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PHD THESIS ABSTRACT

*Contributions to the improvement of energy efficiency in CO₂
Booster refrigeration systems through waste heat recovery*
*Contribuții privind creșterea eficienței sistemelor frigorifice cu
CO₂ tip Booster prin valorificarea căldurii reziduale*

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Introduction

The doctoral thesis entitled CONTRIBUTIONS TO THE IMPROVEMENT OF ENERGY EFFICIENCY IN CO₂ BOOSTER REFRIGERATION SYSTEMS THROUGH WASTE HEAT RECOVERY (CONTRIBUȚII PRIVIND CREȘTEREA EFICIENȚEI SISTEMELOR FROGORIFICE CU CO₂ TIP BOOSTER PRIN VALORIFICAREA CĂLDURII REZIDUALE) is part of the research activities carried out by the Department of Thermotechnics, Engines, Thermal and Refrigeration Equipment (TMETF), Faculty of Mechanical Engineering and Mechatronics (FIMM), within the National University of Science and Technology POLITEHNICA Bucharest (UPB). The thesis was elaborated within the Faculty of Mechanical Engineering and Mechatronics of UPB and presents original contributions to the field of waste heat recovery from CO₂ Booster

refrigeration systems, aiming to enhance their overall energy efficiency. Due to the growing interest in the use of CO₂ (R744) as a natural refrigerant alternative to traditionally used synthetic refrigerants, as well as the need to improve the efficiency of refrigeration systems, this thesis analyzes various possibilities for heat recovery integrated into CO₂ Booster refrigeration systems.

In this thesis, one of the most common research directions in the field of heat recovery from CO₂ Booster refrigeration systems has been addressed and investigated, especially the recovery of waste heat from the high-pressure stage, at the compressors discharge, before the gas cooler. The high values thermodynamic parameters of CO₂ in this section of the installation make the residual heat flux a highly appealing recoverable source, suitable for various recovery solutions capable of producing not only different forms of thermal energy, but also mechanical energy.

The thesis presents original contributions related to the modeling of CO₂ Booster refrigeration systems, as well as the development of computational programs for studying parameter variations, aimed at the comparative thermodynamic and energetic analysis of installations depending on the variation of meteorological parameters recorded in different cities across Romania.

Regarding the recovery of waste heat from CO₂ Booster refrigeration systems for the production of new forms of thermal energy, original contributions were made through the study of the potential implementation of an NH₃-H₂O absorption refrigeration system (ARS NH₃-H₂O) for producing chilled water to supply the cooling coil of a air handling unit (ARS NH₃-H₂O AC) and for generating the heat flux required for the CO₂ subcooling process at the gas cooler outlet (ARS NH₃-H₂O subc). Furthermore, these systems were analyzed in combination with heat recovery units for domestic hot water production (ARS NH₃-H₂O AC + HR DHW and ARS NH₃-H₂O subc + HR DHW).

For the production of mechanical energy, original contributions were made through the study of the potential implementation of various ORC (Organic Rankine Cycle) system configurations aimed at recovering waste heat and generating mechanical work, which could be redirected to the refrigeration compressors to reduce energy consumption. In addition to this primary objective, further original contributions were made by developing a method for determining the optimal evaporation temperature within ORC systems corresponding to the maximum power regime at the expanders, as well as through a comparative analysis of working fluids to select the optimal fluid based on established evaluation criteria.

The thesis is structured into four chapters and comprises 261 single-spaced pages. It includes 29 tables and 249 figures. At the end of this thesis, 161 bibliographic references are presented, listed in the order in which they are quoted in the text.

Chapter 1 presents a literature review focused on identifying and describing the main configurations of transcritical CO₂ refrigeration systems, as well as the methods for heat and mechanical energy recovery commonly used in these installations.

Chapter 2 evaluates the waste heat available for recovery from CO₂ Booster refrigeration systems through a comparative analysis of refrigeration installations used in supermarkets. Starting from similar operating conditions, the comparative analysis is carried out in two points of view: from a thermodynamic perspective, tracking the evolution of the systems coefficient of performance, and from an energetic perspective, through the analysis of their energy consumption. Finally, the waste heat available for recovery from the studied refrigeration systems is presented and analyzed.

Chapter 3 presents the study on the recovery of waste heat produced by the R744 Booster S refrigeration system through the use of domestic hot water preparation systems and absorption refrigeration systems. On one hand, a conventional heat recovery system for domestic hot water production (HR DHW) is analyzed, and on the other hand, the potential use of an NH₃-H₂O

absorption refrigeration system for producing chilled water to supply the cooling coil of a air handling unit (ARS NH₃-H₂O AC) or for generating the heat flux required for the CO₂ subcooling process at the gas cooler outlet (ARS NH₃-H₂O subc) is investigated, as well as combinations of systems such as ARS NH₃-H₂O AC + HR DHW or ARS NH₃-H₂O subc + HR DHW. In addition to analyzing the feasibility of using these heat recovery systems, a second objective is to carry out a thermodynamic analysis of their impact on the performance of the R744 Booster S refrigeration system.

Chapter 4 addresses another method to recover the waste heat from the R744 Booster S refrigeration system through the use of multiple system configurations. Starting with a presentation of the operating principles of ORC (Organic Rankine Cycle) systems, the chapter continues with a description of the potential heat sources from which they can recover energy, a classification of the types of organic working fluids used, an overview of existing system layouts, and an analysis of the current status of ORC installations both worldwide and locally in Romania. The next step involves the thermodynamic analysis of the proposed ORC systems: the basic ORC system (B-ORC), the ORC system with regenerator (R-ORC), the ORC system with reheating (RI-ORC), and the ORC system with dual-pressure levels (DP-ORC). The results obtained were used for a comparative analysis of the working fluids and for selecting the optimal fluid based on the mechanical power generated at the expanders, the thermal efficiency of the ORC systems, the working fluid flow rate, the global warming potential of the fluids, and the purchase cost of each organic fluid. Finally, through the comparative analysis of the R744 Booster S + B-ORC, R744 Booster S + R-ORC, R744 Booster S + RI-ORC, and R744 Booster S + DP-ORC configurations, the chapter highlights the impact of ORC systems on the performance of the R744 Booster S refrigeration system, emphasizing their contribution to increasing the coefficient of performance and reducing energy consumption by recovering waste heat and generating mechanical energy to drive the system compressors.

At the end of the doctoral thesis, the general conclusions are presented, highlighting the author's original contributions as well as directions for future research. The thesis concludes with a list of the full-text publications and the bibliographic references, presented in the order in which they are quoted in the text.

Thanks

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Author

Chapter 1 – Literature review on the possibilities of heat and energy recovery in CO₂ refrigeration systems

This work focuses on the utilization of waste heat from CO₂ booster refrigeration systems to improve their efficiency, through the implementation of thermal systems capable of producing various forms of thermal energy as well as mechanical energy.

Given the extensive involvement of the refrigeration and air conditioning industry in multiple economic fields, it is observed that refrigeration and air conditioning installations constitute a significant component of global electricity consumption[1]. However, the contribution of refrigeration and air conditioning systems to the total energy consumption of supermarkets may depend on climatic conditions and social habits. Refrigeration installations account for 30 – 60% of the total energy consumption of stores, resulting in the highest energy use compared to other systems[4].

Due to regulations regarding the use of refrigerants in existing installations as well as those yet to be commissioned, natural refrigerants have increasingly gained ground over synthetic ones. Carbon dioxide (CO₂) as a natural refrigerant (R744) has regained researchers attention in recent

years, as it represents an environmentally friendly choice for refrigeration systems. R744 does not affect the ozone layer, and its use represents the simplest way to reduce the CO₂ footprint.

