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# Effects of Riblets on Skin Friction and Heat Transfer in High-Speed Turbulent Boundary Layers

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Direct numerical simulations of spatially developing turbulent boundary layers over riblets are conducted to examine the effects of riblets on skin friction and heat transfer at high speeds. Zero-pressure gradient boundary layers under two flow conditions (Mach 2.5 with  $T_w/T_r = 1$  and Mach 7.2 with  $T_w/T_r = 0.5$ ) are considered. Simulations are conducted for boundary-layer flows over a clean surface and symmetric V-groove riblets. The DNS results at Mach 2.5 confirm the few existing experimental observations and show that a drag reduction of approximately 7% can be achieved for riblets with proper spacing. The comparisons in turbulence statistics and flow visualizations between a drag-reducing configuration ( $s^+ \approx 20$ ) and a drag-increasing configuration ( $s^+ \approx 40$ ) demonstrate that drag reduction mechanisms proposed for incompressible flows can still apply for high-speed boundary layers. DNS studies at Mach 7.2 further show that riblets remain effective in reducing drag in the hypersonic regime. The Reynolds analogy holds with  $2C_f/C_h$  approximately equal to that of flat plates for the drag-reducing configuration.

## Nomenclature

$A$	surface area, $m^2$
$C_f$	Skin friction coefficient, dimensionless
$C_h$	Stanton number, dimensionless
$C_p$	heat capacity at constant pressure, $J/(K \cdot kg)$
$C_v$	heat capacity at constant volume, $J/(K \cdot kg)$
$D$	Drag, N
$h$	riblet height, m
$L$	Computational domain size, m
$M$	Mach number, dimensionless
$Pr$	Prandtl number, $Pr = 0.71$ , dimensionless
$R$	radius of riblet tip
$Re_\theta$	Reynolds number based on momentum thickness and free-stream viscosity, $Re_\theta \equiv \frac{\rho_\infty u_\infty \theta}{\mu_\delta}$ , dimensionless
$Re_{\delta_2}$	Reynolds number based on momentum thickness and wall viscosity, $Re_{\delta_2} \equiv \frac{\rho_\infty u_\infty \theta}{\mu_w}$ , dimensionless
$Re_\tau$	Reynolds number based on shear velocity and wall viscosity, $Re_\tau \equiv \frac{\rho_w u_\tau \delta}{\mu_w}$ , dimensionless
$s$	riblet spacing, m
$T$	temperature, K
$T_r$	recovery temperature, $T_r = T_\infty(1 + 0.9 * \frac{\gamma-1}{2} M_\infty^2)$ , K
$u$	streamwise velocity, m/s
$u_\tau$	friction velocity, m/s

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$v$	spanwise velocity, m/s
$w$	wall-normal velocity, m/s
$z_\tau$	viscous length, $z_\tau = \nu_w/u_\tau$ , m
$\alpha$	riblet ridge angle, degree
$\gamma$	specific heat ratio, $\gamma = C_p/C_v$ , dimensionless
$\delta$	boundary layer thickness, m
$\delta^*$	displacement thickness, m
$\kappa$	thermal conductivity, $\kappa = \mu C_p/Pr$ , W/(m·K)
$\theta$	momentum thickness, m
$\mu$	dynamic viscosity, $\mu = 1.458 \times 10^{-6} \frac{T^{3/2}}{T+110.4}$ , kg/(m·s)
$\nu$	kinematic viscosity, $\nu = \mu/\rho$ , m <sup>2</sup> ·s
$\rho$	density, kg/m <sup>3</sup>
<i>Subscripts</i>	
$f$	quantities related to flat plate or clean surface
$i$	inflow station for the domain of principal direct numerical simulation
$n$	surface normal direction
$r$	quantities related to riblets
$rms$	root mean square
$w$	wall variables
$x$	streamwise direction of the right-hand Cartesian coordinate
$y$	spanwise direction of the right-hand Cartesian coordinate
$z$	wall-normal direction of the right-hand Cartesian coordinate
$\infty$	freestream variables
<i>Superscripts</i>	
$+$	inner wall units
$(\cdot)$	averaged variables
$(\cdot)'$	perturbation from averaged variable

## I. Introduction

Viscous or skin friction drag accounts for nearly one half of the total drag for a subsonic transport aircraft and one third of the total drag for a supersonic transport aircraft. Over the past two decades, research on skin friction drag reduction has received considerable attention<sup>1,2</sup> and attempts have progressed in two directions: methods for delaying the boundary layer transition and methods for modifying the turbulence structures in a turbulent boundary layer. Among the various passive techniques for controlling turbulent drag, riblets have been extensively investigated, especially for subsonic boundary layers.<sup>3-5</sup> As reviewed by Walsh,<sup>3</sup> consistent drag reductions up to 8% have been achieved via V-groove riblet surfaces at subsonic speeds. By optimizing the riblet geometry, drag reduction of up to 10% has also been reported.<sup>6</sup>

Several mechanisms by which riblets reduce drag have been suggested, including the weakening of the bursting process near the wall,<sup>7</sup> the inhibition or restriction of spanwise motion of longitudinal vortices,<sup>8,9</sup> an increase in sublayer thickness,<sup>8</sup> the significant retardation of the viscous flow in the valley of the riblet groove,<sup>4,10</sup> and the restriction of the location of streamwise vortices above the wetted surface.<sup>11</sup> However, even for a zero-pressure gradient boundary layer flow, the detailed mechanisms are not clearly understood, largely due to the small groove dimensions and the difficulty for measurements in the close vicinity of the grooves.<sup>5</sup>

For supersonic flows, it is reasonable to expect similar effectiveness of riblets as that in the subsonic regime,<sup>2</sup> due to the fact that the microgrooves will be well immersed in the low-speed velocity field, at least for a moderately supersonic Mach number. So far, very limited riblet data at supersonic speeds are available. The few data include wind tunnel investigations at Mach 2.97 by Robinson,<sup>12</sup> Mach 1.5 by Gaudet,<sup>13</sup> Mach 1.6, 2.0, and 2.5 by Coustols and Cousteix,<sup>14</sup> as well as flight tests at Mach 1.2-1.6 by Zuniga et al.<sup>15</sup> These studies report that skin friction drag reduction of up to 15% has been achieved. However, none of the above studies have provided a detailed investigation of the riblet effects on turbulence statistics and the drag reduction mechanisms. No data are available at hypersonic speeds so far and the effects of riblets on drag and heat transfer are largely unknown.

