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Effects of the nozzle configuration on solar-powered variable geometry ejectors

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ABSTRACT

The variable geometry ejector (VGE) used in solar-powered ejector refrigeration systems enables performance regulation with unstable heat input, which is important in solar energy utilization; however, the ejector performance is significantly affected by the nozzle configuration. To study the effects of the nozzle configuration on the VGE and to optimize the VGE configuration, experimental investigations are conducted on a supersonic nozzle and a subsonic nozzle used in the VGE under a variety of operating conditions. The experimental results show a close relationship between the driving flow behavior and the ejector performance. The driving flow behavior is influenced by the occurrence of Mach waves, which is significantly influenced by the nozzle configuration. Numerical simulations are conducted that further explain the Mach wave behavior as well as the driving flow development inside the VGE. The results are significant for the optimization and application of the variable geometry ejector in solar-powered ejector refrigeration systems.

1. Introduction

1.1. Solar-powered ejector refrigeration system

To alleviate the large energy consumption caused by building air-conditioning, there is a renewed and growing interest in the applications of heat-recovery refrigeration systems. Heat-recovery refrigeration systems directly convert heat to cooling load. This can be a potential alternative to the vapor-compression refrigeration systems. Meanwhile, as the most accessible low-grade energy source, solar energy has been widely adopted to function as a heat source in heat-recovery refrigeration systems.

Currently, the application of heat-recovery refrigeration systems is limited by their low system performance. In addition, even though solar energy is considered to be cost-free, accessible solar energy is usually limited by restricted space for solar heat collectors in urban areas. To effectively harvest solar energy, thermo-mechanical refrigeration systems have been proposed to combine the utilization of heat and electricity. The efficiency of the compression system can be enhanced using the cooling capacity provided by the heat recovery system. Meanwhile, the efficiency of heat recovery refrigeration systems can also be enhanced in a two-stage system, which solves the problem of space requirements for solar collectors. As stated in a review conducted by Abdulateef et al. (2009), ejector refrigeration systems have been widely adopted in thermo-mechanical refrigeration because of merits such as simple-structure, easy-maintenance, and eco-friendly. A schematic of the ejector-vapor compression refrigeration system is shown in Fig. 1. The solar-powered ejector-vapor compression refrigeration system was initially proposed by Sokolov and Hershgal (1993), and it was analyzed further by Sun (1997). Both researches proved the superiority of the hybrid refrigeration cycle over the traditional compression refrigeration cycle. A recent review conducted by Zeyghami et al. (2015) shows that there is an increasing number of investigations on the utilization of solar energy in ejector -vapor compression systems.

The performance of the ejector refrigeration system is crucial to the hybrid system. A number of experimental investigations have been conducted on solar-powered ejector refrigeration systems (Nguyen et al., 2001; Pollerberg et al., 2009; Allouche et al., 2012). The experimental results show the capability of ejector systems in utilizing solar energy; however, unstableness in system performance caused by unstable solar heat input was also been noticed in the studies. Dynamic simulation of the solar-powered ejector refrigeration systems also show the dependence of the ejector system on the variations in seasonal and daily solar radiation

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Nomenclature

A	area, mm^2
d	diameter, mm
L	length, mm
$\dot{m}$	mass flow rate, g s^{-1}
P	pressure, MPa
T	temperature, °C

Greek

σ	nozzle opening, %
β	diffuser diverging angle, °

Abbreviations

AR	area ratio
PR	pressure recovery ratio
ER	entrainment ratio, g g^{-1}
VGE	variable geometry ejector

Subscripts

mt	ejector-to-throat ratio
et	exit-to-throat ratio
c	condenser
e	nozzle exit
ev	evaporator
b	backpressure
d	driving flow
g	generator
s	suction flow
m	mixing section
n	nozzle

