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Performance and exergy destruction analyses of optimal subcooling for vapor-compression refrigeration systems

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ABSTRACT

Performance enhancement and exergy destruction analyses were conducted numerically for vapor-compression refrigeration systems using R22, R134a, R410A, and R717. The first law of thermodynamics combined with finite-temperature-difference heat transfer theory and the second law of thermodynamics were applied to calculate the COP, heat-exchanger area, irreversibility, and friction loss that occurs in heat exchangers used in this system at various condensation and evaporation temperatures. The effects of cooling water in a subcooler, refrigerant pressure drop among heat exchangers, and superheating in an evaporator were also considered. Two dimensionless parameters, which represented initial cost saving and the total exergy destruction of the system, were introduced and evaluated to obtain the optimal degree of subcooling. Compared with evaporation temperature, condensation temperature plays a considerably more crucial role in determining the optimal degree of subcooling for achieving maximal initial cost saving. In addition, the optimal degrees of subcooling obtained according to the second law of thermodynamics were consistently higher than those obtained according to the first law of thermodynamics.

1. Introduction

A substantial amount of heat is released into the environment by the thermodynamic cycle of refrigeration systems because of the widespread application of air conditioning and refrigeration for industrial and domestic use. Saving energy and increasing efficiency has become increasingly critical in refrigeration systems because of the vast amount of energy consumed. The properties of refrigerants strongly affect the performance and apparatus cost of refrigeration systems. Furthermore, manufacturing environmentally friendly refrigerants to achieve zero ozone depletion potential (ODP) and low global warming potential (GWP) is essential for applications of refrigeration systems. Recently, several academics have focused on environmental protection and analyzed the performance of alternative refrigerants. According to the Montreal protocol, the phasing-out deadline for R22 is in 2020. Dalkilic and Wongwises [1] investigated the performance of vapor-compression refrigeration systems at various degrees of subcooling and superheating by using blends of R134a, R152a, R32, R290, R1270, and R600a according to the first law of thermodynamics. At the condensation temperature of 50 °C and evaporation temperatures ranging between −30 °C and 10 °C, the result indicated that the blends of R290/R600a and R290/R1270 were the most suitable alternatives to current refrigerants. To obtain the optimal relative size of condensers, Wu [2] investigated the performance characteristics of a Carnot refrigerator. The relationship between the coefficient of performance and the cooling load of the refrigerator was obtained numerically without considering the heat transfer mechanisms of heat exchangers. The heat transfer coefficient, pressure-drop characteristics, and performance comparisons for 404A, R410A, and R290 were investigated numerically by Spatz and Yana Motta [3]. Based on their result, R410A was proposed to be an efficient and environmentally acceptable option for replacing R22 in medium-temperature applications.

To compare the performance of refrigeration systems, experimental analyses of vapor compression systems were conducted on R22 and its candidate substitutes, which were R407C, R507, and R417A [4,5]. The analysis of R22 and R407C flowing through an expansion valve was conducted experimentally by Zhang et al. [6], and the performance of the refrigeration system was evaluated. In their study, the effects of inlet and outlet pressures on

