Energy Conversion and Management 92 (2015) 431–436

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Performance evaluation of an ejector subcooled vapor-compression refrigeration cycle

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ARTICLE INFO

Article history:
Received 22 October 2014
Accepted 29 December 2014
Available online 16 January 2015

Keywords:
Refrigerating system
Ejector
Subcooling
Performance

ABSTRACT

In this study, a novel vapor-compression refrigeration cycle with mechanical subcooling using an ejector is proposed to improve the performance of a conventional single-stage vapor-compression refrigeration cycle. In the theoretical study, a mathematical model is developed to predict the performance of the cycle by using R404A and R290, and then compared with that of the conventional refrigeration cycle. The simulation results show that the performance of the ejector subcooled cycle is better than that of the conventional cycle. When the evaporator temperature ranges from −40 to −10 °C and the condenser temperature is 45 °C, the novel cycle displays volumetric refrigeration capacity improvements of 11.7% with R404A and 7.2% with R290. And the novel cycle achieves COP improvements of 9.5% with R404A and 7.0% with R290. In addition, the improvement of the COP and cooling capacity of this novel cycle largely depends on the operation pressures of the ejector. The potential practical advantages offered by the cycle may be worth further attention in future studies.

1. Introduction

Vapor-compression refrigeration cycles are widely used in a variety of refrigerator, air conditioner and heat pump systems [1,2]. They contribute an appreciable part of energy consumption in energy use, and thus improving their energy efficiency is of paramount importance. In practical applications, nevertheless, various thermodynamic losses in the cycles make the system performance to degrade, Ahamed et al. [3]. Therefore, many attempts to improve the vapor-compression refrigeration cycle efficiency by using cycle modifications have been made over the past decades. Typically, using mechanical subcooling for COP increase in vapor-compression refrigeration cycles is a known method [4,5]. For examples, Qureshi et al. [6,7] proposed a dedicated mechanical subcooling cycle to enhance the system COP and confirmed that the second-law efficiency of the cycle could be significantly increased through the subcooling. Yang and Zhang [8,9] applied the mechanical subcooling for an integrated supermarket refrigeration system and demonstrated the merits of the mechanical subcooling method with appropriate subcooler designs. Torrella et al. [10] carried out an experimental analysis on a two-stage refrigerating cycle with a subcooler system and showed a gain in COP of the two-stage cycle.

In addition, other subcooling methods have been also proposed in the literatures to improve vapor compression refrigeration cycles. These methods include the air conditioning system utilizing a cold storage unit as a subcooler, the heat pump system with ice storage subcooler and the refrigeration system subcooled by liquid desiccant dehumidification as well as the CO_2 transcritical vapor compression cycle with thermoelectric subcooler [11–15]. Relevant analytical or experimental results in the literatures all confirmed improvements in performance when using the new subcooling methods in vapor compression refrigeration cycles. In general, various active subcooling methods could provide potential way of increasing refrigerating effect and cycle efficiency for conventional vapor-compression refrigeration cycles.

In this paper, a mechanical subcooling method using an ejector is proposed to improve the performance of a single-stage vapor-compression refrigeration cycle. With the use of the ejector and an additional mechanical pump, the equivalent subcooling effect in the cycle can be realized, resulting in the improved cooling capacity and coefficient of performance (COP) of the cycle system. In fact, ejector refrigeration and its combined system are widely investigated by many researchers [16,17]. In the normal ejector refrigeration, ejectors have since been used in steam ejector refrigeration applications driven by heat, where a boiler, an ejector, and a pump are used to replace the mechanical compressor of a conventional vapor compression refrigeration system [18–22]. In a steam ejector refrigeration system, the ejector utilizes the motive

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http://dx.doi.org/10.1016/j.enconman.2014.12.091
0196-8904/

Nomenclature

COP	coefficient of performance
h	specific enthalpy (kJ kg^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
P	pressure (kPa)
q	volumetric capacity (kJ m^{-3})
$\dot{Q}_c$	refrigeration capacity (kW)
t	temperature (°C)
v	specific volume (m^3 kg^{-1})
w	velocity (m s^{-1})
$\dot{W}$	input power (kW)
Greek letters	
μ	entrainment ratio
π	pressure ratio
η	isentropic efficiency
Subscripts	
c	condenser, compressor
d	diffuser
e	evaporator
m	mixed flow
n	nozzle
p	primary flow, pump
s	secondary flow, isentropic process
1	inlet, the first nozzle
2	outlet, the second nozzle
1–10, 9′, 10′	state points of refrigerant

stream generated from the boiler to draw low pressure refrigerant from the evaporator, resulting in the refrigerant to evaporate at low pressure and produce the useful refrigeration. Thus, the ejector plays a vapor compression role in the ejector refrigeration system. It is worth noting that ejector applications in vapor-compression refrigeration cycles have also been concerned in the past. Previous researches have been mainly concentrated on the ejector as an expansion device in vapor compression refrigeration cycles [23–25]. These research revealed the advantage of using the ejector for enhancing the efficiency and cooling capacity of the cycles. This study is to further the ejector application in a single-stage vapor-compression refrigeration cycle for refrigeration, and provide a description of the ejector subcooling method as well as benefits from the use of the technology. The purpose of this work aims at the development of a novel vapor compression cycle for refrigeration with use of the ejector and an additional mechanical pump. The major improvement proposed hereby is a mechanical subcooling method by an ejector device.

