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On subcooler design for integrated two-temperature supermarket refrigeration system

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ABSTRACT

The energy saving opportunity of supermarket refrigeration systems using subcooler between the medium-temperature (MT) refrigeration system and the low-temperature (LT) refrigeration system has been identified in the previous work. This paper presents a model-based comprehensive analysis on the subcooler design. The optimal subcooling control is discussed as well. With optimal subcooler size and subcooling control, the maximum energy savings of integrated two-temperature supermarket refrigeration system using R404A or R134a as working fluid can achieve 27% or 20%, respectively. The load ratio of MT to LT system and the operating conditions have considerable impact on the energy savings.

1. Introduction

Supermarkets are one of the most energy-intensive types of commercial buildings. Significant energy is used to maintain chilled and frozen food in both display cases and storage refrigerators. Annual energy use ranges from about 100,000 kWh/year for the smaller stores to 1.5 million kWh/year or more for the largest [1]. Therefore, supermarkets are looking for energy saving opportunities in different ways. Energy efficient refrigeration system is one of the critical directions. Usually, the supermarket refrigeration system has two temperature levels: medium temperature (MT) for preservation of fresh food and low temperature (LT) for frozen products. Fresh food is maintained between 1 °C and 14 °C. Frozen food is kept at −12 °C or −18 °C. The evaporating temperature of MT system varies between −15 °C and 5 °C, while for a LT system the evaporating temperature ranges from −30 °C to −40 °C [2]. Due to the low evaporating temperature, the *COP*s of LT and MT system are quite low. The typical *COP* values are 1and 2 for LT and MT system, respectively.

From thermodynamic standpoint, further cooling of liquid refrigerant leaving condenser can significantly reduce power consumption and improve the system *COP*. It can be realized by adding mechanical subcooling to a conventional vapor compression cycle. A dedicated mechanical subcooling system was brought up by Couvillion et al. [3] and Thornton et al. [4]. The system used an additional compressor, condenser, and subcooler in the cycle. An integrated mechanical subcooling system was proposed and investigated by Zubair [5,6], Zubair et al. [7], Khan and Zubair [8]. In their work, only one condenser served both the main cycle and the subcooler cycle. Yu et al. [9] discussed a new ejector refrigeration system with mechanical subcooling. An auxiliary liquid–gas ejector was used to enhance subcooling. In short, the above-mentioned mechanical subcooling systems all used additional small vapor-compression cycles to generate subcooling.

In the supermarket refrigeration system, there are two separate refrigeration cycles. *COP* of MT system is twice as high as that of LT system. Therefore, it is viable to have MT system provide subcooling for LT system. Compared with the dedicated or integrated mechanical subcooling cycles mentioned above, there is no auxiliary compressor or condenser in the supermarket mechanical subcooling system. Previously, the authors [10] did comprehensive analysis on the energy saving potential of integrated supermarket HVAC and refrigeration system using multiple subcoolers. It is found that the subcooler between MT and LT system has much more energy saving potential than others. Consequently, how to design the subcooler between MT and LT system should be answered next.

Fig. 1 demonstrates the schematic of the integrated supermarket refrigeration system using mechanical subcooling. A heat exchanger named "subcooler" is placed between the evaporator inlet of MT system and the condenser outlet of LT system. The liquid refrigerant leaving the receiver of LT system passes through the

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Nomenclature

A	heat transfer area (m^2)
$c_1, c_2, \ldots c_{10}$	10 coefficients in compressor model
c_p	specific heat ($J\,kg^{-1}\,K^{-1}$)
COP	coefficient of performance
f	area fraction of each heat transfer zone
h	enthalpy ($J\,kg^{-1}$)
h_{fg}	water latent heat ($J\,kg^{-1}$)
K	air pressure drop coefficient, # of velocity heads based on total face area
m	mass flow rate ($kg\,s^{-1}$)
p	pressure (Pa)
Δp	pressure drop (Pa)
P	power input (W)
Q	heat transfer rate (W)
SST	saturated suction temperature (°C)
T	temperature (°C)
ΔT	log mean temperature difference (K)
U	overall heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
UA	overall heat transfer conductance ($W\,K^{-1}$)
v	specific volume ($m^3\,kg^{-1}$)
V	volume flow rate ($m^3\,s^{-1}$)
W	humidity ratio

