AN EVALUATION OF THE SPALART-ALLMARAS TURBULENCE MODEL FOR THE SIMULATION OF THE BASE BLEED EFFECT

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This study presents results of numerical simulations with the research code named CARBUR (MHEQ team, IUSTI laboratory, Marseilles, France) in order to evaluate the Spalart-Allmaras model, recently added in the code, on base bleed configuration where a heavy-detached base flow interacts with an additional axial injection.

After a preliminary study of the blunt base test case (without injection) [1] which shows a relatively good agreement with experiments, and a quasi-similarity with other previous numerical studies, the highly detailed base bleed test case of Illinois [2,3,4,5] is simulated. Even if quantitatively, differences on base pressure levels are observed, the qualitative description of the flow is improved in comparison with previous laminar computations [6].

INTRODUCTION

Base-bleed principles

The aim of a base bleed system is to increase range of a projectile by increasing base pressure and so decreasing base drag. In the case of heavy detached flow, like base flow, a low pressure recirculating region, also called “dead air region”, exists against the base (Fig. 1, top). With a base bleed injection, this recirculating flow (labeled PRR for Primary Recirculating Region) is detached by the bleed gases, which escape from the bleed hole between the PRR and the external supersonic flow and create a secondary recirculating region (labeled SRR) against the annulus base (Fig. 1, bottom). For typical base bleed system in projectile configuration, gases usually come from the combustion of a propellant block in the base. For the following study, a wind-tunnel configuration is simulated in which the base has no boattail and injection is made axially.

Two parameters are important in base bleed problems: the injected mass flow rate and the temperature of the injected gases. Thermal effects are not investigated here, please refer to [7,8] for a study of the influence of the bleed gases temperature. To define the mass flow rate, the dimensionless injection parameter I is commonly used; it is the ratio of the bleed mass flow rate by the product of the base aera and the freestream mass flux (free stream characteristics are labeled *0*, and what corresponds to the base is labelled *b*):

$$I = \frac{\dot{m}_{bb}}{\rho_0 U_0 A_b} \tag{1}$$

The effect of the bleed rate on the structure of the near wake is classified into three regimes by “multi-component” methods (developed in the 1950’s). In regime I, the injected fluid provides a portion of the mass required for the shear layer entrainment process. The P.R.R decreases in strength, the recompression shock is weakened, and the base pressure increase approximately linearly with the rate of mass injection; this is the regime used for base bleed (Fig. 2). Regime II begins when the bleed flow rate is sufficient to provide all the fluid required by the entrainment process. At this transition point, the recompression shock is considerably weakened, and the base pressure is at a maximum level. As the bleed rate is increased further, the wake opens because the bleed jet contains enough momentum to penetrate through the recirculation region. Regime III is attained as the bleed rate is increased even further, and eventually leads to power-on conditions. The bleed flow acts as a highly underexpanded jet and the base pressure increases with the bleed flow rate. This regime is not used for base bleed applications.

Aim of the study

The main objective of this study is to evaluate the Spalart-Allmaras turbulence model on base bleed configurations. For that, the addition of the S-A model into our code has to be validated first: the well-known supersonic base flow test-case of Herrin & Dutton [1] is used.

MODELS AND NUMERICAL METHODS

The computer code used in this study has been developed in the IUSTI laboratory and was previously devoted to hypersonic flows. An exact Riemann solver and a second order accurate finite volume method, both in space and time, have been used [9].

The Spalart-Allmaras turbulence model has recently been added to the code. It is a single transport equation model for the variable $\tilde{\nu}$ [10]. The turbulent viscosity is calculated with $\mu_t = \rho \tilde{\nu} f_{V1}$ where f_{V1} is a damping function. A modified form of the model, including a compressibility correction [11] has been used:

$$\frac{\partial \bar{\rho}\tilde{\nu}}{\partial t} + \frac{\partial u_j \bar{\rho}\tilde{\nu}}{\partial x_j} = c_{b1}\tilde{S}\bar{\rho}\tilde{\nu} + \frac{1}{\sigma}\left[\frac{\partial}{\partial x_j}\left((\rho\nu + \bar{\rho}\tilde{\nu})\frac{\partial \tilde{\nu}}{\partial x_j}\right) + c_{b2}\frac{\partial \tilde{\nu}}{\partial x_j}\frac{\partial \bar{\rho}\tilde{\nu}}{\partial x_j}\right] - \bar{\rho}c_{w1}f_w\left(\frac{\tilde{\nu}}{d}\right)^2 \quad (2)$$