In addition to its refrigeration efficiency, R744 offers significant potential for the recovery of waste heat as well as mechanical energy. This is made possible through the implementation of advanced technologies that allows the utilization of energy otherwise lost in conventional processes. Thus, the use of R744 as a working fluid in refrigeration systems not only improves their energy efficiency but also contributes to reducing environmental impact, aligning with contemporary sustainability requirements.

The number of transcritical installations in commercial applications is currently increasing, particularly in Europe, where regulations are becoming increasingly strict and where the energy performance of CO₂-based systems is either equivalent to or better than that of conventional subcritical systems using R404A[9].

It can be said that the implementation of CO₂ refrigeration systems has become a standard choice for newly constructed grocery stores, as well as a solution for modernizing existing stores (with CO₂ systems replacing existing installations that use synthetic refrigerants). This trend has led to a stronger focus on improving these refrigeration systems by enhancing energy efficiency, reducing costs, integrating refrigeration systems with air conditioning and heating systems (space heating and domestic hot water production)[10], and adding new auxiliary systems for waste heat recovery.

1.1 Transcritical CO₂ refrigeration systems

Depending on the type of application, there are several types of refrigeration systems that use CO₂ as the working fluid. The literature review focused primarily on transcritical CO₂ refrigeration systems, which are employed in commercial applications such as grocery stores (supermarkets) and logistics warehouses for the storage of refrigerated and frozen food.

Starting from the simplest configuration of a CO₂ refrigeration system, various types of systems have been developed over time to meet complex requirements: a cascade CO₂-NH₃ refrigeration system for quick-freezing processes or the storage of frozen food, a CO₂ refrigeration system operating in transcritical mode for achieving a single temperature level, and a CO₂ Booster transcritical refrigeration system for achieving two or more temperature levels.

In transcritical CO₂ refrigeration systems, heat is rejected to the ambient above the critical point, in the supercritical region. Consequently, the main difference between conventional subcritical refrigeration systems and transcritical CO₂ systems is the replacement of the condenser with a gas cooler, where the refrigerant is cooled at constant pressure.

In single-stage or Booster transcritical CO₂ refrigeration systems (Figure 1.1), the operating mode is dictated by the ambient temperature. Through the gas cooler, the refrigerant discharged from the compressor rejects heat to the ambient, with the refrigerant temperature at the gas cooler outlet being a few degrees higher than the ambient temperature. If the ambient temperature is below the critical temperature of the working fluid, the gas cooler condenses the CO₂ vapors, and the refrigeration system operates in subcritical mode. If the ambient temperature exceeds the critical temperature of the working fluid, the CO₂ vapors reject heat to the ambient without condensing in the gas cooler, and the refrigeration system operates in supercritical mode.

These systems can be optimized by using an additional compressor to take the vapors from the intermediate receiver and compress them up to the gas cooler pressure, achieving higher efficiency due to the higher suction pressure compared to that of the main compressor. Thus, by employing parallel compression, the overall efficiency of the system is improved[17].

Another optimization method is the introduction of ejectors, which replace the high-pressure control valve. The use of ejectors allows the compressor suction pressure to increase, resulting in lower energy consumption and a higher COP[1,18].

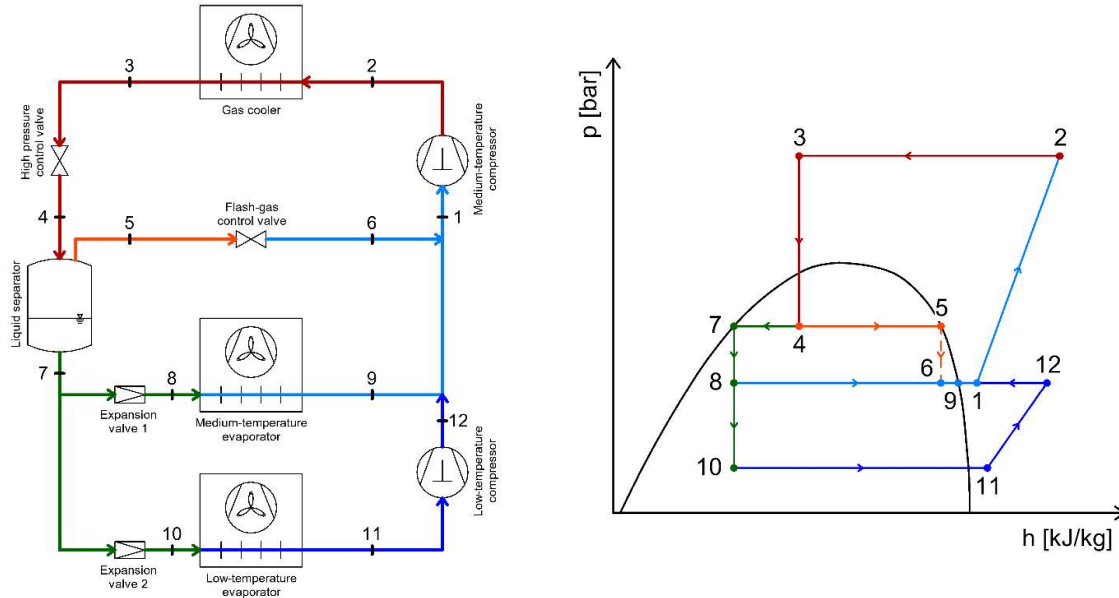


Figure 1.1 Schematic and Operating Cycle in the p–h Diagram of the Standard CO₂ Booster Refrigeration System (R744 Booster S)

The difference between the R744 Booster S and a single-stage CO₂ refrigeration system lies in the additional low-pressure stage, which carries out the freezing process.

1.2 Heat recovery in CO₂ refrigeration systems

Cooling processes generate considerable amounts of heat. When this energy is not utilized, it is considered merely waste heat.

Due to the high operating pressures (which result in high temperatures) of R744 used as a working fluid, it is the perfect refrigerant, taking into account the possibility of heat recovery in the systems where it is used.

In addition to heat recovery from the compressor discharge region, the following can also be considered as heat recovery methods: the use of hot gases for defrosting evaporators in freezing chambers, and the use of internal heat exchangers to carry out superheating and subcooling processes at different points within the system.

Heat recovery from the high-pressure stage is facilitated by the fact that, under normal conditions, the discharge temperature of R744 compressors reaches between 80°C and 120°C, providing a high-temperature heat source from the perspective of heat recovery potential.

As a rule, this type of heat recovery is used in CO₂ Booster refrigeration systems, as these systems are most frequently employed in commercial applications such as grocery stores, where there is a need for heat recovery for domestic hot water preparation and/or space heating, while also reducing energy consumption, thus eliminating the use of other more energy-intensive systems. By installing one or two heat exchangers connected in series on the high-pressure stage before the gas cooler, linked to intermediate circuits for heat storage and distribution, heat can be recovered at different temperature levels, such as: domestic hot water (the temperature of the circuit between the heat exchanger for domestic hot water and the storage tank is 70 – 50°C) and direct space heating

(the temperature of the circuit between the heat exchanger for space heating and the storage tank is 50 – 40°C)[23].

By integrating a heat exchanger before the liquid receiver, it is possible to partially or fully meet the cooling demand of the air conditioning system in the building where the refrigeration system is installed. This method is usually applied to CO₂ booster refrigeration systems, where cooling capacities for the air conditioning system of up to 50 – 250 kW can be produced[26].

Defrosting methods using hot gases or warm glycol can be considered heat recovery processes, as these heat sources originate from the refrigeration system. The use of such a defrosting method contributes positively to the overall coefficient of performance (COP) of the refrigeration system. Moreover, using these methods instead of electric defrosting provides a substantial reduction in energy consumption.

By using the hot gas defrosting method, it has been observed that the defrosting time is reduced compared to other methods, as the heating capacity required for defrosting increases. The hot gas defrosting method can increase the system's COP by up to 8.5%[27].

