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Conclusion

Stricter laws and regulations to reduce ozone depletion and global warming, as well as a growing environmental awareness, have revolutionized the generation and utilization of energy. Supermarkets have been significantly affected by these harsher measures, demanding a major reassessment of the energy consumed in cooling applications [18].

As a consequence of environmental legislations, in certain countries, HFC refrigerants such as R404A, which have been extensively applied in modern supermarket refrigeration systems, must be gradually phased out for their high global warming potential. In addition, the replacement of these refrigerants by more environmental friendly and safe fluids has to take into consideration the energy efficiency and the performance of the cooling system. Hence, the selection of an appropriate working fluid is one of the most discussed topics in commercial refrigeration, since environmental characteristics must be balanced out with favourable thermodynamic properties and safety conditions [190].

When assessing the environmental impact, however, it is important to account not only for refrigerant selection, but also for the architecture of the cooling system. In fact, for commercial refrigeration, considering the relatively high level of direct and indirect refrigerant emissions, changes in design and technology can reflect in significant reductions of the environmental impact [191]. The development of new high-performance, environmental friendly commercial refrigeration solutions, thus, requires that simultaneous attention is given to the working fluid and to the system configuration.

In that sense, many authors compared supermarket refrigeration solutions to the typical supermarket direct expansion (DX) cycle [37]. However, as most of those studies were carried out between systems in real field installations, in which case a number of operating parameters and system requirements are not identical or optimized, it is hard to draw accurate conclusions [37]. Taking that into consideration, a simulation model can be regarded as a valuable design tool for a first comparison of different supermarket refrigeration technologies.

In the first part of this work, thermodynamic models for the pumped CO_2

and the CO_2 booster refrigeration cycles were developed, in order to evaluate and compare their performance to that of a typical DX system. These CO_2-based technologies were selected for investigation for their great contribution in reducting carbon dioxide emissions [41], mainly as a consequence of the environmental-friendly aspect of the CO_2 refrigerant (zero ODP, negligible direct GWP and favourable thermophysical properties [69]).

The secondary coolant technology employing the CO_2 fluid as a two-phase secondary refrigerant has gained increased interest for showing some advantages over conventional single-phase secondary fluid systems, such as lower pumping power, smaller pipe sizes and superior heat transfer properties [77]. Other benefits provided by the pumped CO_2 solution include short supply and return lines, reduced charge and leakage rate, decreased system maintenance, and improved product quality [23, 41].

Comparing the performance of pumped CO_2 and DX systems, both operating with refrigerant R404A in the primary cycle, one can observe, based on the results of the present work, that the energy consumption of the conventional supermarket system is always inferior to that of the alternative CO_2 technology. In warmer geographic locations, the difference was the smallest, with the pumped CO_2 system utilizing about 11% more energy than the DX installation in Rio de Janeiro (Brazil). In contrast, in climate conditions of Stockholm (Sweden), the power consumption of the secondary coolant solution was 19% higher than that of the traditional system. Considering the pumped CO_2 refrigeration system with R407F as the primary refrigerant, energy consumption in Rio de Janeiro and Stockholm is above that of the R404A DX by 5 and 15%, respectively.

Recommendations for future studies include an investigation on the impact of the distribution piping network on system operation, which could be the cause of the conflicting predicted results and field data reported by some authors [41]. Additionally, the effects of the significantly smaller line sizes associated with using CO_2 both as a secondary coolant and, in the future, as a direct expansion refrigeration, also require further examination [41]. Moreover, investigation of good desing practices is, also, key to take full advantage of the benefits of the pumped CO_2 system [23].

The CO_2 booster technology has emerged as a promising candidate for implementation in supermarket refrigeration due to its negligible direct environmental impact, reduction of indirect carbon dioxide equivalent emissions, and potential for heat recovery applications. Other advantages of the system include simpler and cheaper design, with only one fluid and one circuit [69].

Such benefits, though, come at the cost of higher power consumption. It has been demonstrated, in this study, that the total annual energy consumption of the CO_2 booster system is always higher than that of a typical R404A cycle. In geographic locations with long periods of high ambient temperatures, like Rio de Janeiro, the energy consumption of the CO_2 booster system was 47% higher than that of the R404A DX installation. On the other hand, the alternative technology performed significantly better in colder climates, with the annual consumption in Stockholm only 13% above that of the direct expansion installation.

The higher number of hours during the year in which the booster operates in subcritical mode is the main reason for its improved performance in colder regions [69]. Therefore, strategies involving high-side refrigerant pressure optimization, specific compressor selection and enhanced system design require further research. Investigation of advanced heat recovery applications for the CO_2 booster technology could, also, greatly improve its operating performance, specially in warmer climate conditions, where the system is far from competitive, energy-wise.

Regarding both thermodynamic models developed, an essential improvement would be to acquire experimental or field data for further validation of the tools. As previously mentioned, the novel aspect of the design practices still limits the amount of available data in the literature, though such condition seems to be changing, as the number of field installations of with new technologies has been increasing rapidly [41]. The comparison with performance results from other commercial refrigeration technologies, as, for example, the NH_3/CO_2 cascade refrigeration system, is encouraged as well.

Furthermore, enhancements to both the pumped CO_2 and CO_2 booster simulation model builts should also be pursued. Hyphoteses like adiabatic compression and no heat losses in the heat exchangers could be revised, as well as the efficiency-based model employed for the compression devices. The simple temperature difference description utilized to model the heat transfer in the connecting lines also requires improvement. In the specific case of the pumped CO_2 model input data, a constant compressor isentropic efficiency was employed for all refrigerants simulated, which is an approximation that should be improved if a more complex and realistic model is desired.

The second part of the study consisted in the development of a lumped parameter model to simulate the steady-state operation of a typical supermarket DX system. A component-based solution scheme was considered, which allowed for the inclusion of multi-compressor and multi-evaporator packs to the simulation tool. The heat exchangers modeling followed the previous work of the Oak Ridge National Laboratory (ORNL) [89], which modeled air-source condensers and evaporators employing the multizone approach. The ORNL models were improved by means of updated correlations for heat transfer coefficient, pressure drop and refrigerant inventory, with different tube internal surfaces and fin patterns also included.

A life cycle climate performance (LCCP) analysis, employing low-GWP potential replacements for R404A was, then, performed, in order to evaluate the best candidate in regards to the environmental impact. Results obtained, based on a supermaket case study [34], indicated that the LCCP of the multi-compressor multi-evaporator DX refrigeration system was 19% lower when HDR21 was used as drop-in replacement for R404A. Percentual reductions in LCCP were slightly smaller for the other refrigerants, with 17 and 18% calculated for R407F and HDR81, respectively. Since predicted LCCP values within 10% of each other represent, according to the IPCC [186], the same environmental warming impact, the three low-GWP simulated can be considered to perform equally when replacing R404A in traditional multiplex DX systems.

An obvious suggestion for future work would be to further improve the lumped parameter model. There is clear demand to increase the level of detail of component models, specially for the heat exchangers. Another important development would be to enable the simulation of evaporators operating in different temperature levels, as to reflect more realistically a typical supermarket DX system. The modeling approach employed throughout this second part of the study could also be extended to other cooling system configurations. The component models could be utilized to develop, for instance, lumped parameter models for the pumped CO_2 and the CO_2 booster systems, among other alternative technologies.