Greek symbols

ε	heat exchanger effectiveness
η	efficiency

Superscripts and subscripts

$'$	results with mechanical subcooling
1,2,3,4,3′,4′	state points in Figs. 2 and 3
2p	two-phase region
a	air
c	condenser
e	evaporator
f	coil face
in	inlet
lat	latent heat
LT	low temperature system
MT	medium temperature system
min	minimum
max	maximum
sat	saturated
sc	subcooler
sen	sensible heat
sh	superheat
out	outlet
r	refrigerant
ref	reference
tot	total refrigeration system
w	condensate
x	vapor quality

subcooler. Meanwhile, the liquid refrigerant leaving the receiver of MT system is separated into streams "A" and "B". Stream "A" passes through the expansion valve and the subcooler successively. Inside the subcooler, stream "A" further cools the liquid refrigerant of LT system. Stream "B" walks through the liquid line to the sales area. In the end, streams "A" and "B" merge before entering MT compressors. Therefore, stream "A" bypasses the evaporators and works as a vapor compression cycle for providing additional subcooling to LT system. Since the subcooler can transfer an amount of cooling capacity from the higher *COP* MT system to the lower *COP* LT system, total power consumption of the integrated refrigeration system can be reduced.

Models and tools have been developed in recent decade for analyzing supermarket energy use and comparing different system solutions for supermarket refrigeration [11–15]. The mechanical subcooling system illustrated in Fig. 1 has not been well investigated so far. Particularly, there is no best practice for this type of subcooler design.

In this work, a physics-based model is developed to study the subcooler design. *COP*s of LT, MT and the whole refrigeration system at certain subcooling are investigated numerically. The optimal subcooling for subcooler sizing is discussed. The subcooling control strategy is proposed for the whole system operating at near-optimal point. The energy saving percentage is estimated at different load ratios of MT to LT system, at different ambient temperatures, and using different refrigerants R404A and R134a.

2. Description of supermarket refrigeration system

Fig. 1 is an example of the common supermarket multiplex refrigeration system. The system employs direct-expansion air-to-refrigerant coils as evaporators of display cases and walk-in coolers. Compressors and condensers are in a remote machine room located in the back or on the roof of the store. Piping is used to supply and return refrigerant to the case fixtures. Liquid receiver in the system is primarily for pump-down during servicing. LT and MT system have own compressor rack connected with suction and discharge lines.

The basic control architecture of a typical supermarket refrigeration system is illustrated in Fig. 2. The suction pressure is controlled by the compressor rack. The condensing pressure fluctuates with the outdoor ambient temperature or can be controlled by turning on/off a number of fans. The suction superheat is controlled by a mechanical expansion device located at the inlet of evaporators. The temperature in the cold storage room is controlled by the evaporator fan speed. At last, for the refrigeration system with mechanical subcooling, the expansion valve on stream "A" of MT system is used to modulate the flow rate of stream "A" or the suction temperature entering the MT compressor rack.

The pressure–enthalpy diagrams of LT and MT refrigeration system are shown in Fig. 3. The state points in Fig. 3 are labeled in Fig. 2 as well. Compared with the basic system without mechanical subcooling, the LT refrigeration cycle has changed from 1-2-3-4-1 to 1-2-3′-4′-1. The additional subcooling increases the enthalpy difference of evaporation. Therefore, when the LT load is fixed, the demanded refrigerant flow rate will decrease. So does the compressor power consumption. By comparison, the MT refrigerant cycle 1-2-3-4 does not change. However, since stream "A" passes through the subcooler instead of the evaporator, part of MT cooling capacity is used for LT system but not transferred into the MT cabinets. Because MT system consumes less power than LT system for generating the same amount of cooling capacity, the overall energy use can be reduced by mechanical subcooling. Moreover, LT and MT system coexist in most supermarkets. Therefore, using MT system to generate subcooling for LT system is more practical and cost-effective than a dedicated or integrated mechanical subcooling system.

3. Mathematical models of MT and LT refrigeration system

3.1. System definitions

In this section, a physics-based model is developed to do the comprehensive analysis. The target supermarket refrigeration system is defined by the following assumptions. All assumptions are