Numerical investigation of laminar-turbulent transition forced by wall injection in hypersonic boundary layers

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In the context of airbreathing hypersonic flight, a turbulent boundary-layer (BL) coming into the air inlet of the scramjet engine is mandatory to withstand the pressure gradients without separation. Since natural transition is very unlikely to occur, passive or active devices must be used to force the transition efficiently. Passive devices may be isolated or distributed roughness, as investigated during the Hyper-X program [1]. Such passive roughness are designed for a limited range of flight parameters and may not be efficient away from the design point. They may also trigger transition when a laminar BL is preferred. The mechanisms associated with roughness-induced transition are still poorly understood [2], though they are known to be relevant to the transient-growth theory [3]. Active devices, like wall injection, have received less attention and the literature on the subject is scarce. Active devices have obvious advantages over passive ones. They can be turned on or turned off on demand, with adjustable parameters to match any flight conditions. Four decades ago, wall normal sonic jets have been studied experimentally and their effects was found similar to those of isolated spheres [4]. Quite recently, some experimental investigations on active control have been conducted by the Hyper-X transition team [5].

Nowadays, the fast development of numerical methods and the increase in computational power make the numerical investigation of hypersonic BL transition possible. Direct Numerical Simulation is the very expensive cutting-edge research tool [6]. Large-Eddy Simulations (LES) are more affordable for parametric studies. The flow physics of a sonic jet in a supersonic crossflow has been widely studied numerically, using either the RANS approach [7] or the (I)LES technique [8], but none of these studies have focused on the BL transition downstream of injection.

In this study, a fifth order WENO scheme is used to perform the ILES of a flat-plate BL submitted to local sonic wall injection. Details of the WENO/ILES procedure can be found in [9]. The flow conditions match closely the BL edge parameters of a 1:3 scale hypersonic forebody at M_∞=6 in the T-313 blow-down wind tunnel of ITAM Novosibirsk [10]. They are M^e=4.6, P^e=2455 Pa and T^e=76 K. The corresponding self-similar flat-plate laminar profiles at $x = 0.2$ m serve as inlet conditions for the ILES-WENO simulation. The computational domain and grid parameters are $L_x \times L_y \times L_z = 0.985$ m $\times$ 0.025 m $\times$ 0.1 m, $N_x \times N_y \times N_z = 512 \times 192 \times 136$ ($\approx 13 \times 10^6$ grid points), $\Delta x_{min} = \Delta z_{min} = 0.16$ mm, $\Delta y_{min} = 0.038$ mm. A sonic top-hat injection velocity profile is applied 0.12 m downstream from the inlet, with or without pulsation, through a hole of diameter 1 mm. Eight cases

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of injection (table 1) have been tested. Injection of type "$1 \pm \epsilon$" means small amplitude fluctuations around the sonic injection velocity. Injection of type "$0 \leftrightarrow 1$" means fluctuations between $M_{inj} = 0$ and $M_{inj} = 1$. Figure 1 shows the structure of the flow in the injection region for case (c). One can clearly see the barrel shape of the under-expanded jet ending with a Mach disk, the separation zone upstream of the jet and the primary longitudinal vortices. The occurrence of transition is analyzed from wall pressure, and from coherent structures in the BL observed with the Q criterion. Figure 3 shows the instantaneous wall pressure downstream of injection. Clearly, transition occurs in any case without pulsation. In cases (a), (b) et (c), the beginning of transition is $x \approx 0.6$ m. Coherent fluctuations are visible just downstream of injection in cases (d) and (e). We found correlation between height of Mack disk and primary longitudinal vortices. If height of Mack disk is above boundary layer thickness cases (d) and (e), primary longitudinal vortices become unstable (figure 4 and 5). Pulsed injections at frequency 30 kHz (the most unstable for the BL), cases (f) and (g), show a strong harmonic forcing of the flow far downstream that possibly overcome the random turbulent fluctuations. Pulsation at 100 kHz (stable frequency), case (h), is rapidly damped by the BL, hence not felt. Transition is even delayed compared to case (c).

