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Pulsatory phenomenon in a thrust optimized contour nozzle

A. Nebbache *, C. Pilinski

CORIA-LMFN, UMR 6614, INSA de Rouen, BP8, 76801 Saint-Etienne du Rouvray, France

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Abstract

A numerical study of the flow in an axisymmetric overexpanded thrust optimized contour nozzle is presented. The separation flow structures at different pressure ratios are investigated. The start-up process exhibits two different shock structures. For a range of pressure ratios, hysteresis phenomenon occurs between these two separation patterns. For a larger pressure ratio, where the principal separation point is always inside the nozzle, another phenomenon appears. This phenomenon results in an oscillatory longitudinal quasi periodic movement of the separation structure. The computed nozzle wall pressures show a correct agreement with the experimental measurements and the pulsations frequency of the oscillatory phenomenon is also well predicted.

Keywords: Thrust optimized contour nozzle flow; Free shock separation; Restricted shock separation

1. Introduction

Thrust optimized contour (TOC) nozzle are currently used in launcher engines (Vulcain, SSME or J2S). These rocket nozzles are subject to flow separation in transient phase at engine start-up or engine shut-down. This separation phenomenon can also appear in overexpanded nozzle flow at fixed pressure ratio P_{i0}/P_a (P_{i0} and P_a are respectively the chamber and the ambient pressure). The flow separates whenever the wall pressure P_w is much lower than P_a. For example, in the Vulcain engine the separation phenomenon occurs when $P_w \leqslant 0.2 \times 10^5$ Pa. The flow issued from the TOC nozzles exhibit two different kinds of separation patterns for a certain range of pressure ratio P_{i0}/P_a. The first separation pattern is obtained when the separated flow continues as a free jet. In this case, the separation region extends from the separation point downwards the nozzle exit. This separation pattern is called free shock separation (FSS). This FSS pattern can be obtained in many different geometries of nozzles, and was reported in many publications dating from the 50s and 60s. The FSS pattern appears in thrust optimized contour nozzles for low pressure ratios P_{i0}/P_a [10]. The second separation pattern type, which is called the restricted shock separation (RSS), appears in the TOC nozzle for a high pressure ratio P_{i0}/P_a. In this separation pattern, the flow is reattached to the wall downstream of the separation point, forming a closed recirculation bubble. Moreover, the separation pattern evolves from a free shock separation to a restricted shock separation when the pressure ratio increases. Transitions between these two kinds of separation pattern present an hysteresis phenomenon. High peaks of side load are observed during transitions from FSS to RSS and back. This hysteresis phenomenon appears typically during the start-up and the shut-down process. The transition FSS ⇒ RSS occurs for pressure ratio value that is higher than the one observed for the RSS/FSS transition. This phenomenon, still imperfectly understood, was observed in many TOC nozzles. Experimental or numerical tests highlighted it, not only in subscale models supplied with cold air ([3,10,12] and [1]), but also, more recently, in rocket nozzles on real scale with hot gases. Onofri and Nasuti [11] like Frey and Hagemann [4] have observed it numerically in the nozzle of Vulcain engine. These results are in agreement with measurements of wall pressures and the visualization of jets [17]. In thrust optimized contour nozzles

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* Corresponding author.
E-mail address: nebbache@coria.fr (A. Nebbache).

