View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Brunel University Research Archive

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 161 (2019) 268–274

Energy Procedia

www.elsevier.com/locate/procedia

2nd International Conference on Sustainable Energy and Resource Use in Food Chains, ICSEF 2018, 17-19 October 2019, Paphos, Cyprus

Analysis of Typical Booster Configuration, Parallel-Compressor Booster Configuration and R717/R744 Cascade Refrigeration System for Food Retail Applications. Part 2: Energy Performance in Various Climate Conditions.

Konstantinos M. Tsamos[a]*, Carlos Amaris[b], Zoi Mylona[a], Savvas Tassou[a]

[a]Brunel University London, Institute of Energy Futures, RCUK Centre for Sustainable Energy use in Food chains (CSEF), Uxbridge, UB8 3PH, United Kindom
[b]University of Costa Rica, School of Chemical/Mechanical Engineering, San Pedro, CP11501, Costa Rica

Abstract

This paper compares three different natural refrigerants based system configurations in terms of cooling performance, total equivalent warming impact per year and annual power consumption for the proposed refrigeration systems. Two different cooling load levels were selected to represent a typical supermarket and a convenience store applications. The systems selected in this study include the R717/R744 cascade system configuration, a typical R744 booster configuration and a R744 parallel-compressor booster refrigeration system. The weather conditions of London, UK and Larnaca, Cyprus, were used for the modelling of energy consumption and environmental impacts to represent moderate and warm climatic conditions respectively.

© 2019 The Authors. Published by Elsevier Ltd.
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)
Selection and peer-review under responsibility of the 2nd International Conference on Sustainable Energy and Resource Use in Food Chains, ICSEF2018

Keywords: Natural refrigerants; cascade system; parallel-compression

* Corresponding author. Tel.: +44 1895 266659.
E-mail address: Konstantinos.Tsamos@brunel.ac.uk

1876-6102 © 2019 The Authors. Published by Elsevier Ltd.
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)
Selection and peer-review under responsibility of the 2nd International Conference on Sustainable Energy and Resource Use in Food Chains, ICSEF2018.
10.1016/j.egypro.2019.02.091

Nomenclature

GWP	Global Warming Potential
HT	High Temperature
LT	Low Temperature
MT	Medium Temperature
P_{ratio}	Pressure Ratio

1. Introduction

The marriage of two natural refrigerants with low and zero global warming potential number can be a very beneficial solution for food retail stores to supply both medium and low temperature levels for cooling and freezing of products.

Over the last decade, due to component availability on the market, natural refrigerants are receiving increased attention to re-establish their use into applications where previously HFCs were the preferred option. Montreal-Kyoto Protocols in the late 1990s and F-Gas regulations earlier this century describe the necessity to phase-out and eventually eliminate the usage of harmful refrigerants with high Global Warming Potential (GWP). The impact of those has led to renewed interest in natural refrigerants such as ammonia (R717), carbon dioxide (R744) and hydrocarbons (R290/R600a/R1270).

R717 carries a B2 safety classification which indicates that it is a toxic refrigerant with a medium flammability risk [1]. The high toxicity of R717 places some restrictions on where it can be applied in terms of safety. A low-charge R717 system located far away from sales area into a plant room can guarantee safety and overcome the main barrier for this application, its toxicity. Ammonia can be used with R744 in a cascade system where ammonia is employed in the system to condense R744 into a liquid, which is the only refrigerant channeled to the cooling and freezing areas of a supermarket. In addition to the safely aspect, this ensures the subcritical operation of the R744 system all year round even in warm climates and could potentially lead to lower power consumption of the system and reduction of the indirect emissions.

Rezayan and Behbahaninia [2] investigated the thermo-economic optimisation for the R717/R744 cascade refrigeration cycle. The authors proposed method included the thermal and economical aspects of the system design and operation. Based on the proposed design and operation of the system and for a constant cooling capacity of 40 kW the annual cost reduction of the system was equal to 9.34% compared with the base case design. Messineo [3] compared the R744/R717 cascade system with a R404A two-stage system based on similar operating conditions. The author reported the overall COP for different condensing temperatures, degrees of sub-cooling and evaporating temperatures. The experimental analysis of a R717/R744 cascade system for supermarket refrigeration applications has been presented by Sawalha [4]. The R744 refrigerant used to cool-down the LT and MT where a DX and flooded coil were used respectively. Sawalha concluded that the performance for the R717/R744 cascade solution was 50 to 60 % higher than that of a direct R404A system installed in the same laboratory environment. In most of published works, the analysis involved only cascade refrigeration systems where the low stage circuit fed only low temperature evaporators [5, 6, 7, 8].