In conclusion, these preliminary results seem to show that injection without pulsation is paradoxically more efficient than pulsed injection. In-depth theoretical analysis of instability mechanisms, in the framework of the transient growth and optimal perturbation theories will help, together with additional simulations, understanding the breakdown to turbulence.

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Table 1: Wall injection Parameters. In any case, the total/static temperature is 360/300 K

Case	$P_{tot,inj}$ (kPa)	$P_{stat,inj}$ kPa	f (kHz)	type
(a)	19	10	0	—
(b)	38	20	0	—
(c)	96	50	0	—
(d)	191	100	0	—
(e)	382	200	0	—
(f)	96	50	30	$1 \pm \epsilon$
(g)	96	50	30	$0 \leftrightarrow 1$
(h)	96	50	100	$0 \leftrightarrow 1$

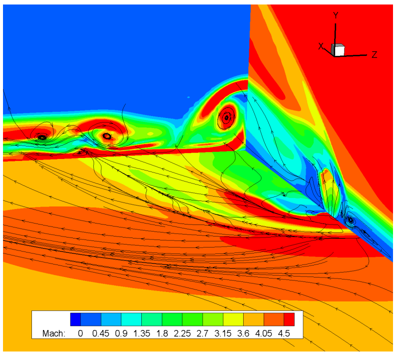

Figure 1: Contour of Mach number in the symmetry plane, wall pressure and vorticity magnitude in the transverse plane, case (c)

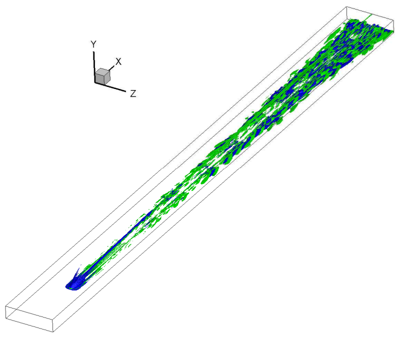

Figure 2: Q criterion for case (c)

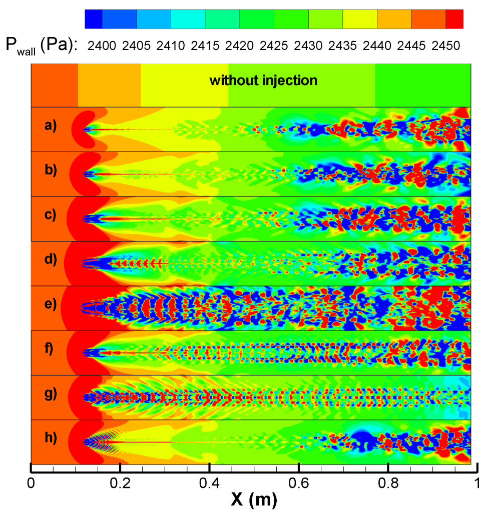

Figure 3: Instantaneous wall pressure.

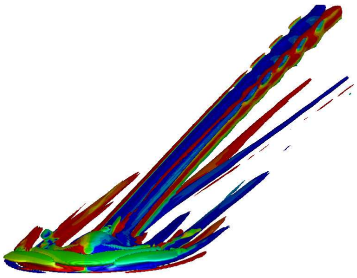

Figure 4: Q criterion for case (c) colored by streamwise vorticity, injection location.

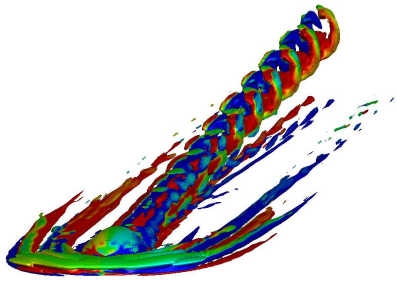

Figure 5: Q criterion for case (e) colored by streamwise vorticity, injection location.