High-fidelity simulations like direct numerical simulations (DNS) and large eddy simulations (LES) pro-

vide a vast amount of accurate data that can be used to analyze the interrelationship between riblets and near-wall turbulence and provide necessary information for understanding the mechanism by which riblets reduce drag. For example, Choi et al.,<sup>11</sup> Chu and Karniadakis,<sup>16</sup> and Goldstein et al.<sup>17</sup> conducted DNS of incompressible channel flows with surface-mounted riblets, in which detailed turbulence statistics are presented and the physical mechanisms that cause drag reduction are hypothesized. More recently, Klumpp et al.<sup>18</sup> performed LES to investigate the influence of an adverse-pressure gradient on the performance of riblets in incompressible turbulent boundary layers. An analysis of riblet effects on drag reduction and heat transfer in the supersonic/hypersonic regime has not been performed and is the target of the present investigation.

In the current paper, we conduct DNS for two spatially developing boundary layers in the high-speed regime. One is at Mach 2.5, which is relevant to supersonic transports, and the other is at Mach 7.2, which falls within the hypersonic regime. Unlike the previous work,<sup>11,16,17</sup> which focused on channel flows, riblets in external flows are examined without any assumption of streamwise periodicity. The effects of riblets on turbulence statistics (skin friction and surface heat transfer, in particular) and large-scale turbulence structures will be addressed. The differences, if any, between the drag reduction mechanisms for incompressible and high-speed boundary layers will be identified.

## II. Flow conditions and numerical methodology

The boundary layer edge conditions and wall parameters for the DNS are given in Table 1, which provides freestream Mach number, density, and temperature ( $M_\infty$ ,  $\rho_\infty$ , and  $T_\infty$ , respectively) as well as the boundary layer thickness and various Reynolds numbers at the inlet of the domain.

**Table 1. Boundary layer edge and wall parameters for the DNS.**

$M_\infty$	$\rho_\infty(\text{kg/m}^3)$	$T_\infty(\text{K})$	$T_w(\text{K})$	$T_w/T_r$	$\delta_i(\text{mm})$	$Re_\theta$	$Re_\tau$	$Re_{\delta_2}$
2.5	0.1	270.4	568.0	1.0	4.58	1719.2	320.7	1006.3
7.2	0.07	65.8	352.0	0.5	9.55	6754.4	392.4	1430.5

### A. Numerical method

To simulate the boundary layer flow over riblets, the compressible Navier-Stokes equations are solved in generalized curvilinear coordinates. The working fluid is assumed to be an ideal gas with a linear (i.e. Newtonian) stress-strain relation. The Fourier law is used to compute the heat flux terms. A 7th order WENO (weighted essentially non-oscillatory) scheme<sup>19</sup> is used to compute the convective flux terms. This particular WENO algorithm combines a high order of accuracy with low dissipation and high bandwidth, which is desirable for time accurate simulations of compressible turbulence. The resolution properties of this scheme are documented in several references.<sup>20,21</sup> For the viscous flux terms, a 4th order central difference scheme is used. The 3rd order low storage Runge-Kutta scheme by Williamson<sup>22</sup> is used for time integration.

### B. Boundary conditions

To enable the simulation of a spatially evolving boundary layer, it is important to prescribe the appropriate distribution of flow variables at the inflow boundary. It would be too computationally intensive to conduct a single DNS of the whole flow field, which includes the complete surface where the upstream boundary layer develops, and the downstream region where the boundary layer interacts with surface-mounted riblets. Instead, we conduct an independent auxiliary DNS of a spatially developing boundary layer which provides the inflow boundary condition for the principal DNS over the domain with riblets. In addition, the single auxiliary DNS can be used to provide an identical inflow for the downstream simulations with and without riblets, thus isolating the influence of riblets on skin friction drag. The computational setup for the auxiliary and principal simulations is sketched in Figure 1.

On the wall, no-slip conditions are applied for the three velocity components and an isothermal condition is used for the temperature. The wall temperature is prescribed to be nearly the recovery temperature, as

shown in Table 1. At the top and outlet boundaries, unsteady non-reflecting boundary conditions based on Thompson<sup>23</sup> are imposed. Periodic boundary conditions are used in the spanwise direction.

### C. Flow configuration and computational mesh

The computational setup for the auxiliary and principal simulations is sketched in Figure 1. The grid characteristics for the auxiliary DNS are consistent with those reported in the literature in the context of previous simulations of turbulent wall bounded flows using comparable numerical algorithms.<sup>24–27</sup> Uniform grid spacings are used in the streamwise and spanwise directions and geometrically stretched grids are used in the wall-normal direction. At the inlet of the auxiliary DNS, the rescaling boundary condition of Xu & Martín<sup>28</sup> is used, with the recycling station located approximately  $8\delta_i$  downstream of the inlet. It is also at this position that the flow slice is temporally sampled and spatially interpolated to provide the inlet boundary condition for the principal DNS with riblets. A similar approach has been successfully applied by Priebe & Martín<sup>29</sup> to provide the inflow for the study of shock wave and turbulent boundary layer interaction.

For the principal DNS, three sets of simulations with different surface topologies have been performed for Mach 2.5. The first is a clean-surface baseline simulation (denoted as M25Clean), and the other two include riblets with nominal riblet spacings of  $s^+ \approx 20$  and  $s^+ \approx 40$ , respectively (denoted as M25s20 and M25s40). Triangular riblets with ridge angle  $45^\circ$  are used for both M25s20 and M25s40 (Figure 2b). The case of smaller riblet spacing corresponds to a drag-reducing configuration and the larger spacing case corresponds to a drag-increasing configuration. Similar riblet topologies have been explored in the experiments of Walsh<sup>30</sup> and DNS of Choi et al.<sup>11</sup> under incompressible conditions. For cases M25s20 and M25s40, the riblets begin at a distance  $x \approx 0.4\delta_i$  downstream of the inlet of the principal DNS, while upstream of this position the surface remains clean to guarantee a nearly unperturbed flow at the inlet. Moreover, the grids consist of a smooth streamwise transition from the clean surface to the riblet surface to minimize the extent of upstream/downstream influence due to the surface variation. The streamwise length for the transitional zone is approximately 4 times that of the riblet height  $h$  with the grid streamwise refined, as is shown in Figure 2a. The streamwise grid becomes uniform past the transitional zone. The riblet zone has a streamwise length of approximately  $7.7\delta_i$  with a resolution of approximately  $\Delta x^+ = 10.5$  in the streamwise direction. The spanwise grids are clustered near the riblet tips and coarsened near riblet valleys, with 32 grid points on the surface of each riblet. To improve smoothness of the grids and avoid singularities when evaluating the Jacobian, the periodic riblet geometry with sharp corners has been approximated by a truncated Fourier series expansion containing the first six terms. The Fourier filtering gives slightly rounded riblet tips and valleys with radius  $R/s \approx 4\%$ . The extent of rounding is within a range where no significant degradation in riblet performances is expected.<sup>31,32</sup> Moreover, the investigation of flow over rounded riblets is of practical relevance since it is hard to precisely machine a riblet surface which assumes sharp peaks, and the tips of riblets mounted on an aircraft fuselage or wing can undergo deterioration as often as every flight operation.<sup>16</sup> A close-up view of riblet geometry and near-wall grids has been sketched in Figure 2b. 20 and 10 riblets are used for M25s20 and M25s40, respectively, which corresponds to a spanwise domain of approximately 440 wall units. At Mach 7.2, two sets of simulations have been performed. The first is a clean-surface baseline simulation (denoted as M72Clean), and the other includes riblets with a nominal riblet spacing of  $s^+ \approx 20$  (denoted as M72s20). The riblet geometry and grid characteristics for M72s20 are similar to those for M25s20.

