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Advanced exergy analysis of a R744 booster refrigeration system with parallel compression

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ABSTRACT

In this paper, the advanced exergy analysis was applied to a R744 booster refrigeration system with parallel compression taking into account the design external temperatures of 25 °C and 35 °C, as well as the operating conditions of a conventional European supermarket. The global efficiencies of all the chosen compressors were extrapolated from some manufactures' data and appropriated optimization procedures of the performance of the investigated solution were implemented.

According to the results associated with the conventional exergy evaluation, the gas cooler/condenser, the HS (high stage) compressor and the MT (medium temperature) display cabinet exhibited the highest enhancement potential. The further splitting of their corresponding exergy destruction rates into their different parts and the following assessment of the interactions among the components allowed figuring out the real achievable improvements. The avoidable irreversibilities of the HS compressor and that of the MT evaporator were mainly and completely endogenous, respectively. On the other hand, the gas cooler/condenser could be predominantly improved by decreasing the inefficiencies of the MT evaporator. As regards the auxiliary compressor, large enhancements were attainable through the drop in the irreversibilities occurring in the remaining components.

1. Introduction

The raising awareness of the environmental preservation and the strict regulation adopted in Europe on the subject of refrigeration have been promoting the use of natural refrigerants and synthetic working fluids with low GWP (Global Warming Potential) in all the sectors. Commercial refrigeration features both high energy consumption, which is accountable for the indirect production of environmentally harmful gases, and large working fluid leakages into the atmosphere, which directly contribute to the global warming effect. Carbon dioxide (R744) is a natural refrigerant which can almost completely work out the issue associated with the direct emissions. Furthermore, it is inexpensive, non-toxic, non-flammable and has good thermo-physical characteristics. Thanks to its great performance in cold climate locations, CO_2 is capable of outperforming high GWP refrigerants as well as of reducing greenhouse gases emissions significantly. On the other hand, the performance of R744 is more depending on the heat sink temperature than in the case of the other working fluids due to its low critical temperature (30.98 °C). The latter causes the occurrence of transcritical operations and consequently large temperature lifts, which penalise the CO_2 machines efficiency considerably with rise in cooling medium temperature. As shown by Cavallini and Zilio [4], in these running modes an optimal heat rejection pressure, which maximizes the COP (Coefficient of Performance), has to be identified as a function of the gas cooler exit temperature.

A large number of researchers have focused on the evaluation of the most suitable configuration for being adopted in warm climates in order to achieve similar consumption to the one exhibited by the systems using conventional refrigerants. The advanced exergy analysis represents one of the most appropriate design tools and, to this end, its application to a CO_2 refrigeration system operating at high outdoor temperatures could be significantly helpful. Such type of evaluation allows identifying, locating and quantifying the irreversibilities occurring in the system under investigation. It can further evaluate the irreversibilities occurring in an individual component and the ones due to the interactions among the components.

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Nomenclature

COP	Coefficient of Performance
$\dot{E}$	Exergy rate [kW]
e	Exergy per unit of mass [$kJ \cdot kg^{-1}$]
GWP	Global Warming Potential [$kg_{CO_2} \cdot kg^{-1}_{refrigerant}$]
h	Enthalpy per unit of mass [$kJ \cdot kg^{-1}$]
$\dot{m}$	Mass flow rate [$kg \cdot s^{-1}$]
p	Pressure [bar]
s	Entropy per unit of mass [$kJ \cdot kg^{-1} \cdot K^{-1}$]
t	Temperature [°C]
y^*	Exergy destruction rate

Abbreviations

AUX	Auxiliary compressor
compr	Compressor
EES	Engineering Equation Solver
evap	Evaporator
exp	Expansion valve
GC	Air cooled gas cooler/condenser
HP	High pressure
HS	High stage
LS	Low stage
LT	Low temperature
MT	Medium temperature
VB	Vapour by-pass

Greek symbols

Δ	Difference
η	Efficiency
χ	Flash gas mass flow rate drawn by the auxiliary compressor [$kg \cdot s^{-1}$]

Subscripts and superscripts

appr	Approach
aux	Auxiliary compressor
AV	Avoidable
compr	Compressor
D	Destruction
el	Electrical
EN	Endogenous
evap	Evaporator
EX	Exogenous
exp	Expansion valve
ext	External
gc	Air cooled gas cooler/condenser
glob	Global
HP	High pressure
HS	High stage
int	Intermediate
isen	Isentropic
k	*k-th* component of the system
L	Loss
LT	Low temperature
MT	Medium temperature
MX	Mexogenous
out	Outlet
PH	Physical
pp	Pinch point
r	*r-th* component of the system
tot	Total
UN	Unavoidable

The adoption of an auxiliary compressor allows enhancing the performance of a R744 conventional system markedly, as proved by Gullo et al. [12], Gullo et al. [13], Polzot et al. [20], Minetto et al. [15] and Bell [2]. From the thermodynamic point of view, the parallel compression enables achieving a remarkable drop in the exergy destruction rate associated with the throttling valve located upstream of the liquid receiver [13]. Such component is characterized by the highest irreversibilities in a R744 transcritical refrigeration system [10]. Besides proving the good effectiveness of the configuration with the auxiliary compressor, Sarkar and Agrawal [21] demonstrated that the performance of the whole system is influenced by the intermediate pressure which, in turn, is affected by the value of the evaporating temperature. The existence of an optimal intermediate pressure was also proved by Bell [2], Minetto et al. [15] and Chiarello et al. [6]. On the other hand, the vapour mass flow rate (χ) compressed by means of the auxiliary compressor is an additional independent variable for the optimization procedure of such system [12].

In this paper, the intermediate pressure and χ were optimized for both the conventional exergy analysis and the advanced one.

The implementation of the advanced exergy analysis to a refrigeration system was carried out by Morosuk et al. [17] to evaluate the potential improvements reachable by a Voorhees refrigerating machine. As a main result, the authors underlined that the enhancement of the system can be accomplished by reducing the inefficiencies taking place in the evaporator.

Chen et al. [5] fulfilled a conventional and an advanced exergy analysis of an ejector refrigeration system. The authors showed that the ejector itself is accountable for more than 50% of the irreversibilities occurring in the system. Furthermore, a drop in the condenser temperature difference would lead to a decrement in the inefficiencies of the heat exchanger itself and to those of the overall system.

Gungor et al. [14] investigated the unavoidable and avoidable irreversibilities associated with the components of a gas engine heat pump. Erbay and Hepbasli [7] demonstrated that the performance enhancement of a ground-source heat pump drying system can be attained through the improvement of the condenser. Açikkalp et al. [1] suggested paying close attention to the turbo air compressor of a trigeneration solution.

The aim of this paper is to evaluate the possible thermodynamic improvements that a R744 booster supermarket refrigeration system with parallel compression can accomplish by employing the advanced exergy analysis. To the best of the authors' knowledge, such evaluation has never applied to any transcritical CO_2 refrigeration systems. The description of the system under consideration and the most important notions of both the conventional exergy analysis and the advanced one are given in Section 2. The main outcomes are then summed up and discussed in Section 3 and in Section 4, respectively. The conclusion are thus provided in Section 5.

2. Methodology

2.1. System description

The R744 booster refrigeration system investigated in this study is schematized in Fig. 1. This configuration serves both the chilled food cabinets and the frozen food counters simultaneously since it