The warm glycol defrosting method involves the presence of an independent glycol circuit between the hot water storage tank of the heat recovery system for space heating and the evaporators requiring defrosting. Using a coil integrated into the hot water storage tank, the glycol is heated and then transported by a circulation pump to the evaporators, which are equipped with an independent coil that warms the cooling coil inside the evaporators. Typically, a 45% propylene glycol solution is used for the defrosting circuit.

Internal heat exchangers in refrigeration systems are used for superheating or subcooling the refrigerant at certain points within the system. Superheating and subcooling processes are necessary when aiming to optimize and enhance the performance of refrigeration systems; however, it is essential to impose a limit on the degree of superheating/subcooling, beyond which these processes may negatively affect the coefficient of performance.

In commercial R744 Booster refrigeration systems, due to their complex configuration and the large number of compressors serving the two pressure stages, internal heat exchangers are integrated to superheat or subcool the CO₂. Thus, internal heat exchangers are used for superheating CO₂ at the suction of the low-temperature, medium-temperature and parallel compressors, and also function as subcoolers for CO₂ at the gas cooler outlet and at the outlet of the liquid receiver.

1.3 Mechanical energy recovery in CO₂ refrigeration systems

Mechanical energy recovery in CO₂ refrigeration systems can be achieved by integrating ejectors or expansion devices at various locations within the system configuration.

The ejector is a simple component, without moving parts, consisting of a nozzle, a mixing chamber, and a diffuser. Its operating principle can be described as follows: the high-pressure primary fluid expands and accelerates through a nozzle, entering the mixing chamber at supersonic velocity, thereby creating a very low-pressure zone at the nozzle exit. The high-velocity primary fluid draws the secondary fluid into the mixing chamber. The mixing of the two streams is considered complete at the end of the suction section, exiting at supersonic velocity. In the mixing section, a shock wave is generated, producing a compression effect, and the flow velocity is reduced to a subsonic level. Further, the compression of the fluid mixture is completed as it passes through the diffuser[43,44].

In transcritical CO₂ refrigeration systems, the ejector is introduced by replacing the high-pressure expansion valve with it. Through the ejector, the compressor suction pressure increases compared to a standard cycle, leading to higher system efficiency (less mechanical work is required for compression)[43]. While the ejector configuration represents an improvement to the refrigeration system, it presents challenges in controlling the operating parameters[46].

Ejectors recover the mechanical work resulting from expansion in the high-pressure valve, pressure which is normally lost. The recovered mechanical work is used to return the liquid and vapors from the suction accumulator of the refrigeration compressor downstream of the refrigeration evaporator back to the liquid receiver. Due to the presence of ejectors and the suction accumulator, the suction temperature of the refrigeration compressor in the system increases by 6K.

Moreover, based on exergetic analyses reported in the literature, the integration of an ejector into the refrigeration system has been found to significantly reduce exergy losses at the compressor[48].

Research on the integration of ejectors in CO₂ Booster refrigeration systems with parallel compression has concluded that the system can achieve an energy consumption reduction of up to 12%[51]. Such a configuration allows for an increase in system efficiency of up to 30% compared to a standard CO₂ Booster solution, particularly during periods of high outdoor temperatures[52].

To reduce losses and recover the expansion mechanical work, expansion devices can be implemented to replace the throttling valve[55]. In general, an ejector is simpler to construct than an expansion device, but its presence requires more complex modifications within the operating cycle. Expansion devices are easier to install and, at the same time, more efficient than ejectors[56].

The use of an expander produces beneficial effects for the system by increasing the cooling capacity without modifying the heat rejected to the ambient, while the mechanical work generated during expansion in the expander is captured and used to reduce the electrical load of the compressor motor or to generate electricity using a generator[55]. Expanders have received increased research attention with the advent of transcritical CO₂ refrigeration systems, where very high pressure drops occur across expansion valves due to the large operating pressure differences[57].

In single-stage or Booster CO₂ refrigeration systems, the expander can be installed in place of the high-pressure control valve or the expansion valves. Studies have shown that the position of the expander has a significant influence on the coefficient of performance. The highest COP values are achieved when the expander is positioned between the medium- and low-pressure stages, except in cases where the evaporation temperature is very high[59].

Chapter 2 – Waste heat available for recovery from CO₂ Booster refrigeration systems

In order to meet the temperature requirements for storing food in different storage rooms of a supermarket, refrigeration systems must be capable of both cooling and freezing processes.

Conventional refrigeration systems using Freon cannot perform both processes within a single system, requiring instead two separate installations, each dedicated to one process (cooling or freezing).

With the need to use natural refrigerants in supermarkets, it became possible to develop a system capable of simultaneously performing both cooling and freezing processes within a single installation. CO₂ refrigeration systems of this type include the R744 Booster S, R744 Booster SP, and R744 Booster SPE, and due to the thermophysical properties of carbon dioxide, these systems operate in a transcritical regime.

This chapter presents the thermodynamic analyses of the main refrigeration systems used in supermarkets: combined Freon R404A systems for cooling and freezing, the R744 Booster S system, the R744 Booster SP system, and the R744 Booster SPE system. Based on the results, the proposed systems are comparatively analyzed from both a thermodynamic and an energy perspective, and, finally, the waste heat available for recovery from the CO₂ systems is evaluated.

For the thermodynamic study of the four systems and to obtain comparable results, similar operating parameters are used, including the same cooling and freezing capacities, as well as identical ambient conditions.

The thermodynamic analysis of the refrigeration systems used in supermarkets begins with a brief description of each system, followed by the presentation of operating parameters and the thermodynamic equations describing their operation, and concludes with the analysis of the variation of the main characteristic parameters of each system as a function of the ambient temperature.

As expected, the results show that the R744 Booster SPE system is the most efficient, exhibiting the highest coefficient of performance across the entire range of considered ambient temperatures ($-10\text{ }^{\circ}\text{C} \dots +40\text{ }^{\circ}\text{C}$).

Regarding the coefficient of performance of the other systems, it can be highlighted that both the R744 Booster S and R744 Booster SP systems have a considerably higher COP than the combined R404A cooling + freezing system, but only while $t_{amb} < +10\text{ }^{\circ}\text{C}$, beyond this point, all three systems exhibit similar values up to the end of the studied temperature range.

For the energy-based comparison, hourly meteorological data (ambient temperature) over two years (01.09.2019 – 31.08.2020 and 01.09.2020 – 31.08.2021) were used for three major cities in Romania[71]. The selection criterion for the cities was to obtain, as much as possible, three different climates within the country. Thus, for the energy study of the four systems, meteorological data from Cluj-Napoca (a city located in the northern part of the Transylvanian Depression), Bucharest (a city located in the plain area), and Constanța (a city located on the coast of the Black Sea) were used.

The results show that, regardless of the system, the total mechanical energy consumption of the compressors is lower in Cluj-Napoca, while the highest consumption is predominantly recorded in Constanța.

Comparing the transcritical CO₂ refrigeration systems with each other, for each selected city over the two-year period, it is observed that the R744 Booster SP system has a total mechanical energy consumption of the compressors that is 1.6 – 2.7% lower than that of the R744 Booster S system, while the R744 Booster SPE system exhibits a total consumption up to 22.3 – 23.1% lower than the R744 Booster S system and 20.6 – 21% lower than the R744 Booster SP system.

To evaluate the availability of recoverable heat from CO₂ refrigeration systems, the parameters in the high-pressure stage (gas cooler region) are analyzed as a function of the ambient temperature: the operating pressure in the gas cooler (high-pressure stage pressure), the refrigerant temperature at the gas cooler inlet, the refrigerant mass flow at the gas cooler inlet, and the heat rejected to the ambient through the gas cooler.

Since CO₂ Booster refrigeration systems have the same operating conditions in the high-pressure stage, the gas cooler pressure is equal for all three systems.

