Evaluating the Performance of an Improved Finite Volume Method for Solving the Fluid Dynamic Equations

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Presentation Outline

- ✓ Introduction
- ✓ CFD: Its Importance & Challenges
- ✓ The NS System of Equations: Its Closure
- ✓ Expectations: Flow Physics Prediction Capabilities
- ✓ The NS Non-Dimensionalization Process
- ✓ The IDS Concepts: From Grids to Points, Cells & Control Volumes; Spatial & Temporal Cells
- ✓ The IDS – Solving the Integral form of the NS Equations
- ✓ IDS – An Explicit Numerical Method, its execution
- ✓ IDS Applications
  - The Hypersonic Flat Plate, the Shock Boundary Layer Interaction and the Cross Flow Injection Problems
- ✓ Conclusion

The Importance of CFD

The impact of CFD: the Boeing 747

www.plane-truth.com

747-100 in service January 1970
Passengers: 366 (3 classes)
Range: 4,300 miles
Thrust: 186,000lb
Fuel: 48,445 gallons
Max. Takeoff Weight: 735,000lb

747-8 to go into service in 2009
Passengers: 467 (3 classes)
Range: 8,000 miles
Thrust: 266,000lb
Fuel: 60,125 gallons
Max. Takeoff Weight: 970,000lb

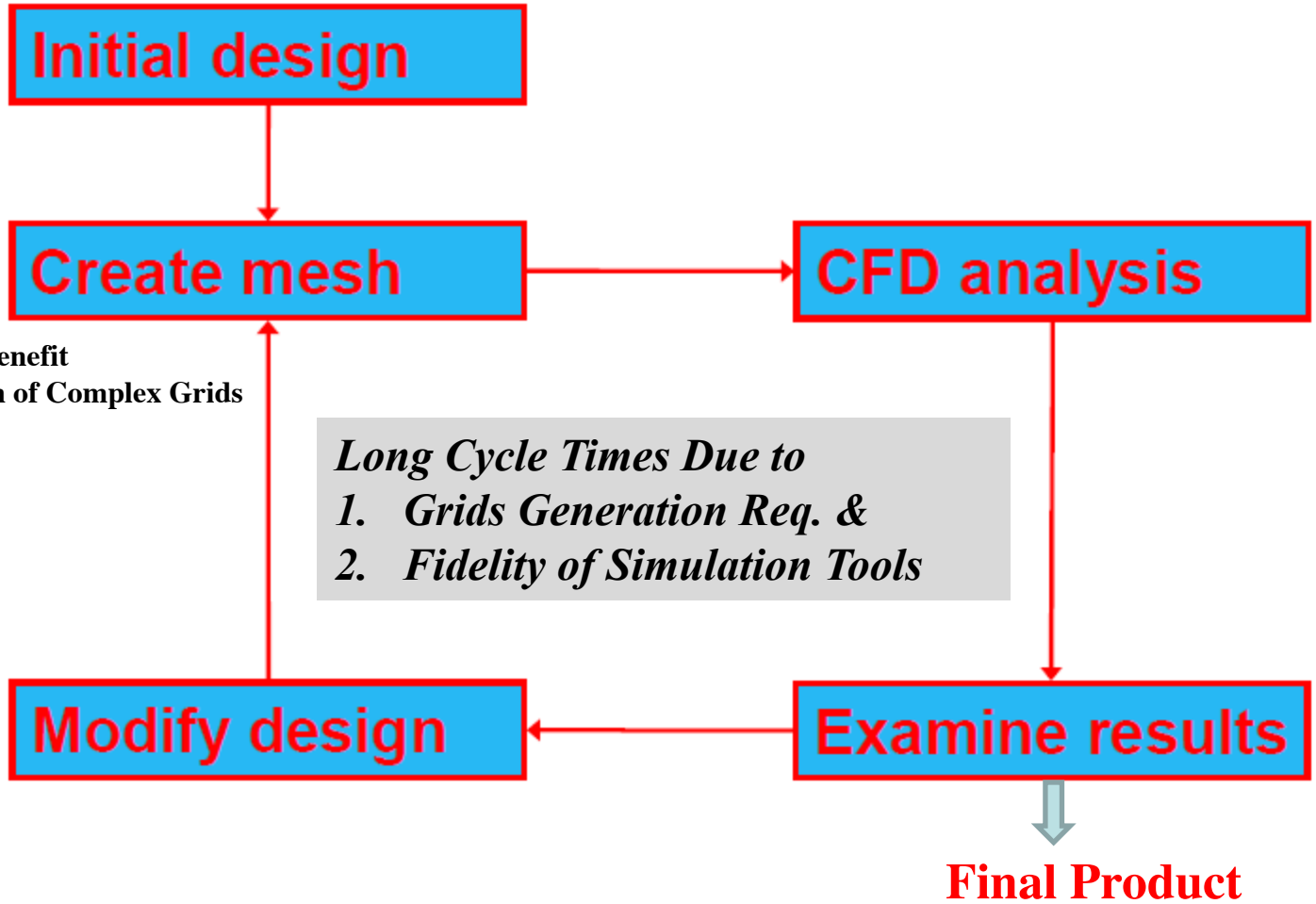
www.boeing.com

Ref. 4 Data

CFD Challenges

Engineering Perspective: Analysis, Not Design

Ref. 4 Data



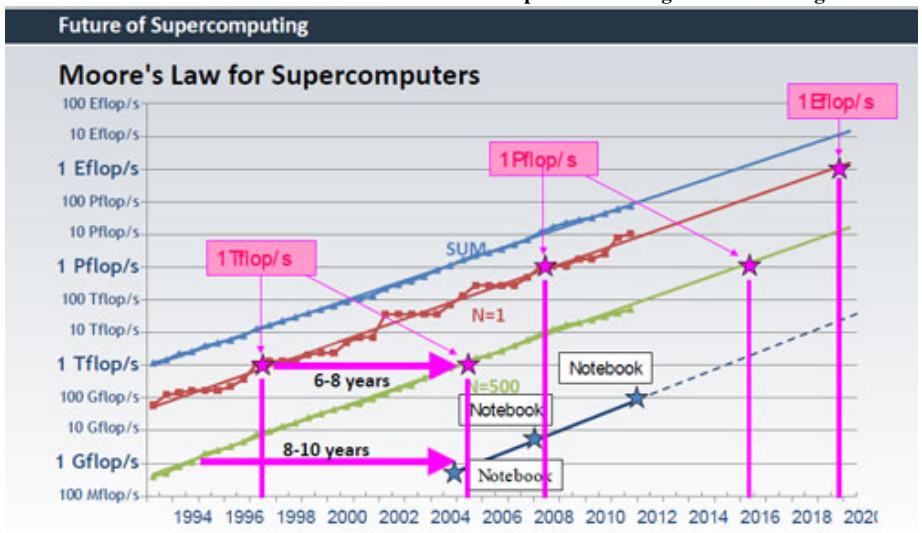
Potential Benefit
Elimination of Complex Grids

Long Cycle Times Due to
1. *Grids Generation Req. &*
2. *Fidelity of Simulation Tools*

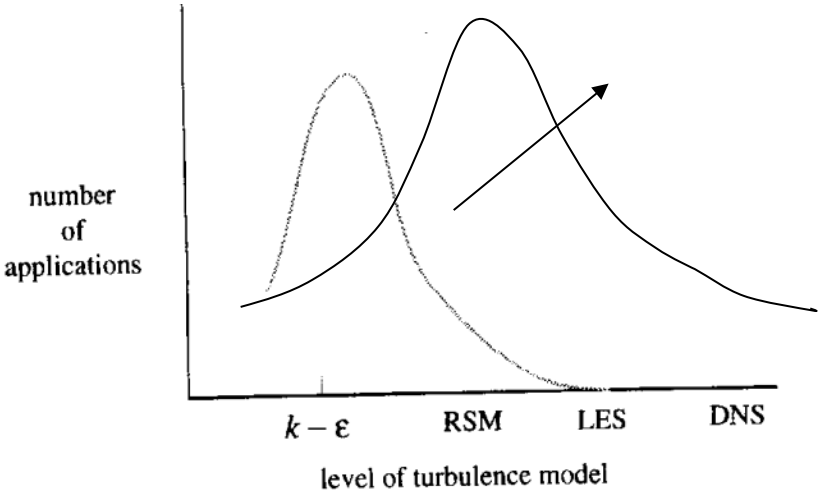
State-of-the-Art in the CFD Industry

!Use DNS/LES Data to Develop Turbulence Models for CFD Applications

http://www.bcs.org/content/conBlogPost/2035



Computer Speed vs. Time (Year)



