Applied Thermal Engineering 64 (2014) 182–191

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Investigation of ejectors in refrigeration system: Optimum performance evaluation and ejector area ratios perspectives

Jianyong Chen, Hans Havtun*, Björn Palm

Division of Applied Thermodynamics and Refrigeration, Department of Energy Technology, Royal Institute of Technology (KTH), Brinellvägen 68, 100 44 Stockholm, Sweden

HIGHLIGHTS

- Ejector model very accurate at optimum working conditions.
- Entrainment & area ratio, mixing pressure most dependent on condenser conditions.
- Ejector efficiencies are crucial parameters in the present model.
- Model suited for parametric analysis and optimum performance evaluation.

ARTICLE INFO

Article history:
Received 28 June 2013
Accepted 16 December 2013
Available online 26 December 2013

Keywords:
Ejector
Refrigeration system
Optimum performance
Entrainment ratio
Area ratio

ABSTRACT

This paper presents an ejector model to determine the optimum performance as well as obtaining the design area ratio of an ejector in a refrigeration system. Working fluid properties and auxiliary dynamic equations are used to model the processes in the ejector. The normal compression shock in the mixing chamber is considered. Experimental data from literature are used to validate the model, and the agreement with the model at optimum operating conditions is very good. The deviation between the model and the experimental data at non-optimum conditions is slightly larger.

A study of working conditions for refrigerants R123 and R141b indicates that the condenser temperature has more influence than the generator and evaporator temperatures on the area ratio and the entrainment ratio in the ejector. Furthermore, area ratios need to keep up the pace with the variation of entrainment ratio as operating conditions are changed. A variable-geometry ejector seems a very promising alternative to ensure that the ejector refrigeration system operates at its optimum conditions. Ejector efficiencies play a very important role in the present model, and the influence of the efficiencies on the ejector performance is investigated. This ejector model may be used for parametric analysis and optimum performance evaluation as well as ejector design.

1. Introduction

The ejector is widely known as a no-moving-part pump device or a non-mechanical compressor, requiring no maintenance and no lubrication. An ejector refrigeration system employs an ejector to fulfill the function of a compressor. The system can be driven by low-grade thermal energy and enables the reduction of mechanical work requirement, which makes it particularly attractive in this energy-conscious era. Numerous theoretical and experimental studies have been conducted to comprehend the mechanisms of the ejector working processes and characteristics of the system performance [1–4]. Results from these studies have generally confirmed a mechanical energy saving, low running cost, as well as an environmentally friendly concept. The ejector refrigeration system has great potential for a wide field of applications.

Fig. 1 shows the schematic diagram of a typical ejector refrigeration system, consisting of a generator, a condenser, an evaporator, an ejector, a circulation pump and an expansion valve. Low-grade heat energy (Q_g) is delivered to the generator for vaporization (g,i → g,o). The high-pressure vapor out from the generator, i.e. the primary flow, enters into ejector nozzle and draws low-pressure vapor from the evaporator, i.e. the secondary flow. The two flows undergo mixing and pressure recovery in the ejector (g,o & e,o → c,i), and is then fed into the condenser, where condensation takes place by rejecting heat to the environment (Q_c). The liquid from the condenser is divided into two parts. One goes through the expansion device (c,o → e,i) to the evaporator (e,i → e,o), where it evaporates and hence produces

* Corresponding author. Tel.: +46 (0) 87907426; fax: +46 (0) 8204161.
E-mail address: hans.havtun@energy.kth.se (H. Havtun).

1359-4311/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.applthermaleng.2013.12.034

Nomenclature

A	area (m^2)
Ar	ejector area ratio
COP	coefficient of performance
Er	relative error
h	specific enthalpy (kJ kg^{-1})
k	heat capacity ratio
$\dot{m}$	mass flow rate (kg s^{-1})
M	Mach number
M^*	critical Mach number
P	pressure (kPa)
P^*	critical pressure (kPa)
P'	mixing pressure (kPa)
Q	heat load (kJ)
s	entropy (kJ kg^{-1} K^{-1})
T	temperature (°C)
u	velocity (m s^{-1})
W	work (kJ)

Greek symbols

μ	entrainment ratio
η	efficiency

Subscripts

c	condenser
cal	calculation result
d	diffuser
e	evaporator
exp	experimental data
g	generator
i	inlet
m	mixing
n	nozzle
o	outlet
pump	circulation pump
0–5	ejector locations in Fig. 2

the refrigerating effect (Q_e). The rest of the liquid is pumped back to the generator via the pump (c,o → g,i), and completes the cycle.

