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Optimum design of ejector refrigeration systems with environmentally benign fluids

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ABSTRACT

A design methodology for simple ejector refrigeration systems of fixed cooling capacity operating with fixed temperatures of the external fluids entering the generator, the condenser and the evaporator is presented and applied for a particular combination of these four parameters. The results establish the existence of optimum values for the refrigerant pressure in the generator (P_G) and the temperature difference in the heat exchangers (ΔT) which minimize the total thermal conductance of the system. These optimum values of P_G and ΔT are particularly interesting since they yield high values for the coefficient of performance and the exergetic efficiency of the system. They have been determined for four refrigerants (R134a, R152a, R290, and R600a). An objective function, which to a first approximation is proportional to the product of the capital and operational costs, is defined and used to compare the performance of the system with these refrigerants.

1. Introduction

Cooling in industrial processes, air-conditioning of buildings and refrigeration of perishable products are common practices throughout the world. In industrialized countries the energy consumption of such installations, used to create and maintain relatively low temperatures, represents an appreciable part of the corresponding total. In Canada, for example, approximately 10% of the total annual energy consumption is used for such operations.

The systems used to achieve heat removal from a low temperature reservoir are driven either mechanically (e.g. compression of vapor refrigerants) or thermally (e.g. absorption systems or ejector driven systems). The former constitute the vast majority of industrial, commercial and residential installations but the latter are attracting a lot of interest since they can be activated by low temperature renewable energy sources (e.g. solar) or industrial waste heat. Absorption systems use a combination of two fluids and have been commercially available for several decades but are quite complex due to the simultaneous heat and mass transfer processes in the absorber and desorber. Furthermore, the fluid combinations used in absorption systems are very limited in number. On the other hand, ejector systems use a single fluid and thus offer great flexibility and promise for the replacement of environmentally unacceptable refrigerants by benign ones. However, except for one very recent automotive application, ejector systems are not available commercially.

The father of ejector technology is Charles Parsons who used them to extract the air from the condensers of steam engines but their first application in refrigeration was introduced in 1910 by Maurice Leblanc as indicated by Chunnanond and Aphornratana [1] who compiled a review of studies on ejectors and their application in refrigeration. The first model of the transformations taking place in the ejector was published by Keenan et al. [2] who used the one-dimensional equations of mass, momentum and energy conservation assuming perfect gas behavior and isentropic expansion. This approach does not reflect the complexities due to real fluid properties. Thus, for example, the entrainment ratio of an ejector does not depend on the ratio of the primary to secondary total pressures, as predicted by perfect gas theory, but on the individual values of these pressures [3,4]. Therefore, recent numerical studies [5–8] use real fluid thermophysical properties for the design of ejectors and the prediction of the off-design performance of ejector refrigerators.

Aidoun and Ouzzane [5] used a one-dimensional, adiabatic, compressible fluid model and the NIST database and subroutines for the refrigerant properties to investigate operation at design and

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Nomenclature

A	area, m^2
COP	performance coefficient
Cp	specific heat, kJ/kg K
Ed	destroyed exergy, kJ/kg
e	specific exergy, kJ/kg
F	objective function
GWP	global warming potential
h	specific enthalpy, kJ/kg
$\dot{m}$	mass flow rate, kg/s
ODP	ozone depletion potential
P	pressure, kPa
Q	heat quantity, kW
s	specific entropy, kJ/kg K
T	temperature, °C
UA	thermal conductance, kW/K
V	velocity, m/s
v	specific volume, m^3/kg
W	power, kW
x	quality of vapor–liquid mixture

Indices

0	reference state
C	condenser
E	evaporator
Ej	ejector
Ex	exergetic
G	generator
i	state
p	primary
s	secondary
t	throat

Greek letters

ΔT	temperature difference in the heat exchangers, °C
η	efficiency
ω	entrainment ratio

off-design conditions for refrigeration and heat pumping applications. They showed that some degree of superheat (around 5 °C) at the ejector inlet is necessary to prevent condensation while excessive superheat is detrimental to the condenser efficiency. Furthermore, they established that internal superheating due to inefficient mixing and normal shocks are very important in off-design operation. Finally, they demonstrated that, for a fixed refrigeration capacity, the performance is significantly influenced by the generator pressure and the evaporator temperature.

