baseline represents a standard CO_2 booster system (without ejectors or parallel compression) operating at a gas cooler outlet temperature of 37 °C. This is compared against the optimized state achieved by the ITB system, which effectively lowers the outlet temperature to 30.65 °C. The thermodynamic properties were validated using the Danfoss Coolselector®2 (R744 ASERP v5.2.3.0) engine.

Table 3. Input data: Operations Conditions 37º C gas cooler outlet versus 30.68 ºC outlet

Variable	37ºC	30.68 ºC
Pressure at gas cooler outlet [kPa]	9457	7793
Mass flows at gas cooler outlet[kg/s] *	0.391	0.35
COP	1.84	2.42

*Note: Mass flow converted from 1408 kg/h (Baseline) and 1262 kg/h (ITB) as per software results.

3.2. Quantified Performance of the Integrated Thermal Buffer (ITB) System

The thermodynamic superiority of the ITB System is evidenced by the global energy balance during peak stress conditions. While standard CO_2 heat recovery racks often sacrifice cooling efficiency (COP ~2.0) by forcing high-pressure operation at 80 bar (8000 kPa), the ITB architecture achieves a **'net energy profit'**. The primary objective was to determine the maximum benefit achievable by the R290 support circuit (Qsubcooling=10.8kW) when the CO_2 cycle operates at its lowest efficiency with a gas cooler exit temperature of 37 °C.

The thermodynamic model confirms that the 10.8 kW of available subcooling power is sufficient to remove a maximum of **30.8 kJ/kg** of heat from the CO_2 flow, considering the enthalpy difference between the two states. By investing **3.52 kW** in the R290 support circuit to provide DHW and subcooling, the system reduces the primary CO_2 compressor load from **26.38 kW** (baseline COP 1.84) to **19.87 kW** (optimized COP 2.42). This results in a gross saving of **6.51 kW** in the refrigeration rack, yielding a **net gain of 2.99 kW** for the entire facility. Consequently, the ITB System achieves an optimized state where the CO_2 exit temperature is significantly lowered to **30.65 °C**, effectively shifting the operation into a high efficiency trans critical regime at **77.93 bar**.

This confirms that the ITB system does not merely recover waste heat but uses it as a driver for systemic efficiency, ensuring 52 kW of cooling capacity with significantly lower grid dependency. The **PVT array** acts as the primary endothermic source, generating electrical power injected directly into the **main grid**. This solar production functions as an energy credit that offsets the operational costs of the support circuit. From a systemic perspective, the electricity generated by the PVT modules effectively defines the 3.52 kW required by the R290 circuit to perform active subcooling.

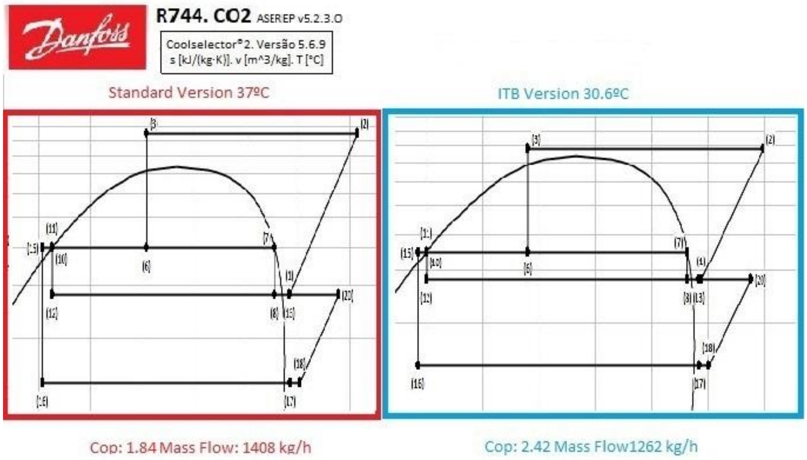

Figure 2. Comparison of CO_2 refrigeration cycles: (Left) Standard trans critical operation at 37 °C with 1.84 COP; (Right) Optimized ITB operation at 30.65 °C with 2.42 COP. The visual shift demonstrates the transition to a high efficiency trans critical regime and the reduction in mass flow from 1408 kg/h to 1262 kg/h.