Table 2 outlines the domain sizes and grid resolutions for various DNS cases. The smallest values of  $\Delta y_{min}^+$  and  $\Delta z_{min}^+$  occur near the riblet tip and the larger values occur near the riblet valley. The clean surface case has similar domain sizes and grid resolution as the case M25s20 for comparison purposes.

Both the domain size and the grid resolution exceed those used by Choi et al.<sup>11</sup> for the riblet simulations, despite the higher order scheme used in the present study. For instance, the domain sizes in the streamwise/spanwise directions for the current riblets simulations ( $L_x^+ \times L_y^+ \approx 2600 \times 440$ ) are significantly larger than those used by Choi et al.<sup>11</sup> ( $L_x^+ \times L_y^+ \approx 570 \times 160$ ). In addition, to further investigate the dependence of viscous drag on spanwise domain size and grid resolution, two test runs have been carried out for the case M25s20, one with the same grid resolution as case M25s20 but half the spanwise width (10 riblets or  $L_y^+ \approx 220$ ), and the other with the same spanwise width but double the grid resolution (64 grid points per riblet). The differences in skin friction drag between the case M25s20 and either test run are within 1.0%. Moreover, the DNS results over flat plates have been compared with existing experimental and well-established numerical data.<sup>24</sup> In particular, Figure 3 shows good agreement between the current DNS and that by Guarini et al.<sup>33</sup> at Mach 2.5 and  $Re_\theta = 1570$ .

**Table 2.** Simulation parameters for the direct numerical simulations of turbulent flows over riblets. The value of  $\Delta x$  corresponds to that in the uniform region (outside of the transitional zone).

Case	$s^+$	$h^+$	$L_x/\delta_i$	$L_y/\delta_i$	$L_z/\delta_i$	$\Delta x^+$	$\Delta y_{min}^+$	$\Delta z_{min}^+$	$N_x \times N_y \times N_z$
M25Clean	NA	NA	8.7	1.4	9.8	10.8	0.28–1.05	0.28	$256 \times 640 \times 120$
M25s20	21.4	10.4	8.2	1.4	9.8	10.4	0.27–1.02	0.20–0.27	$256 \times 640 \times 120$
M25s40	45.3	22.0	8.4	1.4	9.8	11.1	0.67–2.14	0.13–0.28	$256 \times 320 \times 120$
M72Clean	NA	NA	6.9	1.1	13.7	6.3	0.32–0.95	0.30	$425 \times 640 \times 100$
M72s20	19.5	9.5	6.7	1.1	13.7	6.1	0.31–0.92	0.14–0.32	$425 \times 640 \times 100$

### III. Results

In this section, we examine the effects of riblets on skin-friction drag and other turbulence statistics. Statistics are collected near a streamwise location  $x_a \approx 7\delta_i$ , which is significantly downstream of the beginning of the riblet surface to avoid any significant effects due to surface transition. To obtain statistics, averages are first calculated over a streamwise window of  $[x_a - 0.6\delta_i, x_a + 0.6\delta_i]$  and the same spanwise locations over different riblets for each instantaneous flow field; then, an ensemble average over flow field snapshots spanning a time interval of more than  $150\delta_i/u_\infty$  is calculated. Reducing the number of flow fields for the ensemble averaging by one third results in less than 0.5% difference in viscous drag. We use an overbar to indicate an averaged quantity and a prime to indicate perturbations from this average. The origin of the  $z$  coordinate corresponds to the wall location for clean surfaces. For cases with riblets, the riblets are mounted on top of the otherwise clean surface with  $z = 0$  corresponding to the riblet valley. This computational setup mimics the practical applications that riblets are molded into a lightweight plastic film with an adhesive backing and pressed into place on the surface of a vehicle.

#### A. Drag measurement

The total skin-friction drag,  $D$ , is obtained as the integral of the product of the wall shear stress and the differential wetted area

$$D = \int_{A_r} \mu_w \left( \frac{\partial u}{\partial n} \right)_w dA_r = \tau_w^* A_f = \mu_w \left( \frac{\partial u}{\partial n} \right)_f A_f \quad (1)$$

Similarly, the total surface heat flux  $Q$  over a riblet surface  $A_r$  can be obtained as

$$Q = \int_{A_r} \kappa_w \left( \frac{\partial T}{\partial n} \right)_w dA_r = q_w^* A_f = \kappa_w \left( \frac{\partial T}{\partial n} \right)_f A_f \quad (2)$$

where  $A_r$  denotes the wetted area of a riblet surface and  $A_f = A_r \cos(\alpha) = L_x \times L_y$  is its corresponding clean-surface area (see Figure 4).

The skin friction coefficient  $C_f$  and the Stanton number  $C_h$  are defined as

$$C_f = \frac{\bar{\tau}_w^*}{\frac{1}{2}\rho_\infty u_\infty^2}, \quad C_h = \frac{\bar{q}_w^*}{\rho_\infty u_\infty C_p (T_r - T_w)} \quad (3)$$

and the Reynolds analogy factor  $RA$  is defined as

$$RA = \frac{2C_h}{C_f} \quad (4)$$

The wall-shear velocity  $u_\tau^*$  and viscous length  $z_\tau^*$  for riblet surface are defined as

$$u_\tau^* = \sqrt{\frac{\bar{\tau}_w^*}{\rho_w}}, \quad z_\tau^* = \frac{\bar{\mu}_w}{\rho_w u_\tau^*} \quad (5)$$



The superscript  $*$  has been added to  $u_\tau$  and  $z_\tau$  to emphasize their relevance to the global riblet surface and distinguish them from the local values at a particular spanwise location.