Industrial Applications vs CFD Models

Why Algebraic Turbulence Models?
- numerical & memory efficiency
- capture the basic physics of the process

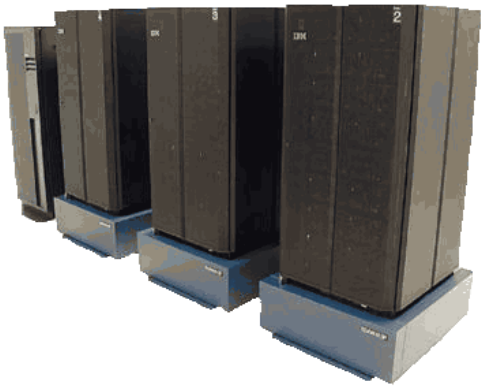
Why Cartesian Grids?
-fast grid generation, numerical & memory efficiency during parallelization

Introduction

Opportunity

- Historically only Analytical Fluid Dynamics (AFD) and Experimental Fluid Dynamics (EFD).
- CFD is the computer simulation of fluid dynamic systems through the use of engineering models (mathematical formulation) and numerical methods (discretization methods and grid generations)
- CFD made possible by the advent of digital computer and advancing with improvements of computer resources (1947, 500 Flops, → 2003 Teraflops, 2003 → 2015 Petaflops → 2020 Exaflops)

Data, Ref. 2



1947 - 500 flops Computer

2003 – 20 Teraflops Computer

Introduction

Research Objective: To Solve the NS Equations

- Applicable to a wide Class of Fluid Dynamic Problems
- Accurate Flow Physics Capturing Capabilities
- Efficient Grid Generation & Solution Process

NS Eqs: System of Conservations Laws

$$\frac{\partial}{\partial t}\oiiint_{v} \rho dv + \oiint_{s} \rho \overline{V} d\overline{s} = 0$$

$$\frac{\partial}{\partial t}\oiiint_{v} \rho \overline{V} dv + \oiint_{s} \left(\rho \overline{V}.d\overline{s}\right)\overline{V} = -\oiint_{s} P d\overline{s} + \oiint_{s} \hat{\tau} d\overline{s}$$

$$\frac{\partial}{\partial t}\oiiint_{v} \rho E dv + \oiint_{s} \rho E \overline{V}.d\overline{s} = -\oiint_{s} P\overline{V}.d\overline{s} + \oiint_{s} \hat{\tau}.\overline{V} d\overline{s} + \oiint_{s} \dot{\overline{q}} d\overline{s}$$

Plus the Boundary & Initial Conditions

Viscous Relations

$$\tau_{xx} = \frac{2}{3}\mu\left(2\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} - \frac{\partial w}{\partial z}\right)$$

$$\tau_{xy} = \tau_{yx} = \mu\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)$$

$$\tau_{yy} = \frac{2}{3}\mu\left(2\frac{\partial v}{\partial y} - \frac{\partial u}{\partial x} - \frac{\partial w}{\partial z}\right)$$

$$\tau_{xz} = \tau_{zx} = \mu\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)$$

$$\tau_{zz} = \frac{2}{3}\mu\left(2\frac{\partial w}{\partial z} - \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}\right)$$

$$\tau_{yz} = \tau_{zy} = \mu\left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z}\right)$$

$$\dot{q}_x = -k\frac{\partial T}{\partial x} \qquad \dot{q}_y = -k\frac{\partial T}{\partial y} \qquad \dot{q}_z = -k\frac{\partial T}{\partial z}$$

Equations and formulas from: J. D. Anderson(1995) : "Computational Fluid Dynamics-The basics with applications", McGraw-Hill, Inc.

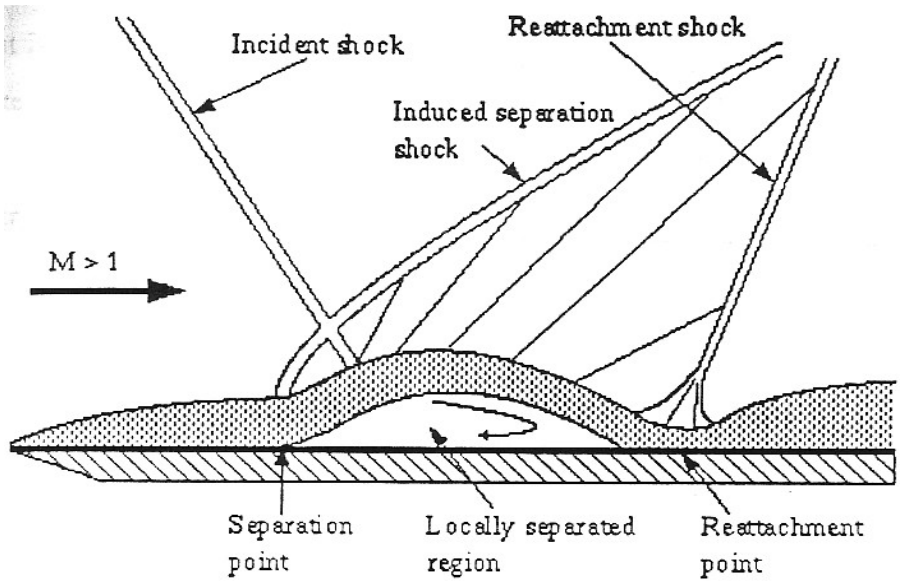
The Closed System of the Equations

- **Additional relations**
  - **Equation of state** $P = \rho R T$
  - **Internal energy** $e = C_v T$
  - **Sutherland's law for viscosity** $\mu = \mu_\infty \left(\frac{T}{T_\infty} \right)^{1.5} \frac{T_\infty + 110}{T + 110}$
  - **Prandtl number** $k = k(T)$
- **The closed system of the equations has only five unknowns**

