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Investigations on driving flow expansion characteristics inside ejectors

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ABSTRACT

This research investigates the Mach wave structure of the driving flow under off-design working conditions by both numerical and experimental methods. By adopting the method of characteristics as the simulation model, prediction of the driving flow regime inside an ejector is obtained. The simulation results are further validated by an experimental visualization method conducted using a Schlieren system. Through this investigation, the influence of Mach wave on the driving flow boundary development is discussed. The expansion wave from the nozzle exit increases the driving flow regime in the under-expanded condition, which has a negative impact on ejector performance. The results show that the Mach wave should be considered when the ejector is operated under off-design working conditions. The results also demonstrate that an appropriate nozzle structure design was able to restrain the effect of the expansion wave, which improves ejector performance. The results are significant for achieving a comprehensive understanding of the mechanism of an ejector, as well as for the applications, such as ejection refrigeration cycles.

1. Introduction

Large-scale applications for air conditioning and refrigeration systems consume huge amounts of energy and cause environmental problems. Efforts to reduce the level of energy consumption in these applications have led to renewed interest in heat recovery systems. Heat recovery refrigeration systems are an alternative to vapor-compression refrigeration systems. In these systems, low-grade heat such as solar energy or exhausted heat can be utilized as the driving energy. The ejection refrigeration cycle is one example of such heat recovery systems, and it has the following advantages: simple-structure, reliability, and low-cost. In recent years, the number of journal papers focusing on ejectors or ejection refrigeration cycles has grown rapidly [1]. Ejectors have been investigated in the field of waste-heat utilization [2] and in ejector–vapor-compression hybrid cycles [3]. In CO_2 heat pump systems, ejectors are employed as expansion devices to reduce throttling losses [4]. In addition, a number of studies on solar-driven ejection refrigeration cycles [5–10] have been conducted.

Fig. 1 shows the structure of an ejector with the flow regime and Mach wave inside. The ejector comprises of a motive nozzle and a suction chamber. High pressure refrigerant, known as the driving flow, is accelerated through the motive nozzle and converted into high velocity flow with low pressure. The suction flow is entrained into the ejector from the suction flow inlet. The flow from the motive nozzle exit is then divided into two regimes: the driving flow regime and the suction flow regime. On the shear layer of the driving flow boundary, part of the kinetic energy from the driving flow is transferred to the suction flow. The two flows will finally mix in the mixing section and jet outward from the diffuser. The performance of the ejector is described by the parameter *ER* (the Entrainment Ratio) and *PR* (the Pressure Ratio) as shown by Eqs. (1) and (2).

$$ER = \dot{m}_{\text{suctionflow}}/\dot{m}_{\text{drivingflow}} \tag{1}$$

$$PR = P_b/P_{s,0} \tag{2}$$

In Fig. 1, P_e and $P_{s,0}$ represent the pressure of the driving flow and the suction flow at the nozzle exit, respectively. There are two locations inside of the ejector where Mach waves may occur. In those locations, the Mach wave could manifest as an expansion wave or shockwave based on the expansion or compression effect on the supersonic flow. The driving flow Mach wave may occur at the nozzle exit, and the mixed flow shockwave may occur in the diffuser, where the mixed flow changes to subsonic from supersonic. There are three conditions for the driving flow: If P_e is larger than $P_{s,0}$, the driving flow is in an under-expanded condition and expansion waves will occur. On the other hand, if P_e is smaller than $P_{s,0}$, the driving flow is in over-expanded condition, and shockwaves will occur. The ideally-expanded condition is reached if P_e is equal to $P_{s,0}$. Mach wave does not occur in the ideally-expanded condition.

