Applied Thermal Engineering 79 (2015) 108–116

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research paper

Thermodynamic analysis of the two-phase ejector air-conditioning system for buses

Şaban Ünal*, Tuncay Yilmaz

Department of Mechanical Engineering, Osmaniye Korkut Ata University, 80000 Osmaniye, Turkey

HIGHLIGHTS

- Thermodynamic analysis of the two-phase ejector refrigeration system.
- Analysis of the COP increase rate of bus air-conditioning system.
- Analysis of the entrainment ratio of the two-phase ejector refrigeration system.

ARTICLE INFO

Article history:
Received 3 August 2014
Accepted 7 January 2015
Available online 16 January 2015

Keywords:
Thermodynamic analysis
Two-phase ejector
Bus air-conditioning
Coefficient of performance

ABSTRACT

Air-conditioning compressors of the buses are usually operated with the power taken from the engine of the buses. Therefore, an improvement in the air-conditioning system will reduce the fuel consumption of the buses. The improvement in the coefficient of performance (COP) of the air-conditioning system can be provided by using the two-phase ejector as an expansion valve in the air-conditioning system. In this study, the thermodynamic analysis of bus air-conditioning system enhanced with a two-phase ejector and two evaporators is performed. Thermodynamic analysis is made assuming that the mixing process in ejector occurs at constant cross-sectional area and constant pressure. The increase rate in the COP with respect to conventional system is analyzed in terms of the subcooling, condenser and evaporator temperatures. The analysis shows that COP improvement of the system by using the two phase ejector as an expansion device is 15% depending on design parameters of the existing bus air-conditioning system.

1. Introduction

Air-conditioning systems are available in almost all buses where the compressor of the air-conditioning system is driven by a pulley connected to the engine shaft. This results in an extra load on the engine and hence the fuel consumption is increased. Another major problem on the buses is the weight of the vehicle where even a slight decrease in the weight is significant. There are obligatory standards regarding the weight of the buses. For instance, the gross vehicle weight of a bus with two axles cannot be over 18 tons and the rear axle load cannot be over 11.5 tons [1]. If the bus has a lighter empty vehicle weights, it can have the more advantageous about the passenger and baggage capacity. Due to the enhancement with the ejector air-conditioner, fuel consumption can be reduced by increase in COP and it is possible to select smaller size air-conditioner elements such as condenser, evaporator and compressor; whereas empty vehicle weight of the bus would be lower.

There are many studies on ejector refrigeration systems. Research on the ejector refrigeration systems commenced early 1900 where a lot of theoretical and experimental studies are presented on the two-phase ejector refrigeration systems. Experimental studies have been generally carried out using small-capacity systems. It was noticed that there has not been any study in open literature on the use of two-phase ejector in bus air-conditioners.

In the beginning of 1900's, ejector refrigeration system, which used water vapor, was developed in order to be used for cooling the train passenger compartments. As well as theoretical modeling, the system was practically applied and tested in a wagon [2]. The studies presented by Keenan et al. [3,4] have been the reference guide for ejector studies. They presented a mathematical model of an ejector assuming the air as the working fluid. Air was assumed as the ideal gas and the mixing zone was assumed to have a constant

* Corresponding author. Tel.: +90 328 827 1000x3687; fax: +90 328 825 0097.
E-mail address: saban.unal@osmaniye.edu.tr (Ş. Ünal).

http://dx.doi.org/10.1016/j.applthermaleng.2015.01.023
1359-4311/

Nomenclature

A	cross sectional area [m^2]
COP	coefficient of performance [-]
E	energy [J]
h	enthalpy [J kg^{-1}]
$\dot{m}$	mass flow rate [kg s^{-1}]
P	pressure [N m^{-2}]
$\dot{Q}$	cooling capacity [W]
s	entropy [J kg^{-1} K]
T	temperature [°C]
V	velocity [ms^{-1}]
W	compressor work [W]
β	kinetic energy ratio [-]
η	efficiency [-]
ω	entrainment ratio [-]

Subscripts

c	condenser
$comp.$	compressor
d	diffuser
$e1$	primary evaporator
$e2$	secondary evaporator
is	isentropic
k	kinetic
n	nozzle
m	mixing section
pf	primary flow
sc	subcooling
sf	secondary flow
$sh1$	superheating for primary evaporator
$sh2$	superheating for secondary evaporator
std	standard

cross sectional area. The theoretical results were concurrently compared with experimental results. In ejectors, the analytical results obtained by an assumption of one-dimensional flow were consistent with the experimental results in literature.