Comparing the three systems, it can be observed that the refrigerant temperature shows similar operating values for the R744 Booster S and R744 Booster SP systems, while in the system with the ejector, although the temperature variation is the same, it is consistently a few degrees lower. At ambient temperatures above $+25\text{ }^{\circ}\text{C}$, the CO₂ entering the gas cooler reaches temperatures above $+100\text{ }^{\circ}\text{C}$, which facilitates the integration of heat recovery processes.

The refrigerant mass flow entering the gas cooler increases with ambient temperature, showing very similar values for all three systems, with the R744 Booster S and R744 Booster SP systems even exhibiting identical flow rates.

As the ambient temperature increases, the heat rejected through the gas cooler becomes progressively higher due to the elevated pressure and temperature of the refrigerant in the high-pressure stage, as well as the high enthalpy of CO₂ in this operating region.

The refrigerant flow rate and the heat flux available at the high-pressure stage exhibit values that allow for heat recovery with high efficiency.

Chapter 3 – Recovery of waste heat from CO₂ Booster refrigeration systems through the use of domestic hot water preparation systems and absorption refrigeration systems

3.1 Introduction

Heat recovery for domestic hot water production is increasingly used in commercial applications (such as supermarkets) because it offers the possibility to further reduce the building's energy consumption[21], as well as its carbon footprint, by eliminating the need for conventional hot water production systems that rely on burning natural gas, coal, etc. The main components of a domestic hot water heat recovery system are: a heat exchanger connected to the heat source, a circulation pump, and a domestic hot water storage tank.

Concerning absorption refrigeration systems, these are systems in which the refrigerant is separated from the liquid absorbent through the addition of heat from a hot source. To ensure the continuous operation of the system, the refrigerant must later recombine with the liquid absorbent, a process that takes place by releasing heat to a cold source.

The most commonly encountered absorption refrigeration systems are those using NH₃-H₂O and LiBr-H₂O[73,74], but there is also considerable research aimed at expanding the working pairs (refrigerant-absorbent) used in absorption systems, including metaline-water, methanol-lithium bromide, as well as other combinations composed of three substances[75].

Absorption refrigeration systems have the advantage that their main components do not contain moving parts, which results in quieter and more reliable operation, as well as a longer lifespan compared to other refrigeration systems. The possibility of using renewable or waste heat sources makes absorption systems frequently employed in industrial and commercial applications, as well as in areas with limited access to electricity.

As disadvantages, absorption refrigeration systems have a lower efficiency compared to vapor-compression refrigeration systems, larger component and overall system sizes, and higher initial costs than conventional refrigeration systems.

In this chapter, the presentation and thermodynamic analysis of systems recovering waste heat from the transcritical CO₂ refrigeration system will be carried out: a heat recovery system for domestic hot water (HR DHW); a single-stage absorption refrigeration system with NH₃-H₂O for producing chilled water that supplies the cooling coil within an air-handling unit (ARS NH₃-H₂O AC); and a system for producing the heat flow required for subcooling CO₂ at the gas cooler outlet (ARS NH₃-H₂O subc). In addition to these three systems, the thermodynamic analysis of the combined configurations ARS NH₃-H₂O AC + RC DHW and ARS NH₃-H₂O subc + HR DHW will also be conducted. This study will be carried out by performing a thermodynamic calculation for each type of heat recovery system, comparing the results, and, through integration into the refrigeration system, analyzing the impact of each recovery system on the performance of the refrigeration system.

3.2 Heat source – R744 Booster S refrigeration system

Following the comparative analysis of transcritical CO₂ refrigeration systems, it was found that all three systems under comparison have a high potential for recovering waste heat from the high-pressure stage. Although the mass flow rate of the refrigerant and the available heat flux in

this region are higher for the R744 Booster SP and R744 Booster SPE systems, the fact that the R744 Booster S exhibits the highest refrigerant temperature led to the decision to consider this system, in the present study, as the heat source for the heat recovery systems presented in the following sections. Another argument supporting this choice is that the mass flow rate and the available heat flux at the high-pressure stage of the R744 Booster S are not significantly lower than those of the other systems, which will not substantially affect the potential of the heat source.

To achieve high efficiency in the heat recovery process, it is necessary for the heat source (R744 Booster S) to exhibit the highest possible parameter values. Therefore, it was considered that the heat recovery systems (the domestic hot water system and the absorption system) should operate only during the warm season, within the ambient temperature range of +20 ... + 40 °C, when the heat source provides the highest temperature, mass flow rate, and available heat flux.

3.3 Thermodynamic analysis of heat recovery systems

The connection of the heat recovery systems to the R744 Booster S refrigeration system (the heat source), whether it involves the DHW recovery system (HR DHW) or the NH₃-H₂O absorption refrigeration systems (ARS), is established on the pipeline between the refrigeration compressor and the gas cooler.

In the case of the HR DHW system, the coupling to the refrigeration installation is achieved using a plate heat exchanger through which heat is transferred from the R744 Booster S to the recovery system. The working fluid in the DHW recovery circuit can be either water or glycol. The working fluid is circulated by a variable-speed pump installed on the outlet pipe of the heat exchanger. The heat absorbed from the CO₂ is stored in a tank and subsequently distributed to the consumers.

It has been determined that, under standard operating conditions of the refrigeration system, without increasing the system's mass flow rate or the compressors discharge pressure, waste heat recovery can lead to a reduction of up to 48% in natural gas consumption for building heating, as well as a decrease of up to 6.2% in operational costs[72].

The domestic hot water heat recovery system was found to be capable of recovering between 12% and 50% of the waste heat available from the R744 Booster S refrigeration system, with the remaining heat being rejected to the ambient environment through the gas cooler.

As the temperature of the heat source increases, both the recoverable heat availability and the recovered heat flux increase; however, a higher water flow rate in the recovery circuit is also required. Practically, the HR DHW system can provide a heat flux ranging from 45 – 256 kW with water parameters of +65 °C/+25 °C and flow rates 983 L/h – 5583 L/h.

In the case of the ARS NH₃-H₂O AC system, the analysis is based on the assumption that it absorbs waste heat from the R744 Booster S system at the level of the generator/boiler and is intended for producing chilled water to supply a cooling coil within an air handling unit (AHU). The connection of the ARS NH₃-H₂O AC system to the R744 Booster S is made directly, without an intermediate heat exchanger, with the CO₂ line connected straight to the generator/boiler.

To highlight the performance of the ARS NH₃-H₂O AC system as a function of the heat source temperature, the following parameters are evaluated: the heat flow delivered to the AHU cooling coil, the mass flow rate of the working fluid supplying the AHU coil, the recovered waste heat, and the system's coefficient of performance.

The heat recovery rate increases nearly linearly as the temperature of the heat source rises. Using the ARS NH₃-H₂O AC system, between 32% and 100% of the waste heat from the R744 Booster S installation can be recovered, while the coefficient of performance of the ARS NH₃-H₂O AC system increases following a logarithmic trend as the heat source parameters become higher.

When followed by a HR DHW system, the ARS NH₃-H₂O AC retains its configuration, with the same components and operational mode. The connection of the ARS NH₃-H₂O AC and HR DHW systems to the R744 Booster S refrigeration installation is made in series on the high-pressure stage, between the refrigeration compressor and the gas cooler.

To ensure the minimum operating conditions of the RC ACM system, specifically, producing hot water at an outlet temperature of $t_{out,DHW} = +65\text{ }^{\circ}\text{C}$, the inlet temperature of the heat source to the system's heat exchanger must be at least $t_{in,HS} = +80\text{ }^{\circ}\text{C}$, thereby guaranteeing the proper execution of the heat transfer process.

Therefore, the temperature of the heat source exiting the boiler generator of the ARS NH₃-H₂O AC system is set at $t_{out,HS} = t_{in,HS} = +80\text{ }^{\circ}\text{C}$.

