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A study on carbon dioxide cycle architectures for light-commercial refrigeration systems

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ABSTRACT

In this study four refrigeration cycles were experimentally investigated in an attempt to enhance the thermodynamic performance of CO_2-based transcritical refrigeration systems under high ambient temperatures. The cycle architectures studied were: i) capillary tube, ii) expansion valve, iii) dual-stage expansion and iv) flash gas chamber. It was found that the coefficient of performance values of the first three cycle designs were almost the same in the temperature range studied. Additionally, performance improvements of around 20% and 28% in the cooling capacity and coefficient of performance were found when an internal heat exchanger was added to the baseline cycle. Performance gains of 10% and 15% in the cooling capacity and coefficient of performance were also found with the flash gas chamber cycle design, without compromising the discharge line temperature.

Une étude sur les architectures de cycles au dioxyde de carbone pour systèmes frigorifiques commerciaux légers

Mots clés : Dioxyde de carbone ; Tube capillaire ; Dispositif d'expansion ; Chambre de vaporisation instantanée ; Cycles frigorifiques

1. Introduction

Low temperatures can be obtained through distinct refrigeration principles, each of them with particularities that limit their application to specific market niches. Among other principles, cold conditions can be produced by vapor compression, absorption, thermoelectric, thermoacoustic, magnetocaloric and also by Stirling and air cycles. Nowadays, cold conditions are mostly produced by vapor compression, mainly due to the inherent low cost and high efficiency of this principle. Vapor compression refrigeration systems are regularly used in homes as well as in large industrial facilities.

The chilling and freezing processes are relatively simple and economically feasible when used, for example, in large-scale food processing and storage centers. However, it is quite a challenge to produce cold conditions for the food retail and domestic markets, both at the end of the food distribution

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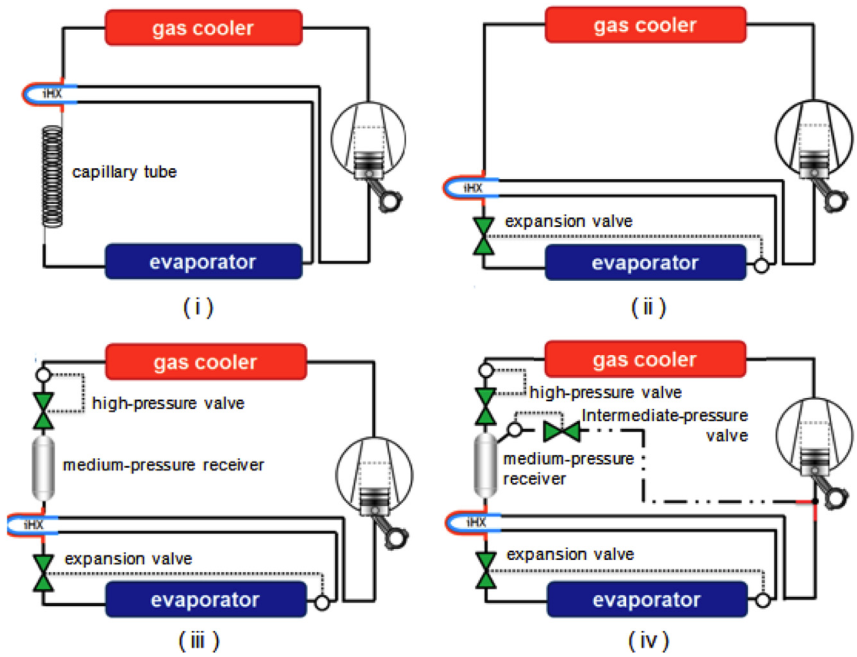

Fig. 1 – Cycle designs: (i) capillary tube, (ii) expansion valve, (iii) dual-stage expansion and (iv) flash gas chamber.

chain, without any appreciable impact on the environment. The light-commercial refrigeration products, in particular, have a significant impact on the environment because they are large in number, consume a considerable amount of electricity and use high Global Warming Potential (GWP) refrigerants. In order to minimize the direct effect of these systems on the environment, the currently used synthetic refrigerants are gradually being replaced by natural refrigerants such as isobutane, propane and carbon dioxide (CO_2). Apart from being a natural fluid, CO_2 is a good option because it is non-toxic, non-flammable, provides high heat transfer rates and has a low GWP and null ODP (Ozone Depletion Potential) (Kim et al., 2004). Below an annual averaged ambient temperature of 15 °C the regular vapor compression cycle with synthetic refrigerants is outperformed by the CO_2 cycle (Matthiesen et al., 2010), which makes the latter an attractive solution for some regions of the globe (Fornasieri et al., 2008; ASHRAE, 2009). In contrast, CO_2 systems are less efficient than those with synthetic refrigerants under high ambient temperatures, which lead to a higher indirect effect on the environment and a higher Total Equivalent Warming Impact (TEWI).

Nonetheless, the performance of CO_2 systems can be significantly improved by introducing modifications at the cycle level, such as the cascade systems applied with great success in a wide range of climates (Matthiesen et al., 2010). However, the light-commercial refrigeration systems require simple and cost-effective designs which prevent the adoption of some of the more complex alternatives available. Examples of viable approaches for this particular sector are the internal heat exchanger cycle (Sánchez et al., 2010a) and the discharge pressure-controlled cycle (Sarkar et al., 2004).

The aim of this article is to compare the thermodynamic performance of four refrigeration cycle designs (Fig. 1) at different ambient temperatures. All designs are comprised of an internal heat exchanger (iHX), but with different expansion processes, namely: (i) capillary tube, (ii) expansion valve, (iii) dual-stage expansion and (iv) flash gas chamber. The first three of these designs have been previously studied by Montagner and Melo (2012), but without an iHX. The authors found that the expansion valve cycle design provided an effective control of the evaporator superheating but led to a penalty in terms of the discharge pressure. In contrast, the capillary tube cycle design provided discharge pressures closer to the optimum values, but without proper control of the superheating. The counteracting effects of the superheating and discharge pressure resulted in almost the same performance for the two designs. This finding is not in line with that reported by Aprea and Mastrullo (2002), who observed a considerably better performance for the expansion valve with respect to the capillary tube cycle design in synthetic refrigerant-based systems. The more complex dual-stage expansion cycle design was able to simultaneously control the superheating and the discharge pressure by adjusting the amount of refrigerant contained in the high- and low-pressure sides of the system. This design provided a COP improvement of up to 10% with respect to the other two designs when the gas cooler outlet temperature was lower than the baseline value of 38 °C. At higher values the performance of the three designs was practically the same.

In the fourth design – flash gas chamber – a small amount of flash gas is removed from the medium-pressure receiver and mixed with the refrigerant at the exit of the internal heat exchanger (Fig. 1-iv). This design offers a certain degree of control of the intermediate pressure and therefore of the specific refrigerating effect, and also lowers the suction and discharge line temperatures (Sánchez et al., 2010b).