Effect of Mass Transfer on Aeroheating in Hypersonic Chemically Reacting Boundary Layers

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Introduction

Heat flux characterization of high-enthalpy boundary layer flows is key to optimize the performance and design of Thermal Protection System of next generation aerospace vehicles [1]. At atmospheric entry hypersonic speeds, ablation as well as surface catalycity impact boundary layer aeroheating. Out-gassing occurring from an ablative surface in planetary entry environment introduces a rich set of problems in thermodynamic, fluid dynamic, and material pyrolysis. Ablation leads to out-gassing and surface roughness, both of which are known to affect surface heating in hypersonic chemically reacting boundary layers via three main routes: gas blowing into the boundary layer from the wall, changing the surface heat transfer due to wall-flow chemical reactions, and modifying surface roughness via ablative processes [2].

Methodology

Modeling mass and heat transfer from porous reactive materials containing several solid phases and a single gas phase to the boundary layer requires a coupling strategy incorporating the ablating surface energy balance and the aerothermal environment calculations as shown in **Fig. 1**. The flow solver provides surface distribution of **pressure** (**P_w**), heat flux coefficient (**C_H**), and **enthalpy at the boundary layer edge** (**h_e**) for a non-blowing wall. These parameters are used as inputs to the material response solver in order to the time-history of **temperature** (**T_w**), **blowing mass flux** (**$\dot{m}_g$**), and **species concentration** (c_i) at the surface. An iterative approach needs to be optimized on thermodynamic properties e.g. **T_w** to ensure adequate protection for the interior payload. Assuming local thermal equilibrium, the material response analysis tool PATO [3] models chemical interaction between solid phases of ablative material and gas phase of the boundary layer flow. The present study uses the Theoretical Ablative Composite for Open Testing database, which is inspired by the low density carbon/phenolic ablators. For the continuum phase of entry, flow field is solved using DPLR [4]. The surface is assumed to be in radiative equilibrium, fully catalytic to ions, but supports only homogeneous surface reactions.

