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Performance analysis and optimization of an ejector refrigeration system using alternative working fluids under critical and subcritical operation modes

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ABSTRACT

Ejector systems are receiving considerable attention due to their simplicity, lower maintenance requirements, use of low grade heat, longer lifespan and low cost. In this paper an improved model to predict the performance of an ejector refrigeration system under both the critical and subcritical modes of operation was developed and validated. The model predicts ejector performance more precisely compared to studies following the same modeling approach in the literature. Using the developed model, performances with environmentally benign refrigerants, including R1233zd(E), HFO1336mzz(Z), R1234ze(Z), R600, RE245fa2, and RE245fa2 as alternatives to R141b and R245fa were investigated. Furthermore, for ejector area ratios between 4.45 and 12.98, evaporator temperatures between 0 °C and 16 °C and condenser temperatures between 20 and 40 °C, the optimal performance of the ejector system was determined. Results show that for each refrigerant, higher area ratios give higher coefficients of performance, but require higher generator temperatures for better critical condensing temperatures. R600 showed the best performance followed by R1234Ze(Z) and R1233Zd(E) for the entire range of parameters considered. Results further show that there is an optimum generator temperature at each area ratio that maximizes performance. The optimal generator temperature increases as the area ratio and the condensing temperature increase. An alternative and more convenient approach to optimize ejector performance has been suggested in this work.

1. Introduction

1.1. Background

Heating, ventilation, air conditioning, and refrigeration (HVAC&R) systems for residential and service sectors account for about 40% of the total primary energy supply in developed countries [1]. The continued reliance on fossil fuels to supply this energy leads to increased emission of CO_2, and significantly accelerating global warming. Another drawback of the current HVAC&R systems is the widespread use of the vapor compression cycle that uses electricity derived mainly from fossil fuels and refrigerants that are harmful to the environment. To reduce energy usage in HVAC&R systems and subsequently curb CO_2 emissions, there are several research and development initiatives toward sustainable, clean, and renewable energy systems. HVAC&R systems that are less reliant on fossil fuels are increasingly being studied and developed. Systems requiring low grade energy from renewable energy resources or waste heat are especially receiving considerable attention. They include absorption refrigeration systems, adsorption systems, desiccant refrigeration systems and ejector refrigeration systems [2].

Among these systems, the ejector refrigeration system is a promising technology that is receiving considerable attention. It is simple, low cost, and does not have moving parts, thus highly durable and less costly to operate when compared to the vapor compression system [3]. Moreover, it can be activated by low grade heat available from several sources, including waste heat, solar energy, and biomass energy, making it easy to deploy in areas with no access to the grid. Several researchers have investigated the performance of ejector refrigeration systems. Both experimental and theoretical studies have been conducted. Modeling and simulation of ejector refrigeration systems provide a means of screening different ejector geometries and investigating performance under different working conditions with ease and at lower costs compared to experimentation. Several models have been proposed and developed for this purpose. Most of the studies are based on the 1-D model initially developed by Keenan et al. [4], who postulated that the pressure of the primary and secondary flow was equal at the nozzle exit

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Nomenclature

a	speed of sound, $m\,s^{-1}$
A	area, m^2
A_3	mixing section cross-section area, m^2
A_{p1}	ejector nozzle exit area, m^2
A_r	ejector area ratio
A_t	nozzle throat area, m^2
c_p	specific heat capacity at constant pressure, $J\,kg^{-1}\,K^{-1}$
COP	coefficient of performance
d	diameter, m
h_{eo}	enthalpy at the evaporator outlet, $J\,kg^{-1}$
h_{ei}	enthalpy at the evaporator inlet, $J\,kg^{-1}$
h_{gi}	enthalpy at the generator inlet, $J\,kg^{-1}$
h_{go}	enthalpy at the generator exit, $J\,kg^{-1}$
h_{co}	enthalpy at the condenser exit, $J\,kg^{-1}$
$\dot{m}$	mass flow rate, kg/s
M	Mach number
P	pressure, Pa
P_c	condensing/back pressure, Pa
P_e	evaporator pressure, Pa
P_g	generator pressure, Pa
R	gas constant, $J\,kg^{-1}\,K^{-1}$
$\dot{Q}_e$	rate of energy flow in the evaporator, J/s
$\dot{Q}_g$	rate of energy flow in the generator, J/s
T	temperature, K
u	velocity, $m\,s^{-1}$
$\dot{W}_p$	pumping power, J/s