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Nomenclature

Notations Units

A	cross-sectional area
A	local sonic velocity
AR	area ratio
C	characteristic curve
Cp	specific heat capacity
D	diameter (mm)
ER	Entrainment Ratio
h	specific enthalpy
I	information of a grid point (x, y, u, v)
Iter	iteration number
M	Mach number
$\dot{m}$	mass flow rate
N	grid number
P	pressure
R	gas constant
T	temperature
U	velocity component in x direction
V	velocity component in y direction
V	velocity
Q	terminologies applied in the finite differential equations
$OS\gamma$	specific heat ratio
β	Mach angle
θ	velocity angle
λ	Mach line angle
σ	flow deflection angle
Δ	constant for axisymmetric flow

Subscripts

b	back pressure
d	driving flow
e	nozzle exit
m	mixing section
n	surface number inside the ejector
max	maximum value
s	suction flow
t	nozzle throat
x	x direction
y	y direction
+	left-running curve
–	right-running curve
0	static condition
1, 2, 3...	numbers of iteration

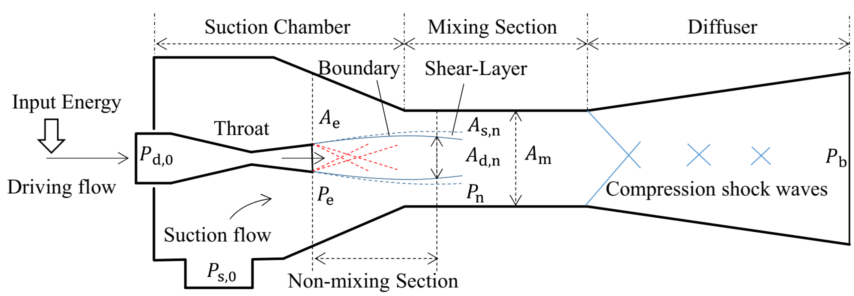

Fig. 1. Schematic of the ejector and the Mach wave positions.

In the one-dimensional theoretical model, the driving flow development is assumed as isentropic-expansion from the nozzle exit. The constant-pressure mixing theory proposed by Keenan et al. [11] and the non-mixing process between the driving and suction flows proposed by Munday and Bugster [12] were adopted to describe the working process of the ejector. In the models, *ER* is obtained from the cross-sectional flow areas of the driving and suction flow in the non-mixing section. Since the ejector structure is fixed, the relationship of the flow areas could be obtained by Eq. (3), and the calculation process of *ER* was introduced in the one-dimensional model developed by Huang et al. [13].

$$A_{s,n} + A_{d,n} = A_m \tag{3}$$

In applications such as waste heat utilization, a relatively stable heat source temperature could maintain the optimum-expand condition for the ejector. Yet, in other cases, especially for solar energy utilization, the driving flow will be in either the over-expanded or under-expanded condition. This is due to the fact that the ideally-expanded condition cannot be maintained because the solar energy input is fluctuating. Under off-design conditions, Mach waves may develop and influence the ejector performance. Shock-waves in the over-expanded condition cause irreversible energy loss in the driving flow. On the other hand, expansion waves in the under-expanded condition creates radial velocity components in the driving flow, which will reduce the flow area of the suction flow regime. To employ ejection cycles in solar energy utilization, the influence of Mach wave should be considered. However, there have not been many studies aimed toward the occurrence of Mach waves and its influence on ejector performance.

In this research, the Mach wave in the gas-ejector at the off-design working condition is discussed. The influence of Mach wave on the driving flow expansion, as well as the ejector performance, is investigated numerically and experimentally. A numerical approach using the method of characteristics model is adopted to predict the driving flow expansion inside an ejector. The simulation results are further validated by visualization experiments conducted using the Schlieren photography method. The research reveals the influence of Mach wave on the ejector performance, which is significant for the application of solar-driven ejection–refrigeration cycles.

2. Prior work on model development of an ejector

Following the models proposed by Keenan et al. [11], Munday, and Bugster [12], Huang et al. established and validated a one-dimensional model in which an isentropic process was considered for the driving flow expansion inside of an ejector [13]. Eames also proposed an ejection–refrigeration cycle evaluation method using