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Annual energy analysis of a water-loop self-contained refrigeration plant and comparison with multiplex systems in supermarkets

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ABSTRACT

Supermarkets are probably the largest energy users in the commercial sector and are responsible for considerable CO_2 emissions. In most cases, refrigeration systems employ direct expansion air refrigerant coils as evaporators in display cases and coolers. Compressors and condensers are kept in a remote machine room located in the back or on the roof of the store. As a consequence, a large amount of refrigerant is needed to charge the refrigeration system. Nowadays advanced supermarket systems can reduce both annual energy consumption and total equivalent warming impact (TEWI). One of these advanced solutions is the water-loop self-contained refrigeration system with modulating compressors (WLSC). In this paper a real WLSC supermarket located in Italy is considered and its annual performances are compared with those of both a simulated multiplex benchmark solution with thermostatic expansion valve (TEV) and fixed evaporation pressure and with those of a simulated multiplex solution with electronic expansion valve (EEV) and floating evaporation pressure.

Analyse énergétique annuelle d'un système frigorifique autonome à boucle d'eau et comparaison avec des systèmes multiplexes dans des grandes surfaces

Mots clés : Supermarché ; Boucle à eau ; Multiplex ; TEV ; EEV ; Evaporation flottante

1. Introduction

Supermarkets are probably the largest energy users in the commercial sector in many countries (Walker, 2001; Arteconi et al., 2008). The IEA (IEA, 2003) reports that 3–5% of the total electricity consumption stems from supermarkets in industrialized countries. Conventional supermarket refrigeration systems are also responsible for considerable CO_2 emissions, due to high energy consumption and large quantities of refrigerant leakages (Tassou et al., 2011).

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Nomenclature

COP	Coefficient of Performance
DC	Dry-cooler
EER	Energy Efficiency Ratio (as in UNI EN 14511–1, 2013)
EEV	Electronic Expansion Valve
GWP	Global Warming Impact
h	Specific enthalpy (kJ kg^{-1})
HP	Heat pump
L	Specific compression work (kJ kg^{-1})
LT	Low Temperature refrigeration line
$MP_{TEV\text{-}Fixed\ suction\ p}$	Multiplex system with thermostatic expansion valve and fixed suction pressure
$MP_{EEV\text{-}Float.\ suction\ p}$	Multiplex system with electronic expansion valve and floating suction pressure
MT	Medium Temperature refrigeration line
p	Pressure (bar)
$P_{el\ n}$	Compressor electric power (kW)
$P_{cooling\ n}$	Compressor cooling capacity (kW)
PID	Proportional, integral and derivative control
SC	Self-Contained solution
T_c	Saturated condensation temperature (°C)
T_{cab}	Cabinet air temperature set point (°C)
T_e	Saturated evaporation temperature (°C)
T_s	Saturated suction temperature (°C)
TEV	Thermostatic Expansion Valve
TEWI	Total Equivalent Warming Impact (kg_{CO_2})
WLSC	Water-Loop Self-Contained systems

The large majority of supermarkets refrigeration systems employ direct expansion air refrigerant coils as evaporators. Compressors and condensers are kept in a machine room located outside the sales area, often on the roof. As a consequence, large amount of refrigerant is needed to charge the refrigeration system. Furthermore, a significant proportion of major annual leakages are due to the large number of piping and pipe joints used. This solution is called "multiplex refrigeration system", where the term "multiplex" indicates that multiple compressors have a common suction line and discharge manifolds. The discharge gas is piped to a remotely located condenser, and then piped back to the compressor rack in a liquid receiver. Supermarkets usually have two compressor racks, one for the medium and one for the low temperature refrigeration line.

A traditional multiplex supermarket is usually equipped with thermostatic expansion valve (TEV) and operates with a fixed suction pressure ($MP_{TEV\text{-}Fixed\ suction\ p}$). Using an electronic expansion valve (EEV) allows the supermarket to operate with lower head pressures (Lazzarin et al. 2009), increasing the refrigeration line efficiency. Other energy benefits are obtainable by adopting a floating (instead of fixed) suction pressure regulation strategy, as described in Section 3.2. Though a multiplex supermarket with EEV and a floating suction pressure regulation strategy ($MP_{EEV\text{-}Float.\ suction\ p}$) leads to appreciable annual energy savings (Lazzarin et al. 2009), this solution does not significantly contribute to decrease the total equivalent warming impact (TEWI), which mainly depends on both refrigerant charge and refrigerant leakages.

Advanced supermarket systems able to reduce both annual energy consumption and total TEWI would be welcome. One of the advanced refrigeration systems considered by Walker (2001) is the "water-loop self-contained system" (WLSC). This solution implies that each cabinet is equipped with its own compressor and condensing unit. A fluid loop, refrigerated in a central chiller, is used for heat rejection. According to Walker (2001), the fact that water is being circulated throughout the sales area instead of refrigerant, the refrigerant charge can be drastically reduced if compared with a traditional multiplex system.

Nevertheless simulations carried out by Walker (2001) and Zhang (2006) assert that a WLSC system is less efficient if compared to the benchmark multiplex solution. However a continuous loading-unloading capacity control was provided for the scroll compressors in the simulation.

Nowadays several alternatives are available for capacity control. One of these alternatives is the use of variable speed inverter driven compressors. If compared with continuous loading-unloading compressors, variable speed compressors have several advantages, such as:

- Lower on-off cycling frequency, thus allowing less cycling losses related to the inefficiencies which characterize the cabinet start-up periods (Bagarella et al., 2013);
- Possible higher EER of the unit at partial loads, related to the lower compression ratios obtainable when modulation is required (Aprea et al., 2006).

As reported by Karlssons and Fahlen (2007) and by Madani et al. (2011) it should be considered that higher EERs of the unit at partial loads are not always possible. In fact, the possibility to increase the EER at partial loads depends on many factors, such as the efficiency of both compressor and inverter at low speeds. Anyway, if compressors optimized for variable speed operation (possibly equipped with both high efficiency brushless direct current motors and inverters) and working with low compression ratios are considered, the mentioned advantages might drastically increase cabinets' performances at partial loads, and might positively affect the efficiency of the whole WLSC refrigeration system too. To the authors' best knowledge no analysis had been produced in literature evaluating the possible increase performance of refrigeration systems when operated at partial load.

In this paper the layout of a real WLSC supermarket with variable speed compressors located in Bologna (Italy) is presented. The survey and recording of the main parameters of the plant over 12 months allowed analysis of seasonal supermarket performance, realizing a comparison with the two traditional systems recalled above: $MP_{TEV\text{-}Fixed\ suction\ p}$ and $MP_{EEV\text{-}Float.\ suction\ p}$.

2. Water-loop self-contained supermarket

As several authors have already described in the past the layout of multiplex supermarkets (Ge and Tassou, 2011;