Greek symbols

ϕ_p	loss coefficient between the nozzle exit and mixing section
ϕ_m	mixing loss coefficient
ϕ_{mp}	mixing loss coefficient for the breakdown model
ϕ_p	loss coefficient between the nozzle exit and mixing section
k	isentropic index
η_p	nozzle efficiency
ρ	density, $kg\,m^{-3}$
μ	entrainment ratio

Subscripts

cc	critical mode of operation
ci	subcritical mode of operation
cb	ejector breakdown point
c	condenser
e	evaporator
g	generator
m	mixing/mixed flow
$m2$	mixed flow for the breakdown model
p	primary flow
$p1$	nozzle exit
$2p$	primary flow at the mixing section
$2s$	secondary flow at the mixing section
s	secondary flow
t	nozzle throat
xp	primary flow at section *x-x,* only for the breakdown model
xs	secondary flow at section *x-x,* only for the breakdown model
3	diffuser inlet

and that the mixing of the two fluids begins at the start of the constant area section. This theory has been adopted widely in most research studies on ejector systems [5,6]. Table 1 highlights the experimental and theoretical studies on ejector refrigeration systems.

As the reviewed studies in Table 1 show, in ejector modeling, the precise prediction of ejector performance requires correct specification of ejector loss coefficients. Most studies in the literature have used constant ejector loss coefficients with significant errors [5,6,18]. The recent works by Li et al. [21,22] indicated that these coefficients should be functions of the ejector area ratio and the ejector pressure ratio for improved accuracy. As the first objective of this study, correlations of the loss coefficients have been derived to improve the 1-D model in Huang et al. [5] following the same approach in this widely used model. In addition, a simpler and easier approach using non-linear regression is followed to determine the ejector coefficients compared to the more complicated sparsity-enhanced optimization technique in Li et al. [21].

1.2. Review of studies on ejector systems using environmentally friendly working fluids

The choice of working fluids (refrigerants) in ejector refrigeration systems plays a fundamental role in determining the system's performance. In addition to safety, toxicity, flammability and corrosivity considerations, the mounting regulatory pressure now dictates that high global warming potential (GWP) refrigerants are phased out [24]. Therefore, several researchers have looked at different environmentally benign working fluids for use in ejector systems over the years. Cizungu et al. [25] investigated the performance of an ejector refrigeration system working with 'environmentally benign' refrigerants including, R123, R134a, R152a, R717 and R11. R11 and R123 have since been banned owing to their ozone depletion potentials (ODP) being greater than zero [26], while R134a has a high GWP and in the process of being phased out [24]. Dahmani et al. [27] obtained ejector performance with R134a, R152a, R290 and R600a as working fluids. Kasperski et al. [28] studied the performance of an ejector system working using R236ea, R236ca, R245ca, R245fa, R356mfc, RC318, Acetone, Benzene, Cyclohexane, Cyclopentane and Toluene as working fluids. They relied on the Huang et al. [5] model which predicts ejector performance with significant errors. Chen et al. [29] considered performance of an ejector refrigeration system under overall working modes with R134a, R152a, R290, R430A, R245fa, R600, R600a and R1234ze as working fluids. The ejector component efficiencies were considered constant in the study.

Tashtoush et al. [30] examined the performance of an ejector system under superheated flow conditions with R152a, R290, R141b, R123, R600a, R600, R717 and R134a using a 1-D modeling approach based on the ideal gas model. They used the model proposed in Chen et al. [18] which gave significant deviations from experimental data. Roman and Hernandez [31] investigated an ejector system using R290, R152a, R134a, R600a, R600 and R123 as working fluids. The system with R290 had the highest COP while that with R123 gave the lowest COP. In a recent study, Gill and Kasperski [32] considered the use of ethers and fluorinated ethers as refrigerants in the ejector refrigeration cycle. They obtained maximum COP values of 0.30 and 0.25 for dimethyl ether and diethyl ether, respectively which have GWPs of 1 and 4, respectively [32]. Like their earlier study in Kasperski et al. [28], a computer program based on the modeling approach of Huang et al. [5] was used.

From the above literature review, most of the earlier studies in the literature have considered refrigerants with high GWPs or ones with ODPs greater than zero. Refrigerants R141b, R123, R245fa, and R134a have been widely considered as working fluids in the ejector