Table 4. Global Energy Balance and System Profitability Analysis

Operational Parameter	Baseline (Stress Scenario)	ITB System (Optimized)	Net Impact
Gas Cooler Exit Temperature	37ºC	30.65ºC	High efficiency transcritical regime
Discharge Pressure	9461 kPa	7793 kPa	-17.6% Pressure Stress
Global COP	1.84	2.42	+31.5 % Efficiency
Rack Power Input (CO_2)	26.38 kW	19.87 kW	-6.51 kW Saving
Support Power Input (R290)	0.00 kW	3.52 kW	3.52 kW Investment
PVT Solar Production	0.00 kW	Energy Credit	Grid Offset
Total Facility Power Consumption	26.38 kW	23.39 kW*	2.99 kW Net Profit

*Note: The final grid dependency is lower than 25.01 kW due to the direct injection of PVT-generated power into the main grid, effectively offsetting the R290 circuit consumption.

Source: System modelling results derived from Danfoss Coolselector®2 (R744 ASERP v5.2.3.0) based on NIST REFPROP database compliance.

3.3. Discussion and development solutions for the future.

The performance demonstrated confirms that a successfully integrated system must be monitored across several operational aspects. The fundamental challenge remains the dynamic management of DHW production coupled with the refrigeration cycle. Future control systems must integrate data from the sub-cooler plate exchanger directly into the refrigeration rack controller to realize the system's full potential.

Specifically, by utilizing the thermal inertia of the glycol solution, parametric simulations conducted in EES confirm that it is theoretically possible to obtain CO_2 exit temperatures as low as 25 °C by increasing the subcooling power to 18.06 kW (Run 10). Achieving this requires a modulation logic that uses general heat transfer equations to precisely control the temperature, ensuring that the **net energy profit of 2.99 kW** identified in this study is maintained even under fluctuating solar irradiance. This development will open new scenarios for the widespread application of simplified, ITB-based architectures in water-scarce regions.

Highlights:

- **Net Energy Profit:** The ITB system integration generates a net power saving of **2.99 kW**, as the load reduction in the CO_2 rack (6.51 kW) significantly outweighs the consumption of the support unit (3.52 kW).

- Operational Stability: Active subcooling of 10.8 kW stabilizes the gas cooler exit temperature at 30.65 °C, allowing the cycle to operate in a high efficiency trans critical regime at 77.93 bar, even under thermal stress conditions (37 °C).
- **Efficiency Gain:** The system achieves a global **COP of 2.42**, representing a **31.5% increase** compared to the trans critical baseline (COP 1.84), without the requirement for extreme discharge pressures of 95 bar.
- **Decarbonization & Resource Savings:** The architecture eliminates dependency on adiabatic cooling, ensuring a 100% reduction in process water consumption and significantly reducing grid demand through **PVT solar injection** into the main grid.

4. Conclusions

The present study successfully validated the thermodynamic viability of the ITB System, demonstrating it as a robust solution for high-ambient temperature climates. The integration of a secondary R290 circuit for DHW production, assisted by a PVT solar array, acts as a strategic driver for systemic efficiency, shifting the cycle from a stressed trans critical state to a high efficiency trans critical regime.

The core findings, supported by Danfoss Coolselector®2 simulations, confirm that by investing **3.52 kW** in active subcooling, the system achieves a gross reduction of **6.51 kW** in the primary CO2 compressors power consumption (falling from 26.38 kW to 19.87 kW). This results in a **net energy profit of 2.99 kW**, allowing the facility to maintain 52 kW of cooling capacity with a global **COP of 2.42**. Furthermore, the PVT electrical production injected into the **main grid** functions as an energy credit, effectively offsetting the operational costs of the support circuit.

This "thermal symbiosis" provides a simplified and sustainable pathway not only for food retail but also for **hospitality sectors (hotels, SPAs, and swimming pools)** and **healthcare units**, where simultaneous high-grade heat and cooling are mandatory. By substituting mechanical complexity with strategic energy integration, the ITB architecture ensures operational stability at **77.93 bar**, eliminating the need for water-intensive adiabatic cooling. This modular approach positions the ITB system as a cornerstone for the decarbonization of commercial and medical infrastructures in temperate regions.

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