Figure 5 shows the time history of plane-averaged wall-shear rate  $(\frac{\partial u}{\partial n})_f^*$  (defined by Equation 1) for various cases. Relative to the clean surface, the drag reduction for M25s20 and the drag increase for M25s40 are clearly seen. Table 3 further shows the time-averaged skin friction and the drag variation relative to the clean surface for the two riblet cases. Drag is reduced by approximately 7% for the  $s^+ \approx 20$  case and increased by approximately 4% for the  $s^+ \approx 40$  case. The drag reduction for the smaller riblet-spacing case confirms the observations of the few existing experiments under supersonic conditions.<sup>13-15</sup> The drag variations are also similar to several incompressible results. For comparison, with similar riblet geometries, the experiments by Walsh<sup>30</sup> report a drag reduction of 2% for  $s^+ \approx 20$  and drag increase of 3% for  $s^+ \approx 40$ , and the DNS by Choi et al.<sup>11</sup> give drag reduction of 5% for  $s^+ \approx 20$  and drag increase of 2% for  $s^+ \approx 40$ .

At Mach 7.2, the riblets retain their effectiveness in drag reduction and achieve approximately 6.8% drag reduction for  $s^+ \approx 20$  (Table 3). A slightly larger reduction (8.1%) is observed for the surface heat flux, with the Reynolds analogy factor assuming similar values as those for hypersonic flat-plate boundary layers. For comparison, the experimental data reviewed by Hopkins and Inouye<sup>34</sup> give  $1.1 < RA < 1.3$ . The relatively larger variation in heat transfer than that in viscous drag is consistent with the arguments by Maciejewski and Rivir<sup>35</sup> and Stalio and Nobile<sup>36</sup> for low-speed boundary layers that Reynolds analogy holds with increased heat transfer efficiency relative to drag.

To distinguish the different contributions from riblet tips and valleys to the total drag, Figures 6 and 7a plot the wall-shear rate as a function of spanwise position along the riblet for Mach 2.5 and Mach 7.2 cases, respectively. It is seen that, at both conditions, the wall shear rate at riblet tips is significantly higher than the flat-plate value, while the wall shear rate at riblet valleys is well below the flat-plate value. Whether riblets reduce or increase drag depends on whether the reduction in the riblet valleys is sufficient to overcome the skin-friction increase near riblet tips. Compared with M25s40, the  $s^+ \approx 20$  case has relatively smaller wall shear throughout most spanwise locations, consistent with the smaller total drag, but it actually has slightly higher wall shear at the tip. Figure 7b further shows that the wall-normal temperature gradient assumes similar spanwise distribution as the wall-shear rate for M72s20, which is consistent with the validity of the Reynolds analogy.

**Table 3.** Area averaged skin friction  $C_f$ , Stanton number  $C_h$ , Reynolds Analogy factor  $RA$ , friction velocity  $u_\tau^*$ , and viscous length  $z_\tau^*$  for various cases. In the fourth and fifth columns, + and - denote the drag/heat increase and decrease, respectively, relative to the smooth wall.

Case	$C_f \times 10^3$	$C_h \times 10^3$	$RA = 2C_h/C_f$	$\Delta C_f/C_f$	$\Delta C_h/C_h$	$u_\tau^*/u_\infty$	$z_\tau^*/\delta_i$
M25Clean	2.506	NA	NA	NA	NA	0.0512	0.00315
M25s20	2.331	NA	NA	-7.0%	NA	0.0493	0.00327
M25s40	2.616	NA	NA	+4.4%	NA	0.0523	0.00309
M72Clean	1.054	0.618	1.17	NA	NA	0.0512	0.00260
M72s20	0.983	0.568	1.15	-6.8%	-8.1%	0.0493	0.00269

## B. Virtual origin

In this Section, we introduce the concept of virtual origin to account for the surface geometry conditions and facilitate the comparison of boundary-layer profiles among various surface topologies.

The virtual origin of a riblet surface is defined as the location  $z_0$  of an imaginary flat surface which has the same drag as the riblet surface and matches the riblet velocity profile above the viscous sublayer. The use of virtual origin can be justified by the lack of spanwise variations in the streamwise velocity above certain  $z$ -location, as shown by the streamwise velocity contour in the transverse plane (Figure 8). The spanwise variation in the velocity occurs only near the riblets and there is no apparent variations of mean velocity in the spanwise direction above  $z^+ = 50$ . Similar observations have also been reported for incompressible flows by multiple researchers.<sup>11, 37, 38</sup>

Several methods of evaluating the virtual origin have been proposed by multiple researchers.<sup>8, 9, 11, 37</sup> For

example, Bechert and Bartenwerfer<sup>9</sup> evaluated the virtual origin based on the variation in the mean velocity and obtained

$$z_0 = z_{mid} + \beta s \quad (6)$$

where  $z_{mid}$  is the midpoint between the riblet tip and valley, and  $\beta$  is a constant depending only on the ridge angle ( $\beta = 0.11$  for V-groove riblets with ridge angle of  $45^\circ$ ). Choi et al.<sup>11</sup> evaluated the virtual origin based on the wall-normal shift in the location of maximum turbulent kinetic energy production (or the maximum intensity of the streamwise velocity fluctuation), and proposed

$$z_0 = \frac{(z_{mr}^+ - z_{mf}^+) \nu_w}{u_\tau^*} \quad (7)$$

where  $z_{mr}$  and  $z_{mf}$  are the locations of maximum turbulent kinetic energy production (or the maximum streamwise velocity fluctuation intensity) for riblet and flat surfaces, respectively. This definition is considered more reliable because it takes into account the combined influence of riblet geometry and the flow parameters.

Table 4 outlines the locations of virtual origins based on Equation 7 for the two riblet cases. The difference in  $\beta$  between M25s20 and M25s40 indicates that the virtual origin is not only a function of the ridge angle as predicted by Equation 6, but also depends on the riblet spacing. As a result, Equation 7 will be used in the rest of the paper to calculate the location of virtual origin.

The effects of virtual origin can be demonstrated by comparing the mean velocity profiles plotted with and without the introduction of virtual origin. Figure 9a shows that riblets push the mean location of the no-slip surface further into the flow, and such displacement increases with riblet height. After the introduction of the virtual origin, the mean velocity profiles largely overlap except very close to the riblets, as shown by Figure 9b. Similar trend can be observed for the M72s20 case.

**Table 4. Location of virtual origin for each riblet configuration. Note,  $z = 0$  corresponds to the riblet valley. The virtual origin  $z_0$  is calculated following Equation 7 with  $z_{mf} = 12.5$  for Mach 2.5 and  $z_{mf} = 14.5$  for Mach 7.2.  $z_{tip}^+ = (z_{tip} - z_0)u_\tau^*/\nu_w$ , and  $\beta$  is computed from Equation 6 given  $z_0$ .**

Case	$z_0^+$	$z_{tip}^+$	$\beta$
M25s20	7.7	2.7	0.117
M25s40	17.0	5.0	0.132
M72s20	6.5	2.9	0.090

### C. Turbulence statistics

Turbulence statistics are plotted using the virtual origin calculated above to take into account the shift in the mean location of the no-slip surface due to riblets, as  $z^+ = (z - z_0)/z_\tau^*$ . The turbulence statistics are normalized either by the freestream quantities to demonstrate the changes in absolute magnitude, or by the wall units to investigate the structural variations in near-wall turbulence characteristics.