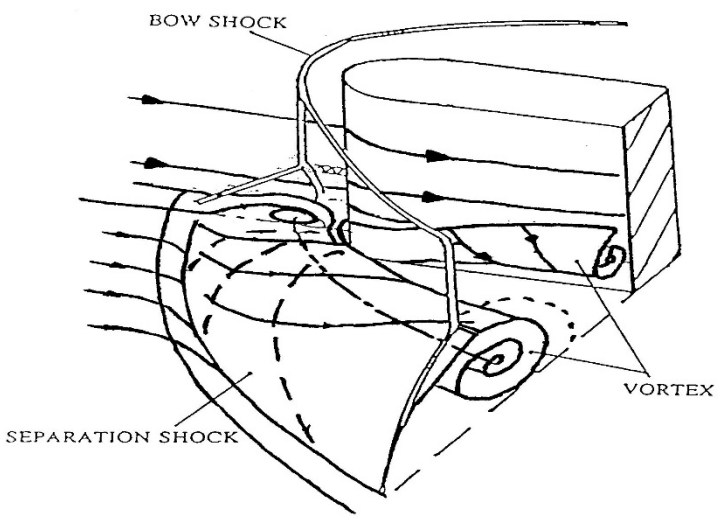
$$(\rho, u, v, w, T)$$

Capability: Predicted Flow Physics

!Examples of Problems to be solved



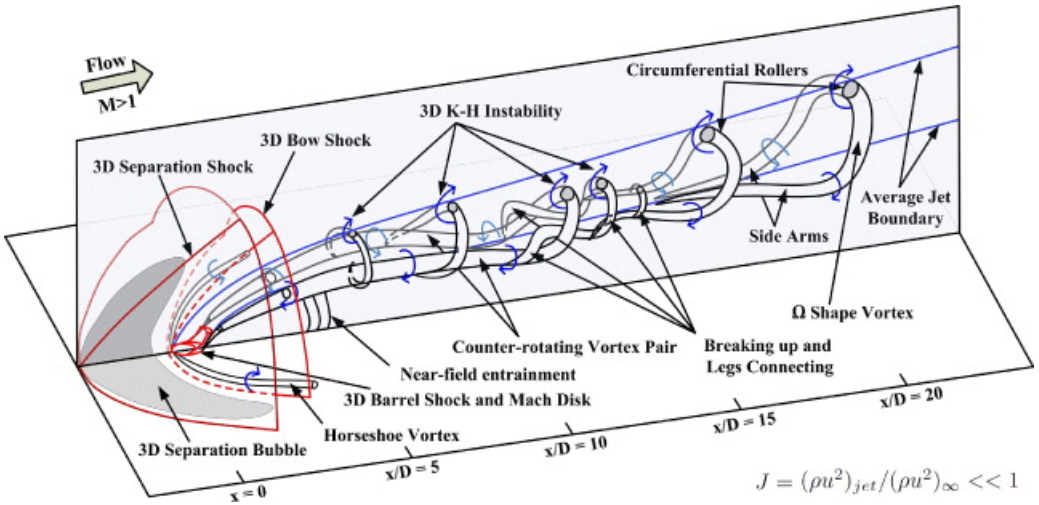
Shock/Boundary Layer Interaction



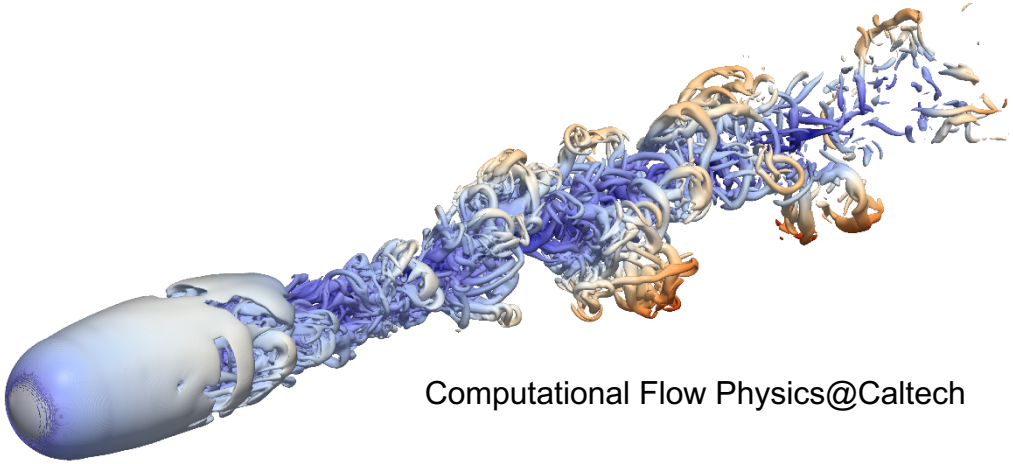
Flow Over Blunt Body

Capability: Predicted Flow Physics

!Examples of Problems to be solved



Ref. Y. You, et al: Flow physics of a low momentum jet in supersonic crossflow



Computational Flow Physics@Caltech

IDS: Non-Dimensionalization Process

Geometric Variables

$$\bar{x} = \frac{x}{L} \qquad \bar{y} = \frac{y}{L} \qquad \bar{z} = \frac{z}{L}$$

Fluid Properties

$$\bar{\mu} = \frac{\mu}{\mu_\infty} \qquad \bar{k} = \frac{k}{k_\infty}$$

Fluid Parameters/IDS Solution Variables

$$\bar{\rho} = \frac{\rho}{\rho_\infty} \qquad \bar{u} = \frac{u}{u_\infty} \qquad \bar{v} = \frac{v}{u_\infty} \qquad \bar{w} = \frac{w}{u_\infty} \qquad \bar{T} = \frac{T}{T_\infty}$$

IDS Code Inputs:
+
Grids & I&B Cdts

$$L,\ V_\infty,\ \rho_\infty,\ T_\infty,\ \mu_\infty,\ k_\infty,\ \gamma,\ R_{air}$$

IDS: Non-Dimensionalization Process

Derived No-Dim Variables

$$\bar{t} = \frac{t}{t_\infty} = \left| t_\infty = \frac{L}{u_\infty} \right| = \frac{u_\infty t}{L} \qquad \bar{P} = \frac{P}{\rho_\infty u_\infty^2} \qquad \bar{a} = \frac{a}{a_\infty} = \sqrt{\frac{\gamma R T}{\gamma R T_\infty}} = \sqrt{\bar{T}}$$

Properties Computed from Inputs

$$C_v = \frac{R_{air}}{(\gamma - 1)}, \quad C_p = \frac{\gamma R_{air}}{(\gamma - 1)}, \quad \mathrm{Re}_\infty = \frac{\rho_\infty V_\infty L}{\mu_\infty}, \quad \mathrm{Pr}_\infty = \frac{\mu_\infty C_p}{k_\infty}; \quad M_\infty = \frac{V_\infty}{\sqrt{\gamma R T_\infty}}$$

Non-Dim Properties to be Computed

$$\bar{\mu} = \frac{\mu}{\mu_\infty} = \left(\bar{T}\right)^{1.5} \frac{1.0 + 110/T_\infty}{\bar{T} + 110/T_\infty}$$

$$\bar{k} = \frac{k\left(\bar{T} T_\infty\right)}{k_\infty} = \frac{{}^k C_3 \left(\bar{T} T_\infty\right)^3 + {}^k C_2 \left(\bar{T} T_\infty\right)^2 + {}^k C_1 \left(\bar{T} T_\infty\right) + {}^k C_0}{k_\infty}$$

IDS: Non-Dimensionalization Process

Non-Dim Properties to be Computed

$$\overline{P} = \frac{1}{\gamma M_\infty^2}\overline{\rho}\,\overline{T} \qquad \overline{e} = \frac{e}{V_\infty^2} = \frac{1}{\gamma(\gamma-1)M_\infty^2}\overline{T} \qquad \overline{h} = \frac{h}{V_\infty^2} = \frac{1}{(\gamma-1)M_\infty^2}\overline{T}$$

$$k\overline{e} = \frac{V^2}{V_\infty^2} = \frac{1}{2}\left(\overline{u}^2 + \overline{v}^2 + \overline{w}^2\right) \qquad \overline{E}_{Total} = \overline{e} + k\overline{e}; \quad \overline{H}_{Total} = \overline{h} + k\overline{e}$$

IDS NS Coefficients

$$^{NS}C_1 = \frac{1}{\gamma(\gamma-1)M_\infty^2}; \quad ^{NS}C_2 = \frac{1}{\gamma M_\infty^2}; \quad ^{NS}C_3 = \frac{1}{(\gamma-1)M_\infty^2};$$

$$^{NS}C_4 = \frac{2}{3}\frac{1}{\mathrm{Re}_\infty} \quad ^{NS}C_5 = \frac{1}{\mathrm{Re}_\infty}; \quad ^{NS}C_6 = \frac{1}{(\gamma-1)}\frac{1}{\mathrm{Re}_\infty}\frac{1}{\mathrm{Pr}_\infty}\frac{1}{M_\infty^2}$$

The conservation of mass , momentum, and energy equations

$$\oiiint_{v} \frac{\partial \rho}{\partial t} dv + \oiint_{s} \rho \overline{V} d\overline{s} = 0$$

