Applied Energy 179 (2016) 1020–1031

Contents lists available at ScienceDirect

Applied Energy

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

Effects of design conditions and irreversibilities on the dimensions of ejectors in refrigeration systems

Mohammed Khennich, Nicolas Galanis, Mikhail Sorin *

Mechanical Engineering Department, Université de Sherbrooke, Sherbrooke, QC, Canada

HIGHLIGHTS

- New model uses polytropic efficiencies η_{pol} and determines all ejector dimensions.
- The effects of η_{pol} on ejector dimensions and mixing efficiency are evaluated.
- The effects of inlet/outlet conditions on ejector dimensions are evaluated.
- The total exergy losses increase linearly when the mixing efficiency decreases.
- Inlet/outlet pressures which reduce exergy losses and total length are determined.

ARTICLE INFO

Article history:
Received 15 March 2016
Received in revised form 12 July 2016
Accepted 15 July 2016

Keywords:
Thermodynamic model
Polytropic efficiency
Ejector dimensions
Flow field determination

ABSTRACT

A thermodynamic model for the design of ejectors is described, validated and applied for conditions prevailing in refrigeration systems. Contrary to previous models the present one determines all the dimensions of the ejector and uses polytropic (instead of isentropic) efficiencies thus taking into account the effects of the pressure ratio on the entropy increase during the irreversible acceleration and deceleration processes. The results include dimensions and fluid properties for a base case as well as a parametric study which analyzes the effect of inlet and outlet conditions on the dimensions and efficiencies of the acceleration, deceleration and mixing processes. The parametric study coupled to recommended constraints from the literature leads to the determination of design conditions for which the axial evolution of pressure, temperature and velocity are determined. The effects of the polytropic efficiency on the ejector dimensions and the efficiencies of the processes taking place in the ejector are also presented and analysed. It is also shown that the total exergy losses increase linearly when the mixing efficiency decreases.

1. Introduction

Ejectors, also known as jet pumps, are simple mechanical devices using the low pressure created by the accelerated stream of a primary (or motive) fluid to aspirate and compress a secondary (or entrained) fluid. Their overall efficiency is generally lower than that of competing technologies such as mechanical compressors. However, they offer important advantages over these technologies because they do not have any moving parts. As a result the cost of fabrication is small and maintenance requirements are low.

Ejectors have multiple and diverse applications: they are used in steam and nuclear power plants, in the handling of granular materials, in medical uses and in certain desalination plants [1]. They are also used as vapour compressors in ejector operated refrigeration systems [2,3], which were popular in the early 1930s, and are receiving renewed interest since they can be activated by low-grade thermal energy from renewable sources [4–6] or thermal wastes from combustion engines [7,8] thus reducing the use of fossil fuels or improving the efficiency of their usage. Although in some applications one of the two fluids can be a liquid and the two fluids may be different, the present study focuses on the case where the two fluids are identical vapours.

Despite the simplicity of ejectors, the flow field within them is complex and includes subsonic and supersonic velocities, shock waves interacting with boundary layers and mixing of streams with very different velocities and densities. Thus the design of an ejector for a given application is often based on empirical correlations even though many studies have proposed models for this purpose. These models can be classified as thermodynamic (or one-dimensional) and 2D or 3D differential models using CFD techniques for their solution [9]. All of them are based on appropriate

* Corresponding author.
E-mail address: Mikhail.V.Sorin@USherbrooke.ca (M. Sorin).

http://dx.doi.org/10.1016/j.apenergy.2016.07.053
0306-2619/

Nomenclature

A	cross-sectional area (mm^2)
D	diameter (mm)
Ex	exergy flux (kW)
e	specific exergy (kJ/kg)
F	force (N)
f	friction coefficient (–)
h	specific enthalpy (kJ/kg)
L	length (mm)
M	Mach number (–)
$\dot{m}$	mass flowrate (kg/s)
P	pressure (kPa)
PR	compression ratio = P_1/P_6 (–)
s	specific entropy (kJ/kg K)
T	temperature (°C, K)
V	velocity (m/s)
X	position of nozzle exit (mm)

Greek letters

ε	wall roughness (mm)
η	efficiency (–)
φ	half-angle (deg)
ω	entrainment ratio = $\dot{m}_s/\dot{m}_p$ (–)

Subscripts

4, 7	thermodynamic states
D	diffuser
d	downstream of shock
is	isentropic
mix	mixing
p	primary
s	secondary
th	throat
tot	total
u	upstream of shock

steady-state expressions of the mass, energy and momentum conservation principles and neglect heat transfer between the fluids and the ejector walls.