Figures 10a, 10c, and 10e show that all three components of turbulence intensity for M25s20 decrease relative to the clean surface case, consistent with the reduction in  $C_f$  for this case. For M25s40, much stronger spanwise variations are found because of the larger penetration of riblets into the boundary layer. The peak values above the tip are larger than those of the clean surface while the peak values above the valley are smaller, which is consistent with spanwise variation in the wall-shear rate (Figure 6) and the consequent overall increase in the viscous drag. The introduction of virtual origin largely accounts for the upward shift in profiles due to riblets. When normalized using  $u_\tau^*$ , which takes into account the drag variation, a much better collapse with the clean-surface profiles is achieved for M25s20, as shown in Figures 10b, 10d, and 10f. For M25s40, however, the collapse in profiles with the clean-surface profile is not as good as that of M25s20. The Reynolds shear stress, shown in Figure 11, demonstrates a similar trend to turbulent intensities for both riblet cases. The changes in turbulence intensities and Reynolds shear stress are consistent with the experimental observation by Robinson<sup>12</sup> at Mach 2.97 and are similar to several incompressible results.<sup>11, 17</sup>



Studies at Mach 7.2 show that the influence of riblets with  $s^+ \approx 20$  on turbulence statistics at Mach 7.2 is similar to that at Mach 2.5. In particular, Figures 12a and 12b demonstrate the damping effects of riblets on both the Reynolds shear stress and the Reynolds heat flux. The similar influences of riblets on turbulent transports of momentum and heat further confirm the validity of the Reynolds analogy and are consistent with the numerical findings at low speeds by Stalio and Nobile.<sup>36</sup>

#### D. Near-wall turbulence structures and drag reduction mechanisms

In this subsection, near-wall turbulence structures are investigated in order to identify the mechanism by which riblets reduce drag. We focus on the comparison between the two configurations corresponding to a drag reduction and a drag increase, respectively, at Mach 2.5.

Figure 13b and Figure 13d plot cross-flow velocity vectors  $(v,w)$  and contours of the streamwise vorticity component in the transverse plane for Cases M25s20 and M25s40, respectively. For the drag-reducing configuration (M25s20), Figure 13b shows that most streamwise vortical structures are limited by the small riblet spacing and, hence, stay above the riblets. As a result, only a limited area near the riblet tips is exposed to the downwash of high-speed fluid induced by these vortical structures and the high shear rates (red contours) are consequently restricted to the tips, as indicated by Figure 13a. For the drag-increasing configuration, however, Figure 13d shows that the streamwise vortical structures are able to penetrate further into the valleys of the riblets and a larger area is exposed to the high-speed downwash, resulting in a larger region of high shear rates (Figure 13c). Similar observations have been reported by Choi<sup>11</sup> while investigating incompressible channel flows over riblets, conforming that the dynamics of riblet flows is not significantly modified by compressibility effects up to a Mach number of 2.5.

### IV. Conclusions

This paper presented direct numerical simulations of turbulent boundary layers over riblets at Mach 2.5 and Mach 7.2. The DNS results at Mach 2.5 show that drag reduction of approximately 7% is achieved for riblets with  $s^+ \approx 20$ , similar to the drag reduction measured in the few existing experiments at supersonic Mach numbers. In addition, the DNS results show that the effects of riblets on turbulence statistics and large-scale structures closely resemble those at low speeds. In particular, riblets damp turbulence intensities and Reynolds shear stress near the wall for the drag-reducing configuration. The flow visualizations of near-wall structures seem to support the hypothesis of Choi et al.<sup>11</sup> that riblets with small spacing reduce viscous drag by restricting the location of streamwise vortices above the wetted surface so that only a limited area is exposed to the downwash of high-speed fluid induced by these streamwise vortices. The DNS study at Mach 7.2 shows that riblets with  $s^+ \approx 20$  remain effective in reducing drag in the hypersonic regime as well. The Reynolds analogy factor for the drag-reducing configuration is approximately equal to that of flat plates.

The DNS results provide evidence that the effectiveness of riblets would prevail under supersonic speeds, although further investigations for a broader set of flow parameters and riblet geometries are still necessary to establish the dependence of drag reduction on Mach number, wall cooling, and Reynolds number.

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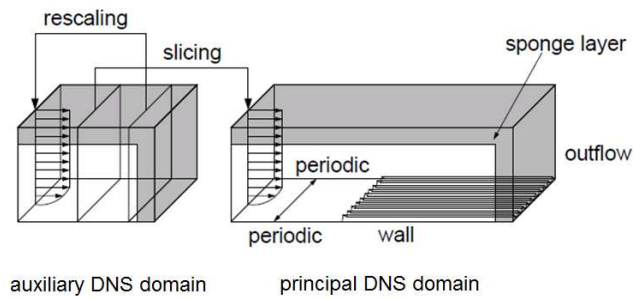
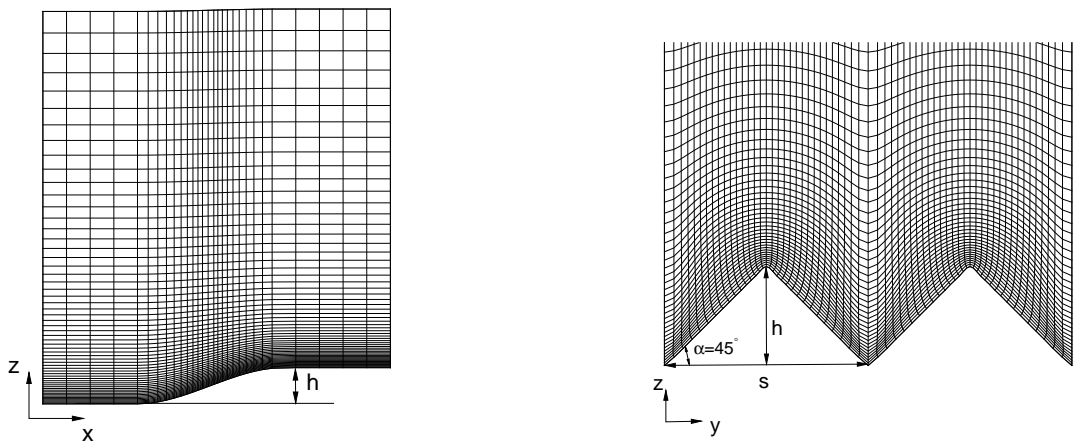


Figure 1. Sketch of DNS domain for spatial simulations (modified from Klumpp<sup>18</sup>)



(a) Side view of the transition from clean surface to riblets

(b) Close-up view of riblet configuration

Figure 2. Computational mesh near riblets for M25s20.

