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Experimental and numerical investigation of the effect of shock wave characteristics on the ejector performance

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ABSTRACT

The entrainment performance and the shock wave structures in a three-dimensional ejector were investigated by Computational Fluid Dynamics (CFD) and Schlieren flow visualization. The ejector performance was evaluated based on the mass flow rates of the primary and secondary flows. The shock wave structures in the ejector mixing chamber were captured by the optical Schlieren measurements. The results show that the expansion waves in the shock train do not reach the mixing chamber wall when the ejector is working at the sub-critical mode. Decreasing of the shock wave wavelength increases the secondary mass flow rate. A three-dimensional CFD model with four turbulence models was then compared with the experimental data. The results show that the RNG k-ε model agrees best with measurements for predictions of both the mass flow rate and shock wave structures.

Etude expérimentale et numérique de l'effet des caractéristiques d'onde de choc sur la performance de l'éjecteur

Mots clés : Ejecteur ; Schlieren ; Modélisation à l'aide de la mécanique des fluides numérique ; Longueur d'onde de choc ; Modélisation de la turbulence

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Nomenclature

m	mass flow rate, kg s^{-1}
P	pressure, MPa
T	temperature, K
ω	entrainment ratio, m_S/m_P

Subscripts

P	primary flow at nozzle inlet
S	secondary flow at ejector inlet
B	ejector outlet
t	nozzle throat

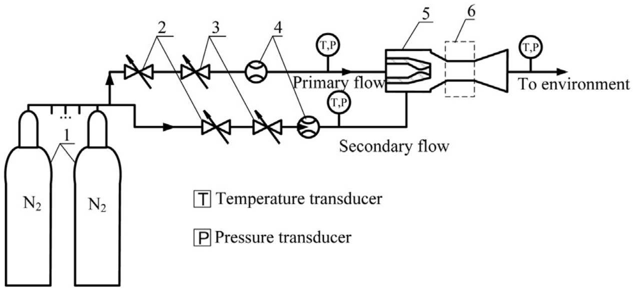

Fig. 1 – Experimental rig. 1 – High pressure N$_2$ tanks; 2 – Pressure relief valves; 3 – Terminal and control valves; 4 – Mass flow meters; 5 – Ejector; 6 – Schlieren measurement area.

1. Introduction

An ejector uses the venturi effect to convert the pressure energy of a motive primary fluid to kinetic energy to draw in and entrain a secondary fluid. The ejector is also known as a vacuum jet, jet pump or thermo-compressor for its different applications, where the primary and secondary fluids may be a liquid, steam or any other gas. The three different operational modes for ejectors are the critical mode, the subcritical mode and back flow mode. The ejector performance decreases linearly when working in the subcritical and the back flow modes. In the critical mode, the primary flow expands after the nozzle exit introducing a series of oblique shocks in the suction chamber and accelerates the secondary flow to choking in the mixing chamber, then the mixed flow shocks again in the diffuser. This phenomenon is known as double-choking (Huang et al., 1999). In the subcritical mode, the flow does not reach the choking condition in the diffuser (Single-choking) (Huang et al., 1999). Since the shock wave characteristics directly affect the ejector performance, a thorough understanding of relationship between the shock wave structure and the ejector entrainment is essential to design high performance ejectors.

Several ejector models have been used for theoretical performance evaluation. Keenan and Newman (1942) used a one-dimensional model to analyze ejectors. This model was later modified by Keenan et al. (1950) who introduced the concept of constant pressure mixing. Munday and Bagster (1977) used the "effective area, Ae" located some distance downstream of the primary nozzle to develop a theoretical ejector model. Huang et al. (1999) developed a 1-D analysis to predict the ejector performance based on the constant-pressure mixing assumption. Zhu et al. (2007) proposed a shock circle model to analyze the actual non-uniform velocity distribution by introducing a "shock circle" at the entrance of the constant-area mixing chamber.

The influences of the ejector operating conditions and geometric parameters on the performance have been analyzed numerically and experimentally. The experimental studies of Sun (1996), Chunnanond and Aphornratana (2004), Yapici et al. (2008), Ruangtrakoon et al. (2011) and the CFD studies reported in Riffat and Omer (2001), Bartosiewicz et al. (2005), Rusly et al. (2005), Sriveerakul et al. (2007), Hemidi et al. (2009), Ruangtrakoon et al. (2013) showed that moving the nozzle into the mixing chamber reduces the ejector performance. Aphornratana and Eames (1997) further studied the effect of the nozzle position on the system performance using an ejector with a movable primary nozzle. Zhu et al. (2009) investigated the effects of the primary nozzle exit position and the mixing section converging angle on the performance to obtain the optimum nozzle exit position and mixing section converging angle. Nakagawa et al. (2011) experimentally analyzed the effect of mixing length on the ejector system performance. The mixing length significantly affected the entrainment ratio and the magnitude and profile of the pressure recovery. Liu et al. (2012) investigated a variable geometries two-phase flow ejector to show that the motive nozzle efficiency decreases as the ejector throat area decreases. More recently, Kawamura and Nakagawa (2013) analyzed the characteristics of the two-phase flow oblique shock waves in the supersonic carbon dioxide two-phase flow.

The flow field distribution and the shock wave structure define the complex flow phenomena and the performance characteristics. Experimental flow visualizations have been

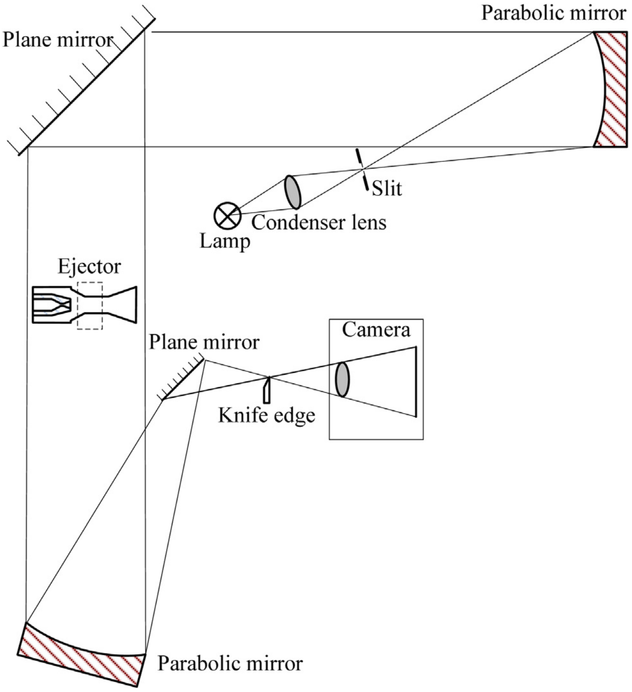

Fig. 2 – Schematic drawing of the Schlieren system.