2. Cycle description and modeling

The cycle configuration for the proposed vapor-compression refrigeration cycle with mechanical subcooling is shown in Fig. 1(a). Compared to a conventional vapor-compression refrigeration cycle (CVRC), the cycle has a main circuit coupled with a subcooling circuit. The main circuit consists of a compressor, a condenser, a flash tank, an evaporator and two expansion valves (EVs). The subcooling circuit includes a mechanical pump and an ejector. In the cycle, the refrigerant liquid leaving the condenser (point 4) is separated into two streams, and the main refrigerant flow expands through the first expansion valve and enters the flash tank (point 5). The saturated refrigerant liquid coming from the flash tank (point 7) is diverted through the second expansion valve to the evaporator (point 8) to produce refrigerating effect. The refrigerant vapor from the evaporator (point 1) is compressed by the compressor, and then is discharged to the condenser (point 2). Another portion of refrigerant liquid leaving the condenser is driven through the compression process of the mechanical pump to the ejector (point 9) to entrain the saturated refrigerant vapor from the flash tank (point 6), and the two-phase mixed refrigerant fluid (point 10) returns to the condenser. Then, the two fluids from both the compressor and ejector are again mixed and diverted to the condenser (point 3). The corresponding *P*–*h* (pressure–specific enthalpy) diagram for the cycle is shown in Fig. 1(b). In the *P*–*h* diagram, process paths 9–9′, 9′–10′ and 10′–10 are the expansion process, mixing process and compression

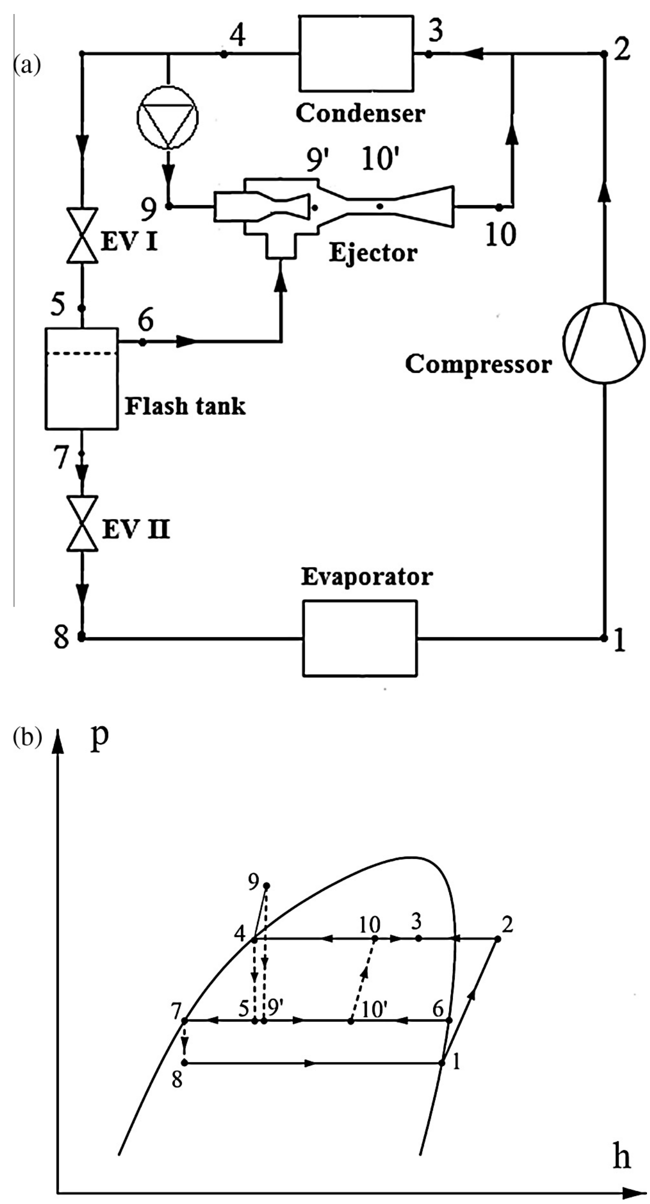

Fig. 1. The ESVRC cycle: (a) schematic system; (b) *P*–*h* diagram.