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Performance evaluation and optimal design of supermarket refrigeration systems with supermarket model “SuperSim”. Part II: Model applications

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ABSTRACT

As described in Part I, the supermarket simulation software “SuperSim” with its integrated refrigeration, building and HVAC system models, can be used to evaluate, compare and optimize alternative supermarket refrigeration systems. In Part II the model was used to evaluate and compare the performance of a CO₂ booster refrigeration system with that of a conventional R404A multiplex system in a supermarket application. Floating head pressure control was implemented for both systems when they were in subcritical cycles. For the CO₂ system, when the system was in transcritical cycle due to higher ambient air temperature, the head pressure was optimized through extensive thermodynamic cycle analysis as a function of ambient air temperature. The performance of the CO₂ booster system in the supermarket was then simulated during a one year period and compared with that of the R404A system. As a result, the system performance will benefit from a lower ambient temperature and a sizeable heat recovery for the CO₂ system.

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Evaluation de la performance et conception optimale de systèmes frigorifiques pour supermarchés à l'aide du modèle « SuperSim ». Partie II : applications du modèle

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1. Introduction

Alongside the other application areas such as heat pumps and automotive air conditioning, CO₂ refrigerant has attracted significant attention for application to supermarket

refrigeration systems. The energy consumption of a typical supermarket in the UK is within the region of 1000 kW h/m², of which 30–50% is used for refrigeration (Tassou, 2007). This substantial consumption of energy in the form of grid electricity and gas makes a significant contribution to indirect

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Nomenclature

c_1 – c_6	coefficients
ΔT	temperature difference (K)
h	enthalpy (J kg ⁻¹)
P	pressure (Pa or bar)
Q	capacity, heat load (kW)
R	ratio
T_{amb}	ambient air temperature (°C)
t, T	temperature (°C)
T_T	transition temperature (°C)
W	power (kW)
x	quality
y	mass flow rate ratio

Greek symbol

η	efficiency
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Subscripts

amb	ambient
cd, min	minimum condensing
cp	compressor
ev	evaporator
fan	condenser fan
H	high side
is	isentropic
P	pressure
ss	saturated suction
vent	ventilation

CO₂ emissions. HFC refrigerants such as R404A, which are currently used in modern supermarket refrigeration systems, also contribute significantly to direct CO₂ emissions. In contrast to the aforementioned HFC refrigerants, CO₂ refrigerant is more environmentally friendly, due to its zero Ozone-Depletion Potential (ODP) and negligible direct Global Warming Potential (GWP <1). It also has favourable thermo-physical properties which include higher density, latent heat, specific heat, thermal conductivity and volumetric cooling capacity, and lower viscosity than HFC refrigerants that lead to better heat transfer. The application of CO₂ refrigerant to supermarket refrigeration systems can almost entirely eliminate direct CO₂ emissions and has even the potential to reduce indirect emissions. However, CO₂ has a relatively high operating pressure and low critical temperature, such that an air cooled CO₂ system will not be able to condense the refrigerant in the condenser during periods of high ambient temperatures. The higher pressure and transcritical operation during periods of high ambient temperatures can lead to higher energy consumption for CO₂ systems compared to R404A when they are designed on the principle of the basic single stage vapour compression cycle and used for chilled food applications with evaporating temperatures down to around –10.0 °C (Sarkar et al., 2005). The efficiency of CO₂ systems can be improved through the implementation of more sophisticated cycles and advanced control techniques.

In general, three types of CO₂ system designs have been applied in supermarket refrigeration applications (Sawalha, 2008a,b): indirect systems (Hinde et al., 2009), cascade systems (Eggen and Aflek, 1998) and all CO₂ transcritical systems (Nekså and Girotto, 2002; Schiesaro and Kruse, 2002). For the indirect system application, the CO₂ fluid is used as a two-phase secondary coolant which has shown some advantages over conventional single-phase fluids, such as lower pumping power, smaller pipe sizes and excellent heat transfer properties. On the primary side, however, an HFC refrigerant such as R404A or R507C is still commonly used. For a cascade system, a fluid such as R404A, R134a, NH₃, a hydrocarbon, or even CO₂ can be employed in the higher cascade for heat rejection, and CO₂ operates in a subcritical cycle in the lower cascade. The cascade CO₂ system has several advantages, including reduced low-temperature

compressor sizes, the absence of a liquid pump and fewer stages of heat transfer compared to indirect or ‘booster’ systems (Kim et al., 2004). It has also been reported that the energy consumption of the cascade system can be either neutral or less than that of conventional R404A systems (Christensen and Bertelsen, 2003). However, many indirect and cascade CO₂ systems tend to use HFC refrigerants in the primary side, which will not facilitate to entirely eliminate any direct environmental impact.

For an all CO₂ booster system, advantages reported include simpler and cheaper system designs with one fluid and one circuit (at medium temperatures and low temperatures) and heat recovery potential although the utility was found significantly low during winter period (Arias and Lundqvist, 2006). It has been discovered, however, that the total annual energy consumption of an all CO₂ system in a hot climate can be higher than that of a conventional R404A system (Girotto et al., 2003, 2004). Systems installed in Northern European countries such as Sweden, Denmark, Germany and Switzerland, in contrast, can have an equivalent or lower annual energy consumption than R404A systems, due to the higher number of hours during the year in which such systems operate in the subcritical mode (Girotto et al., 2004).

In this paper, an all CO₂ booster system is considered and its performance compared with that of an R404A system in a supermarket application in the North of England using the SuperSim model. For both systems optimum head pressure control is implemented with respect to ambient temperature.

2. CO₂ booster refrigeration system

2.1. System layout

A schematic of a typical CO₂ booster system used in supermarket refrigeration applications is shown in Fig. 1. The booster cycle has four pressure regions, high, intermediate, medium and low. The high pressure region extends from the outlet of the high stage compressor (COMP_HI) to the gas cooler or condenser, depending on ambient conditions, the suction line heat exchanger (SHX), and to the high pressure control valve (CV_HP). The intermediate pressure region begins

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