Budget of Turbulent Kinetic Energy in a Shock Wave/Boundary-layer Interaction (Analysis of unsteady simulations to inform turbulence modeling)

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Outline

Introduction

- Motivation
- What is being done here?
- Simulation details

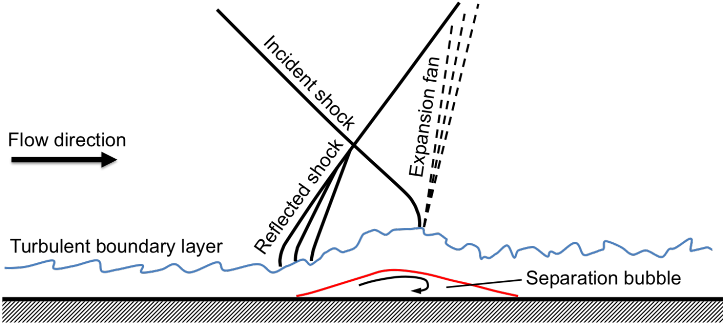
Results

- Logistics
- Validation of upstream boundary layer
- Budget within SBLI

Conclusions

References

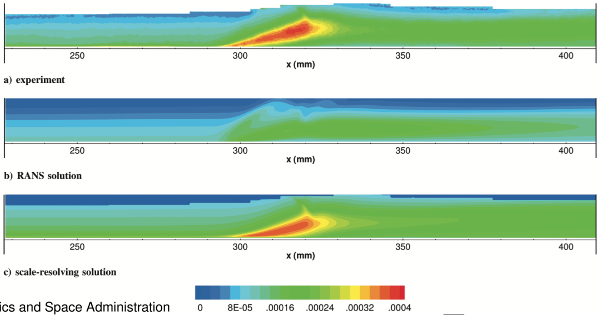
The problem...



- unsteadiness associated with incoming turbulent boundary layer, separation bubble, shear layer, and corner separation
- incipiently separated flow correlates with incoming turbulent boundary layer and reflected shock/separation bubble correlates with large separation
- inhomogeneous and anisotropic

State of the art in turbulence modeling

- one-equation models: linear, quadratic constitutive relation
- two-equation models: linear, non-linear constitutive relations corrections
- Reynolds-stress models: non-linear algebraic, solving for Reynolds-stress—expensive
- For Mach = 2.25 and $\theta = 8.0$, turbulence intensity: $\sqrt{\overline{u'^2}}/U_\infty^2$



Study the transport of turbulent kinetic energy

The transport equation:

$$\frac{\partial(\bar{\rho}k)}{\partial t} + \frac{\partial(\bar{\rho}\tilde{u}_j k)}{\partial x_j} = \mathcal{P} + \mathcal{T} + \mathcal{D}_\nu - \bar{\rho}\epsilon + \mathcal{D}_p + \Pi + \mathcal{M} \tag{1}$$

- production: the rate of transfer of kinetic energy from the mean flow to the turbulence
- turbulent transport: propagation of the turbulent kinetic energy
- molecular diffusion: viscous transport of the turbulent kinetic energy
- dissipation: conversion of turbulent kinetic energy to thermal internal energy
- pressure diffusion: transport due to pressure and velocity-gradient interaction
- compressible terms: pressure dilatation and mass flux

A closer look...

$\mathcal{P} = -\bar{\rho}\widetilde{u_i'' u_j''}\tilde{u}_{i,j}$	Production	(2)
$\mathcal{T} = -\left(\overline{\rho u_j'' \frac{1}{2} u_i'' u_i''}\right)_{,j}$	Turbulent Transport	(3)
$\mathcal{D}_\nu = \left(\overline{t_{ij} u_i''}\right)_{,j}$	Molecular Diffusion	(4)
$\bar{\rho}\epsilon = \overline{t_{ij} u_{i,j}''}$	Dissipation	(5)
$\mathcal{D}_p = -\left(\overline{p' u_i''}\right)_{,i}$	Pressure Diffusion	(6)
$\Pi = \overline{p' u_{i,i}''}$	Pressure Dilatation	(7)
$\mathcal{M} = \overline{u_i''}\left(\bar{t}_{ij,j} - \bar{p}_{,i}\right)$	Mass Flux	(8)