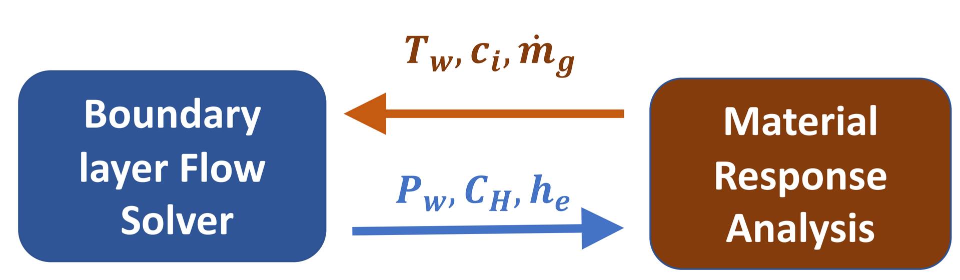

Fig. 1 Coupling flow solver with material response analysis

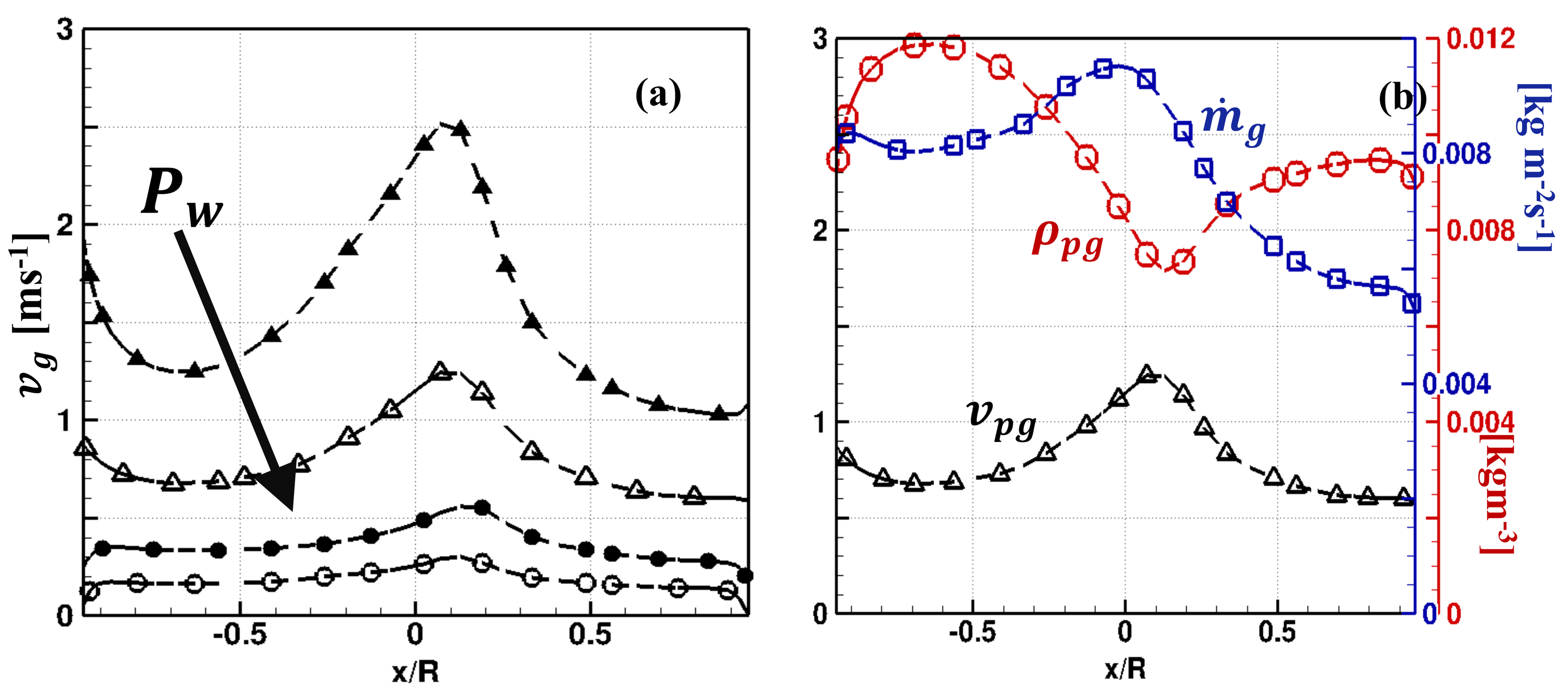

Fig. 2 Centerline distribution of (a) pyrolysis gas velocity at the surface for different time of entry and (b) mass flux, density and velocity at 65 sec along trajectory flight using PATO.

We employ the 18-species finite rate chemistry model of the atmosphere of 97% CO_2 and 29% N_2 [5] and the algebraic Baldwin-Lomax turbulence model [6]. Based on the first iteration of the computed blowing mass flux of pyrolysis gas (here CO) from the material solver analysis shown in **Fig. 2**, two different idealized configurations of the surface outgassing on the heatshield are numerically examined.

Results & Discussion

To model the effect of ablation-induced out-gassing on the surface aeroheating, a baseline non-injecting gas boundary layer is compared with the cases with various blowing rates in two configurations of uniformly blowing only near apex (**config. I**) and blowing on the entire aeroshell, including frustrum and nose (**config. II**) for both laminar and turbulent flows as shown in **Fig. 3**. The blowing rate is characterized by a non-dimensional parameter $F_w = (\rho_e u_e A_{tot})^{-1} \int_0^{A_w} \rho_w v_w dA$, such that the blowing surface areas (A_w) and only vertical component of velocity at the wall are considered. Scaled by Stanton number, $C_H = q_w(h_w - h_e)^{-1}$, F_w yields to F_w^* [7]. The variation of Stanton number normalized by its non-blowing value as a function of the modified blowing rates at different locations of the aeroshell are shown in **Fig.4**

