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Research Paper

Novel integrated CO_2 vapour compression racks for supermarkets. Thermodynamic analysis of possible system configurations and influence of operational conditions

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HIGHLIGHTS

- Parallel compression can be effective at ambient temperatures as low as 15 °C.
- Dedicated ejectors for integrated AC are interesting at high temperatures.
- A pivoting suction system increases the flexibility of standardised racks.
- A novel winter-operation configuration could be used at least up to −10 °C.

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ABSTRACT

An increasing number of supermarket chains are opting for the utilisation of centralised carbon dioxide refrigeration systems. However, the need to improve their efficiency in order to make them economically and environmentally sustainable worldwide becomes ever more important. One of the most common approaches is to integrate all the energy demands (cooling, air conditioning, heating, domestic hot water) into the same unit. In addition, operation at high ambient temperatures can be made more energy-efficient with the use of parallel compression and ejectors for expansion work recovery.

This paper describes the new proposals for the system architecture of integrated transcritical CO_2 refrigeration installations. A sample system with parallel compression with multiple ejectors has been modelled numerically. The results prove the decrease in the overall power consumption of the system when using parallel compression compared to a standard booster system (reduction of 19% at 30 °C). The use of one group or two groups of ejectors allow the power consumption to be further diminished (around 5% and 8%, respectively). With the appropriate operating conditions (e.g. discharge pressure, liquid receiver pressure) and an optimized design of the air conditioning and cooling systems (which allows the evaporation pressure to be increased) an important reduction in power consumption can be achieved (for example greater than 7% when the evaporation pressure of the medium-temperature cabinets increases from 28 bar to 32 bar). In addition, the simulations allowed the comparison of three separate modes proposed for low-ambient-temperature conditions (temperatures close to or lower than 0 °C), which are challenging for current carbon dioxide refrigeration systems.

1. Introduction

The reintroduction of CO_2 (R744) in supermarket refrigeration is a fact today and will have a major impact on the environmental footprint of this sector. The works of Lorentzen [1] triggered, particularly in Northern Europe, the use of this refrigerant by food retailers [2]. Nevertheless, the development of cost- and energy-efficient units able to operate in all regions and for all climates constitutes a remarkable challenge.

Abbreviations: AC, air conditioning; CB, conventional booster; EJ_{AC}, AC multi-ejector; EJ_{MT}, MT multiejector; EVAP, evaporator; FGV, flash gas bypass valve; HPV, high pressure valve; HVAC, heating, ventilation and air conditioning; IESPC, integrated ejector supported parallel compression; IHX, internal heat exchanger; LT, low temperature; MOPD, maximum operation pressure difference; MT, medium temperature; PC, parallel compression; S, system; VSD, variable-speed drive; WM, winter mode; WMV, winter mode valve.

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The concept of integrated R744 vapour compression units for supermarkets is relatively new (2010 onwards). The principal idea is to meet with a single unit the needs of refrigeration at the temperature levels specific for supermarkets, as well as the heating, ventilation and air conditioning (HVAC) and hot water demands. Integrated units are normally tailor-made installations, designed specifically according to the individual requirements for a given store. There are a few examples of the successful application of such systems. The first installation was developed in the EnOB project, involving Aldi Süd in Germany in cooperation with the Fraunhofer Institute for Solar Energy Systems, which introduced a monovalent and geothermally supported R744 compressor rack [3]. The system provided commercial cooling for the chiller cabinets and freezers in the sales area and for the cold stores in the storage area, as well as space heating or cooling and pre-heating and pre-cooling for the ventilation system. Thus, neither separate heat generators nor an air conditioning (AC) system were required. The target of the EnOB project was to reduce the primary energy consumption by up to 29%, although the actual reduction reached 20% shortly after its implementation. Another example is the unit that resulted from the CREATIV project, developed by SINTEF, the Research Council of Norway and REMA 1000, and described in Hafner et al. [4]. The refrigeration system was utilised as a heat pump in the winter season and provided cooling for the air handling unit in the summer season. The surplus heat from the refrigeration system was applied for heating different areas of the supermarket or stored both in water tanks and in the ground (energy wells). The active integration of the energy wells allowed free cooling and the meeting of different heating and cooling demands with low energy consumption. This concept of the integrated unit led to annual energy saving of 30% compared to similar supermarkets in the area.