This paper compares three different natural refrigerants based system configurations in terms of cooling performance, total equivalent warming impact per year and annual power consumption. The systems selected in this study include the R717/R744 cascade system configuration, a typical R744 booster configuration and a R744 parallel-compressor booster refrigeration system. First and second law thermodynamic analysis has been previously discussed in Part 1 of this work. The weather conditions of London, UK and Larnaca, Cyprus, were used for the modelling of energy consumption and environmental impacts to represent moderate and warm climatic conditions respectively. Continuing from the previous work, the simulation models of the proposed refrigeration systems will be used to investigate different sizes of food retail applications including supermarket and convenience store with different cooling loads.

2. Description of the systems

The R717/744 cascade refrigeration system consists mainly of two loops: the upper-side loop fed with R717 and a lower-side loop with R744 as working fluid. Both sides are exchanging heat through the cascade heat exchanger, which operates as an evaporator for the R717 side and condenser for the R744 side. The cascade system solution guarantees a subcritical operation all year round for the R744 system and higher performance when this is used in warm climate applications. Additionally, the high-pressure R744 expansion valve is no longer required due to the low condensation temperature of the R744. The upper-side loop consists of an R717 screw compressor, an air-cooled condenser, an expansion valve, and the upper side of the cascade heat exchanger (evaporator). The R744 low-side consists of a liquid receiver, and direct expansion (DX) medium temperature (MT) and low temperature (LT) evaporators. Double stage compression is employed to serve both LT and MT loads of the system. A heat exchanger (HX) is used for sub-cooling the R744 flow before entering the LT expansion valve and to ensure superheated vapour at the suction line of the low-pressure compressor.