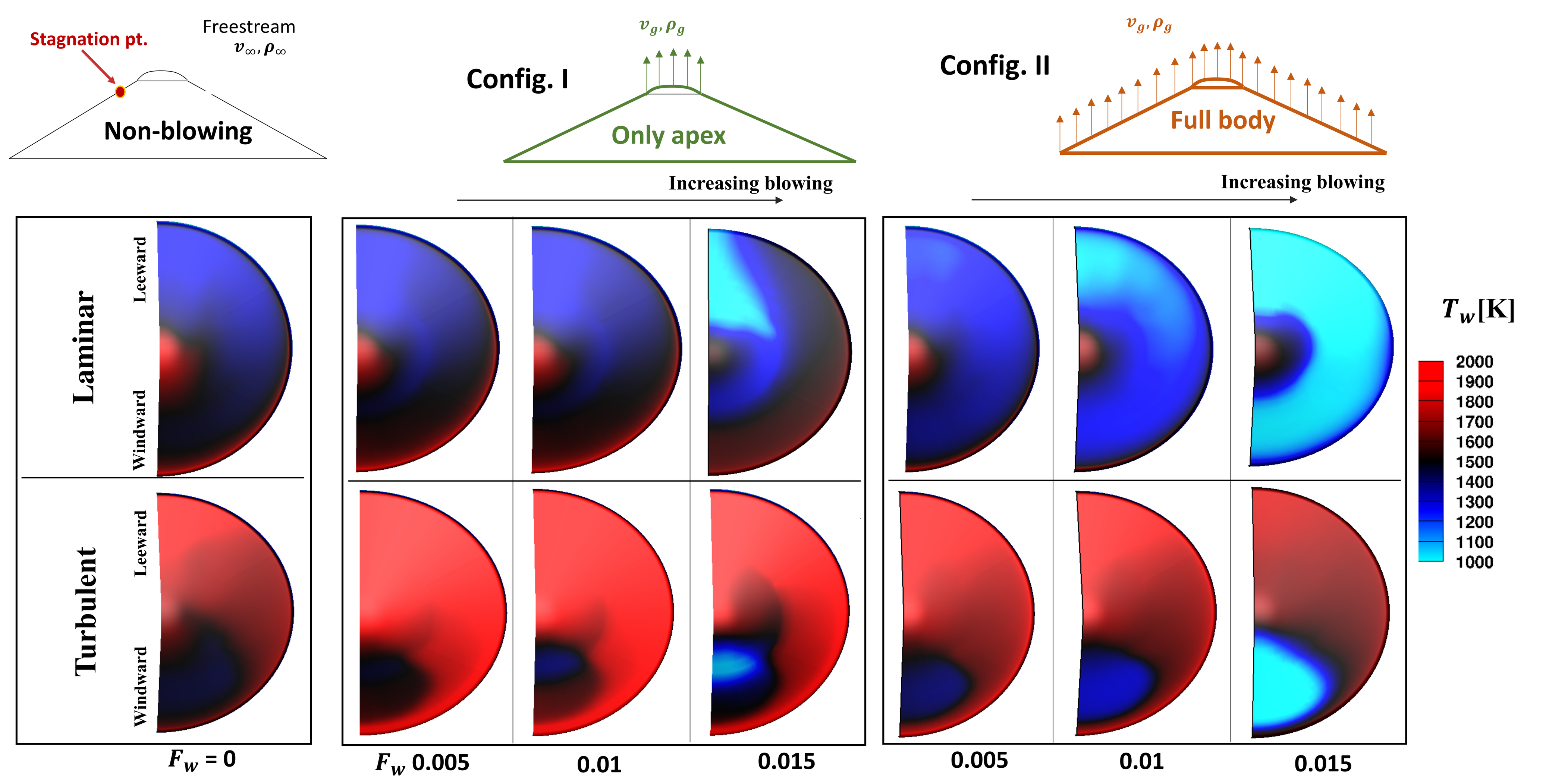

Fig. 3 Surface temperature of configuration I (near apex blowing) and II (entire heatshield blowing) at different blowing rates contrasted against the non-blowing case for laminar (top) and turbulent (bottom) solutions at 65 sec along trajectory flight at α=16°, M_∞=26.56 and Re_∞ =2.867 ×10^5 (1/m).