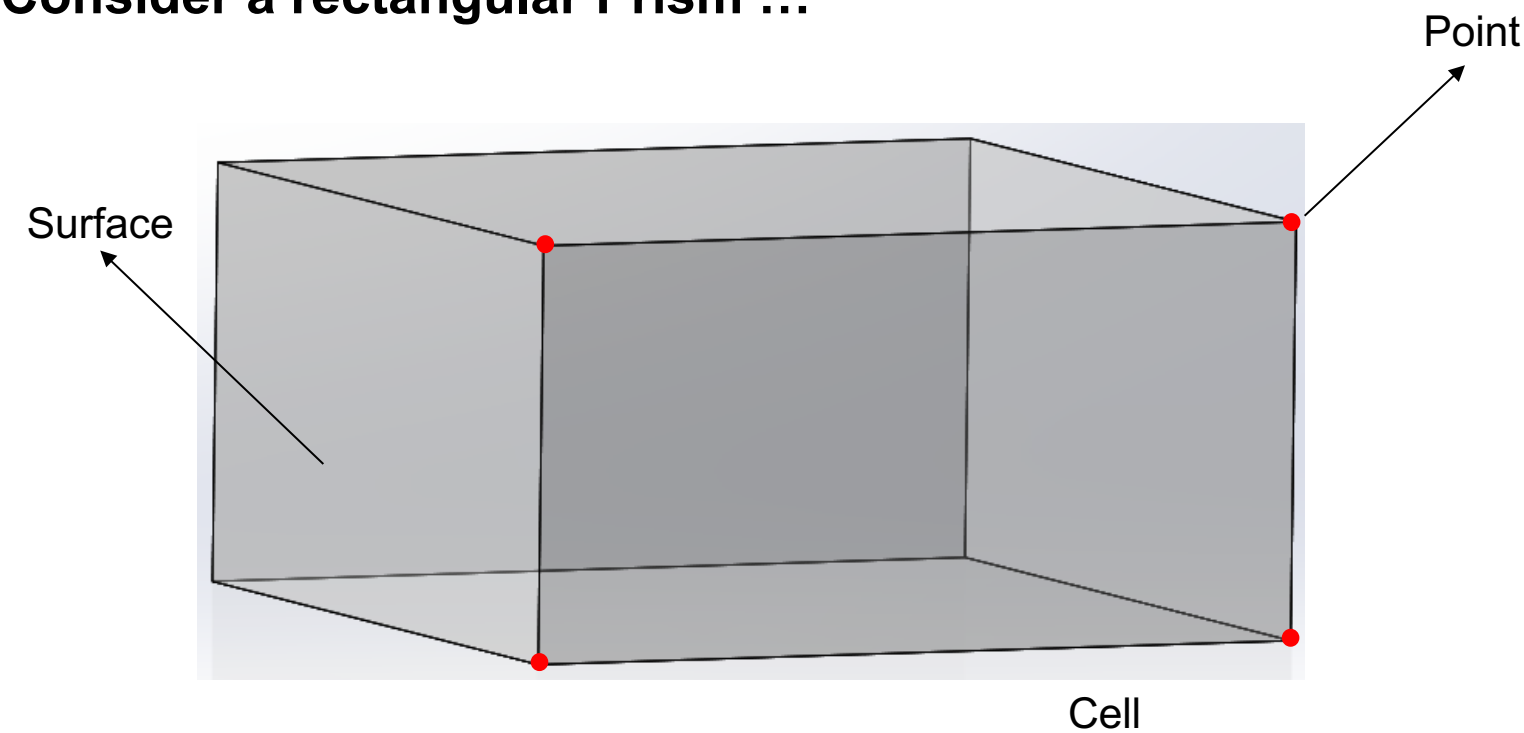
$$\frac{\partial}{\partial t} \oiiint_{v} \rho \overline{V} dv + \oiint_{s} \left(\rho \overline{V} . d\overline{s} \right) \overline{V} = -\oiint_{s} P d\overline{s} + \oiint_{s} \hat{\tau} d\overline{s}$$

$$\frac{\partial}{\partial t} \oiiint_{v} \rho E dv + \oiint_{s} \rho E \overline{V} . d\overline{s} = -\oiint_{s} P \overline{V} . d\overline{s} + \oiint_{s} \hat{\tau} . \overline{V} d\overline{s} + \oiint_{s} \dot{\overline{q}} d\overline{s}$$

An IDS Cell != Control Volume

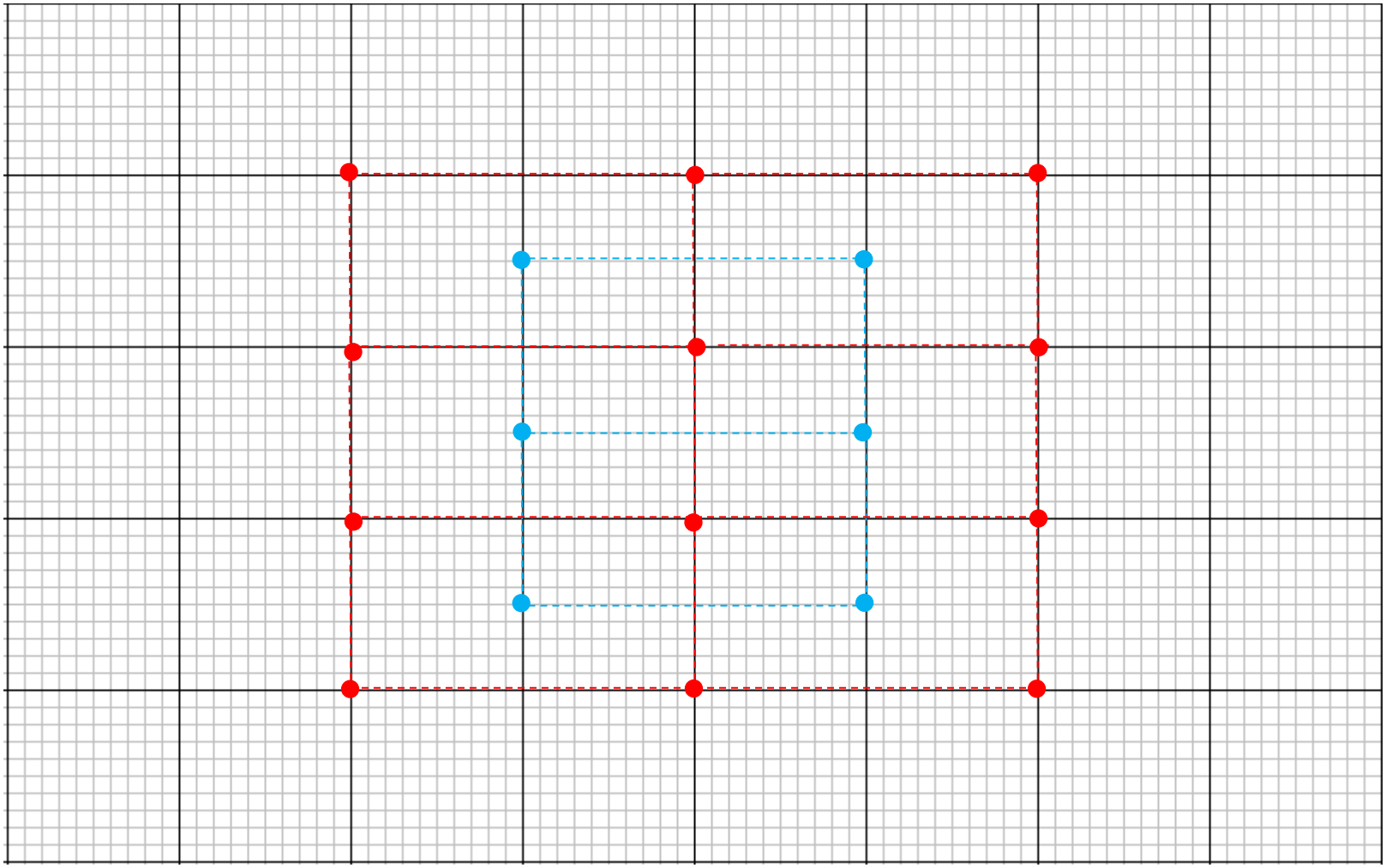
- It's A Physics based Approach
- It consists of points, cells & surfaces

