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Separated nozzle flow

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ABSTRACT

A separated turbulent flow in an axisymmetrical nozzle is studied numerically. Two configurations nozzle are investigated. The first one is the truncated ideal contour nozzle, DLR-TIC, is fed with nitrogen. The second configuration is called the thrust optimized contour nozzle or TOC type, ONERA-TOC, where the operating gas is a hot air. The classical pattern of a free shock separation is obtained for different values of the nozzle pressure ratio. The results are compared and validated using experimental data.

1. Introduction

The objective of this work is to simulate the turbulent nozzle flow. The ONERA-TOC nozzle without wall film cooling and the DLR-TIC nozzle are the configuration of the nozzle that are studied. The ONERA-TOC nozzle is like a nozzle of the Vulcain-2 rocket engine, which has downstream of its throat section a system to inject wall film cooling.

The ONERA-TOC nozzle is subject to flow separation in transient phase at start-up or shut-down. This separation phenomenon can also appear in overexpanded nozzle flow at a fixed nozzle pressure ratio (NPR), where $NPR = p_c/p_a$ (p_c and p_a are respectively the chamber and the ambient pressure). The flow issued from the TOC nozzle exhibits two different kinds of separation patterns for a certain range of pressure ratio. 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's 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 1950s and 1960s. The FSS pattern appears in thrust optimized contour nozzles for low pressure ratios p_c/p_a. The second separation pattern type, which is called the restricted shock separation (RSS), appears in the TOC nozzle for a high pressure ratio. 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 a 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 [10], [8], [3] and [11], but also, more recently, in rocket nozzles on real scale with hot gases. Onofri and Nasuti [12], like Frey and Hagemann [9], have observed it numerically in

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the nozzle of Vulcain engine. In thrust-optimized contour nozzles, 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 that is called by European engineers *cap shock*. This pattern is observed in the plume of the axisymmetric nozzle of Vulcain engine. This shock structure deflects the flow and the slip line away from the nozzle's 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's axis. The restricted shock separation with the cap shock pattern was confirmed by the Navier–Stokes computations [8], [9], [12] and [3], which show, at the steady state, the presence of a recirculating core behind the Mach disk. The existence of the vortex behind the Mach disk has been confirmed experimentally by a laser velocimetry campaign on the plume of an axisymmetrical onera-toc nozzle tested in the ONERA-R2Ch wind tunnel [13]. This 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 [13]. This flow structure is associated with an inverse Mach reflection process of internal shock [13].

The experimental or numerical overexpanded LEA-TIC nozzle flow studies [1] and [2] use cold dry air as operating gas at a stagnation temperature close to 270 K. For high nozzle pressure ratios ($NPR > 30$), the condensation phenomenon of oxygen appears in a region located behind the separation shock structure. Therefore, the flow becomes a two-phase one. In this condition, the perfect gas hypothesis is not fully valid. The two-dimensional axisymmetric numerical code used in that study does not take the effect of condensation into account. Nevertheless, the numerical results show wall pressure and separation point location distributions in reasonable agreement with measurements until the condensation of oxygen of air begins.

This calculation code does not deal with two-phase flows. At ONERA ("Office national d'études et de recherches aérospatiales") and DLR ("Deutsches Zentrum für Luft- und Raumfahrt"), experiments or numerical simulations on nozzle flows use hot air to avoid the condensation of oxygen occurring in the divergent nozzle.

Nevertheless, let us note that among the works relating to the two-phase flow, there is the study of I. Shih Chang [16] concerning the numerical simulation of a two-phase flow, gas-particle, in a nozzle. This work follows the need for a better understanding of the flow in rocket engine nozzle that uses a solid propellant. The combustion products are then burned gases and solid particles. The gas burned is supposed to be inviscid. The volume occupied by solid particles is assumed to be very low. The numerical scheme used is that of MacCormack [17].

The present paper concerns a separated turbulent flow in an axisymmetrical nozzle both DLR-TIC and ONERA-TOC without film injection. The gas operating used in the DLR-TIC nozzle is nitrogen. The ONERA-TOC nozzle flow is fed with hot air. The study of this turbulent nozzle flow has been carried out by solving the Reynolds averaged Navier–Stokes equations. The numerical method that is used is the two-stage explicit–implicit finite volume method developed by MacCormack [4]. The accuracy of this predictor–corrector method is second order in time and space. Turbulence is modeled by the two-equation $k - \omega$ Shear–Stress–Transport (SST) approach of Menter [5].

2. Viscosity and the fluid operating

The fluid operating is assumed to obey the perfect gas law ($p = \rho r T$). The isentropic exponent of nitrogen or air is $\gamma = 1.4$. The gas constants are set to $r = \frac{\mathbf{R}}{\mathbf{M}} = 297.0\ \mathrm{J{\cdot}kg^{-1}{\cdot}K^{-1}}$ for nitrogen and $r = 287\ \mathrm{J{\cdot}kg^{-1}{\cdot}K^{-1}}$ for air.

The molecular viscosity μ of air varies with temperature T. It is given by the Sutherland law as:

$$\mu = \mu_0 \sqrt{\frac{T}{T_0}} \frac{(1 + S/T_0)}{(1 + S/T)}$$

with $\mu_0 = 1.716 \times 10^{-5}\ \mathrm{kg{\cdot}m^{-1}{\cdot}s^{-1}}$, the molecular viscosity at reference temperature $T_0 = 273$ K, and $S = 111$ K.

The molecular viscosity of nitrogen varies also with temperature T, and it is computed as:

$$\mu = 0.694909\ 10^{-4} \left(1 + 0.323 \log\left(\frac{T}{91.46}\right)\right) \sqrt{\frac{T}{91.46}}$$

3. Computational domain and boundary conditions

For the two nozzle configurations, DLR-TIC and ONERA-TOC, the axisymmetrical domain (Figs. 4 and 5) is splitted into three parts: nozzle, jet, and bottom domain.

The sketch of the computational domain (see Fig. 5) shows the profile of the ONERA-TOC nozzle, which represents a kind of backward-facing step in its divergent. R_{exit} is the radius of the nozzle's exit. Along the nozzle wall or walls Σ_1, Σ_2, and Σ_3, the no-slip condition is assumed. These walls are considered to be adiabatic. The normal pressure gradient at these walls is close to zero. At the wall, the turbulent quantities are:

$$k = 0 \quad ; \quad \omega = \frac{60 \nu_w}{\beta_1 y_{\mathrm{n}_1}^2} \quad ; \quad \beta_1 = 0.075$$

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