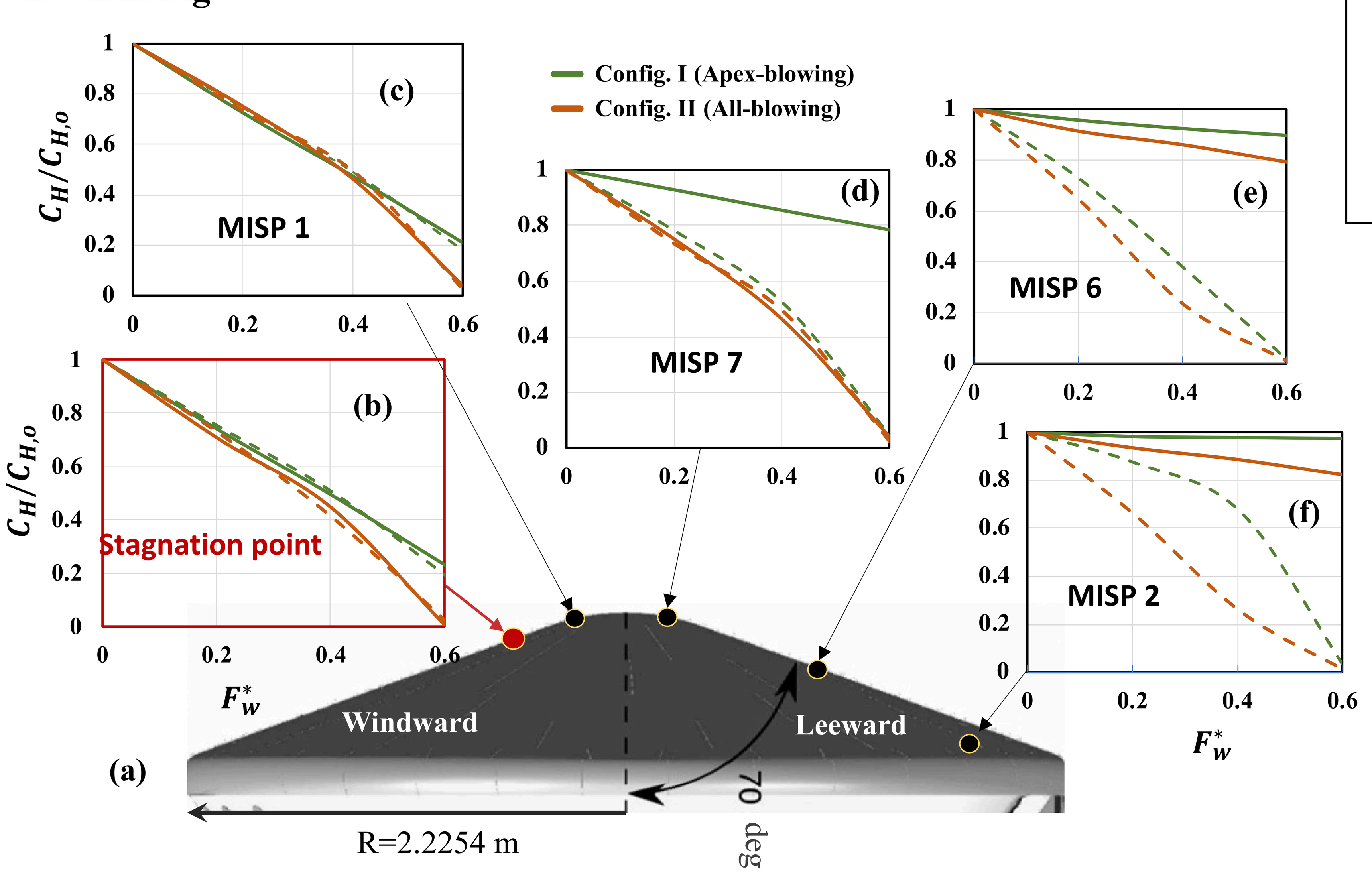

Fig. 4 (a) Schematic of the aeroshell of Mars Science Laboratory and the local heat transfer coefficients vs. blowing parameter at the stagnation point (b) and four thermocouple Plugs (MISP) point of thermocouples (c-f) for turbulent (solid lines) and laminar solution (dashed lines).

