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Numerical and experimental evidence of the Fabri-choking in a supersonic ejector

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ABSTRACT

The purpose of a supersonic ejector consists in the mixing of two fluids with different stagnation pressures in order to obtain a fluid at an intermediate stagnation pressure at the discharge. Depending on the geometry of the ejector and on the operating conditions, the entrained secondary stream may reach sonic/supersonic velocities within the ejector, leading to the capping of the entrained mass flow rate for fixed reservoir conditions. Although the associated limitation of the entrainment ratio (due to choking) is a well known phenomenon, there is still a lack of understanding of the complex flow phenomena at play within supersonic ejectors, and further detailed knowledge and modeling of the choking process is necessary. This paper presents a detailed analysis of the choking phenomenon through advanced post-processing of CFD calculations which are validated with experimental results both at the global and the local scales. This in-depth investigation of the choking phenomenon within the ejector is proposed both qualitatively and quantitatively for given reservoir conditions. The complex flow signature highlighted by means of the numerical results is then investigated and corroborated through experimental shadowgraphy. Studies combining experimental results (including visualizations) with numerical simulations are rather scarce in the open literature and to the knowledge of the authors, this study is the first one that proposes such a detailed analysis. For the present ejector geometry and operating conditions, the choking phenomenology of the secondary stream is found to closely correspond to the model of the Fabri-choking early postulated in Fabri and Siestrunck (1958).

1. Introduction

Supersonic ejectors are passive devices used in a wide range of applications, including refrigeration systems (Besagni et al., 2016) and propulsion (Tillman and Precz, 1995) to name but a few. Within a supersonic ejector, two fluids with different stagnation pressures are mixed to obtain a fluid with an intermediate stagnation pressure at the discharge. The stream with high stagnation pressure is known as the primary (or motive) stream while the entrained fluid with low stagnation pressure is referred to as the secondary (or suction) stream. In the present study, they are identified with the indices 1 and 2, respectively. The typical layout of an ejector is shown in Fig. 1. It essentially consists in a primary nozzle placed in a secondary nozzle whose throat is extended, thereby forming a *mixing duct*, also termed *mixing chamber*. Depending on whether the exit section of the primary nozzle lies in the converging part or in the constant-area section of the secondary nozzle, one generally refers to 'constant-pressure' or 'constant-area' mixing ejectors, respectively (Chunnanond and Aphornratana, 2004a).

Although the geometrical structure of a supersonic ejector is relatively simple, the compressible turbulent mixing occurring within is rather complex (He et al., 2009; Rao and Jagadeesh, 2014; Besagni et al., 2016). In a similar way to a single nozzle flow, the primary stream reaches sonic conditions in the vicinity of the throat of the primary nozzle and the primary mass flow rate, $\dot{m}_1$, is therefore not sensitive to downstream conditions. Hence it only depends on the primary reservoir conditions. This limitation of the mass flow rate in a nozzle is generally referred to as the *choking* condition (Shapiro, 1953). The primary stream further accelerates in the diverging part of the primary nozzle and thus comes out as a supersonic jet with high velocity and low static pressure. The secondary stream accelerates towards this low pressure region and is entrained within the ejector through a turbulent transonic mixing layer.

Depending on the geometry of the ejector and on the operating conditions, the secondary stream may also reach sonic/supersonic velocities within the ejector. As a consequence, for fixed reservoir conditions, the secondary mass flow rate, $\dot{m}_2$, may choke below a critical back-pressure, indicated as $p^*(x_b)$. Under these circumstances, the

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Nomenclature

ER	Entrainment ratio [-]
e_t	Specific total energy [J/kg]
$\overline{\boldsymbol{F}}_\xi$	Total mean-flow total exergy flux vector field [kg/s^3]
h_t	Specific total enthalpy [J/kg]
H_1	Height of the exit of the primary nozzle [m]
H_m	Height of the mixing duct [m]
I_ξ	Cumulative transfer of mean-flow total exergy [-]
k	Turbulent kinetic energy [J/kg]
M	Mach number [-]
$\dot{m}$	Mass flow rate [kg/s]
p	Static pressure [bar]
R	Specific gas constant [J/K/kg]
s	Specific entropy [J/K/kg]
T	Static temperature [K]
$\mathbf{u}$	Velocity vector field [m/s]
x	Horizontal coordinate [m]
x_b	Horizontal coordinate at the outlet of the ejector [m]
x_c	Horizontal coordinate at the choking position [m]
x_{nxp}	Horizontal coordinate at the nozzle exit position [m]
y	Vertical coordinate [m]
z	Span-wise coordinate [m]

Special characters

Δ	Gain in exergy of the secondary stream [-]
ξ_t	Specific total exergy [J/kg]
Π_Θ	Cumulative mean-flow total exergy losses related to heat transfer [-]
Π	Cumulative mean-flow total exergy losses related to viscous dissipation [-]
ρ	Density [kg/m^3]
ω	Specific turbulence dissipation rate [1/s]