Solver

FDL3DI

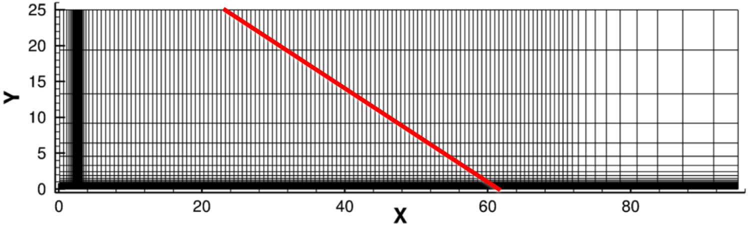
- Fifth-order bandwidth- and order-optimized weighted essentially non-oscillatory (WENO) scheme
- Roe for inviscid fluxes and viscous fluxes were computed using sixth-order compact scheme
- Implicit time integration with Beam-Warming using two sub-iterations and approximate factorization
- Counterflow force model used to trip the boundary layer

Flow and boundary conditions

Property	Experiment	Simulation
M_∞	2.33	2.33
U_∞, m/s	556.0	556.0
P_∞, Pa	23,511.0	2351.1
T_0, K	295.6	295.6
T_w, K	269.7	269.7
δ_{99}, m	5.3×10^{-3}	5.3×10^{-3}
Re_δ	175,202.0	17,520.2

- Laminar boundary-layer profile imposed at the inflow
- No slip wall with expected adiabatic wall temperature to freestream static temperature set to 1.95
- Shock imposed using Rankine-Hugonoit relations by specifying pre- and post-shock conditions

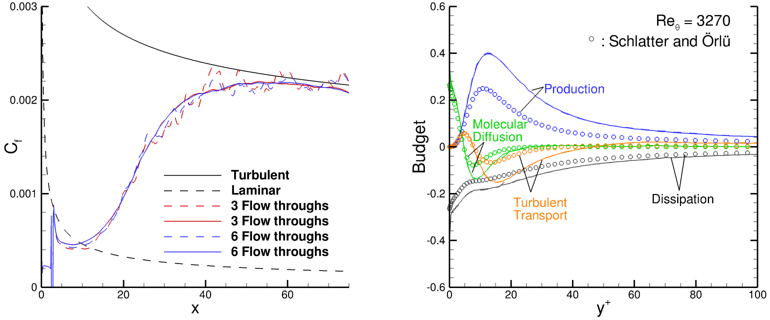
Grid



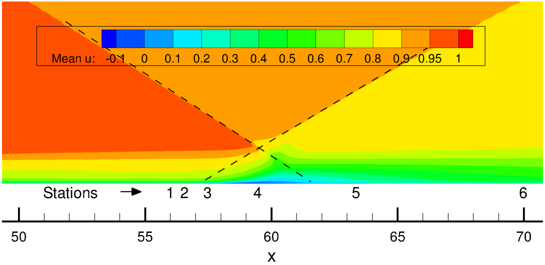
- X, Y, and Z = 95, 25, and 5 non-dimensionalized by δ_{99}
- 1301 $\times$ 251 $\times$ 201 for a total of approximately 66M grid points
- 1000 points in the constant area section
- Shock imposed at $x = 23.2$

Data averaging?

- How long should the case be run before collecting statistics? - 6 flow-through time
- Flow-through times necessary to converge the high-order statistics? - 3 and 6 flow-through times
- Centerline versus span-averaged statistics