Consider a rectangular Prism …



IDS Control Volume Representation

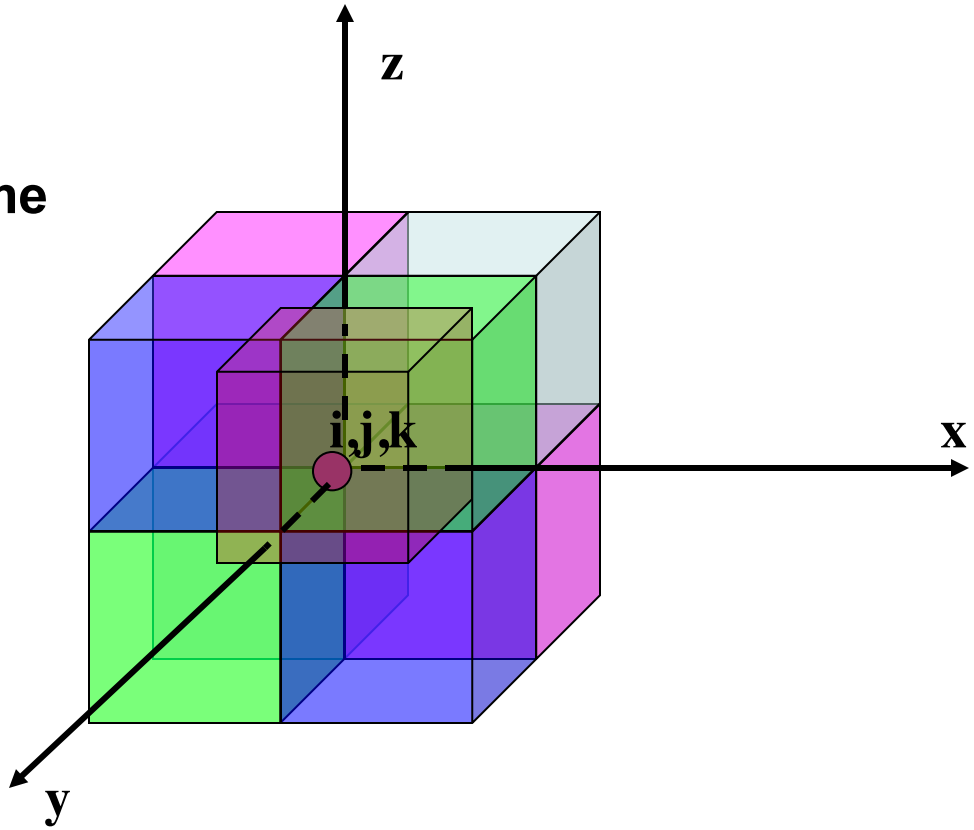
- The Spatial & Temporal Cells
- The 2D Control Volume



An IDS Control Volume

Key Features

- ✓Points
- ✓Cells
- ✓Control Volume



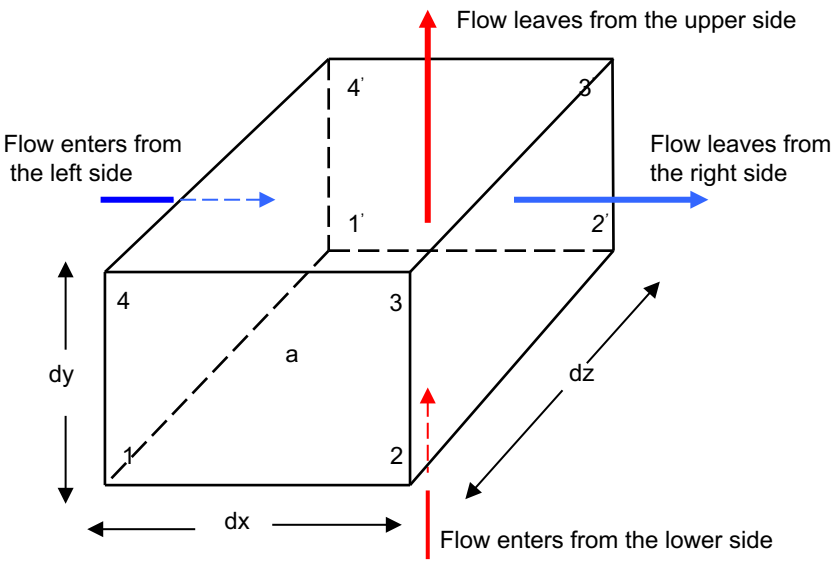
The Mass Conservation Equation in an IDS Cell

$$\frac{\partial}{\partial t}\oiiint_{v} \rho dv + \oiint_{s} \rho \bar{V} d\bar{s} = 0$$

$$\left(\frac{\partial \rho}{\partial t}\right)_{cell}^{average} = \frac{1}{4\Delta x}\left\{\begin{matrix}\left[(\rho u)_{1'} + (\rho u)_{2'} + (\rho u)_{3'} + (\rho u)_{4'}\right]_{\min us} - \\ \left[(\rho u)_{1} + (\rho u)_{2} + (\rho u)_{3} + (\rho u)_{4}\right]_{plus}\end{matrix}\right\}$$

$$\frac{1}{4\Delta y}\left\{\begin{matrix}\left[(\rho v)_{1'} + (\rho v)_{2'} + (\rho u)_{3'} + (\rho v)_{4'}\right]_{\min us} - \\ \left[(\rho v)_{1} + (\rho v)_{2} + (\rho v)_{3} + (\rho v)_{4}\right]_{plus}\end{matrix}\right\}$$

$$\frac{1}{4\Delta z}\left\{\begin{matrix}\left[(\rho w)_{1'} + (\rho w)_{2'} + (\rho w)_{3'} + (\rho w)_{4'}\right]_{\min us} - \\ \left[(\rho w)_{1} + (\rho w)_{2} + (\rho w)_{3} + (\rho w)_{4}\right]_{plus}\end{matrix}\right\}$$

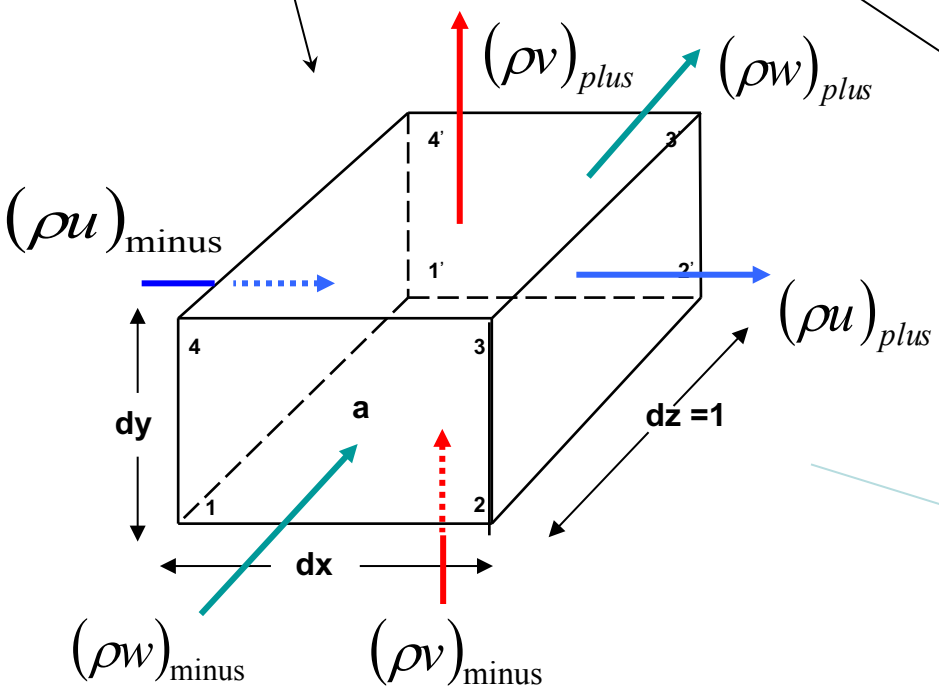


The Mass Conservation Equation in an IDS Cell

Example of the IDS –Spatial Scheme

$$\frac{\partial}{\partial t}\oiiint_{v} \rho dv + \oiint_{s} \rho \bar{V} d\bar{s} = 0$$

$$\left(\frac{\partial \rho}{\partial t}\right)_{cell}^{average} = \frac{1}{4\Delta x}\left\{\begin{matrix}[(\rho u)_1+(\rho u)_2+(\rho u)_3+(\rho u)_4]_{minus} - \\ [(\rho u)_1+(\rho u)_2+(\rho u)_3+(\rho u)_4]_{plus}\end{matrix}\right\} + \frac{1}{4\Delta y}\left\{\begin{matrix}[(\rho v)_1+(\rho v)_2+(\rho u)_3+(\rho v)_4]_{minus} - \\ [(\rho v)_1+(\rho v)_2+(\rho v)_3+(\rho v)_4]_{plus}\end{matrix}\right\} + \frac{1}{4\Delta z}\left\{\begin{matrix}[(\rho w)_1+(\rho w)_2+(\rho w)_3+(\rho w)_4]_{minus} - \\ [(\rho w)_1+(\rho w)_2+(\rho w)_3+(\rho w)_4]_{plus}\end{matrix}\right\}$$

