Effect of significant deceleration on boundary layer properties of a laminar flat plate

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Abstract:

It has been shown that the flow field surrounding an airframe undergoing deceleration is significantly different to that of an airframe in steady state motion when compared at the same instantaneous Mach numbers. Deceleration dependent behaviour of the shockwave dynamics on the surface of aerofoils and projectile spheres decelerating from supersonic and transonic regimes to subsonic have been found to affect the aerodynamic drag, lift and moment forces. The aim of this paper is to investigate whether deceleration dependent behaviour exists on both the oblique shockwave and boundary layer on a flat plate in the hypersonic Mach number range between Mach 4 and Mach 7. The airframe considered here is a 2-dimensional laminar flat plate with length 0.1m in rectilinear deceleration from Mach 7 to Mach 4 in a steady outer compressible fluid.

The computational analysis is done using the opensource software OpenFOAM. The simulation is performed from the non-inertial frame, here the flat plate is stationery and deceleration is achieved by addition of source terms in the conservation equations for momentum and energy. The implementation allows for a stationary mesh approach for resolving the flow. Steady state simulations are obtained at Mach 7, the flat plate is then decelerated with a constant deceleration magnitude of 1000g to Mach 4. The effect of deceleration is determined by comparing the unsteady results with the steady state results at the same instantaneous Mach numbers.

Figure 1 shows that there is no deviation in the hydrodynamic and thermal boundary layers between the steady state and the deceleration profiles at Mach 6.97 and Mach 4.02 at the beginning and end of the deceleration event. Although results of two Mach numbers have been shown here, analysis of the entire deceleration event shows that there is no deviation. In the non-inertial perspective, as the flat plate decelerates from Mach 7 to Mach 4 the freestream velocity decreases rapidly. The external compressible fluid should not have enough time to attain equilibrium as compared to a corresponding steady state flow. One would expect that due to the concept of flow history, the flow at lower Mach numbers should still contain features from the high Mach numbers at the start of the deceleration event. Further analysis of the local skin friction coefficient in Figure 2 shows that the deceleration does not affect the wall shear stress at the surface of the plate in the hypersonic Mach numbers considered here which is contrary to previous results in the subsonic regime. This result suggests that the induced pressure due to the deceleration is negligible in the hypersonic regime. While the surface properties are not affected by the deceleration magnitude considered here, Figure 3 shows that there is a slight deviation of the oblique shockwave angle in deceleration.

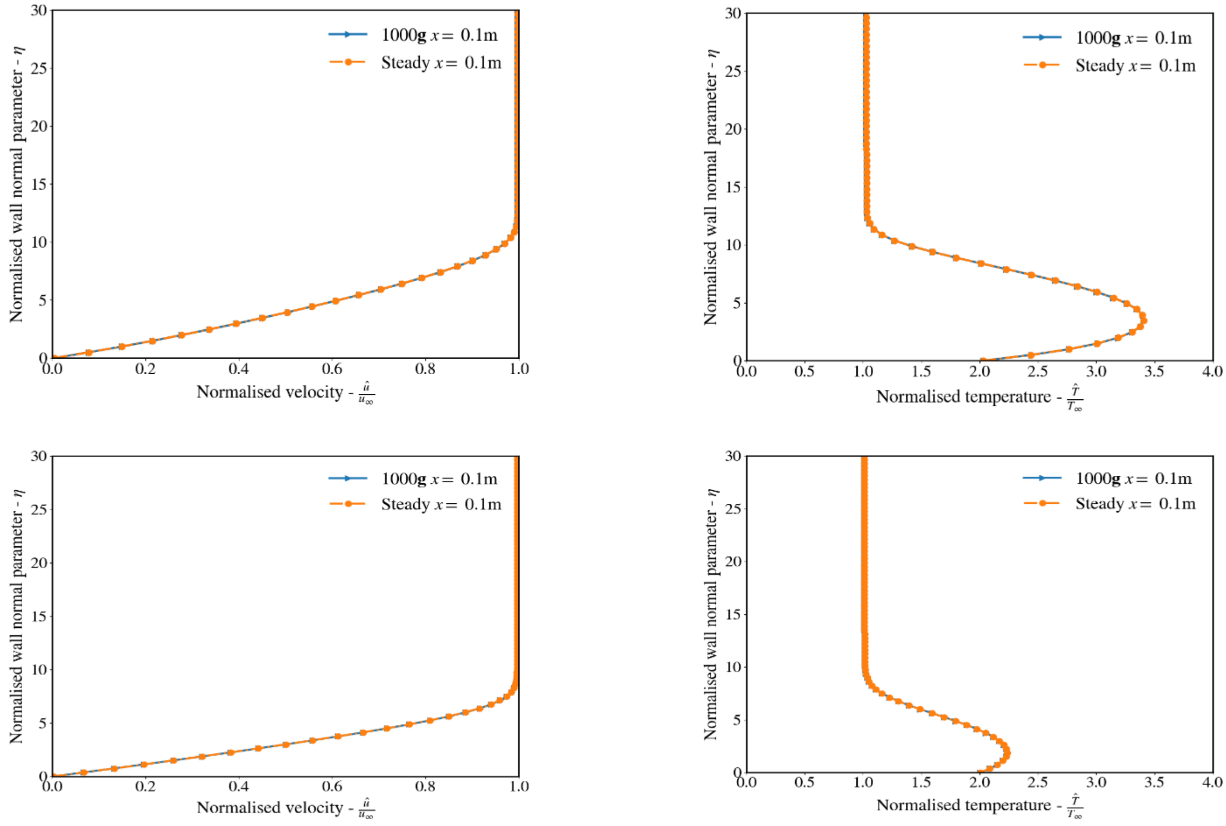

Figure 1: Comparison of instantaneous velocity and temperature profile through laminar boundary layer at Mach 6.97 top and Mach 4.02 bottom.

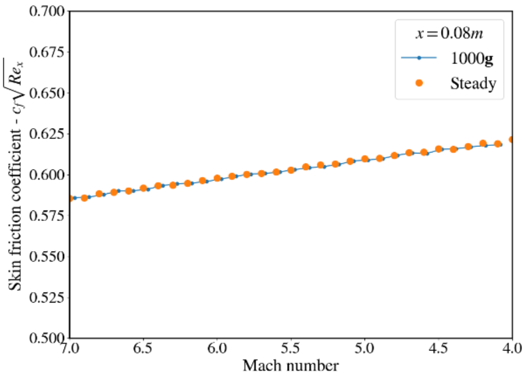

Figure 2: Local surface skin friction coefficient with decreasing Mach number

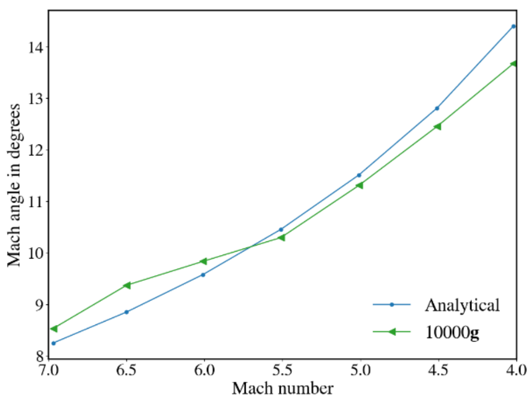

Figure 3: Deceleration effect on mach angle compared to isentropic flow analytical solution