Neither of the previously mentioned examples comprised the use of ejectors for expansion work recovery. There are several works in the literature that showed that these devices improve the performance of transcritical CO_2 refrigeration systems [5–9]. The concept of ejectors in CO_2 vapour compression systems for supermarkets, particularly for hot and warm climates, was proposed by Hafner et al. [10]. They replaced the ordinary expansion valves and enabled the recovery of up to 30–35% of the total expansion work [11]. With respect to the use of fixed geometry ejectors in such systems, the main challenge, which is to achieve a smooth control to adapt to the existing load and ambient conditions, was handled by the use of multiejector blocks, i.e. bunches of separate ejector geometries working in parallel. Multiejector blocks are step-wise controlled multiple ejectors with different ejector geometries (different cross sections in the motive nozzles) that can be enabled and combined as a function of the existing requirements [10].

There are a number of recent examples of ejector-supported parallel compression units for supermarkets. The first commercial (though of prototype-design) application of a prototype of a multiple-ejector system was carried out in the MIGROS Supermarket in Bulle in Switzerland in 2013 for a conventional, non-integrated CO_2 compressor rack [12]. On-site test campaigns proved that it is possible to raise the medium-temperature (MT) evaporation conditions from −8 °C to −2 °C with flooded evaporator operation and liquid ejectors. Liquid ejectors pump the liquid that accumulates at a liquid separator downstream of the evaporators, reducing the risk of liquid at the suction of the compressors. The increase of the evaporation temperature allows the power consumption of the compressors to be reduced. Both laboratory and field tests revealed that liquid ejectors at subcritical conditions are able to return the liquid refrigerant from the liquid separator back to the liquid receiver. Fredslund et al. [13] analysed experimentally the energy consumption of different installations (with and without AC load), with and without multiejectors and with flooded or direct expansion evaporators. The authors observed that energy savings of 4% (at 27 °C ambient temperature) were achieved in real supermarkets without AC load due to the use of the multiejectors. These values increased up to 15% (at 30 °C ambient temperature) in supermarkets with AC load. The authors stated that it is crucial to design compressor packs that match the load, as well as to reduce and adapt the required pressure lift of ejectors (difference between the pressure at the liquid receiver and at the MT evaporators) in order to maintain smooth operation throughout the year.

In order to design, manufacture and safely operate an integrated supermarket installation equipped with multiple ejectors, a number of technical challenges must be tackled. All the installations commissioned so far were dimensioned for given, individual load conditions and geographical location of the shops. Thus, no standardisation (and consecutive reduction of capital costs) has been reached to date. Therefore, new knowledge that could invoke the technological development and lower investment costs of integrated CO_2 vapour compression units for supermarkets is required. SuperSmart-Rack project (Research Council of Norway No. 244009/E20) aims to contribute in this line of research both from numerical and experimental points of view, focusing on the environmental conditions existing in Norway.

This paper introduces several innovative features to be applied in CO_2 transcritical commercial refrigeration units, such as:

- Integration of an ejector supported air conditioning suction group.
- Control strategies for the control of the pressure level at the gas coolers with ejector blocks working in parallel but with different functions (suction from the MT pressure level and air conditioning from an elevated pressure level).
- Pivoting the suction port of compressors from the base group to the parallel group and vice versa.
- Increase of the evaporation temperature in refrigeration cabinets due to the operation under flooded conditions.
- Special configuration for efficient operation with low-temperature environmental conditions, or winter mode.

The energy performance of the novel solutions, solutions that are just emerging on the market as well as the solutions that have been well established in commercial refrigeration were modelled numerically in the Dymola-Modelica environment. The layout of the developed numerical model replicates the facility newly installed at the SINTEF/NTNU laboratory that will serve to experimentally verify the numerical findings in the nearest future. Multiple steady-state simulations were performed for different possible system configurations and in changeable operating condition considering maximum loads of a typical medium-sized supermarket in Norway.

2. General system architecture

2.1. Functional requirements

The concept of an R744 integrated ejector supported parallel compression (IESPC) refrigeration unit is an alternative solution for the less environmentally friendly installations that use individual systems to meet the different loads of supermarkets, normally operating with HFCs or using boilers. The approach is to employ a single unit to meet the demands of the shop, including cooling at medium temperature (MT) and low temperature (LT) for the different cabinets, as well as providing heating or air conditioning, if requested.