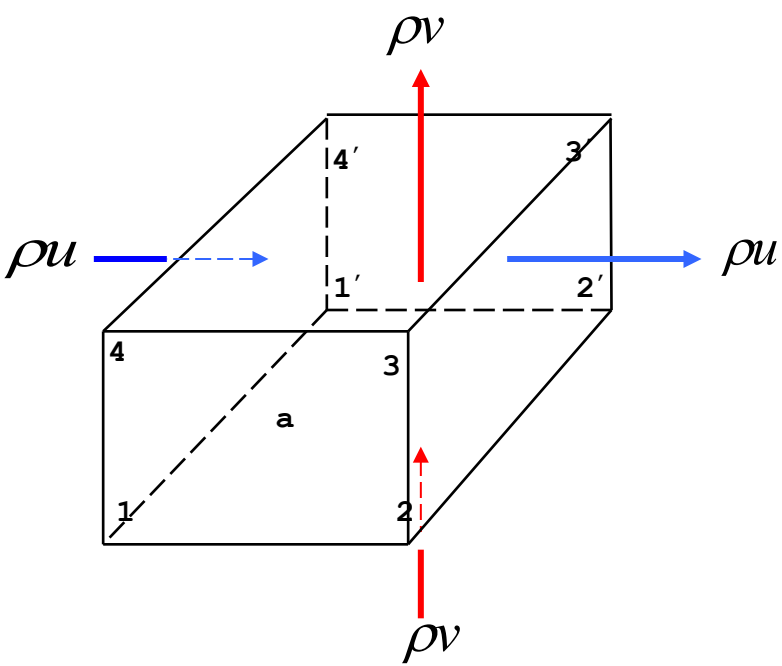


$$\sum_{Surface=i}^{Surface=6} \rho_{s_i}\left(\vec{V}\cdot\vec{n}\right)_{s_i} ds_i = (\rho u)_{+nx}^{Avg} dydz - (\rho u)_{-nx}^{Avg} dydz + \ldots$$

$$\left[\frac{\partial \rho}{\partial t}\right]_{\substack{Cell\\Center}} dxdydz$$

Mass Conservation in an IDS Cell/2D Concept

$$\left(\frac{\partial \rho}{\partial t}\right)^{average} = \left[\frac{((\rho u)_1 + (\rho u)_4) - ((\rho u)_2 + (\rho u)_3)}{2\Delta x}\right] + \left[\frac{((\rho v)_1 + (\rho v)_2) - ((\rho v)_3 + (\rho v)_4)}{2\Delta y}\right]$$



Assumptions for 2D IDS Concept

- **2 Planes are identical**
- **dz = 1.0**

Momentum Conservation in an IDS Cell/2D Concept

$$\left(\frac{\partial(\rho u)}{\partial t}\right)^{average} = \left[\frac{\left((\rho u^2)_1 + (\rho u^2)_4\right) - \left((\rho u^2)_2 + (\rho u^2)_3\right)}{2\Delta x}\right] + \left[\frac{((\rho vu)_1 + (\rho vu)_2) - ((\rho vu)_3 + (\rho vu)_4)}{2\Delta y}\right] + \frac{1}{\gamma M_\infty^2}\left[\frac{((\rho T)_1 + (\rho T)_4) - ((\rho T)_2 + (\rho T)_3)}{2\Delta x}\right] - \frac{1}{\mathrm{Re}_L}\left[\frac{\left((\tau_{xx})^{left} - (\tau_{xx})^{right}\right)}{\Delta x} + \frac{\left((\tau_{xy})^{lower} - (\tau_{xx})^{upper}\right)}{\Delta y}\right]$$

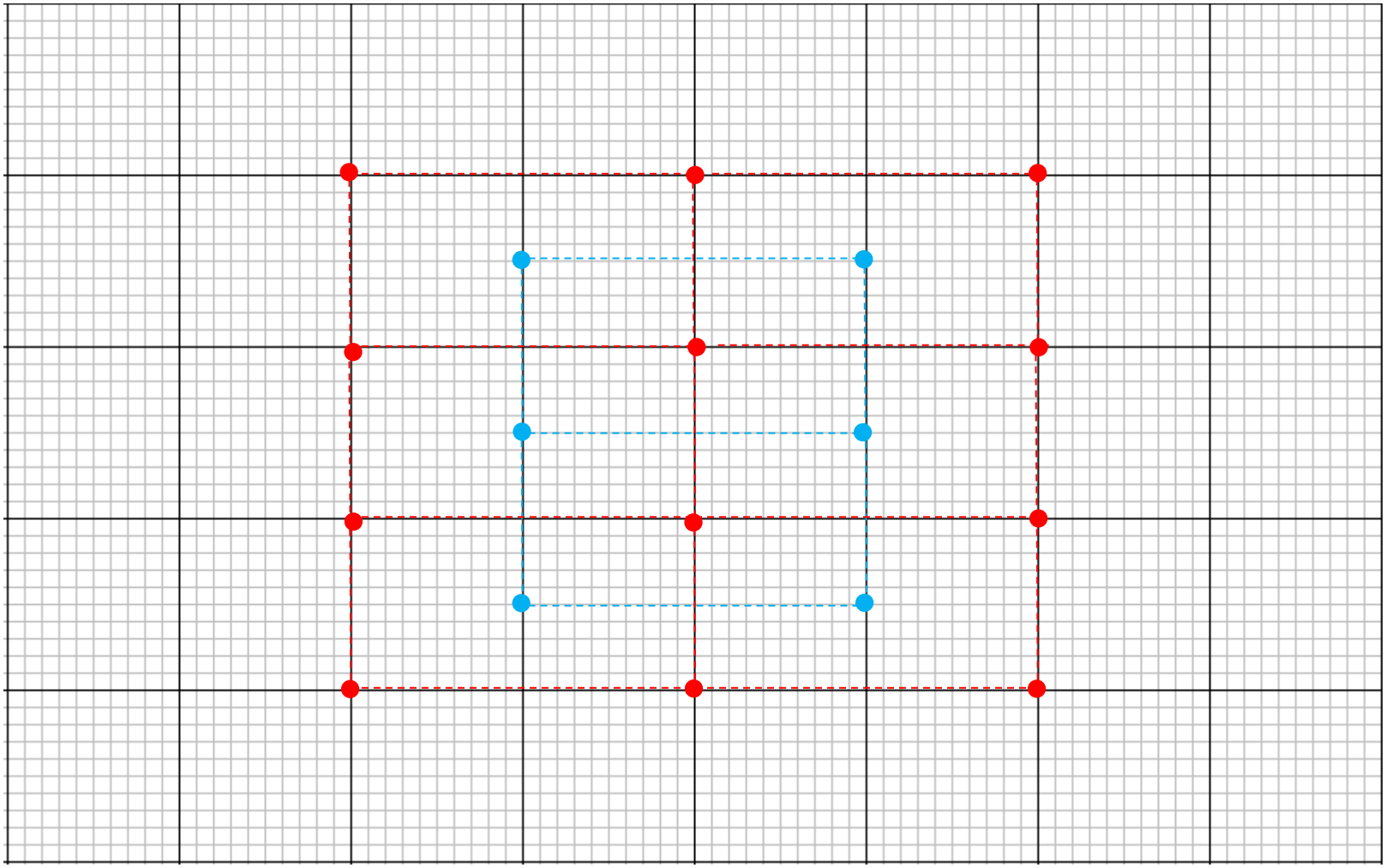
$$\left(\frac{\partial(\rho v)}{\partial t}\right)^{average} = \left[\frac{\left((\rho v^2)_1 + (\rho v^2)_2\right) - \left((\rho v^2)_3 + (\rho v^2)_4\right)}{2\Delta y}\right] + \left[\frac{((\rho uv)_1 + (\rho uv)_4) - ((\rho uv)_2 + (\rho uv)_3)}{2\Delta x}\right] + \frac{1}{\gamma M_\infty^2}\left[\frac{((\rho T)_1 + (\rho T)_2) - ((\rho T)_3 + (\rho T)_4)}{2\Delta y}\right] - \frac{1}{\mathrm{Re}_L}\left[\frac{\left((\tau_{yy})^{lower} - (\tau_{yy})^{upper}\right)}{\Delta y} + \frac{\left((\tau_{xy})^{left} - (\tau_{xy})^{right}\right)}{\Delta x}\right]$$