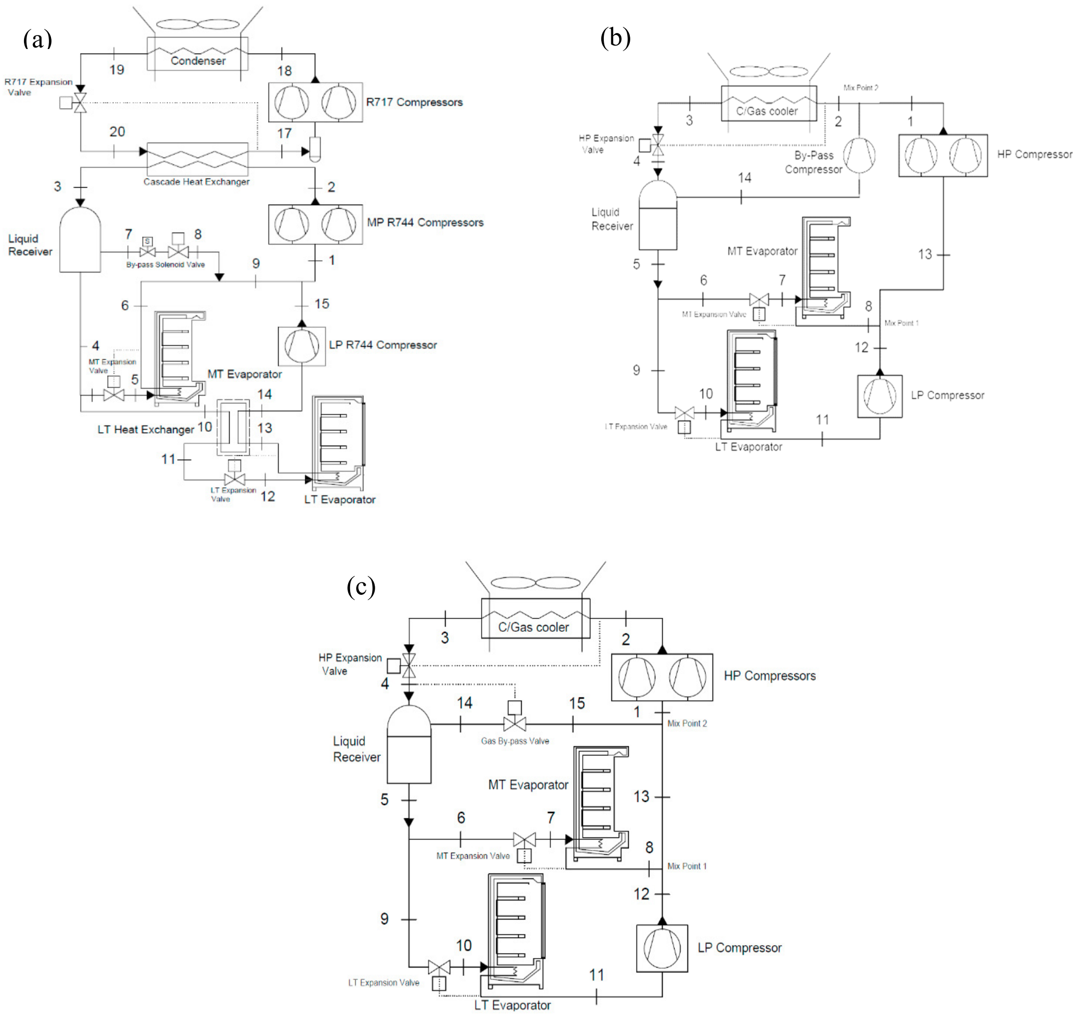

Fig. 1. Schematic diagram of (a) Cascade System, (b) Parallel-Compressor Booster System, and (c) Booster System.

The diagram of a R744 parallel-compressor booster refrigeration system is presented in Fig. 1b. As in the previous system, the parallel-compressor booster system can also operate in both subcritical and trans-critical modes depending on the ambient temperature. Fig. 1b shows that the main difference of this present system with respect to the typical booster system, Fig 1c, is the use of a by-pass compressor instead of the by-pass valve. In this case, the discharge of the compressor is located at the mix point 2 where the refrigerant mixes with the flow coming from the HP compressor.

For this configuration, the pressure is also controlled by the HP expansion valve and the variable speed fan of the gas cooler/condenser. The refrigerant from the LT evaporator outlet is drawn into the first stage low-stage compressor suction line. The discharge from the LP compressor mixes with the outlet of the MT evaporator, point 1.

Before the mixed refrigerant enters the suction line of the high-temperature stage compressors and compressed to gas cooler/condenser pressure, it is mixed with the gas by-pass refrigerant from the R744 liquid receiver. At that stage, the pressure is controlled by the HP expansion valve and the variable speed fan of the gas cooler/condenser. The most common disadvantage of this system is the reduction of COP due to the higher quantities of flash gas by-pass and the higher pressures, which lead to higher electrical power consumptions. Figure 1c illustrates a typical booster refrigeration system to serve both MT and LT by implementing a double stage compression between low-to-medium and medium-to-high pressure levels. The system has previously presented by Tsamos et al [9].

3. Thermodynamic Models

In order to assess the performance of the three selected systems data from a typical European supermarket and typical convenience store were used. For the case of the supermarket the refrigeration capacity was assumed to be 100 kW MT and 25 kW LT. The power consumption of the MT and LT evaporator fans, lights and defrost were set to 14 kW, while the condenser or gas cooler fan power consumption was set to 5 kW. The convenience store cooling capacity was assumed equal to 25 kW and 5 kW of MT and LT respectively. For this study the MT and LT evaporator fans, lights and defrost were set to 4.5 kW, while the condenser or gas cooler fan power consumption was set to 1.5 kW.

The MT evaporating temperature was assumed to be -10 °C and for the case of LT application equal to -32 °C. For both temperature levels superheating at the outlet of the evaporators assumed 7 K. For the proposed cascade R717/R744 configuration the temperature difference across the cascade heat exchanger is 5 K. The LT heat exchanger effectiveness is 0.4.

In the case of cascade configuration, the global efficiency of the R717 compressor was estimated employing correlation (5) as presented by Lee et al. [10]. For the low side of the cascade system and all R744 configurations the global compressor efficiency was calculated by using correlation (6) as presented by Lee et al. [10]. The control strategies for the high pressure side, including pressure control of the condenser/gas cooler for all only CO_2 configurations were derived from experimental test results as well as the transition temperature between subcritical and transcritical operation [9].

In addition, all valves in the systems were treated as isenthalpic devices in the simulations. The pressure drop across the condenser/gas cooler and evaporators were found to be small compared to the high pressures in the system and was not included in the simulations [11]. Each refrigeration system was simulated performing mass and energy balances on each one of the components of the whole system.

The thermodynamic analysis of each system was conducted assuming that the refrigeration system operates under steady-state conditions, and kinetic and potential energy through the system components are negligible.

$$\eta_{comp,R717} = -0.00097{P_{ratio}}^2 - 0.01026P_{ratio} + 0.83955 \quad (1)$$

$$\eta_{comp,R744} = -0.00476{P_{ratio}}^2 - 0.09238P_{ratio} + 0.89810 \quad (2)$$

4. Climate Conditions

The weather conditions for London, UK considered as moderate conditions, and Larnaca, Cyprus, considered as warm, were used for the modelling of the three different configurations. The ambient temperature variations for these locations were obtained from EnergyPlus software [12]. Weather files were derived from EnergyPlus weather files converted from .epw files to .csv files. Files for both locations are IWEC (International Weather Files for Energy Calculations) data files by ASHRAE, which are 'typical' weather files. The files are derived from up to 18 years of hourly weather data supplemented by solar radiation estimated on an hourly basis from earth-sun geometry and hourly weather elements, particularly cloud amount information.