Performance of the conventional refrigeration cycle can be improved using a two-phase ejector as an expansion device. Kornhauser [5] investigated the effect of using of two-phase ejector in a vapor compression refrigeration system for various refrigerants on the coefficient of performance of the system. Seven refrigerants have been investigated, namely R11, R113, R114, R500, R502, R22 and R717. According to his results, refrigerant R502 had the highest performance and he showed that 21% increase in COP can be obtained by integrating ejector to the system. Disawas and Wongwises [6,7] used two-phase ejector as an expansion device in the vapor compression refrigeration system. Their experimental results showed that the coefficient of performance of the ejector refrigeration system was higher as compared to a conventional system. They reported COP improvement of 5–10 % using R134a when operating the standard two-phase ejector cycle as a liquid recirculation cycle. The effects of the throat section and the exit diameter of the nozzle were examined, and the related experimental results were given by Chaiwongsa and Wongwises [8,9]. They indicated that COP of a R134a system would be highest or lowest while the nozzle throat diameter is 0.8 mm or 1.0 mm, respectively. Pottker et al. [10] presented experimental results for using R410A as the refrigerant in the ejector refrigeration system. They specified that the coefficient of performance is between 8.2% and 14.8% higher than the conventional system using the same working conditions. Also, Hu et al. [11] investigated the nozzle parameters numerically and experimentally for R410A ejector air conditioning system. They explained that the ejector with adjustable nozzle can meet the requirements of different operating conditions according to experimental results. Redrick et al. [12] indicated that, 11% improvement in COP can be achieved compared to the conventional system when the ejector is used as an expansion device in a vapor compression refrigeration system with R134a. In a theoretical study which aimed to improve coefficient of performance by increasing the pressure in the entry of the compressor, it was stated that 10.5%–30.8% of improvements can be provided as compared to a conventional system [13]. Lawrence and Elbel [14] conducted an experimental study on ejector refrigeration system where R134a and R1234yf refrigerants were used. They stated that the coefficient of performance was increased 6% and 5% for R1234yf and R134a, respectively. Also, Lawrence and Elbel [15] examined the ejector refrigeration system concerning the first and second law of thermodynamics. They explained that the standard two-phase ejector cycle has lower availability destruction and higher second law efficiency than the alternate ejector cycles despite having the same theoretical COP. In the alternate two-phase ejector refrigeration cycle, the liquid at the outlet of the condenser is split into two separate streams; one stream is sent to the motive nozzle of the ejector, and the other is sent to the expansion valve. The refrigerant is vaporized in the secondary evaporator and sent to the suction nozzle of the ejector. Then the two streams mix in the ejector mixing section and enter a primary evaporator, where they are vaporized before returning to the compressor. Bilir Sag et al. [16] performed the energetic and exergetic analysis of the ejector expander refrigeration systems. This experimental study was conducted on vapor compression refrigerators using R134a refrigerant for the purpose of achieving energy recovery and decreasing the effects of irreversibility. They showed that when the ejector was used as the expander in the refrigeration system, the coefficient of performance was higher than in the basic system by 7.34–12.87%, while the exergy efficiency values were 6.6–11.24% higher than in the basic system. Ameur et al. [17] presented a mathematical model for the design and simulation of two-phase ejectors. They indicated that the computational results were quite compatible with experimental data. Preliminary experimental results on the R134a refrigeration system using a two-phase ejector as an expander were given by Ersoy and Bilir Sag [18]. They specified the work recovery in the ejector was between 14% and 17%. It was found that the COP can be improved by 6.2–14.5% compared with the conventional system by using the two-phase ejector as an expander. Lin et al. [19,20] investigated the adjustable ejector in a multi-evaporator refrigeration system experimentally and numerically. They showed that the pressure recovery ratio can reach 20% compared with the experimental results. Li et al. [21] presented a study on experiment and analysis of variable area ratio ejector used in a multi-evaporator refrigeration system. The investigation results indicate that the entrainment ratio, pressure recovery ratio and critical area ratio are strongly affected by the primary and secondary pressures.

In this study, the bus air-conditioning system with two-phase ejector is introduced, and then a mathematical model is developed for the thermodynamic analysis. In general, R134a is used as the refrigerant in current air-conditioning system with of buses. Therefore, two-phase ejector refrigeration cycle is analyzed for the bus air-conditioning application with refrigerant R134a. It was