Setting the temperature of the heat source at the outlet of the ARS NH₃-H₂O AC system and at the inlet of the HR DHW system enables the implementation of this combined solution. However, the performance of each system individually is lower than when each heat recovery solution is applied independently, since the residual heat flux available for recovery in each system is reduced and constrained by this intermediate temperature point of $+80\text{ }^{\circ}\text{C}$.

Thus, using the ARS NH₃-H₂O AC system, between 6% and 41% of the residual heat produced by the R744 Booster S refrigeration system can be recovered, while the HR DHW system allows for the recovery of between 6% and 16% of the same residual heat.

The coefficient of performance of the ARS NH₃-H₂O AC system and the efficiency of the HR DHW system both increase as the heat source exhibits higher parameters. It is noteworthy that the ARS NH₃-H₂O AC maintains the same coefficient of performance regardless of whether it is followed by the HR DHW system or not.

Regarding the ARS NH₃-H₂O subc system, the CO₂ discharged from the high-pressure compressors passes through the generator, where it transfers heat to the ARS NH₃-H₂O subc system. The remaining residual heat is then rejected via the gas cooler, and upon exiting it, the CO₂ enters the absorption system's evaporator for subcooling before passing through the high-pressure expansion valve, after which the refrigeration cycle continues. For the subcooling process, three scenarios regarding the degree of subcooling achieved were analyzed: $\Delta t_{subc} = 3\text{ K}$, $\Delta t_{subc} = 5\text{ K}$, $\Delta t_{subc} = 10\text{ K}$.

By applying subcooling to the working fluid in the R744 Booster S system at the gas cooler outlet, the CO₂ mass flow rate and the recoverable residual heat decrease significantly, while the discharge temperature and pressure of the compressors remain unchanged.

The coefficient of performance of the ARS NH₃-H₂O subc system increases as the heat source parameters rise. The lower the degree of subcooling applied, the higher the coefficient of performance, resulting in more efficient system operation.

In the case where it is followed by a domestic hot water heat recovery system, the NH₃-H₂O absorption refrigeration system for subcooling (ARS NH₃-H₂O subc) does not undergo any configuration changes, maintaining the same components and operating principle. The connection of the ARS NH₃-H₂O subc and the DHW heat recovery system (HR DHW) to the R744 Booster S refrigeration unit is carried out in series on the high-pressure stage, between the refrigeration compressor and the gas cooler.

As in the previous case, in order to ensure the minimum operating conditions of HR DHW, the inlet temperature of the CO₂ into the system's heat exchanger must not fall below $+80\text{ }^{\circ}\text{C}$, thereby guaranteeing the effective execution of the heat transfer process.

The degree of heat recovery increases with the rise in the hot source temperature, both for the ARS NH₃-H₂O subc and for the HR DHW systems. It is also observed that a lower degree of subcooling allows both systems to recover a greater residual heat flux.

The coefficient of performance of ARS NH₃-H₂O subc and the efficiency of HR DHW both increase as the hot source parameters rise. Moreover, the lower the degree of subcooling considered, the higher the coefficient of performance of the ARS NH₃-H₂O subc and the efficiency of the HR DHW, resulting in more efficient system operation.

3.4 Thermodynamic analysis of the impact of heat recovery systems on the performance of the R744 Booster S refrigeration system

For the comparative thermodynamic analysis of the impact of the proposed heat recovery systems on the performance of the R744 Booster S refrigeration plant, calculation formulas for the overall coefficient of performance of the couplings between the refrigeration system and the heat recovery systems are defined, in order to track its evolution across the studied range of ambient temperatures.

Although the stand-alone HR DHW increases the overall coefficient of performance by up to 81% at maximum ambient temperature, it is important to highlight that the domestic hot water demand in supermarkets is relatively low. Consequently, this method of heat recovery is not entirely suitable as long as the actual demand does not match the production capacity of the system.

The results indicate that the R744 Booster S + ARS NH₃-H₂O AC + RC ACM system exhibits superior performance compared to the configuration without RC ACM (R744 Booster S + ARS NH₃-H₂O AC), but only up to an ambient temperature of approximately $t_{amb} = +32,5\text{ }^{\circ}\text{C}$. Beyond this threshold, the R744 Booster S + ARS NH₃-H₂O AC system outperforms the combined solution.

When an absorption refrigeration system for subcooling (ARS NH₃-H₂O subr) is integrated into the standard R744 Booster refrigeration system, its impact on the overall coefficient of performance is markedly positive, as it provides a substantial increase regardless of the subcooling level considered. Furthermore, if a domestic hot water heat recovery unit (RC ACM) is also incorporated, the overall coefficient of performance exhibits an even more pronounced improvement, with the magnitude of this enhancement increasing in proportion to the selected degree of subcooling.

Chapter 4 – Recovery of waste heat from CO₂ Booster refrigeration systems through the use of Organic Rankine Cycle (ORC)

4.1 Introduction

Organic Rankine Cycle (ORC) systems are thermal systems through which heat (thermal energy) extracted from a heat source is converted into mechanical energy, which can then be used directly or transformed into electrical energy via an electric generator[84].

By using an ORC system to recover waste heat from CO₂ refrigeration installations, electrical energy can be generated, which can either be fed back into the refrigeration system or supplied to other systems requiring electrical power.

The Organic Rankine Cycle (ORC) is a thermal cycle that operates on the same principles as the traditional Rankine cycle (used in steam turbine systems), with the main distinction being that the working fluid is not water but an organic fluid. These organic working fluids are typically refrigerants used in refrigeration systems[85]. The ORC operates between two pressure levels: the working fluid pressure at the evaporator (evaporation pressure) and at the condenser (condensation

pressure). The difference between these two operating pressures also determines the enthalpy drop across the expander.

An important aspect when discussing ORC systems is the selection of a suitable working fluid. The chosen working fluid will affect the system's efficiency, the size of the components, the stability and safety of the installation, as well as when considering its environmental impact[89].

Analyzing the most recent data, ORC systems are currently widely used in many regions across the world. The main heat sources utilized for ORC systems at a global level are geothermal energy, biomass combustion, solar energy, and waste heat.

4.2 Thermodynamic analysis of ORC systems for heat recovery

Within this analysis, four ORC systems were considered: the basic configuration ORC system (B-ORC), the ORC system with a regenerator (R-ORC), the ORC system with reheating (RI-ORC), and the ORC system with two pressure levels (DP-ORC).

From the perspective of the organic fluid used by ORC systems coupled with the R744 Booster S installation, the study was designed as a comparative analysis, examining the possibility of using several working fluids (R124, R142b, R236ea, R236fa, R600, R600a), followed by the selection of an optimal working fluid in terms of all imposed conditions.

For the thermodynamic analysis of the studied ORC systems, the method for the selection of the evaporation temperature is carried out through numerical simulation of the ORC system operation, using an iterative calculation in which the evaporation temperature is variable. In this case, the evaporation temperature is chosen according to the maximum mechanical power developed by the ORC expander, even if the ORC systems fail to recover the entire amount of waste heat available from the R744 Booster S installation. This mode of operation was set to maximize the efficiency of the ORC systems.

The coupling of the ORC systems to the R744 Booster S refrigeration installation (the heat source) is carried out at the high-pressure stage, on the segment between the refrigeration compressor discharge and the gas cooler inlet, directly, without an intermediate fluid loop. The refrigerant passes directly through the ORC evaporator, and then releases the remaining waste heat to the ambient through the gas cooler.

The thermodynamic analysis aims to highlight the variation of the main parameters of the ORC systems as a function of the heat source temperature: the working fluid mass flow rate, the heat flux recovered from the heat source, the mechanical power produced by the expanders, the mechanical power required to drive the pumps, the thermal efficiency, as well as the working fluid mass flow rate and the heat flux required and available at the cold source.

The obtained results show that the performance of the studied ORC systems depends on the CO₂ temperature at the high-pressure stage, being able to produce increasingly more mechanical energy as the CO₂ temperature rises.