Boumaraf and Lallemand [6] used a steady-state simulation program to investigate the effect of different refrigerant mixtures and pure refrigerants on the performance of ejector cooling systems. Their results show that the use of a binary mixture does not always increase the performance of the system. Generally, when the mixture is strongly zeotropic (e.g. R22/RC318), the cooling efficiency of the system decreases. However, when the mixture is mildly zeotropic (e.g. R134a/R142b), or almost azeotropic (e.g. R134a/R152a), the cooling and exergetic efficiencies increase.

Selvaraju and Mani [7] developed a computer code based on one-dimensional ejector theory which includes the effects of friction in the mixing chamber. Since a better performance with higher entrainment ratio is obtained when the ejector is operated at chocking-mode they used the code to establish the relation between operating parameters, the ejector area ratio and the entrainment ratio.

Yu et al. [8] also used a similar one-dimensional approach and real fluid properties to compare the performances of a conventional ejector refrigeration system with a novel one incorporating an additional liquid–vapor jet pump. The variation of the new system's coefficient of performance with generator temperature and condenser pressure was analyzed for two refrigerants (R134a and R152a). Their results show that the COP of the new system is higher but that it also requires more pump power.

It should be noted that three of the four numerical studies mentioned above (i.e. Refs. [5,7,8]) only model the thermodynamic processes of the refrigerant and do not consider the three external fluids which supply or receive heat in the generator, evaporator and the condenser. Furthermore, to the best of our knowledge, no study of such systems has attempted to establish a relation between their performance and the size, or at least the thermal conductance, of these three heat exchangers. This constitutes one of the objectives of the present study.

Experimental results have been reported by Eames et al. [9] who tested an ejector refrigeration system using low pressure steam (2–3.6 bar, or 120–140 °C, at the boiler) and found that the experimental data was approximately 85% of the theoretical values. These experiments also showed that choking of the secondary flow plays an important role in the system performance. Maximum COP was obtained when the ejector was operated at its critical flow condition.

Other interesting experimental results were presented by Aphornratana and Eames [10] who showed the benefit of using an ejector with a primary nozzle that can be moved axially in the mixing chamber, by Huang and Chang [11] who tested 15 ejectors using R141b as the working fluid and by Selvaraju and Mani [12] who studied the influence of generator, evaporator and condenser temperatures on the performance of an ejector refrigeration system using R134a as the working fluid. They reported that for a given ejector geometry and fixed condenser and evaporating temperatures, there exists an optimum temperature of the primary vapor which maximizes the entrainment ratio and the COP.

In two conference presentations [13,14] the present authors have analyzed ejector refrigeration systems using R134a as the working fluid. In the present study we show and discuss analogous results based on classical and finite size thermodynamics for four different refrigerants selected on the basis of thermodynamic and environmental criteria. Contrary to experimental studies which normally determine the effect of variable operating conditions on a system of fixed configuration and size, the objective of the present study is to analyze the design of such systems for typical engineering conditions. For this purpose the cooling capacity of the system and the temperature of the external fluids entering the three heat exchangers (vapor generator, condenser, evaporator) are fixed. The model of the system as well as the numerical procedure for its solution are described. The calculated results for a particular combination of the four previously mentioned parameters show the effects of the refrigerant and two independent variables (the pressure of the refrigerant in the vapor generator and the temperature difference in the three heat exchangers) on the COP and exergetic efficiency of the system, on the primary and secondary mass flow rates of the working fluid, on the mass flow rate of the three external fluids and on the total thermal conductance of the three heat exchangers. A non-dimensional objective function, proportional to the total thermal conductance of the three