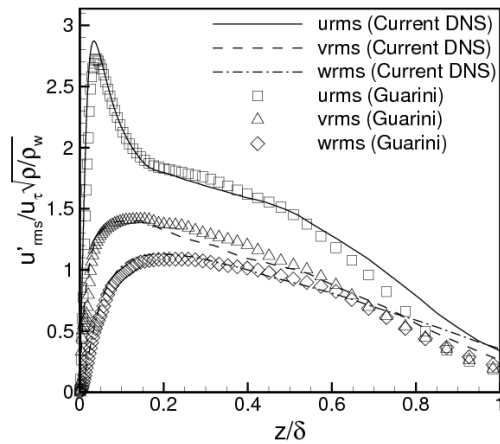


Figure 3. RMS of velocity components compared with the DNS by Guarini et al.<sup>33</sup>

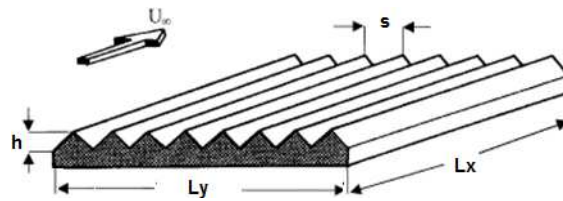


Figure 4. Sketch of riblet geometry (modified from Robert<sup>39</sup>)

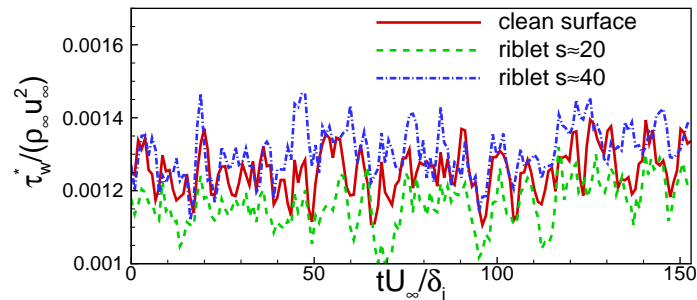


Figure 5. Time history of wall-shear rates for various Mach 2.5 cases.

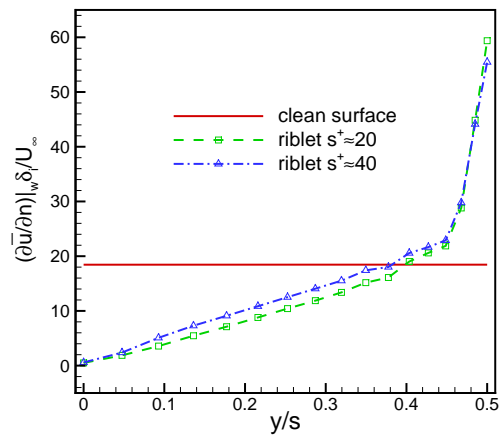


Figure 6. Wall-shear rates at various spanwise positions on riblet surface for Mach 2.5 cases.

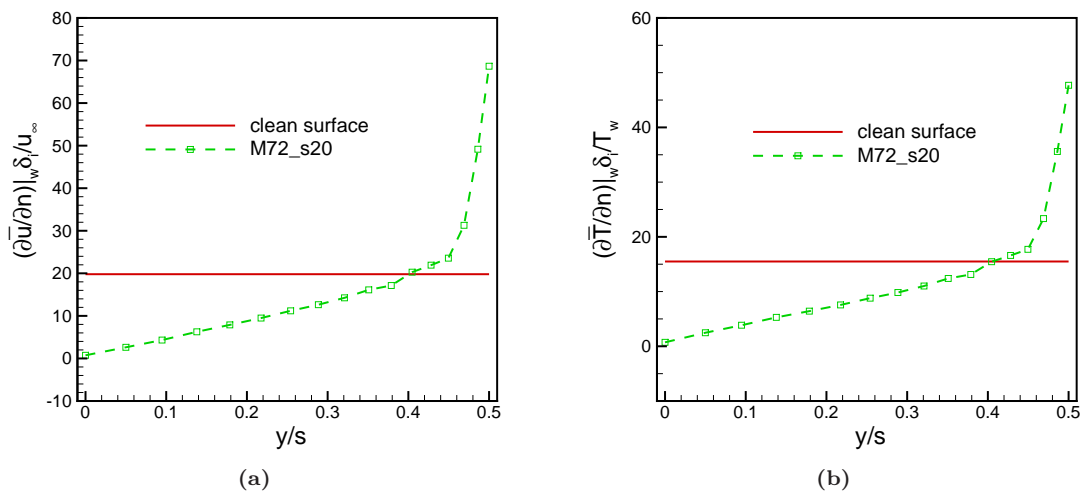


Figure 7. Wall-shear rates and wall-normal temperature gradient at various spanwise positions on riblet surface for Mach 7.2 cases.



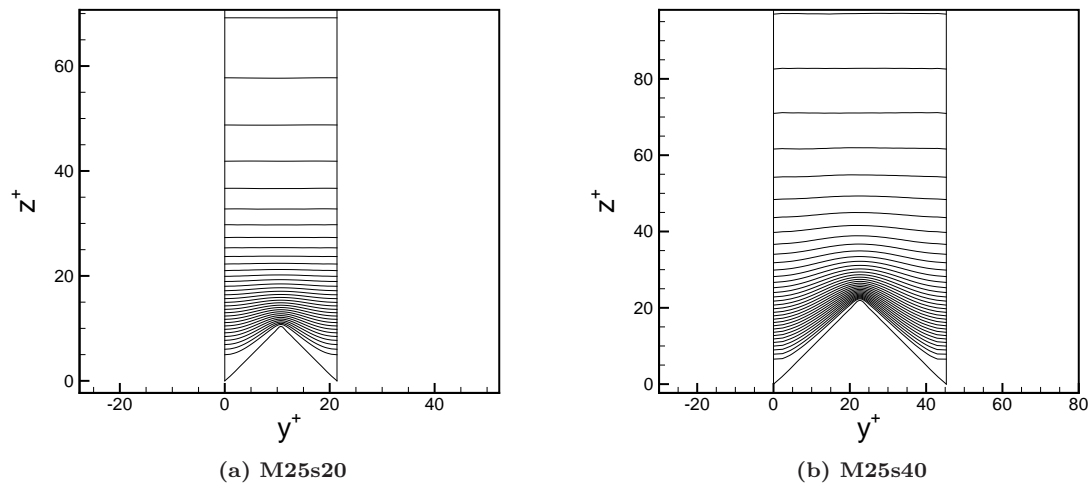


Figure 8. Contours of the mean streamwise velocity in the  $(y, z)$  plane. The contour levels normalized by  $u_\infty$  range from 0.05 to 0.95 by increments of 0.0225 for Mach 2.5 cases.