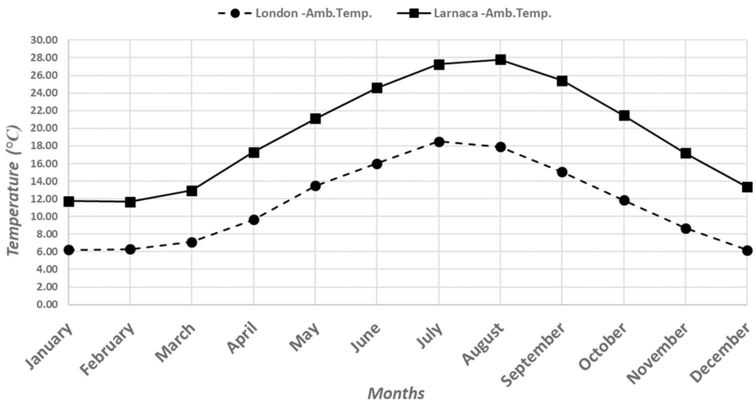

Fig. 2. Monthly mean temperatures for London, UK and Larnaca, Cyprus

5. Results and Discussion

Equation 3 was used to determine the COP of the three different configurations for comparison purposes. These results are presented and discussed in 'Part 1: Thermodynamic analysis 'of this work.

$$COP = \frac{Q_{MT}+Q_{LT}}{W_{com,HT}+W_{com,LT}+W_{MT,fans}+W_{LT,fans}+W_{\frac{C}{GC},fans}} \quad (3)$$

This part of the work is dealing with annual power consumption and total equivalent warming impact for the proposed refrigeration systems. Two different cooling load levels were selected to represent a typical supermarket and convenience store applications as discussed previously.

Table 1. Annual Energy Consumption, Medium supermarket application.

London – UK (MWh)		
R744 Booster	R744 Booster parallel-comp.	R717/R744 Cascade
565	477	520
Larnaca, Cyprus (MWh)		
R744 Booster	R744 Booster parallel-comp	R717/R744 Cascade
696	620	565

The energy consumption of the three different configurations for London and Larnaca for the case of medium supermarket application is shown in Table 1. It can be seen that R744 booster refrigeration system with parallel-compressor solution has the lowest annual energy consumption for the investigated climate condition of London. On the other hand, in case of Larnaca with higher ambient temperatures the proposed R717/R744 cascade system shows lower annual energy consumption compared to the all-R744 refrigeration systems.

Due to the lower cooling capacities required, the overall size of the system and other system restriction in case of convenience store the R744 booster with parallel-compressor configuration is showing lower annual energy consumption for both climate conditions as presented in Table 2.

Table 2. Annual Energy Consumption, Convenience store application.

London – UK (MWh)		
R744 Booster	R744 Booster parallel-comp.	R717/R744 Cascade
130	121	154
Larnaca, Cyprus (MWh)		
R744 Booster	R744 Booster parallel-comp.	R717/R744 Cascade
157	142	162

Table 3 illustrates the results of the TEWI calculations for the three system configurations, two climate conditions and two different size applications. The environmental impacts of a refrigeration system can be determined as the sum of direct and indirect GHG emissions as presented by Tsamos et al. [9]. For R717, the GWP is equal to 0 which eliminates the direct emissions. The GWP for R744 is 1. The annual leakage rate was assumed to be 15%. The operating lifetime of the system is 10 years. For all-R744 configurations the refrigerant charge was assumed to be 1.2 kg/kW. For low side of cascade system, the R744 refrigerant charge is 1 kg/kW. The indirect emissions factor was taken 0.51 kgCO2/kWh for London and 0.77 $kgCO_2/kWh$ for Larnaca.

Table 3. TEWI emissions

Refrigeration Systems	Medium Supermarket ($tones CO_2$)		Convenience Store ($tones CO_2$)	
	London	Larnaca	London	Larnaca
R744 booster	2882	5358	665	1212
R744 booster parallel-comp.	2427	4771	572	1090
R717/R744 Cascade	2650	4350	785	1245

From the energy consumption results in Tables 1 and 2, it can be seen that R744 booster with parallel-compressor has the lowest life cycle TEWI. On the other hand, due to higher ambient temperature all year round in the case of Larnaca the R717/R744 cascade system shows lower TEWI for the supermarket application. For the convenience store at both ambient conditions, the R744 with parallel-compressor has the lowest TEWI emissions, arising primarily from the lowest energy consumption.