4.3 Comparative analysis of working fluids

To select the most suitable working fluid among those considered, a comparative analysis of the working fluids was performed, applying several differentiation criteria to which percentage weights were assigned in order to indicate the relative importance of each criterion. To establish a ranking of the fluids for each ORC system, scores from 1 to 6 were assigned for each criterion, with six fluids being examined.

For a proper comparison of the thermodynamic parameters developed by the studied working fluids (mechanical power produced at the expander, thermal efficiency, and the working fluid flow rate in the ORC system), the average values of the results obtained in the previous thermodynamic study were used over the entire range of heat source temperatures.

Table 4.1 Overall score of the working fluids

Systems	R124	R142b	R236ea	R236fa	R600	R600a
B-ORC	4,50	2,95	2,65	3,15	2,95	4,20
R-ORC	4,35	2,35	2,95	3,60	3,10	4,40
RI-ORC	4,65	3,05	2,40	3,30	2,95	4,40
DP-ORC	3,65	2,60	3,35	4,30	2,20	4,65
Overall score	4,29	2,74	2,84	3,59	2,80	4,41

Analyzing the scores obtained for each system individually, as well as the overall score, it can be concluded that there is no ideal organic working fluid for all types of ORC systems (none of the studied fluids achieved an overall score close to 6). However, among the working fluids examined for the proposed ORC systems, the fluids that tend to achieve remarkable performance across all four ORC systems are R600a and R124.

4.4 Comparative analysis of the impact of ORC systems on the performance of the R744 Booster S refrigeration system

The comparison of ORC-type heat recovery systems coupled with the R744 Booster S refrigeration installation aims, from a thermodynamic perspective, to highlight the impact that these ORC systems have on the overall performance coefficient of the coupling between the R744 Booster S refrigeration installation and the ORC systems.

It is assumed that the mechanical power developed by the ORC expanders is fed into the refrigeration installation to contribute to the mechanical power required to drive the compressors.

The values of the overall performance coefficient for the R744 Booster S refrigeration installation coupled with the ORC systems are higher than when the refrigeration installation operates without a recovery system. A notably higher COP is observed in the case of the R744 Booster S + DP-ORC system, while the other systems exhibit lower and similar values.

The mechanical power developed by the ORC system expanders influences the increase in the performance coefficient of the refrigeration installation to which they are coupled. The DP-ORC system shows an average COP increase of +7.83%, the B-ORC and R-ORC systems +6.00%, and the RI-ORC system +5.55%.

The comparison of the systems from an energy perspective is carried out to identify the impact of the ORC systems on the R744 Booster S refrigeration installation. The energy comparison is performed by evaluating the total energy consumption of the combined R744 Booster S + ORC system relative to the total energy consumption of the R744 Booster S refrigeration installation. For the energy comparison, meteorological data (ambient temperature) collected from Cluj-Napoca, Bucharest, and Constanța over two years were used: Year I (01.09.2019 – 31.08.2020) and Year II (01.09.2020 – 31.08.2021), considering only the interval $t_{amb} = +20 \dots +40$ °C.

Considering the total studied period (Year I + Year II), ORC systems coupled with the R744 Booster S refrigeration installation can achieve an energy consumption reduction of up to 4.72% (in Cluj-Napoca), 5.66% (in Bucharest), and 4.89% (in Constanța). The DP-ORC system exhibits the largest decrease in energy consumed by the refrigeration installation, recording the highest percentage reduction in mechanical energy consumption in the city of Bucharest.

Conclusions

C1. Overall conclusions

The primary aim of this thesis is to identify and investigate thermal systems capable of utilising the waste heat generated by CO₂ Booster refrigeration installations employed in supermarket-type stores, with the objective of enhancing refrigeration efficiency. Today, the recovery of waste heat from refrigeration systems represents a viable solution for reducing overall energy consumption by harnessing thermal energy that would otherwise be lost, while simultaneously contributing significantly to the improvement of system performance. This doctoral thesis focused on the recovery and utilization of waste heat from CO₂ Booster refrigeration installations through heat recovery systems for domestic hot water production, absorption refrigeration systems for generating chilled water to supply the cooling coil of an air handling unit, or for providing the heat necessary for the CO₂ subcooling process at the gas cooler outlet, as well as through ORC systems with various configurations for mechanical energy generation. The most substantial source of waste heat from CO₂ Booster refrigeration installations is located at the high-pressure stage, where the working fluid exhibits very high temperature and pressure, and the waste heat flow, which is conventionally released to the environment, is considerable.

The literature review presented in **Chapter 1** aimed to highlight the possibilities for recovering heat and mechanical energy from CO₂ refrigeration installations used in commercial and industrial applications. The implementation of multiple heat and mechanical energy recovery methods plays a significant role in increasing the efficiency of refrigeration systems and reducing their negative environmental impact. Although the integration of heat and mechanical energy recovery systems into CO₂ refrigeration installations entails additional costs, these solutions contribute substantially to lowering the energy consumption of the buildings in which they operate, while also enabling the production of secondary energy outputs (such as domestic hot water or thermal energy for space heating), which are typically obtained through other thermal systems with a negative environmental impact.

The most commonly used CO₂ refrigeration installations were presented and analyzed comparatively from both a thermodynamic and an energy perspective in **Chapter 2**. The main objective of this analysis was to determine the waste heat available for recovery. The inclusion of traditional R404A refrigeration and freezing systems in the comparative analysis showed that, although CO₂ Booster installations are more complex than R404A systems, they are more compact, being capable of performing both refrigeration and freezing processes within the same installation, an aspect of great importance in supermarket-type applications, where it is necessary to preserve food at different temperature levels.

According to the thermodynamic analysis, the R404A refrigeration + freezing configuration and the R744 Booster S and R744 Booster SP installations exhibit comparable performance as long as the ambient temperature is above +10 °C, whereas the R744 Booster SPE installation with ejectors is clearly superior in terms of the performance coefficient, regardless of the ambient temperature. According to the energy analysis, when comparing CO₂ refrigeration installations, it was found that improving the standard system by adding parallel compressors and subsequently ejectors considerably reduces energy consumption. Specifically, the parallel compressor provides mechanical energy savings of up to 2.70% compared to the standard configuration, while the installation with a parallel compressor and ejectors reduces mechanical energy consumption by up to 23.10% compared to the standard installation and by up to 21.00% compared to the installation equipped only with parallel compressors, based on the imposed operating conditions. The results obtained using the ambient temperature profiles recorded in Bucharest, Cluj-Napoca, and Constanța

during the period 01.09.2019 – 31.08.2021 confirmed that CO₂ Booster refrigeration installations perform better at lower ambient temperatures. In this context, the lowest mechanical energy consumption was recorded in Cluj-Napoca due to the city's geographical location, which allows for lower ambient temperatures throughout the year.

From the perspective of the heat available for recovery from CO₂ refrigeration installations, it can be concluded that these installations have a high potential for waste heat recovery. This is due to the fact that, at ambient temperatures above +25 °C, CO₂ Booster refrigeration installations reach high-pressure stage fluid temperatures at the gas cooler inlet exceeding +100 °C, which facilitates the integration of heat recovery processes. Furthermore, the working fluid flow rate and the available heat flux are sufficient to allow heat recovery with high efficiency. It is noteworthy that the installation with the highest waste heat parameters was found to be the R744 Booster S, and the subsequent study was based on this installation as the heat source for the proposed heat recovery systems.