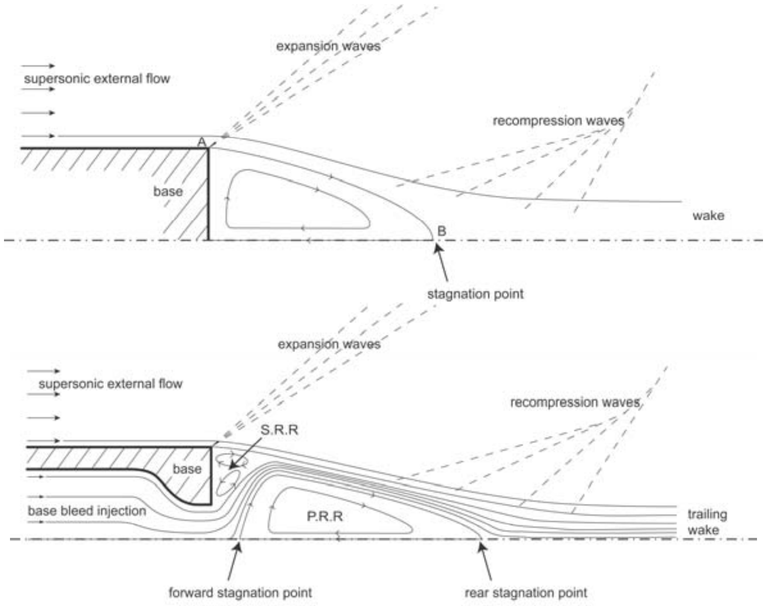

FIGURE 1 – (Top) Sketch of a blunt afterbody flow (without injection)
(Bottom) Sketch of a blunt base flow with base bleed – Wind tunnel configuration

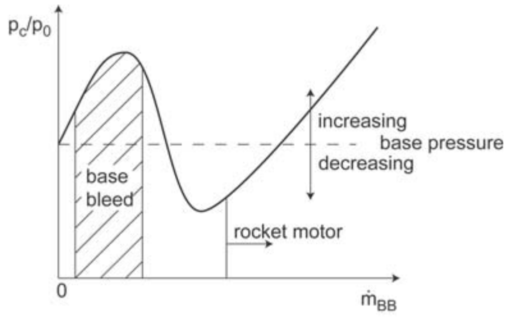

FIGURE 2 – Effect of basebleed on the base pressure ratio

PRELIMINARY STUDY: BLUNT BASE WITHOUT INJECTION

This first case is an experimental study from University of Illinois at Urbana Champaign by Herrin & Dutton [1] on a 63.5mm cylindrical afterbody. A supersonic air flow with the following characteristics: Mach number of 2.45 and Re = 52.10^6/m is considered. The major result of this experiments is a base pressure versus freestream static pressure ratio of P_b/P_0 =0.55 with a quasi-constant base pressure profile; this result is still a major objective for present research on turbulence models.

Results

The solution of the detached-flow is presented on figures 3 and 4. Contours of Mach number (Fig. 3) clearly show expansion waves centered on the base corner, recompression waves near the reattachement point (situated a x/R = 2.4) and the recirculating region against the base surface. Turbulent viscosity is produced in the approaching turbulent boundary layer, but only the high levels in the near wake - resulting from mixing mechanisms – can be observed on figure 4; the maximum value ($\mu_T / \mu_{lam} \approx 2500$) is reached near the reattachment point.

Axial velocities in the reverse flow reach a value of U/Uo = - 0.62 on the symetry axis (Fig. 5), which corresponds to a supersonic Mach number of 1.18. These over-estimated reverse velocities lead to a non-constant base pressure profile (Fig. 6): base pressure is over-estimated at the stagnation point on the axis, and under-estimated along the base surface. The mean base pressure value of P_b/P_0 = 0.35 is highly underestimated in comparison with experiments.

These results show a poor agreement with experiments but are still very interesting. First, they show a much better agreement than laminar computations, and secondly, they validate the implantation of the Spalart-Allmaras model in our code, as Paciori *et al.* show quasi-identical results with this model on the same configuration [12].