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Nomenclature

A	heat transfer area of heat exchanger (m^2)
A_i	inside surface area of the tubes in heat exchanger (m^2)
A_o	outside surface area of the tubes in heat exchanger (m^2)
A_{sub}	the total heat-exchanger area of system with subcooler (m^2)
A_{nsc}	the total heat-exchanger area of system without subcooler (m^2)
A_N	ratio of ($A_{sub} - A_{nsc}$) to A_{nsc}, Eq. (27)
COP	ratio of Q_{eva} to W_{com}, Eq. (25)
COP_N	ratio of COP_{sub} to COP_{nsc}, Eq. (26)
c_p	specific heat of cooling water (kJ/kg °C)
D	tube diameter of heat exchanger (m)
D_h	hydraulic diameter (m)
ED_N	dimensionless parameter of total exergy destruction, Eq. (29)
g	gravitational acceleration (m/s^2)
h	heat transfer coefficient (W/m^2 °C)
I	irreversibility (kW)
i	specific enthalpy of refrigerant (kJ/kg)
k	thermal conductivity (W/m °C)
L	length of the tube (m)
L_t	thickness of tube wall (m)
M	molecular weight of refrigerant (g/mole)
N	number of horizontal tubes in vertical row
m	mass flow rate (kg/s)
P	pressure (kPa)
ΔP	pressure drop (kPa)
P_N	dimensionless parameter of total friction loss on water side, Eq. (16)
P_r	Prandtl number, $c_p\mu/k$
Q	heat transfer rate (kW)
q	heat flux (W/m^2)
Re	Reynolds number, VD_h/v
s	specific entropy (kJ/kg °C)
T	temperature (°C)
T_{ci}	refrigerant inlet temperature of saturated region in condenser (°C)
T_{co}	refrigerant outlet temperature of condenser (°C)
T_{cwi}	cooling water inlet temperature of condenser (°C)
T_{cwo}	cooling water outlet temperature of condenser (°C)
T_{ei}	refrigerant inlet temperature of saturated region in evaporator (°C)
ΔT_{mean}	logarithmic mean temperature difference in heat exchangers (°C)
T_o	environmental temperature (°C)
U	overall heat transfer coefficient for a shell-and-tube heat exchanger (W/m^2-°C)
V	velocity (m/s)

Greek symbols

γ	dimensionless parameter of initial cost saving, Eq. (28)
ρ	density (kg/m^3)
μ	dynamic viscosity (Pa-s)
v	kinematic viscosity (m^2/s)

Subscripts

com	compressor
con	condensation, condenser
eva	evaporation, evaporator
f	liquid
g	vapor
i	inlet, inside
max	maximal
min	minimal
o	outside, optimization
r	refrigerant
t	total, tube wall
w	water
sat	saturation
sup	superheating
sub	subcooling
nsc	nonsubcooling
N	normalized

mass flow rates at various condensation and evaporation temperatures and degrees of subcooling were proposed. Park et al. [7] experimentally investigated the thermodynamic performance of R431A and R22 in an air conditioner. The COP of R431A was reported to perform 3.5–3.8% more favorably than that of R22. Furthermore, an internal heat exchanger was applied to a vapor-compression refrigeration system to increase the performance of the system.

Subcooling can be used to increase the cooling capacity and efficiency in vapor-compression refrigeration systems. Aprea and Greco [8] experimentally studied the performance of R22, R134a, and R407C in a vapor-compression refrigeration system at various degrees of subcooling and superheating. Hsiao et al. [9] investigated the enhancement of thermal performance for an air conditioning system equipped with a subcooler. Their experimental results indicated that the COP of the system using subcooling performed 15.6% higher than those not using subcooling for fixed cooling loads of 3.5 kW. Llopis et al. [10] presented the experimental comparison of R404A and 507A regarding cooling capacity, compressor power consumption, and energy efficiency in vapor-compression systems. Han et al. [11] compared the performance of R161, R32, and R410A in a small-scale refrigeration system under a fixed degree of superheating in an evaporator and subcooling in a subcooler. Their results indicated that the COP of R161 was 10% and 17.8% higher than that of R32 and R410A, respectively. Qureshi et al. [12] experimentally investigated a simple vapor-compression refrigeration cycle with subcooling. A high cooling capacity and high second-law efficiency was obtained using subcooling at approximately 5–8 °C.

Increasing the efficiency of components is essential for improving the performance of a refrigeration system. The multi-stage compression method, which was driven by the turbine of a Rankine cycle with waste heat recovery, was illustrated numerically by Staicovici [13] to improve the COP of the vapor-compression refrigeration system. The heat transfer coefficients of condensation for R744, R410A and R134a were investigated experimentally with various saturation temperatures [14,15]. In addition, the heat transfer coefficients of evaporation for R134a were studied experimentally with various saturation pressures and mass flow rates in micro-channels [16,17].

Based on the performance and economic viewpoint, determining the optimal subcooling temperature is crucial to reduce the total heat-exchanger area of the vapor-compression refrigeration system at various condensation and evaporation temperatures. Characteristic of refrigeration performance is a function of both cooling capacity and heat exchanger area. A simple thermodynamic model revealed by Chua et al. [18] can be used to predict optimal operating conditions when heat exchanger