In **Chapter 3**, a conventional heat recovery system for domestic hot water preparation was analyzed, and the possibility of implementing NH₃-H₂O absorption refrigeration installations for chilled water production, supplying the cooling coil of an air handling unit, and for generating the heat flow required for the CO₂ subcooling process at the gas cooler outlet was studied, as well as combinations of systems composed of an absorption refrigeration installation and a conventional heat recovery system for domestic hot water preparation. The results showed that, in addition to refrigeration and freezing capacity, when it is necessary to supply a cooling coil of an air handling unit for air conditioning, an absorption system can be effectively used to cover at least part of the building's air conditioning demand. If domestic hot water production is required, the conventional hot water heat recovery system (HR DHW) will successfully meet the building's total demand, at least when used individually. Furthermore, if ambient conditions are unfavorable (very high ambient temperatures), an absorption system for subcooling will significantly improve the efficiency of the refrigeration installation by reducing the mass flow rate of the working fluid entering the evaporators, while simultaneously increasing the refrigeration capacity of the installation and allowing a decrease in the optimal operating pressure at the high-pressure stage.

Whether it concerns the heat recovery system for domestic hot water preparation, absorption refrigeration installations, or combinations thereof, the comparative analysis showed that, first, these systems can produce usable energy outputs within the buildings in which they operate, and second, they have a positive impact on the overall performance coefficient of the system. Thus, the R744 Booster S refrigeration installation is transformed into a fully integrated thermodynamic system, capable of producing multiple heat streams at different temperature levels and environmentally friendly through the use of only natural working fluids (CO₂, NH₃, water).

Following the analysis of the proposed recovery systems, it was found that when the recovery systems are integrated individually with the R744 Booster S, their performance is very high. However, when the systems are coupled in series ARS NH₃-H₂O AC + HR DHW or ARS NH₃-H₂O subc + HR DHW, their performance decreases considerably due to the necessary limitations imposed to enable the simultaneous operation of both recovery systems. Even so, there are applications in which these couplings can be very useful, with the impact of the absorption system being clearly visible on the refrigeration installation, and the heat flow produced by the HR DHW system being sufficient, particularly for smaller supermarket-type stores with lower energy demands.

The analysis of the impact of recovery systems on the refrigeration installation shows that the HR DHW system, when coupled individually with the R744 Booster S, increases the overall performance coefficient by up to 81.37%, due to the fact that the recovery system has access to a heat source with very high parameters, thereby enabling the recovery of a substantial heat flux.

When the R744 Booster S is coupled with the ARS NH₃-H₂O AC system, the overall performance coefficient increases by up to 36.17%, and when coupled with ARS NH₃-H₂O AC + HR DHW, the overall performance coefficient increases by up to 30.01%. The reduction in the percentage increase after adding the HR DHW system following the ARS NH₃-H₂O AC system is due to limitations imposed on the operating temperatures. Regarding the ARS NH₃-H₂O subc system, it increases the overall performance coefficient by up to 5.39% at a 3 K subcooling, up to 15.07% at 5 K, and up to 29.53% at 10 K. If an HR DHW heat recovery system is additionally integrated, the overall performance coefficient increases even more significantly, reaching up to 18.73% at 3 K subcooling, up to 29.53% at 5 K, and up to 52.84% at 10 K subcooling.

Finally, it was observed that, irrespective of the specific energy output for which they are designed, the two proposed solutions for recovering waste heat from the R744 Booster S refrigeration installation constitute an excellent choice from an energy efficiency standpoint, as their only mechanical work requirement is associated with the circulation pumps, whose energy consumption is virtually negligible.

Chapter 4 focused on a detailed analysis of four Organic Rankine Cycle (ORC) configurations designed to recover waste heat from the R744 Booster S installation and convert it into mechanical work to assist in driving the compressors, thereby reducing the energy consumption of the refrigeration system. The thermodynamic parameter values exhibited by CO₂ at the high-pressure stage indicated that it can serve as a heat source for ORC system configurations utilising a low-temperature heat source.

The performance of ORC systems is variable, depending on several factors, including the organic working fluid used, the type and temperature level of the heat source, the type and temperature level of the cold source, as well as the system configuration.

To ensure a comprehensive analysis, four ORC system configurations commonly reported in the literature for various heat recovery applications were considered: B-ORC, R-ORC, RI-ORC, and DP-ORC. The analysis was conducted comparatively for six organic working fluids with different thermodynamic properties and environmental impacts (R124, R142b, R236ea, R236fa, R600, R600a), with the aim of determining the optimal working fluid for the ORC systems within the R744 Booster S + ORC coupling.

From the perspective of the comparative thermodynamic analysis of the proposed ORC systems, the results highlighted that, regardless of the working fluid used, the mechanical power developed by the expanders is highest in the DP-ORC system and lowest in the RI-ORC system. Although the primary goal was the recovery of waste heat from the R744 Booster S installation and the production of the maximum possible mechanical work, the evaluation and comparison of other operating parameters of the ORC systems provide a more detailed overview of their behavior within the R744 Booster S + ORC coupling. It is worth noting that, among the four ORC systems, the highest thermal efficiency was observed in the RI-ORC system, while the B-ORC system exhibited the lowest values. Regarding the working fluid mass flow rate in these systems, it was observed that the DP-ORC system has the highest mass flow rate, whereas the RI-ORC system has the lowest. It is also noteworthy that, based on the results, the R-ORC system consistently ranked between the other ORC systems, regardless of the evaluated operating parameters.

Regarding the comparative analysis of the working fluids for determining the optimal fluid, it was shown that there is no ideal fluid for all four studied ORC systems. The proposed evaluation system was a scoring method based on several criteria, each weighted according to the purpose for which the ORC systems are used: mechanical power developed at the expander with a weight of 40%, ORC system thermal efficiency with a weight of 15%, working fluid mass flow rate in the ORC system with a weight of 15%, global warming potential (GWP) of the fluid with a weight of 25%, and the purchase cost of the fluid with a weight of 5%. Accordingly, based on the results and

using a scoring scale from 1 to 6, the organic fluids R600a and R124 obtained the highest scores, with values above 3.50 for each ORC system. Considering that environmental impact is an important criterion in selecting the working fluid, it was concluded that R600a is the most suitable fluid among those proposed for the ORC systems studied in this work, due to the fact that $GWP_{R600a} = 3$, while $GWP_{R12} = 527$.

As part of the evaluation of the impact of ORC systems on the R744 Booster S refrigeration installation, a comparative thermodynamic analysis was performed by assessing the performance coefficient of the refrigeration installation before and after the integration of the ORC systems. Additionally, a comparative energy analysis was conducted by evaluating the energy consumption of the refrigeration installation both individually and when coupled with the ORC systems, using the ambient temperature profiles recorded in Bucharest, Cluj-Napoca, and Constanța during the period 01.09.2019 – 31.08.2021, as presented in Chapter 2.

Thus, following the thermodynamic analysis, it was observed that the ORC systems increase the overall performance coefficient of the R744 Booster S + ORC coupling under the imposed operating conditions by up to 10.24% for the B-ORC and R-ORC systems, up to 9.00% for the RI-ORC system, and up to 13.46% for the DP-ORC system. It is evident that the DP-ORC system stands out for having a greater impact on the performance coefficient of the refrigeration installation compared to the other studied systems.

From an energy perspective, considering the ambient temperature profiles recorded over the two studied years, the ORC systems can generate up to 11 MWh in Cluj-Napoca, 35 MWh in Bucharest, and 24 MWh in Constanța. As expected, the DP-ORC system can produce the highest amount of mechanical energy, exceeding that of the other systems: up to +29% compared to the B-ORC or R-ORC systems and up to +35% compared to the RI-ORC system. The integration of ORC systems into the R744 Booster S refrigeration installation reduces its energy consumption over two years by up to 4.72% when operating in Cluj-Napoca, up to 5.66% in Bucharest, and up to 4.89% in Constanța. The highest percentage reduction in energy consumption is consistently achieved by the DP-ORC system, as it produces the largest amount of mechanical energy, which is subsequently fed into the refrigeration installation.