Energy Conservation in an IDS Cell/2D Concept

$$
\begin{aligned}
\left(\frac{\partial E}{\partial t}\right)^{average} = & \left[\left(\frac{(\rho E u)_1 + (\rho E u)_4}{2\Delta x}\right) - \left(\frac{(\rho E u)_2 + (\rho E u)_3}{2\Delta x}\right)\right] + \\
& \left[\left(\frac{(\rho E v)_1 + (\rho E v)_2}{2\Delta y}\right) - \left(\frac{(\rho E v)_3 + (\rho E v)_4}{2\Delta y}\right)\right] + \\
& \frac{1}{\gamma M_\infty^2}\left[\left(\frac{(\rho T u)_1 + (\rho T u)_4}{2\Delta x}\right) - \left(\frac{(\rho T u)_2 + (\rho T u)_3}{2\Delta x}\right)\right] + \\
& \frac{1}{\gamma M_\infty^2}\left[\left(\frac{(\rho T v)_1 + (\rho T v)_2}{2\Delta y}\right) - \left(\frac{(\rho T v)_3 + (\rho T v)_4}{2\Delta y}\right)\right] - \\
& \frac{1}{\mathrm{Re}_L}\left[(\tau_{xx})^{left}\left(\frac{u_2 + u_3}{2\Delta x}\right) - (\tau_{xx})^{right}\left(\frac{u_1 + u_4}{2\Delta x}\right)\right] - \\
& \frac{1}{\mathrm{Re}_L}\left[(\tau_{xy})^{lower}\left(\frac{v_3 + v_4}{2\Delta y}\right) - (\tau_{xy})^{upper}\left(\frac{v_1 + v_2}{2\Delta y}\right)\right] - \\
& \frac{1}{\mathrm{Re}_L}\left[(\tau_{yy})^{lower}\left(\frac{v_3 + v_4}{2\Delta y}\right) - (\tau_{yy})^{upper}\left(\frac{v_1 + v_2}{2\Delta y}\right)\right] - \\
& \frac{1}{\mathrm{Re}_L}\left[(\tau_{xy})^{left}\left(\frac{u_2 + u_3}{2\Delta x}\right) - (\tau_{xy})^{right}\left(\frac{u_1 + u_4}{2\Delta x}\right)\right] + \\
& \frac{1}{\mathrm{Re}_L\,\mathrm{Pr}\,M_\infty^2}\left[\frac{\left((\dot{q}_{xx})^{left} - (\dot{q}_{xx})^{right}\right)}{\Delta x} + \frac{\left((\dot{q}_{yy})^{lower} - (\dot{q}_{yy})^{upper}\right)}{\Delta y}\right]
\end{aligned}
$$

IDS Control Volume Representation

- The Spatial & Temporal Cells
- The 2D Control Volume



IDS Implementation Steps for Control Volume

Construct the solution using Taylor Series Expansion

$$(U_m)_{i,j,k}^{t+\Delta t} = (U_m)_{i,j,k}^{t} + \left(\frac{dU_m}{dt}\right)_{i,j,k} \Delta t$$

$$U_m = \begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \\ U_5 \end{bmatrix} = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ E \end{bmatrix}$$

- Control volume of center *i,j,k; surrounded by* 8 cells-3D/4 cells-2D. Evaluate the generic function *U* as an arithmetic average.

$$(U)_{i,j,k}^{t} = \frac{1}{8}\sum_{cell=1}^{8} U_{cell}^{average}$$

- The time derivative at node *i,j,k* is obtained as an arithmetic average of the time derivatives at the cell centers.

$$\left(\frac{dU_m}{dt}\right)_{i,j,k} = \frac{1}{8}\sum_{cell=1}^{8}\left(\frac{dU_m}{dt}\right)_{cell}$$

IDS Implementation Steps

- **Use the following CFL Criterion to evaluate the time step**

$$(\Delta t_{CFL})_{i,j,k} = \left[\frac{|u_{i,j,k}|}{\Delta x} + \frac{|v_{i,j,k}|}{\Delta y} + \frac{|w_{i,j,k}|}{\Delta z} + a_{i,j}\sqrt{\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} + \frac{1}{\Delta z^2}} + \frac{2}{\mathrm{Re}_L} \nu'_{i,j,k}\left(\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} + \frac{1}{\Delta z^2}\right) \right]^{-1}$$

$$\nu'_{i,j,k} = \max\left[\frac{\frac{4}{3}\mu_{i,j,k}, (\gamma \mu_{i,j,k} / \mathrm{Pr})}{\rho_{i,j,k}} \right]$$

- **Update the solution**

$$(U_m)^{new}_{i,j,k} = (U_m)^{old}_{i,j,k} + \left(\frac{dU_m}{dt}\right)_{i,j,k} \Delta t$$

- **Decouple the new variables**

$$\rho^{new}_{i,j,k} = (U_1)^{new}_{i,j,k}$$

$$u^{new}_{i,j,k} = \left(\frac{U_2}{U_1}\right)^{new}_{i,j,k}$$

$$v^{new}_{i,j,k} = \left(\frac{U_3}{U_1}\right)^{new}_{i,j,k}$$

$$w^{new}_{i,j,k} = \left(\frac{U4}{U_1}\right)^{new}_{i,j,k}$$

$$T^{new}_{i,j,k} = \left(\frac{U_5}{U_1} - \frac{u^2 + v^2 + w^2}{2}\right)^{new}_{i,j,k} \gamma(\gamma - 1) M_\infty^2$$

Test Case 1: The Inviscid-Viscous Interaction Problem: Illustrative Physics of the Inviscid-Viscous Interaction Flow field