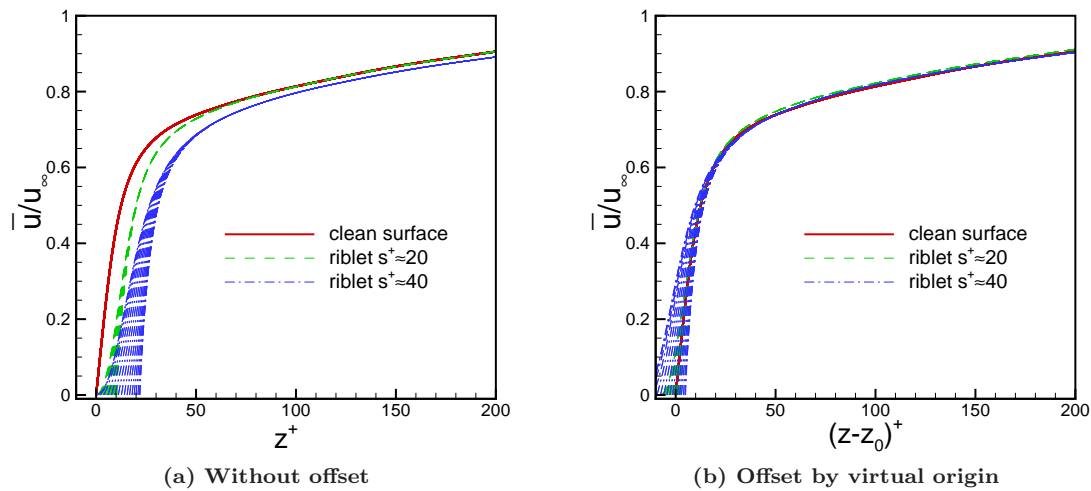


Figure 9. Mean streamwise velocity profiles near riblets without and with offset by virtual origin for Mach 2.5 cases. The virtual origin is defined by Equation 7.

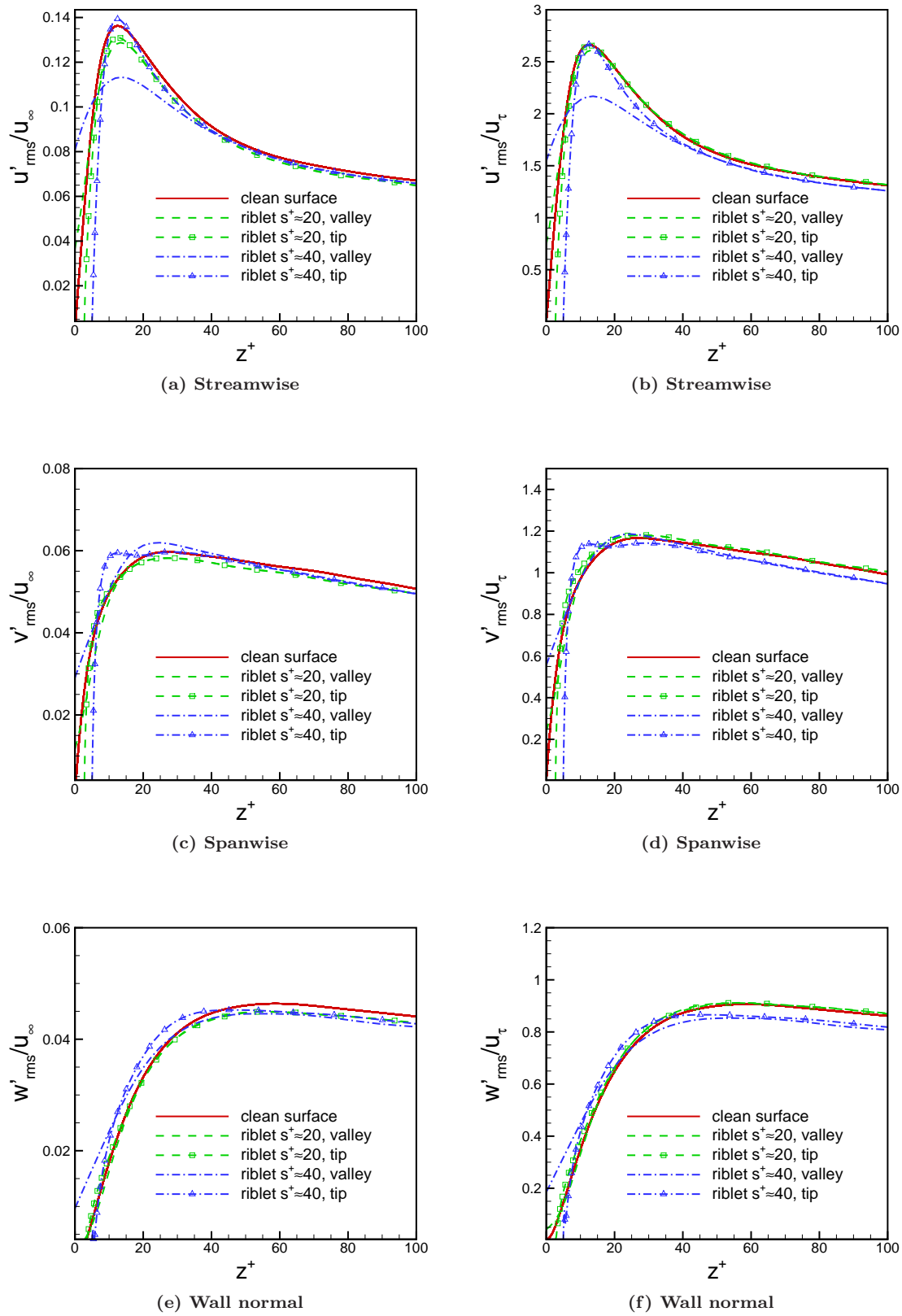


Figure 10. Turbulence intensities normalized by freestream velocity  $u_\infty$  (Left) or friction velocity  $u_\tau^*$  (Right) for Mach 2.5 cases.