The results obtained from the analysis of the potential integration of ORC systems within the R744 Booster S refrigeration installation indicate that, under the imposed operating conditions, these systems can increase the performance coefficient of the refrigeration installation by an average of 11% and reduce energy consumption by an average of 5%, particularly in regions with warmer climates and predominantly higher ambient temperatures. These findings suggest that ORC systems for recovering waste heat from the R744 Booster S represent a viable alternative for reducing the amount of waste heat released into the environment via the gas cooler and constitute a solution worth considering for enhancing the performance of the installation.

The initial parameters and operating conditions imposed on the studied heat recovery systems were aimed at ensuring efficient system operation, even though, as the results have shown, this approach prevents the systems from fully recovering all the waste heat available from the R744 Booster S refrigeration installation.

In the case of CO₂ refrigeration installations operating in the supercritical regime within supermarket-type applications, the thermal potential available for recovery is considerable. However, its utilisation for domestic hot water production is limited compared to industrial applications due to the significantly lower demand. Therefore, for installations intended for the commercial sector, identifying alternative solutions for thermal energy recovery is essential. During nighttime periods, the refrigeration installations operate at partial loads, and domestic hot water consumption is negligible. In this context, integrating an absorption refrigeration system for subcooling is justified, as subcooling allows for reduced energy consumption and an increased

performance coefficient, even under low-load operation. Additionally, the electrical energy available at night, obtained through Organic Rankine Cycle (ORC) systems, can be used to power service lighting, sensor systems, or other auxiliary loads of the refrigeration installation, and when coupled with a photovoltaic system, it can contribute to charging electrical storage batteries.

Depending on the specific characteristics of the geographical region and, consequently, the recorded ambient temperature values, the implementation of different energy recovery strategies is warranted. In this context, in regions with elevated temperatures, the integration of an absorption refrigeration system for subcooling emerges as the optimal solution, as it contributes both to a reduction in electrical energy consumption and to an enhancement of the overall system performance coefficient.

In the context of accelerated climate change and recent legislative developments, the implementation of thermal systems such as absorption refrigeration installations or ORC systems, which enhance the efficiency of CO₂ Booster refrigeration systems through the recovery of waste heat, represents an important step in identifying alternative solutions for energy efficiency and consumption reduction, as well as in achieving climate objectives both at the EU level and globally.

C2. Author's original contribution

Based on the general conclusions presented above, the author's original contributions within this doctoral thesis can be summarized as follows:

- development of a detailed classification of transcritical CO₂ refrigeration installations and investigation of the current state of all potential methods for recovering heat and mechanical energy within these systems;
- development of computational tools for the thermodynamic analysis of the studied thermal systems, employing the open-source CoolProp library and EES software, with capabilities for input parameter modification and immediate generation of results;
- mathematical modeling of the thermodynamic performance of the gas ejectors within the R744 Booster SPE refrigeration installation;
- performing an energy analysis of CO₂ Booster refrigeration installations operating in three Romanian cities with distinct climatic conditions (Cluj-Napoca, Bucharest, Constanța), based on actual meteorological data capturing the ambient temperature variations in these locations over the period 01.09.2019 – 31.08.2021;
- integration into the R744 Booster S refrigeration installation, aimed at waste heat recovery, of an absorption refrigeration system (ARS NH₃-H₂O) for the generation of chilled water to supply the cooling coil of a humid air handling unit, as well as for producing the heat flux necessary for the CO₂ subcooling process at the gas cooler outlet;
- integration within the R744 Booster S refrigeration installation, aimed at waste heat recovery, of an absorption refrigeration system coupled with a domestic hot water heat recovery system (ARS NH₃-H₂O + HR DHW);
- development of a method for determining the optimal evaporation temperature in ORC systems corresponding to the maximum power output at the expander level;
- comparative analysis of working fluids for the selection of the optimal fluid using a ranking system based on established criteria;
- integration within the R744 Booster S refrigeration installation of four Organic Rankine Cycle (ORC) configurations (B-ORC, R-ORC, RI-ORC, DP-ORC) with the aim of recovering waste heat and generating mechanical work to be redirected to the refrigeration compressors in order to reduce energy consumption;
- conducting an analysis of the impact of the B-ORC, R-ORC, RI-ORC, and DP-ORC systems on the efficiency of the R744 Booster S refrigeration installation, assuming

operation in Cluj-Napoca, Bucharest, and Constanța during the period 01.09.2019 – 31.08.2021.

C1. Future research directions

Future research directions may involve:

- analysis of the impact of absorption refrigeration systems and ORC systems on CO₂ Booster refrigeration installations, taking into account a wide range of cooling capacities commonly encountered in supermarket-type stores, as well as in other types of refrigeration applications;
- assessment of the feasibility of integrating the proposed heat recovery systems into existing CO₂ Booster refrigeration installations;
- evaluation of the waste heat available for recovery from CO₂ Booster refrigeration installations under different operating conditions, such as day–night or warm–cold seasons, and assessment of the feasibility of integrating absorption refrigeration systems and ORC systems in all these scenarios;
- analysis of scenarios in which the proposed heat recovery systems are connected in parallel to two or more CO₂ Booster refrigeration installations, with the aim of increasing the mass flow rate of the heat source;
- evaluation of the feasibility of using alternative cold sources, in place of water, for the proposed absorption refrigeration and ORC systems, within the current context of the global natural resource crisis;
- identification of higher-performance organic working fluids for ORC systems and investigation of the feasibility of using CO₂ as a working fluid within these systems;
- conducting an economic analysis of the integration of the proposed heat recovery systems into both new and existing CO₂ Booster refrigeration installations, taking into account all associated costs (implementation, operation, etc.).

Published articles

Uță Iulian; Apostol Valentin; Pop Horațiu; **Pavel Constantin**; Alqaisy Saleh Jassim Saleh; Bădescu Viorel; Taban Daniel; Ioniță Claudia, „Mathematical modeling of an Evaporator by using different criterial equations”, **INMATEH-AGRICULTURAL ENGINEERING**, Vol. 67, Issue 2, Page 562-572, Published MAY-AUG 2022, Indexed 2022-11-21. Lucrarea este indexată în **BDI (Scopus)** DOI [10.35633/inmateh-67-55](https://doi.org/10.35633/inmateh-67-55) și ISI Thomson Reuters **WOS:000883607300001**, ISSN 2068-4215, eISSN 2068-2239. Conform JCI Category **AGRICULTURAL ENGINEERING** in ESCI edition, Category Rank 14/17, Category Quartile Q4.

Uță Iulian; Apostol Valentin; Pop Horațiu; Bădescu Viorel; **Pavel Constantin**; Ioniță Claudia, „Heat transfer characteristics of an evaporator equipping an air handling units for cereal seed storage facility”, **INMATEH-AGRICULTURAL ENGINEERING**, Vol. 69, Issue 1, Page 597-608, Published JAN-APR 2023, ISSN 2068-2239. Lucrarea este indexată în **BDI (Scopus)** DOI [10.35633/inmateh-69-57](https://doi.org/10.35633/inmateh-69-57) și ISI Thomson Reuters **WOS:000996501400046**, ISSN 2068-4215, eISSN 2068-2239. Conform JCI Category **AGRICULTURAL ENGINEERING** in ESCI edition, Category Rank 14/17, Category Quartile Q4.

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Vol. 70, Issue 2, Page 549-556, Published 2023. Lucrarea este indexată în [BDI \(Scopus\) DOI 10.35633/inmateh-70-53](#) și ISI Thomson Reuters [WOS:001061835600004](#), ISSN 2068-4215, eISSN 2068-2239.

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Pop Horațiu Lucian (prim autor), Apostol Valentin (coordonator), **Pavel Constantin**, Toader Melisa Gabriela, Uță Iulian, „Procese în instalațiile de condiționare a aerului”, ISBN 978-606-9608-57-9, CIP nr. 18027/03.08.2023, Editura POLITEHNICA PRESS, București, 2023, 151 pagini.

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