Subscripts

ref	Reference conditions
0	Reservoir conditions
1	Value associated to the primary stream
2	Value associated to the secondary stream

Superscripts

*	Value calculated from the averaged flow quantities

ejector is said to operate in on-design (or critical) conditions. One also refers to double-choking operation since both flows are choked within the ejector. Beyond the critical pressure, the secondary flow is *unchoked* and is therefore sensitive to downstream conditions. The secondary mass flow rate rapidly decreases with increasing back-pressures until it reaches zero when the back-pressure equals a breakdown value. Between the critical and the breakdown back-pressures, the ejector is said to operate in off-design (or sub-critical) conditions. This regime is logically also known as single-choking operation as solely the primary stream is choked for this mode of operation.

A convenient way to depict the different operating modes of a supersonic ejector for fixed reservoir conditions is to show the characteristic curve of the ejector which represents the evolution of the entrainment ratio, $ER = \dot{m}_2/\dot{m}_1$, versus the back-pressure. A typical characteristic curve is shown in Fig. 2 where one may easily identify the different operating conditions outlined above.

Even though the limitation of the entrainment ratio for fixed reservoir conditions is a well known phenomenon, there is still a lack of understanding of the complex flow phenomena at play within supersonic ejectors (He et al., 2009). Hence, there is no generally accepted methodology for the design of ejectors to this day (Galanis and Sorin, 2016). This issue mainly stems from the difficulty of predicting the choked flow condition that exists in the ejector (Chou et al., 2001; Ruangtrakoon et al., 2013). Indeed, as pointed out in Chou et al. (2001), the performance of supersonic ejectors is limited by this choking condition which is consequently critical in their design and operation. Therefore, further detailed knowledge and modeling of the choking process is necessary (Mazzelli et al., 2015; Besagni et al., 2016).

From a general point of view, there are two main categories of models regarding the flow within supersonic ejectors: one-dimensional models (1D) and models based on computational fluid dynamics (CFD). Studies resorting to 1D models are plentiful, some of which date back to the early 1950's when (Keenan et al., 1950) applied a control volume analysis to the mixing of two streams using mass, momentum and energy conservation equations. A few years later, based on shadowgrams of the flow within a rectangular ejector, Fabri and Siestrunck (1958) imagined two phenomenologies concerning the choking of the secondary flow. According to the authors, when the stagnation pressure of the secondary fluid is sufficiently high, the maximum induced mass flow rate may be limited by the geometric throat located in the primary nozzle exit plane. In other words, in such cases, the secondary stream reaches sonic conditions at the location where it comes into contact with the primary stream. The authors named this phenomenology of choking the *saturated supersonic* flow pattern, which is also referred to as *choke I* in Chou et al. (2001). Obviously, the choking of the secondary flow in the saturated supersonic flow pattern does not require any

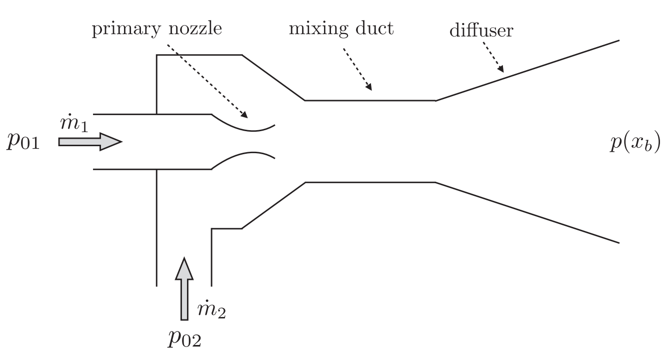

Fig. 1. Typical layout of a supersonic ejector.

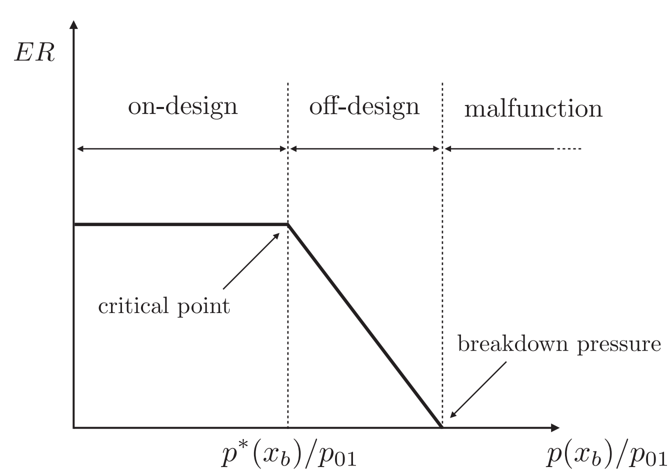

Fig. 2. Typical characteristic curve of a supersonic ejector.