Fig. 1a shows the main parts of an ejector and defines the half-angles of converging and diverging parts as well as the lengths of the ejector parts. It can be used to describe qualitatively its operation. The converging-diverging nozzle serves to accelerate the primary fluid, which can be saturated or superheated vapour, from its stagnation conditions at state 4 (P_4, T_4, $V_4 = 0$) through the throat (state th) to supersonic conditions with a very low pressure at its exit (state 7p). This low pressure aspirates and accelerates the secondary fluid from its stagnation conditions at state 6 (P_6, T_6, $V_6 = 0$) to the low-pressure high-velocity state (7s). In general at cross-section (7) the pressure, temperature and velocity of the two streams are not the same. The two streams then mix in a highly irreversible process which may include oblique shocks. The resulting supersonic homogeneous fluid undergoes a second series of shocks somewhere in the constant area duct which causes an important increase of its pressure. This shock train is depicted as a normal shock in Fig. 1a as in all 1D models of flow in ejectors. At the inlet of the diffuser (state 8) the flow is therefore subsonic and decelerates towards the exit conditions (state c) where the velocity is very low and the pressure is higher than at state 8. The corresponding stagnation conditions are (P_1, T_1, $V_1 = 0$).

Fig. 1b illustrates the typical performance of an ejector. It shows that for a given geometry and fixed inlet conditions the entrainment ratio ($\omega = \dot{m}_s/\dot{m}_p$) is independent of the back pressure (P_1) when the latter is below a critical value P^*; for such conditions the primary and secondary flows are choked so that any variations of the back pressure have no influence upstream of Section 7. For back pressures higher than P^* the secondary flow is subsonic and its flowrate $\dot{m}_s$ decreases rapidly as the back pressure increases. It becomes zero when the back pressure reaches the limiting value P_{lim}; for back pressures higher than P_{lim} the ejector malfunctions, i.e. part of the primary flowrate $\dot{m}_p$ is diverted and exits through the secondary inlet. If the pressure of the motive fluid P_4 is increased the maximum entrainment ratio decreases while the critical and limiting back pressures increase.

By assuming perfect gas behaviour as well as isentropic expansions for the primary/secondary fluids and for the compression in the diffuser Keenan et al. [10] proposed one of the first models for one-dimensional ejector flow. However, this model does not reflect accurately the operation with real fluids, such as refrigerants, and does not take into account the inevitable irreversibilities.

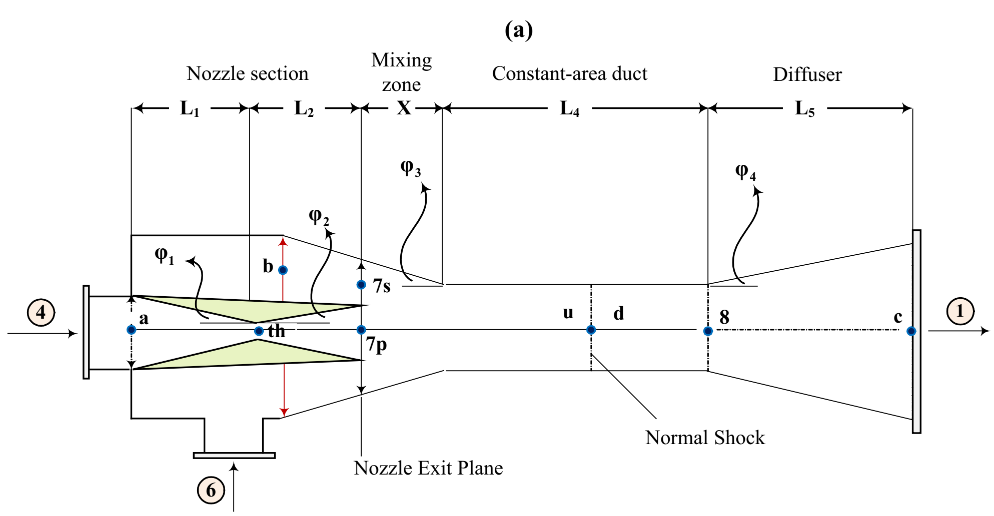

Fig. 1a. Ejector geometry, parts and main cross-sections.