6. Conclusions

In this paper, comparative studies of three different natural refrigerant based commercial refrigeration system configurations are reportedd. The evaluation was carried out for moderate and warm weather conditions and varying ambient temperatures. The weather conditions of London and Larnaca were used to represent the moderate and warm respectively. In addition, two different cooling load levels were selected to represent a typical supermarket and convenience store applications in terms of cooling load requirements. The following conclusions can be drawn from the study.

- From all three investigated system configurations, the R744 booster refrigeration system with parallel compressor was found to have the lowest annual energy consumption in the case of London for medium supermarket application. The energy consumption reduction was found to be in the region of 8.4% and 8.6% compared to typical R744 booster and R717/R744 cascade systems respectively.
- In the case of warm climate conditions of Larnaca, the R717/R744 cascade system was found to have the lowest annual energy consumptions over the other two systems due to transcritical operation for the medium supermarket application. The cascade system was found to have 11.6% and 9.2% lower energy consumption comparing to the typical R744 booster and R744 booster with parallel-compressor.
- From the alternative system configurations, the R744 booster system with parallel-compressor was found to have the lowest energy consumption for both moderate and warm climate conditions for the case of convenience store applications. In the case of London this system showed 16.6% and 15% less energy consumption compared to R717/R744 cascade and typical R744 booster system respectively. In case of the warm climate of Larnaca, this was found to be 2.7% and 10.6% respectively.

Acknowledgement

This study was supported by the Research Councils UK Energy programme, Grant No: EP/K011820/1. The authors wish to acknowledge the support received from Brunel University London and the RCUK National Centre for Sustainable Energy use in Food Chains (CSEF). All data used for the analysis can be found in the paper. Further information and data if needed can be obtained from the corresponding author.

References

[1] BS EN 378-1:2016, Refrigerating systems and heat pump. Safety and environmental requirements. Basic requirements, definitions, classifications and selection criteria. British Standards, December 2016.

[2] Rezayan A., Behbahaninia A. “Thermoeconomic optimization and exergy analysis of CO2/NH3 cascade refrigeration systems.” Energy 36 (2011): 885-895.

[3] Messineo A. “R744-R717 Cascade Refrigeration System: Performance Evaluation compared with a HFC Two-Stage System.” Energy Procedia 14 (2012): 56-65.

[4] Sawalha S. “Theoretical evaluation of trans-critical CO2 systems in supermarket refrigeration. Part I: Modelling, simulation and optimization of two system solutions.” International Journal of Refrigeration 31 (2008): 516-524.

[5] Mosaffa A.H., Garousi Farshi L., Ferreira C.A., Rosen M.A. “Exergoeconomic and environmental analyses of CO2/NH3 cascade refrigeration systems equipped with different types of flash tank intercoolers.” Energy Conversion and Management 117 (2016): 442-453.

[6] Sun Z., Liang Y., Liu S., Ji W., Zang R., Liang R., Guo Z. “Comparative analysis of thermodynamic performance of a cascade refrigeration system for refrigerant couples R41/R404A and R23/R404A.” Applied Energy 184 (2016): 19–25.

[7] Nasruddin N., Sholahudin S., Giannetti N., Arnas. “Optimization of a cascade refrigeration system using refrigerant C3H8 in high temperature circuits (HTC) and a mixture of C2H6/CO2 in low temperature circuits (LTC).” Applied Thermal Engineering 104 (2016): 96-103.

[8] Kilicarslan A., Hosoz M. “Energy and irreversibility analysis of a cascade refrigeration system for various refrigerant couples.” Energy Conversion and Management 51 (2010): 2947–2954.

[9] Tsamos K.M., Ge Y.T., Santosa ID.M.C., Tassou S.A., Bianchi G., Mylona Z. “Energy analysis of alternative refrigeration system configurations for retail food applications in moderate and warm climates.” Energy Conversion and Management 150 (2017): 822-829.

[10]. Lee T.S, Liu C.H., Chen T.W. “Thermodynamic analysis of optimal condensing temperature of cascade refrigeration systems.” International Journal of Refrigeration 29 (2006): 1100 - 1108.

[11] Tsamos K.M., Ge Y.T., Santosa ID.M.C., Tassou S.A. Experimental investigation of gas cooler/condenser designs and effects on a CO2 booster system, Applied Energy 186 (2017) 470-479.

[12] EnergyPlus, Engineering Reference. The Reference EnergyPlus Calculations, (2018). https://energyplus.net/weather