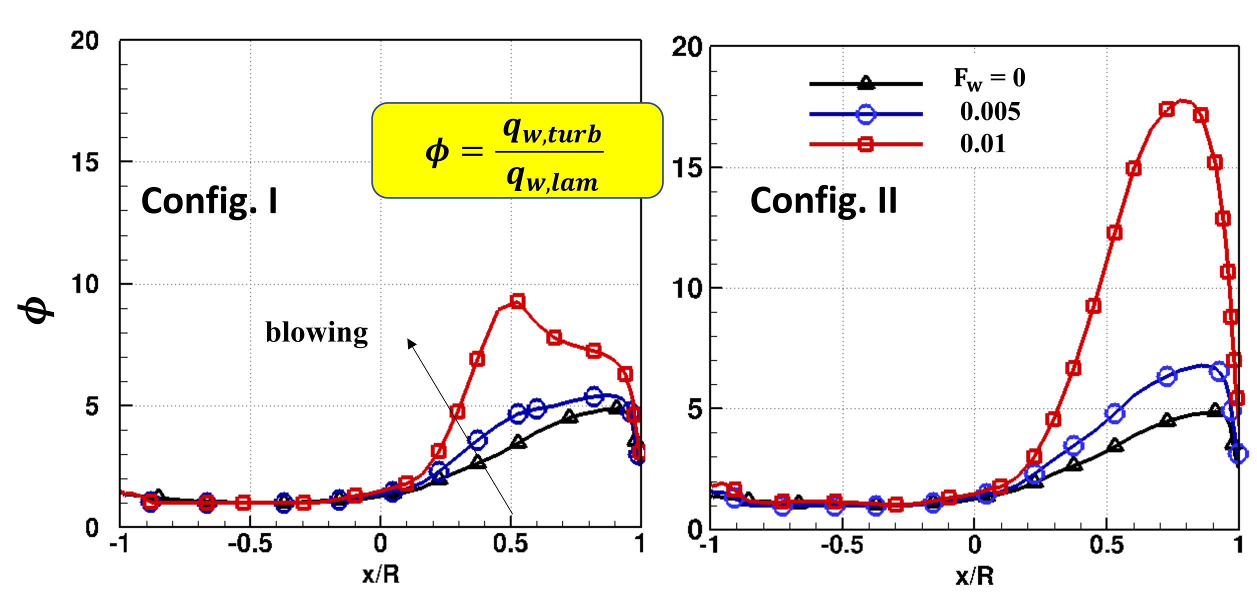

Fig. 6 Turbulent augmentation (ϕ) of convective heat flux due to surface out-gassing

Turbulent augmentation of the surface heat transfer shown in **Fig. 6** is more enhanced for the configuration with all surface blowing as the viscous layer is completely blown off the surface. There is a threshold of blowing strength on surface cooling as Stanton number can approach zero far enough from stagnation point as shown in **Fig. 4 (e) & (f)**.

Out-gassing dramatically reduces the stagnation-point heat transfer to the surface of laminar boundary layer regardless of the initial blowing distribution. Outgassing-induced turbulence diminishes wall effective viscosity measured based on the reference temperature, in agreement with previous findings [8], as depicted in **Fig. 5**.

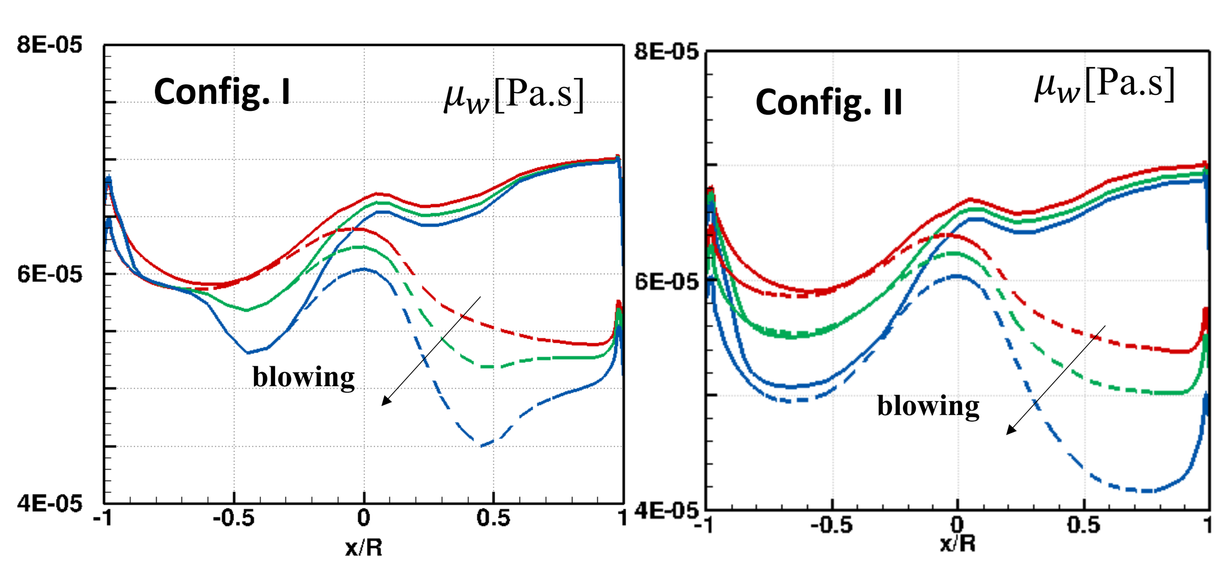

Fig. 5 Distribution of the wall total viscosity (μ_w) for laminar (dashed) and turbulent (solid lines) at different blowing rates.

Conclusion & Outlook

Effects of injecting pyrolysis gases into the boundary layer on surface aeroheating in hypersonic flows is examined by a series of numerical experiments. Out-gassing dramatically reduces heat transfer to the surface of the laminar boundary layer. At the same rate of blowing, laminar solutions experience more surface cooling than turbulent counterparts. Next step is to implement a local distribution of the blowing rate at the corresponding wall temperature. Also to better mimic the ablative boundary condition, an inert foreign species with respect to the freestream gas mixture needs to be blown to the boundary layer.

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