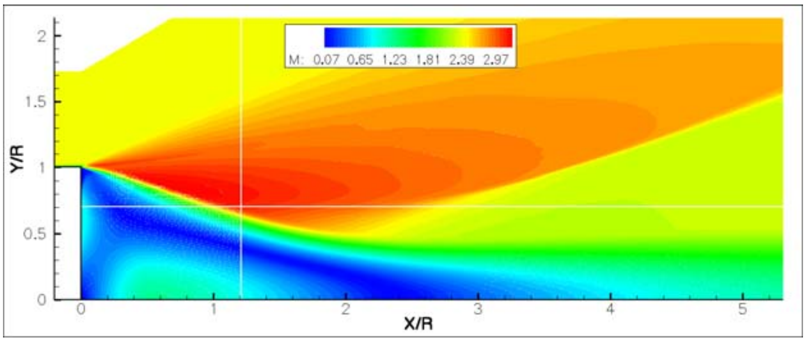

FIGURE 3 – Contour of Mach number – Blunt base without injection

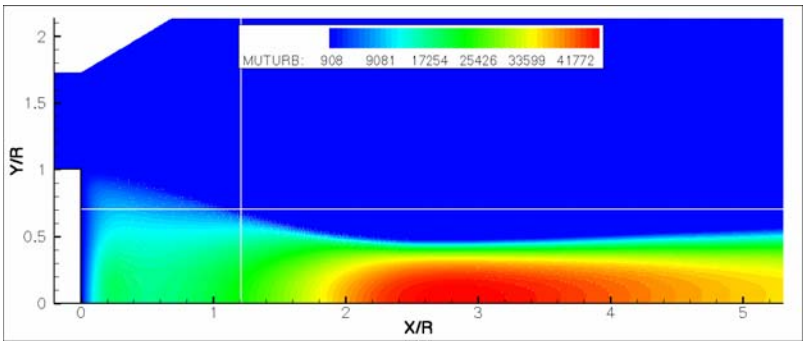

FIGURE 4 – Contour of turbulent viscosity – Blunt base without injection

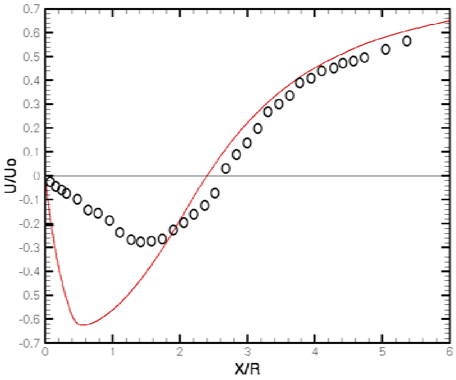

FIGURE 5 – Axial velocity profile on the symetry axis (O: experiments [1]) – Blunt base without injection

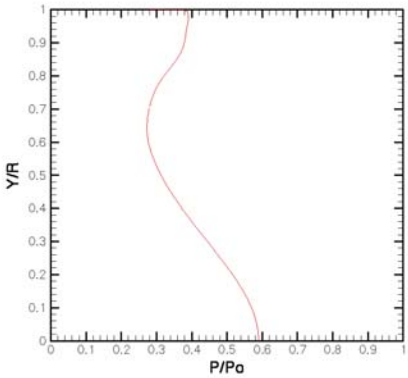

FIGURE 6 – Pressure profile on the base – Blunt base without injection

BASE BLEED CASE

The test case

We are now interested in compare our model to experimental data obtained on a base bleed configuration [2,3,4]. The external flow characteristics are the same as in the previous no-injection case, but now, an additional air injection is made through a 0.4 caliber bleed orifice.

Results on base pressure

The effect of base-bleed injection parameter I on average base pressure ratio p_c/p_0 is shown in figure 7 for both experimental, turbulent computations and laminar computations. For turbulent computations, base pressure behaviour is the same as experiments: first, it increases with bleed rate for low bleed rates (regime 1), a peak value is then attained before it decreases for higher bleed rates (regime 2). Regime 3 has not been investigated in this study.

As for experiments, the peak base pressure is observed with I = 0.0148 but has a value of $P_b/P_0 = 0.55$ (0.67 in the experiments). Even if base pressure levels are much smaller than for experiments, its behaviour is really similar. In comparison, laminar computations show unrealistic variations of the base pressure with bleed rate.

Bleed jet behaviour

Bleed jet axial velocity on the axis is shown in figure 8. Reverse velocity in the primary recirculation region are clearly visible for I=0.0038 and I=0.0113. For I=0.0226, bleed jet velocity reaches 350 m/s and the reverse velocity zone disappears.

Bleed gas mass fraction contours are shown in figure 9. We can make a comparison of these results with mean PLIF images obtained by Bourdon and Dutton [5]. Good agreement is found as the bleed jet, in both cases, is deflected outward and escapes toward the outer shear layer for low bleed rate. As the bleed rate is increased, the forward stagnation point - where the bleed jet meets the reverse flow - shifts downstream. The recirculation region size diminishes. Past the optimum bleed rate I=0.0148, the PRR disappears as the bleed jet contains sufficient momentum to penetrate through the PRR, it goes directly in the wake.