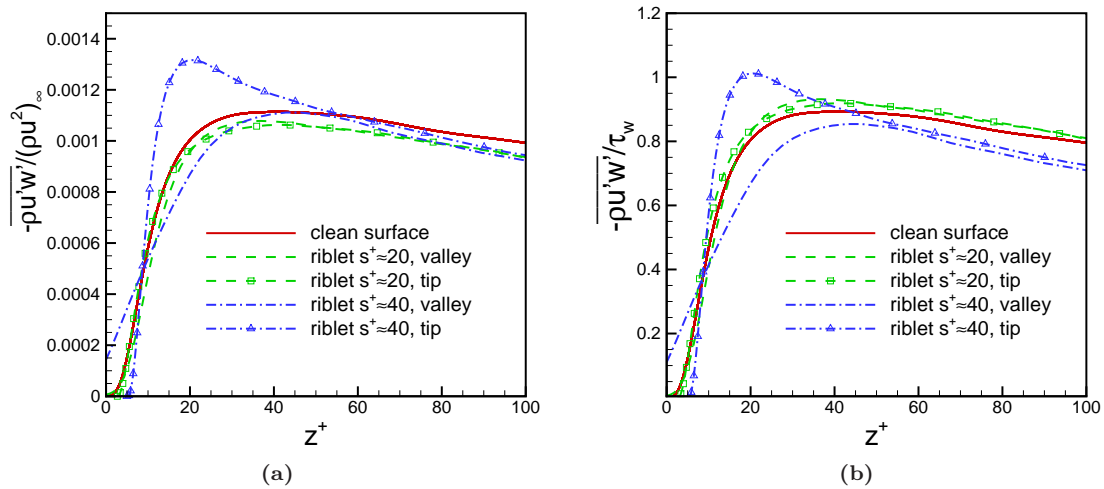


Figure 11. Reynolds shear stress normalized by freestream or wall quantities for Mach 2.5 cases.

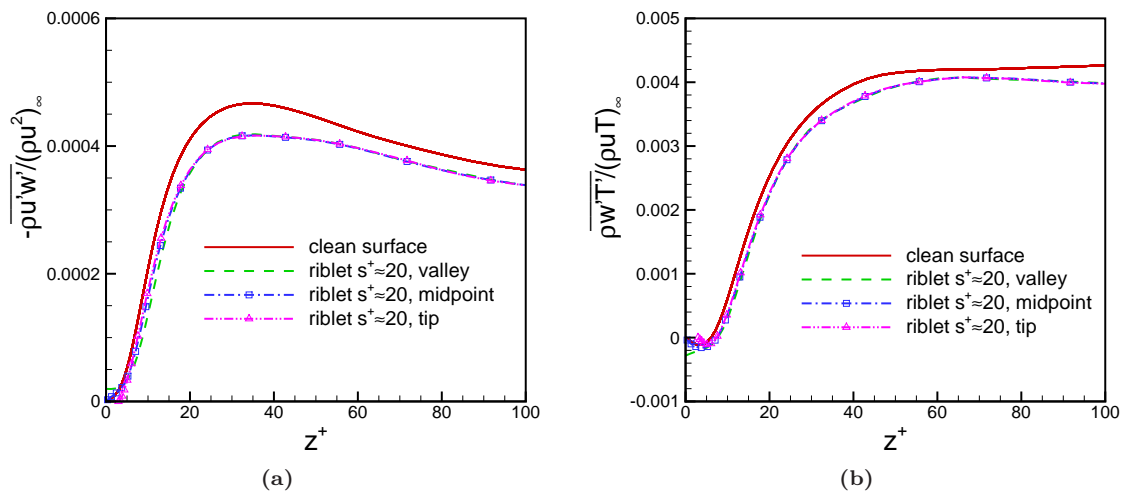


Figure 12. Reynolds shear stress and Reynolds heat flux normalized by freestream quantities for Mach 7.2 cases.

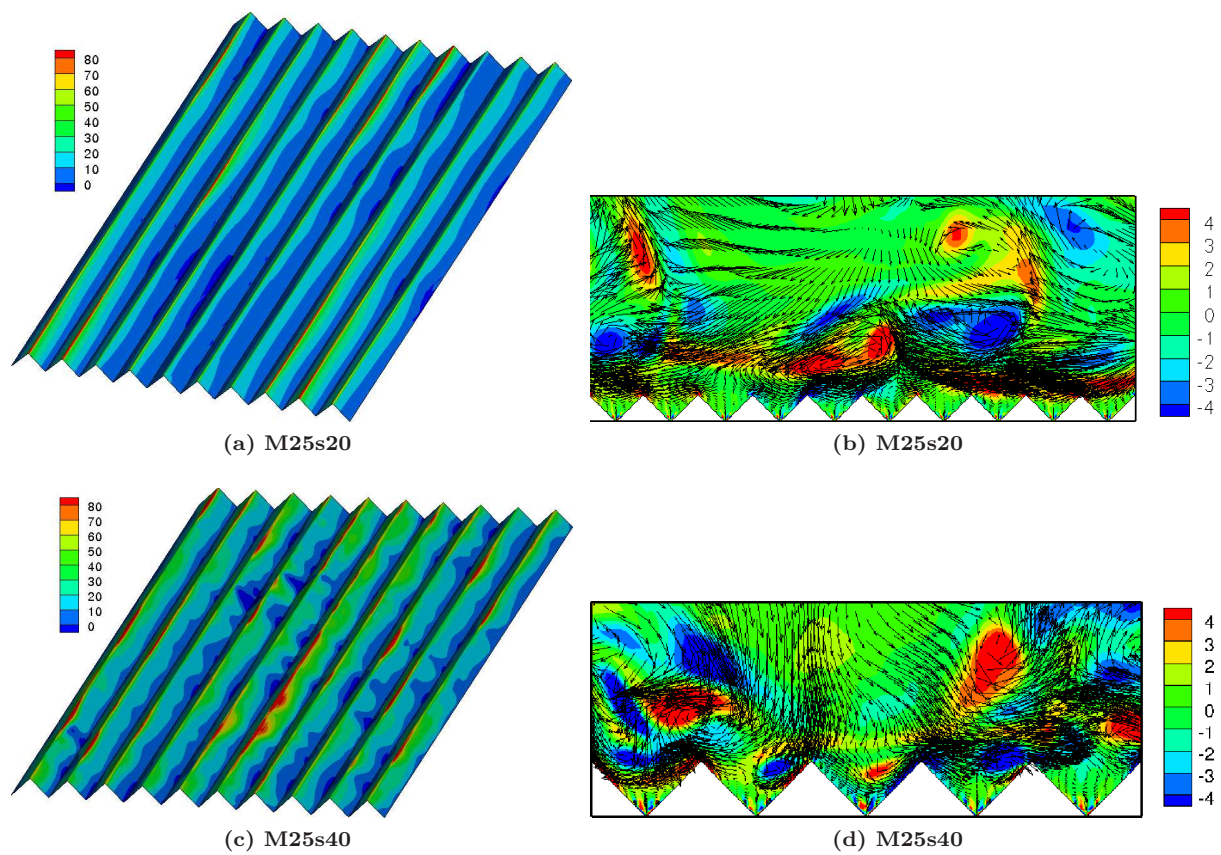


Figure 13. Instantaneous flows over riblets: (a,c) contours of the wall-shear rate on the riblet surfaces; (b,d) cross-flow velocity vectors ( $v,w$ ) and contours of the streamwise vorticity in the  $(y,z)$ -plane for Mach 2.5 cases.