RANS transition model predictions on hypersonic three-dimensional forebody configuration

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Abstract. Future space transportation systems will heavily rely on predicting and understanding Boundary Layer Transition (BLT) during atmospheric entry, especially in the hypersonic phase. Several models, compatible with RANS solvers, have yet been proposed, but not validated in the hypersonic regime. This paper focuses on evaluating prediction capabilities for such models on complex 3D geometries, using the International Boundary Layer Transition (BOLT) Flight Experiment as a test case.

Introduction

The success of future “Apollo” or “Shuttle”-like spacecraft programs and other concepts based on air-breathing propulsion will require an accurate prediction of Boundary Layer Transition (BLT) given that a boundary layer turbulence can amplify surface heating by a factor in excess of five with respect to laminar conditions. The Reynolds-averaged Navier–Stokes equations (RANS equations) are widely used for modeling turbulent flows, but they can’t predict laminar-to-turbulent transition. This limitation arises from the RANS averaging procedure itself, which effectively removes the influence of linear disturbance growth—an essential factor in the transition process. A common approach is then to combine the turbulence model with a transition criterion based on experimental correlations. Correlation-based models are frequently linked to an intermittency transport equation, such as that developed by Steelant and Dick [1] or more complex formulations as proposed by Suzen et al. [2], even though these models require nonlocal information to trigger the transition. More recently, several local correlation-based transition modeling (LCTM) methods have been developed and implemented into in modern parallel RANS code. Examples include models developed by Menter [3][4], based on solving one or more differential equations or even based on fully algebraic frameworks [5]. Furthermore, based on the LCTM framework, extensions targeting the hypersonic flow regime have been developed [6]. In all cases, these models have only been partially explored for hypersonic flows, and rely on a large number of constants to tune the results.

Expanding on the prior research conducted in a previous paper [9], we will now apply the 2015 and 2021 Menter's models to a three-dimensional configuration. The primary goal is to validate their predictive abilities when multiple transition mechanisms such as Mack waves, crossflow instabilities, Goertler vortices, and others may simultaneously occur. The configuration selected is the one proposed in the International BOundary Layer Transition (BOLT) Flight Experiment, which was specifically designed to have multiple mechanisms to transition that interact with each other. The geometry was extensively tested in several wind tunnels, including full-scale tests at the CUBRC LENS II wind tunnel, [7].

Models description

The 2015 Menter γ transition model[4], from now on referred as Model-1, is based on the solution of the $k-\omega$ equations (accordingly to the SST turbulence model [8]) and an additional transport equation for intermittency:

$$\frac{\partial(\rho\gamma)}{\partial t}+\frac{\partial(\rho U_j\gamma)}{\partial x_j} = P_\gamma - E_\gamma + \frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_f}\right)\frac{\partial\gamma}{\partial x_j}\right]. \quad \textbf{(1)}$$

The transition to turbulence is controlled by the F_{onset} factor in the intermittency production term, $P_\gamma = F_{lenght}\rho S\gamma(1-\gamma)F_{onset}$, which can be triggered from both the streamwise and crossflow transition modes:

$$F_{onset} = \max(F_{onset,sw}, F_{onset,cf}). \quad \textbf{(2)}$$

The model can effectively incorporate information from freestream turbulence and the streamwise pressure gradient using only local variables, and, by activating the cross-flow transition term, it can also account for local variations in the flow direction. The labels Model-1A and Model-1B will refer to the version without and with the crossflow transition term, respectively.

Menter recently introduced a new algebraic correlation for intermittency in the 2021 version of his γ transition model [5], thus avoiding the solution of an independent transport equation for it. Similar to Model-1, this new fully algebraic γ transition model, referred to as Model-2 from now on, can consider the streamwise pressure gradient, but currently not the crossflow transition.