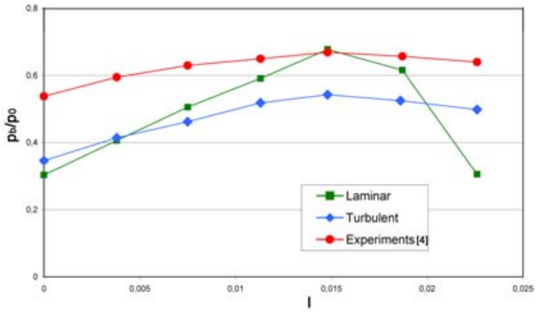

FIGURE 7 – Base pressure vs. Injection parameter

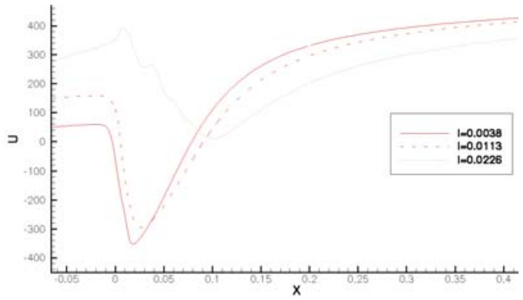

FIGURE 8 – Axial velocity along the symmetry axis

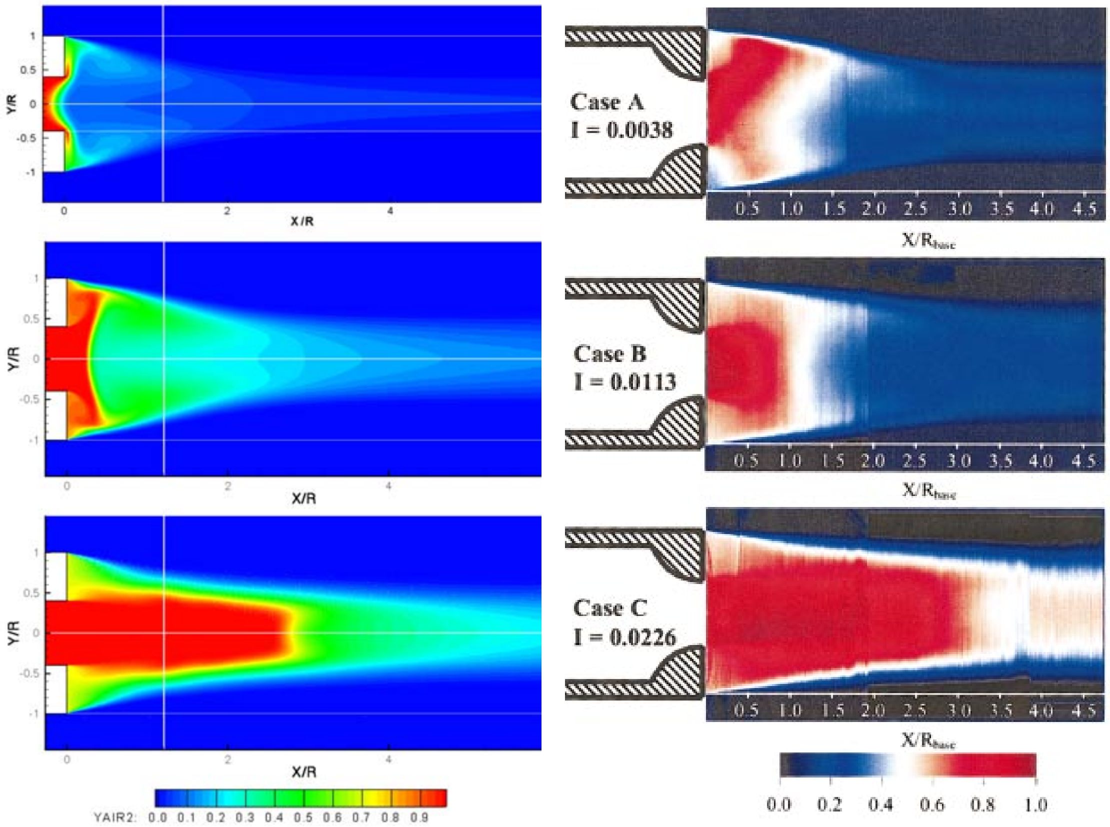

FIGURE 9 – Left: Bleed gas mass fraction (present study); Right: PLIF mean images from [5] for increasing bleed rates (a) I=0.0038; (b) I=0.0113; (c) I=0.0226

CONCLUSION

The Spalart-Allmaras model has been successfully implemented in the CARBUR research code. The validation test case was a Mach 2.45 axisymetric flow past a cylinder. Agreement with experiments is better than for laminar computations, and a excellent agreement with previous turbulent simulations is observed.

Then, a wind-tunnel base bleed configuration has been computed. Good qualitative agreement is found when observing the transition between the different flow regimes and the base pressure behaviour. Base pressure levels are too low in comparison with experimental data.

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