The ejector, as the key component, is essential to the system performance and the cost of system operation. A better understanding of the flow phenomena inside the ejector is very important for ejector design and operation. Mathematical modeling provides an efficient approach to study the ejector performance for the purpose of identifying the technological options for geometry, operation conditions, refrigerant properties, real fluid behavior, etc. [5]. The very first ejector model was proposed by Keenan et al. [6] who used one-dimensional method and assumed two mixing models: the first is that the primary flow and secondary flow are mixed at constant pressure (known as the constant-pressure mixing theory), the second is that mixing of the two flows occurs at a constant area (known as the constant-area mixing theory). Munday and Bagster [7] explained the well-known constant capacity constraint of a fixed-geometry ejector by two choking phenomena: one in the primary through the nozzle and the other in the secondary flow. They claimed that the primary flow fans out without mixing with the secondary flow and induces a converging duct for the secondary flow accelerating it to sonic velocity at some place with a hypothetical throat area, called the "effective area, A_e". By assuming that the "effective area A_e" is located in the constant area section of the mixing chamber and using constant-pressure mixing, Huang et al. [8] postulated a 1D model to analyze the ejector

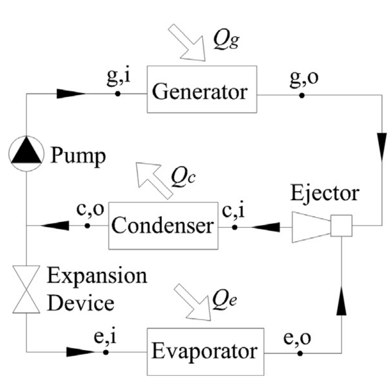

Fig. 1. Typical ejector refrigeration system.

performance at critical mode operation with R141. Yu et al. [9] applied the working fluid properties in an ejector model to compare the performance of a conventional ejector refrigeration system with a new system which incorporated an auxiliary liquid–gas ejector to enhance subcooling for the refrigerant from condenser. Zhu et al. [5] derived a two-dimensional exponential expression for the velocity distribution by introducing a "shock circle" at the entrance of the constant area section, and proposed a shock circle model for prediction of the ejector performance at the critical mode operation. El-Dessouky et al. [10] developed a semi-empirical model for designing or evaluation of steam ejectors. A few empirical models, based on the experimental data, have also been proposed [11–13]. During the last few decades, the Computational Fluid Dynamics (CFD) technique has been widely employed to investigate the effects of ejector geometrical parameters on its performance. The typical models and methods for ejector analysis are categorized in Table 1.

The main findings of these studies are: (1) the constant-pressure mixing theory is more extensively used in ejector refrigeration systems than the constant-area mixing theory; (2) both the ejector behavior and the whole system performance significantly depend on the ejector geometries, operating conditions and working fluid properties; (3) for a fixed-geometry ejector, there exists a critical back pressure limiting the flow rate. The performance will worsen dramatically beyond this critical condition; (4) empirical and semi-empirical models are restricted to specific ranges of applications, and other analytical models are more general and based on some assumptions for simplification; (5) most of these models are either used for ejector design, where the ejector refrigeration system operating conditions and the entrainment ratio are predefined, or applied to performance evaluation, where operating conditions and the ejector geometry are known. Moreover, they are mainly dealing with fixed-geometry ejectors.

In practice and theory, the mixing pressure in the ejector is lower than the secondary flow pressure to entrain the flow from the evaporator in the real ejector working process [16]. However, this mixing pressure is sometimes simply assumed to be the same as the secondary flow pressure [9]. In this paper, a one-dimensional model is developed based on the ejector model proposed by Yu et al. [9]. It further takes into account the lower mixing pressure and the shock process, using of auxiliary dynamic equations for coupling the mixing pressure. A correlation