Application to 3D geometry

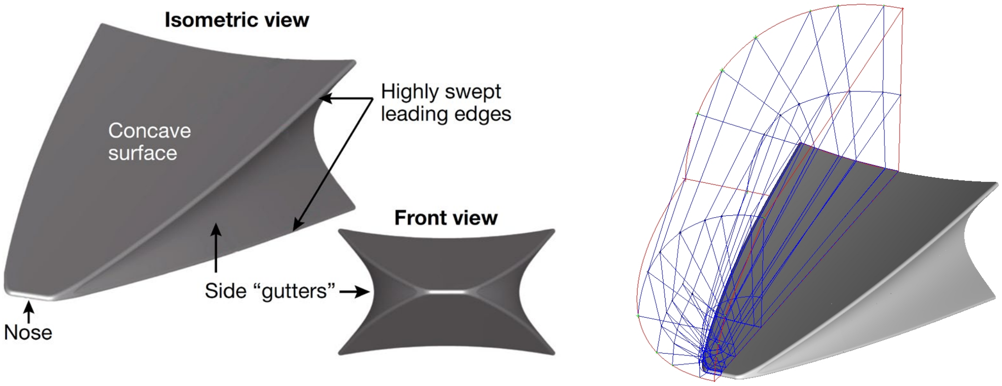

Fig. 1 (left) BOLT geometry, from [7]; (right) domain decomposition for a quarter of the body.

Test case consists in the numerical rebuilding of some of the ground experiments carried out on the geometry of the BOLT (BOundary Layer Transition) project which was designed to investigate the hypersonic boundary layer transition on a low-curvature concave surface with highly swept leading edges, Fig. 1. A full-scale model of the BOLT geometry underwent extensive ground test experimentation in the LENS-II hypervelocity reflected shock tunnel at CUBRC, and here the conditions of RUN-03 in [7] will be used as reference. These conditions are here briefly summarized: $M = 5.17$, $Re_L = 3.92 \cdot 10^6$[m^{-1}], with stagnation pressure and temperature equal to 1.5[MPa] and 1130[K], respectively. A wall temperature of 294.4[K] was imposed. Four inlet values of the turbulent intensity level, $Tu_\infty = [0.1, 0.3, 0.5, 1.0]\%$, were selected to study the effect of freestream turbulence intensity on the transition onset, provided that no specific information on tunnel noise or specific freestream turbulence measures are available. A quarter of the forebody was meshed (exploiting both symmetries). Two shock-fitted structured multi-blocks meshes with 3.5M and 24M cells were used. All the BOLT simulations presented in this paper are based on the 24M cell mesh. All the simulations have been carried out using Ansys Fluent 2021R2.

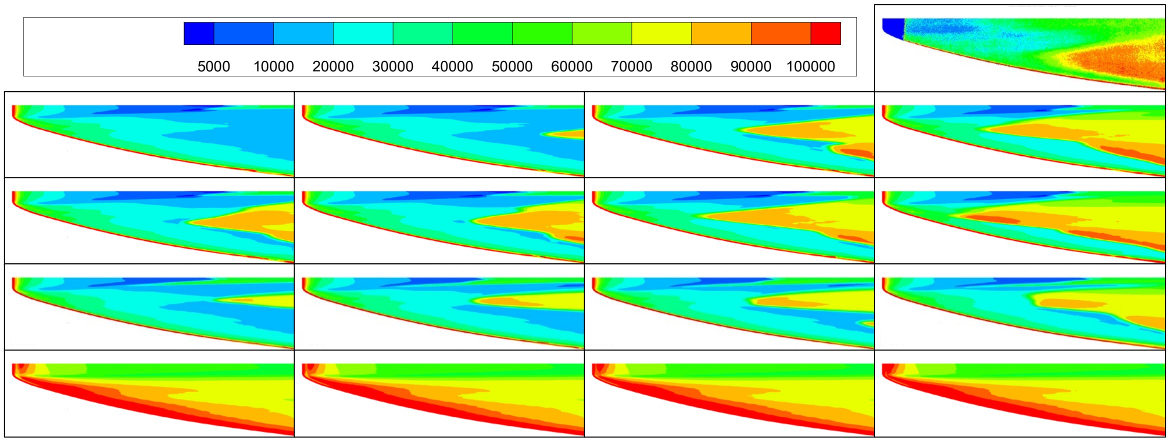

Fig. 2 Heat flux contour map on the primary surface, progressing from Model-1A at the top to Model-2 at the bottom. It showcases various levels of freestream turbulent intensity, ranging from 0.1% leftmost to 1.0% rightmost. Fully turbulent results are also reported for comparisons.