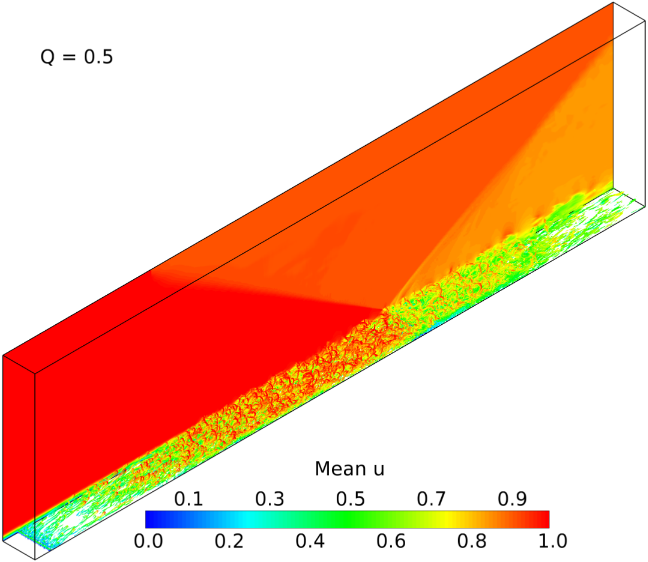


Key stations

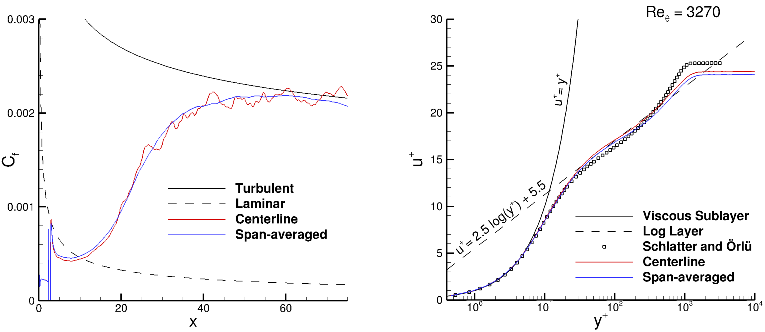


Station	Location	x	Re_θ
1	Incoming flat plate boundary layer	56.0	3270
2	Upstream of the reflected shock	56.6	3280
3	Downstream of the reflected shock	57.5	3300
4	Separation bubble	59.5	-
5	Downstream of the impinging shock	63.4	-
6	Recovered flat plate boundary layer	70.0	-

Iso-surface of Q-criterion

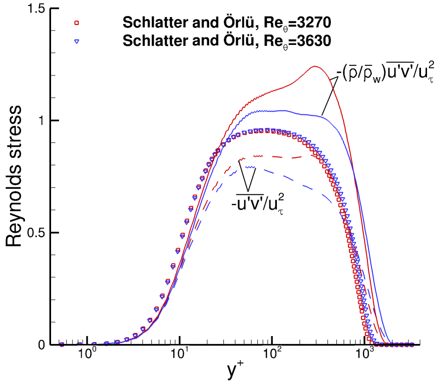


Skin friction and normalized velocity



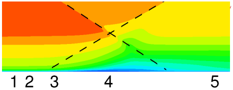
- Beyond $x = 60$, centerline skin friction oscillates about the theoretical turbulent skin friction, but span-averaged was marginally lower
- An even finer mesh should help provide a better match, but at a higher computational cost

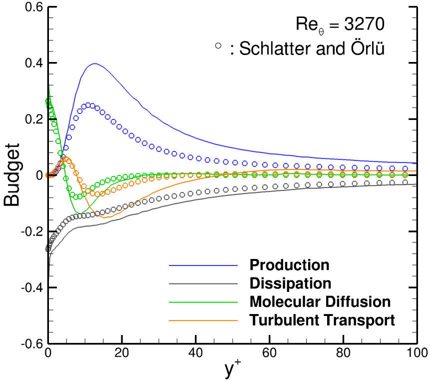
Reynolds shear stress



- Density scaling necessary
- Boundary layer has not reached an equilibrium state at $Re_\theta = 3270$
- $-\overline{uv}^+ = 0.0008y^+$ holds true, which was shown by Patel et al. [1]

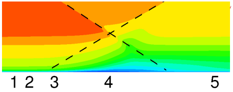
Turbulent kinetic energy budget

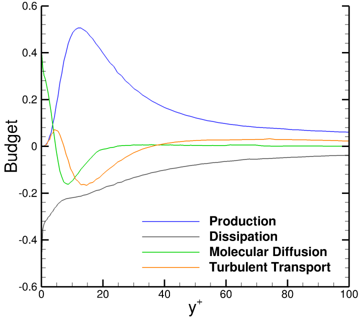


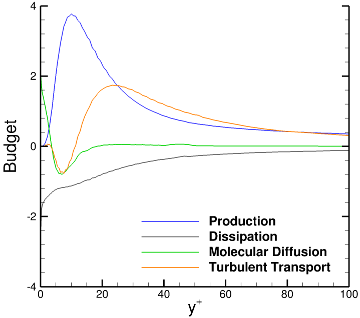


- Similar trends in comparison with the incompressible DNS, but current simulations shows larger magnitude
- Can be attributed to the lack of mesh resolution at the simulated Reynolds number—finer mesh or lowering simulated Reynolds number will improve comparison