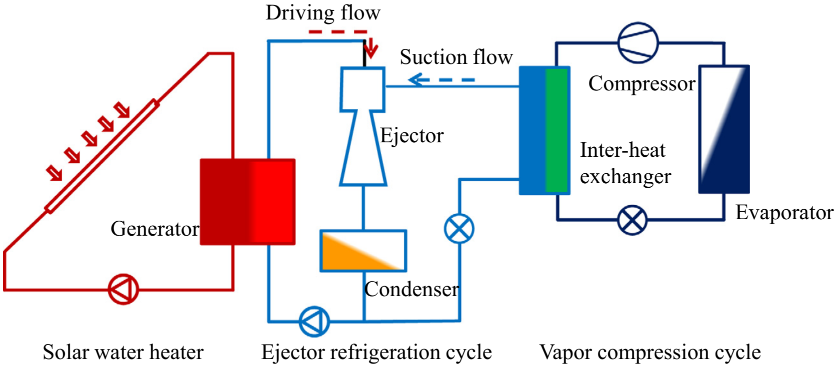

Fig. 1. Schematic of an ejector-vapor compression refrigeration system.

(Pridasawas and Lundqvist, 2007; Ersoy et al., 2007; Tashtoush et al., 2015; Vidal et al., 2006). Solutions to the unstableness in system performance have been proposed, and these include solar panel optimization (Zhang et al., 2012) or the addition of an additional heat reservoir to store the abundant solar heat (Diaconu, 2012; Joemann et al., 2016). These solutions have contributed to solar energy utilization efficiency and to the stability of system performance; however, the use of additional parts add to the complexity of the ejector refrigeration system.

Meanwhile, the variable geometry ejector (VGE) has been adopted in solar-powered ejector systems, and this has enabled the regulation of system performance. The application of VGE retains the simplicity of the ejector system, and therefore it has been widely investigated and applied in solar-powered systems.

1.2. Variable geometry ejector

An ejector comprises of a nozzle and a chamber as shown in Fig. 2. The driving flow with high initial pressure is converted to a fast flow with low pressure through the nozzle. Meanwhile, the suction flow is entrained into the mixing section. Part of the kinetic energy is transferred from the driving flow to the suction flow inside the mixing section. The suction flow is therefore accelerated in the mixing section and pressurized in the diffuser. In effect, the ejector functions as a compressor in the ejector refrigeration system. Eqs. (1) and (2) show two factors of the ejector performance evaluation. The entrainment ratio (*ER*) indicates the entrainment efficiency of an ejector and the pressure recovery ratio (*PR*) shows the suction flow pressurization ability of an ejector.

$$ER = \dot{m}_{\text{suction flow}}/\dot{m}_{\text{driving flow}} \tag{1}$$

$$PR = (P_\text{b} - P_\text{s})/P_\text{s} \tag{2}$$

$$AR_\text{mt} = A_\text{m}/A_\text{t} \tag{3}$$

A variable geometry ejector enables performance regulation by adjusting the ejector configuration, which is defined by the area ratio between the mixing section and nozzle throat as shown in Eq. (3). The experimental investigation conducted by Yapici et al. (2008) shows that a certain ejector-to-throat area ratio is exclusively correlated to only one defined operating condition. This characteristic indicates that a fixed-geometry ejector can only be optimized for a stable heat source, and the fixed-geometry ejector is incapable of providing stable performance with an unstable heat input. Fig. 3(a) shows the performance characteristics of a fixed geometry ejector. There is an upper limit of the backpressure (critical backpressure) to maintain consistency in performance. As the input heat is insufficient, the critical backpressure of the ejector falls below the actual backpressure, and the entrainment ability is therefore restrained by the backpressure. On the other hand, with an abundant heat input, the driving flow rate increases, and the mixing section diameter cannot be enlarged to entrain extra suction flow to consume the additional heat input. An experiment on the solar-powered ejector refrigeration system conducted by Smierciew et al. (2014) also confirmed such performance characteristics.