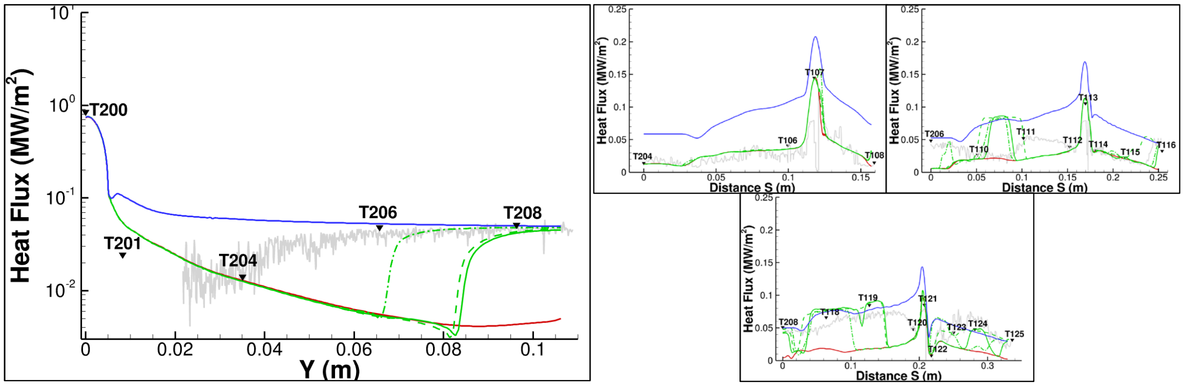

Fig. 3 (left) Heat flux profiles on primary symmetry line; (right) Heat flux profiles at x=10,20, and 30 inches sections. —*: TSP heat flux,* ▼ *thin-films heat flux,* —*: Fully laminar,* —*: Fully turbulent,* —*: Model-1A,*– –*: Model-1B,* – · –*: Model-2. Numerical results for* $Tu = 0.5\%$.

Results from computations using different transition models can be seen in Fig. 2. Here, four set of results per freestream turbulence intensity level are available, three sets employing a different transition model and one fully turbulent. An experimental heat flux map obtained with TSP for this run is also shown.

Figure 2 shows quite clearly the dependence of the transition front position on the transition model choice. It is also evident that Model-1A and Model-2 show a significant dependence of their transition front position on Tu_∞, with a trend towards earlier transition for increasing Tu_∞ levels as expected, [10][9]: at extremely low Tu_∞ levels, both transition models tend to converge towards the laminar solution (not reported here for the sake of brevity). On the other hand, when the correction for cross-flow transition is activated by using Model-1B (and BOLT geometry was specifically designed to experience this mode of transition) the solutions seem to be less sensitive to the Tu_∞ levels, suggesting that crossflow term is entirely responsible for predicting a transition front even at very low Tu_∞ levels: only at the highest value considered, $Tu_\infty = 1\%$, the streamwise onset terms became predominant and shift significantly forward the transition front.

With respect to the TSP contour map reported in the top right corner of Fig. 2, it seems that all the three transitional results provide the best alignment with the experiment when the Tu_∞ is set at 0.5%: notably, the transition front obtained with Model-1B demonstrates a tendency to be closer to the lateral leading edge, similar to what observed in the experimental map. Then, a significant difference between the models appears in central part of the primary surface (a symmetry plane in the simulations), where Model-2 systematically predicts an earlier transition.

The aforementioned tendency becomes more apparent in Fig. 3(left), which provides a quantitative comparison between experimental and numerical heat flux profiles. Here, the heat flux at the stagnation point (T200) is accurately predicted, but at the second point (T201) location, where the flow is still laminar, all the numerical results consistently overestimate the experimental value. The authors intend to investigate the effects of a non-homogeneous wall temperature distribution, closer to the experimental conditions. Additionally, when observing the temperature-sensitive paint (TSP) data on the same graph, it becomes evident that the transition needs approximately 0.04 m to fully take place, being extensively distributed across the surface. Conversely, the simulations predict a rapid but delayed transition to turbulence onset, with only Model-2 displaying slightly less delay. Finally, the cross-cut sections in Fig. 3(right) clearly show that Model-1B is everywhere capable of predicting a wider transition zone with respect to all the other models.

Summary

Two transition models have been investigated, one of which equipped with a specific term for crossflow transition. This latter proves to be especially valuable at lower Tu_∞ values, although an accurate turbulence characterization of the experiment is mandatory for reducing uncertainties.

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