Forward and aft of the reflected shock

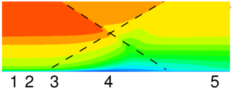


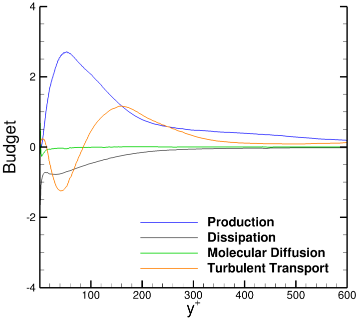


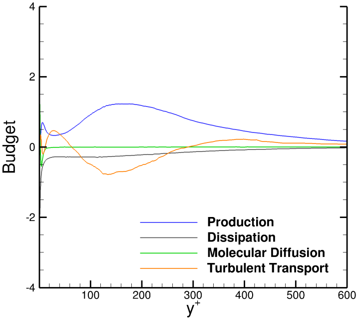


- The production and dissipation terms increased by an order of magnitude aft of the reflected shock
- The trough in the buffer layer of the turbulent transport term moved closer to the wall and a new peak developed at the beginning of the log layer

Forward and aft of the impinging shock

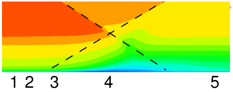


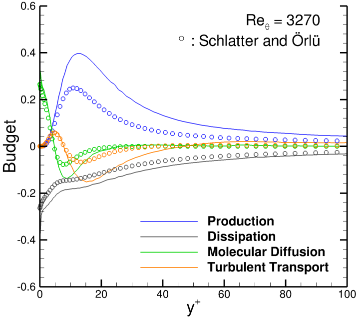


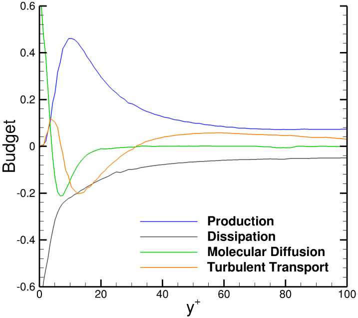


- In the separation bubble, the peak in the production term moved away from the wall and into the beginning of the log layer
- The peak in the turbulent transport term also shifted away from the wall
- Aft of the impinging shock budget was reminiscent of the boundary layer forward of the interaction region

Aft of the interaction region

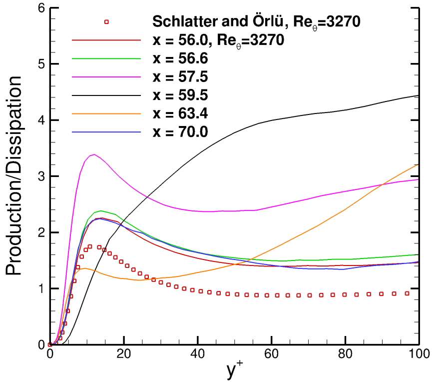






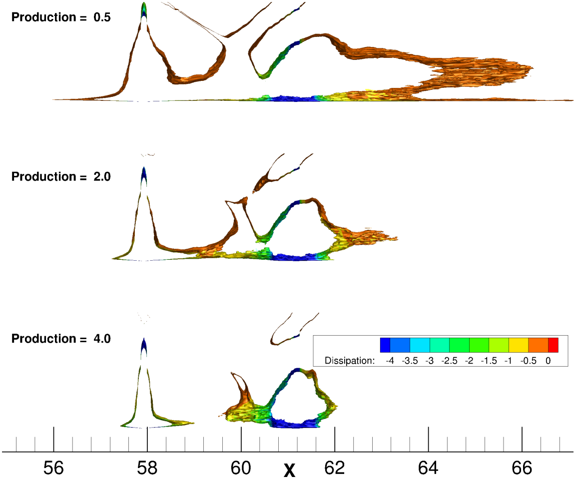
- A return to undisturbed pre-shock budget profiles
- Production and turbulent transport terms remained active in the log and outer layer regions ($10^2 < y^+ < 10^3$) with secondary peaks and troughs.

Ratio of production-to-dissipation



- $\mathcal{P}/\epsilon$ ratio does not become unity in the log layer
- But, a good match with the incompressible DNS in the viscous sublayer

Iso-surfaces of the production and dissipation



Conclusions

- Budgets of the turbulent kinetic energy calculated using the ILES framework
- Current fine mesh was inadequate to resolve the buffer and log layer regions even at a reduced Reynolds number
- The station upstream of the interaction did not reach a complete equilibrium
- Matching trends with that of the incompressible DNS
- Current work: improved inflow and a finer mesh

Questions?

References

[1] Virendra C. Patel, Wolfgang Rodi, and Georg Scheuerer. Turbulence models for near-wall and low reynolds number flows: A review. *AIAA Journal*, 23(9):1308–1319, January 1985.