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The effect of refrigerant combinations on performance of a vapor compression refrigeration system with dedicated mechanical sub-cooling

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ABSTRACT

Performance characteristics due to use of different refrigerant combinations in vapor compression cycles with dedicated mechanical sub-cooling are investigated. For scratch designs, R134a used in both cycles produced the best results in terms of COP, COP gain and relative compressor sizing. In retrofit cases, considering the high sensitivity of COP to the relative size of heat exchangers in the sub-cooler cycle and the low gain in COP obtained due to installation of a dedicated sub-cooling cycle when R717 is the main cycle refrigerant, it seems that dedicated mechanical sub-cooling may be more suited to cycles using R134a as the main cycle refrigerant rather than R717. With R134a as the main cycle refrigerant, no major difference was noted, by changing the sub-cooler cycle refrigerant, in the degradation of the performance parameters such as COP and cooling capacity, due to equal fouling of the heat exchangers.

Les effets de différentes combinaisons de frigorigènes sur la performance d'un système frigorifique à compression de vapeur muni d'un dispositif de sous-refroidissement mécanique

Mots clés : Système frigorifique ; Frigorigène ; Sous-refroidissement ; Compresseur ; Système multi-étagé

1. Introduction

Air-conditioning systems consume a large amount of the world's generated electrical power, which are predominantly of the air-cooled type due to water shortage and, therefore, operate under large temperature differences. The large temperature difference between the condenser and evaporator implies less refrigeration effect and greater compressor-power consumption per unit of refrigerant. This may cause the compressor of an air-conditioning system to operate for extended periods under extreme conditions in order to meet the desired cooling demand, which may be harmful to the

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Nomenclature

C_p	constant pressure specific heat (J kg^{-1} K^{-1})
$\dot{C}$	thermal capacitance rate (kW K^{-1})
COP	coefficient of performance (-)
f_h	ratio defined by Eq. (13) (-)
K	total heat exchanger inventory (kW K^{-1})
$\dot{m}$	refrigerant mass flow rate (kg s^{-1})
P	pressure (kPa)
$\dot{Q}$	rate of heat transfer (kW)
T	temperature (°C)
$\dot{V}$	volumetric flow rate (m^3 s^{-1})
$\dot{W}$	power requirement (kW)

Greek symbols

α	main cycle evaporator inventory (kW K^{-1})
β_{main}	main cycle condenser inventory (kW K^{-1})
β_{sub}	sub-cooler cycle condenser inventory (kW K^{-1})
η	efficiency (-)
ε	effectiveness (-)
θ	dimensionless sub-cooler saturation temperature (-)

Subscripts

cd	condenser
cp	compressor
dl	discharge line
ev	evaporator
in	entering
is	isentropic
m	main cycle
min	minimum
nsc	no sub-cooler cycle
sc	sub-cooler cycle
sl	suction line

system (Abdel-Nabi et al., 1990). At EPRI, a study was performed which showed that supermarkets provide important loads in the United States for many utilities and are significant contributors to their system peaks (EPRI, 1984). Refrigeration systems constitute the major area of supermarket energy usage and account for approximately 50–60% of the total energy consumption. Simple vapor-compression refrigeration systems are commonly used for cooling supermarket display cases and cold storage applications where the evaporator temperature may vary from −40 °C to 7 °C (Zubair, 1990).

Energy can be saved by incorporating a mechanical sub-cooling loop to existing refrigeration and air-conditioning systems. Dedicated mechanical sub-cooling is one of the types of sub-cooling in which both the main cycle and the sub-cooler cycle has its own condenser. Thornton et al. (1994) used a refrigerant property-based thermodynamic model to study the performance of a dedicated mechanical-subcooling system for various values of the sub-cooling saturation temperature. Couvillion et al. (1988) developed a mathematical model of a dedicated mechanical-subcooling system by considering the individual component models of the equipment involved in the system. They found an improvement of 6–80% in the coefficient of performance (COP) and 20–170% in the capacity over a conventional simple cycle. Using R134a, a study was carried out on a dedicated mechanical sub-cooling system by Khan and Zubair (2000) which showed that the performance of the overall cycle is improved compared to the corresponding simple cycle and that this was related to the refrigerant saturation temperature of the sub-cooler. The model also predicted that the optimum distribution of the total heat exchanger area between the evaporator and condenser was achieved when this was equally distributed. Recently, Yang and Zhang (2011) showed that, for an optimal sub-cooler design, energy savings of an integrated two-temperature supermarket refrigeration system, using R404A or R134a as the working fluid, can be as much as 27% or 20%, respectively.

At present, the following six refrigerants are being used as alternatives for various applications: R134a, R407C, R410A, R404A, R717 and R290. These are replacements for refrigerants, e.g. R12, R22 and R502 that harm the ozone layer and are part of the increasing worry about their global warming potential due to the greenhouse effect (Kyoto Protocol, 1997). Even though these six working fluids are virtually harmless to the ozone layer, they can add to global warming sometimes due to leaks but more so, in an indirect way, through energetic performance of the refrigeration plant (Calm, 2002; Sand et al., 1999). There are two possible situations where a dedicated mechanical sub-cooling system can be applied: complete design or by retrofitting the existing system. R134a is a common substitute for R12 and R22 (at high-temperature levels) whereas R717 is a common substitute for R502 and similarly the other refrigerants (Trott and Welch, 2000). Since the sub-cooler cycle is a comparatively higher temperature cycle, therefore, refrigerants that are commonly utilized for high- and medium-temperature applications (i.e. R134a, R410A and R407C) should be used in it.

Thus, in this paper, refrigerant combinations are explored based on the two situations described above (i.e. complete design and retrofitting) for application of a dedicated sub-cooling system with R134a, R410A and R407C used in the sub-cooling cycle. For this purpose, a refrigerant property-dependent thermodynamic model that accounts for the irreversible losses existing due to the finite temperature difference in the heat exchangers as well as the losses due to the non-isentropic compression and expansion in the compressors and the expansion valves, respectively, was used.

2. Cycle description and model

The main components of the system under consideration include two compressors, two expansion valves, two condensers, one evaporator and a sub-cooler. The system consists of two simple cycles coupled to each other via a sub-cooler as shown in Fig. 1(a), while its pressure–enthalpy diagram is shown in Fig. 1(b). In Fig. 1(a), the lower cycle is known as the main cycle and the upper cycle is known as the