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a weak internal shock is induced in the throat region, where the circular arc forming the nozzle throat turns into the further expansion contour. The role of this internal shock seems essential in the set up of a particular shock structure which is called by European engineers *cap shock*. This pattern is observed in the plume of the axisymmetric nozzle of Vulcain engine [4]. This shock structure deflects the flow and the slip line away from the nozzle axis, whereas, the free shock separation pattern leads to the classical Mach reflection where the slip line and the flow were deflecting towards the nozzle axis. The restricted shock separation with the cap shock pattern was confirmed by the Navier–Stokes computations ([3, 4,11] and [12]) which show at steady state, the presence of a recirculating core behind the Mach disk. This flow structure is associated to inverse Mach reflection process of internal shock [15]. The existence of the vortex behind the Mach disk has recently been confirmed experimentally by a laser velocimetry campaign on the plume of axisymmetrical nozzle [15]. The presence of the recirculation bubble behind the Mach disk, can be conveniently interpreted as a reaction of the flow to insure that the static pressure is always lower than the stagnation pressure [15]. The knowledge of nozzle separation phenomenon requires, primarily, a better prediction and understanding of the aerodynamic field. Therefore, the aim of this study is to simulate numerically the overexpanded turbulent TOC nozzle flow separation. The axisymmetrical subscale nozzle retained here for investigation is called LEA-TOC, and is currently tested at the Laboratoire d'Etudes Aérodynamiques (LEA) of Poitiers-France. Measurements on the LEA-TOC nozzle flow were realized by Nguyen et al. [1] to characterize the nozzle flow separation and the side loads. In addition to the experimental results obtained by Nave and Coffey [10] on the nozzle of a J-2S rocket engine, Nguyen et al. highlight an uncommon phenomenon at high pressure ratio. This phenomenon occurs in the TOC nozzle when the closed recirculation bubble, at the nozzle wall, opens to the surroundings under the effect of the displacement of the separation structure downstream of the nozzle. This phenomenon appears in experiments [1] in LEA-TOC nozzle for $P_{i0}/P_a = 44.8$, and results in a quasi periodic oscillatory longitudinal movement of the separation structure pattern. The operating gas used here is cold dry air at a stagnation temperature close to 270 K. For some stagnation conditions, the strong overexpansions of air in the divergent of the nozzle can lead to the condensation of oxygen. This condensation phenomenon leads to an increase of pressure and temperature by comparison with the ideal situation without condensation. The study of this nozzle flow has been carried out by solving the Reynolds averaged Navier–Stokes equations. Turbulence is modeled by the two-equation k–ω Shear-Stress-Transport (or SST) of Menter [9]. The SST model combines Wilcox's k–ω and k–ε high-Reynolds-number of Jones and Launder. This turbulence model has already been tested in a axisymmetrical truncated ideal contour nozzle flow (LEA-TIC nozzle) [14] and in a two-throat nozzle separated flow [13]. It has been also compared with other turbulence models [12] (the k–ε low-Reynolds-number model of Jones and Launder [6], the algebraic stress model of Apsley–Leschziner [2] and the multi-scales model of Kim [7]). In the same way, this model has shown a good accuracy in predicting separated flows. As the present calculations do not take into account the condensation phenomenon and its thermodynamic effects, noticeable differences between our simulation results and experiments must be expected, especially when the stagnation pressure is larger than the pressure which produces the condensation phenomenon. The objective of the study is to investigate numerically the turbulent overexpanded LEA-TOC nozzle flow with several pressure ratios values P_{i0}/P_a in the range 10.2 to 48.2. The numerical computations of the transient flow during start-up and shut-down allow to find and to check the thresholds of hysteresis phenomenon between FSS and RSS patterns. Then the study is devoted to a numerical reproduction of the oscillatory or pulsatory phenomenon.

2. Results and discussions

The numerical method that is used to solve the Reynolds averaged Navier–Stokes equations is the two-stage explicit-implicit finite volume method developed by MacCormack [8]. The accuracy of this predictor–corrector method is second order in time and space. The implicit step of the method removes the classical stability limitations of the explicit one. The block-pentadiagonal system resulting from the implicit step is solved by a line Gauss–Seidel method. The second order flux splitting technique is used in both explicit and implicit step. It was proposed by Steger and Warming [16] and is employed here to capture the shock wave. It also allows to maintain stability in high pressure gradient regions. The simulations are performed over a grid involving 484×160 cells inside the nozzle and 152×284 cells outside the nozzle. The two numbers correspond respectively to the streamwise and to the normal directions. In the normal direction, the mesh is refined close to the nozzle wall, in order to have a y^+ value less than 1 for the first cell.

2.1. Hysteresis phenomenon and the influence of pressure ratio

The hysteresis cycle could be obtained in LEA-TOC nozzle by numerical simulations. We search the successive steady states corresponding to FSS or RSS patterns for different given pressure ratio values. The first steady state for the pressure ratio of 10.2, is obtained by a start-up process. This first starting uses particular initial conditions. Thus at the inlet of the nozzle, the pressure and the temperature are equal to their stagnation values ($P_{i0} = 10.2 \times 10^5$ Pa and $T_{i0} = 270$ K), elsewhere, they are $p = P_a = 10^5$ Pa, $T = T_a = 288$ K and velocities are set to zero. Thereafter,