M =8.6, Re=4.37861*10.0E+5, Pr=0.70, γ= 1.4

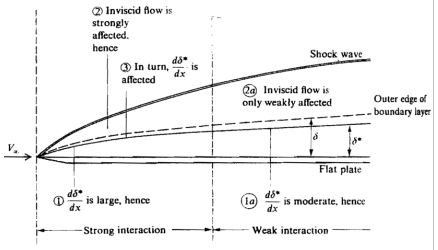
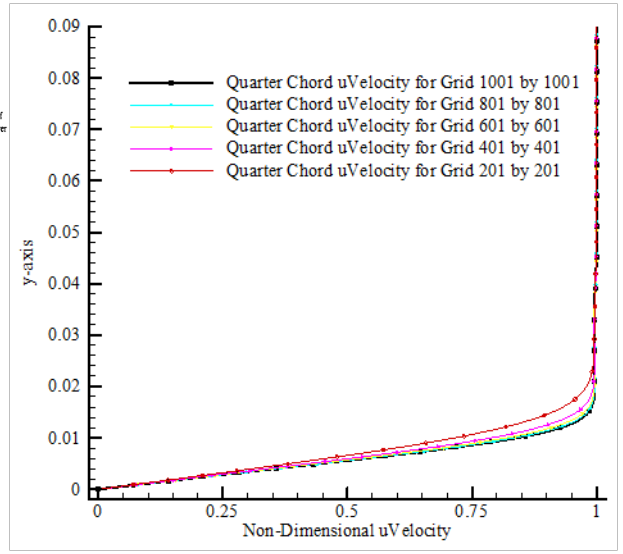
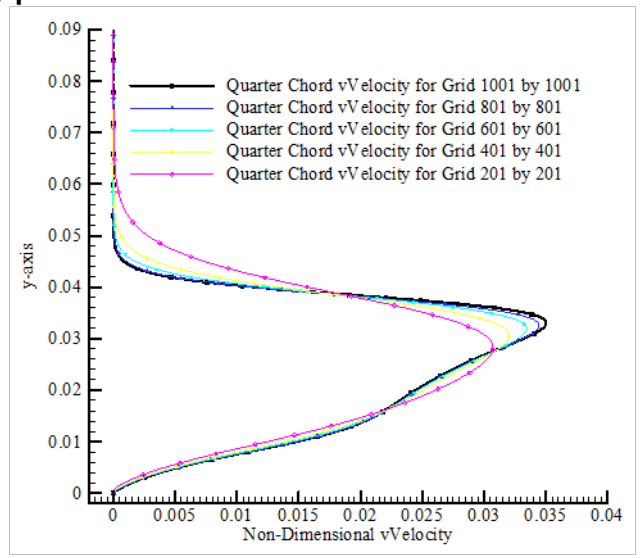
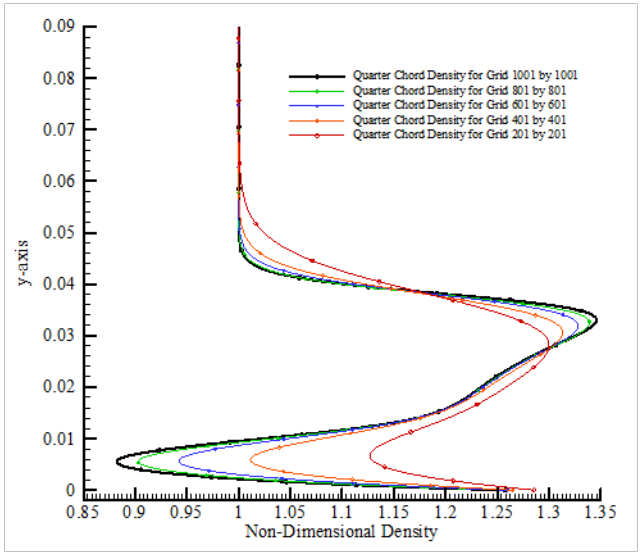
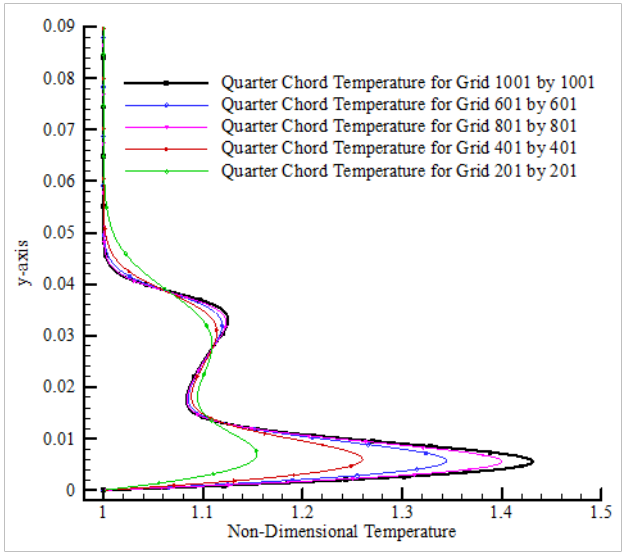


Fig. 7.3 Illustration of strong and weak viscous interactions.









Test Case 1: The Inviscid-Viscous Interaction Problem: Grid Independence: Validation Flow Parameters

M =8.6, Re=4.37861*10.0E+5, Pr=0.70, γ= 1.4

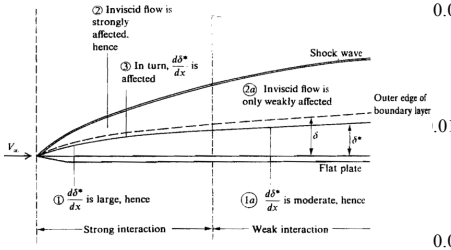
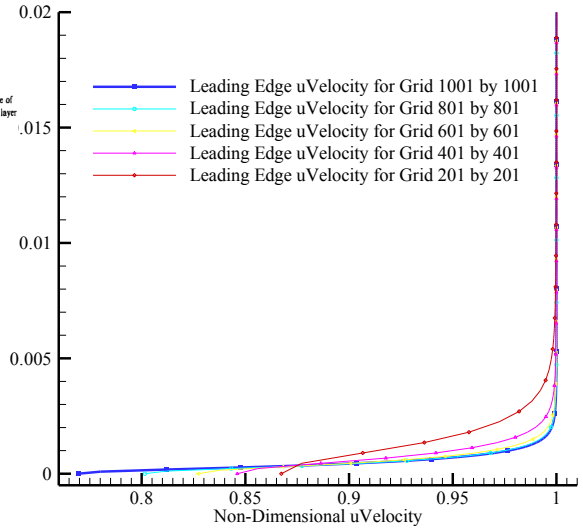
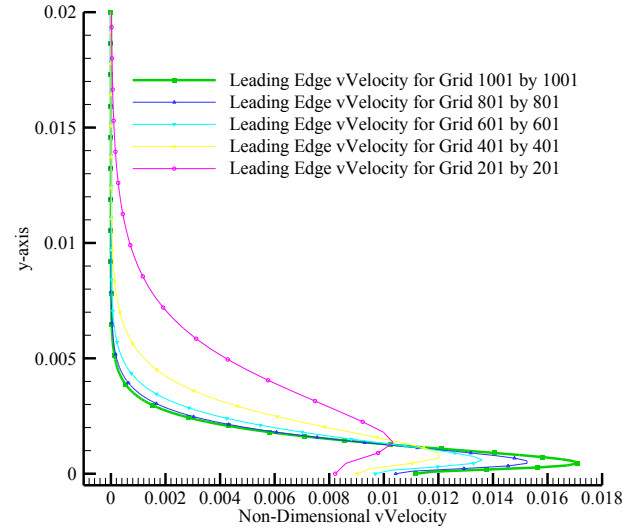
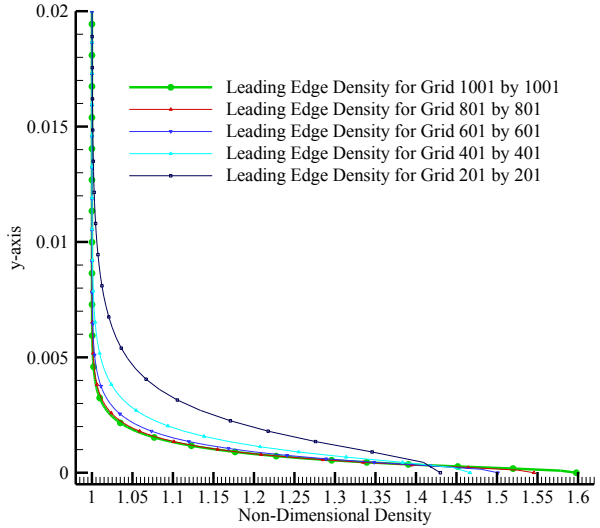
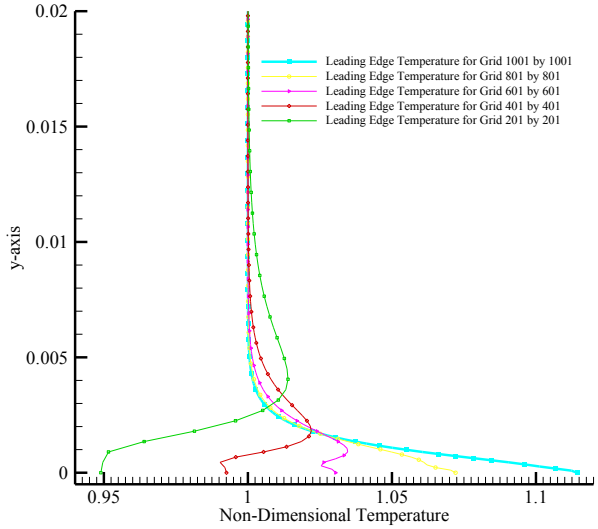


Fig. 7.3 Illustration of strong and weak viscous interactions.









Test Case 1: The Inviscid-Viscous Interaction Problem: Illustrative Physics of the Inviscid-Viscous Interaction Flow field

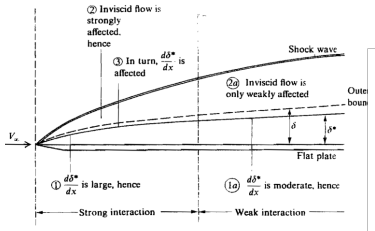
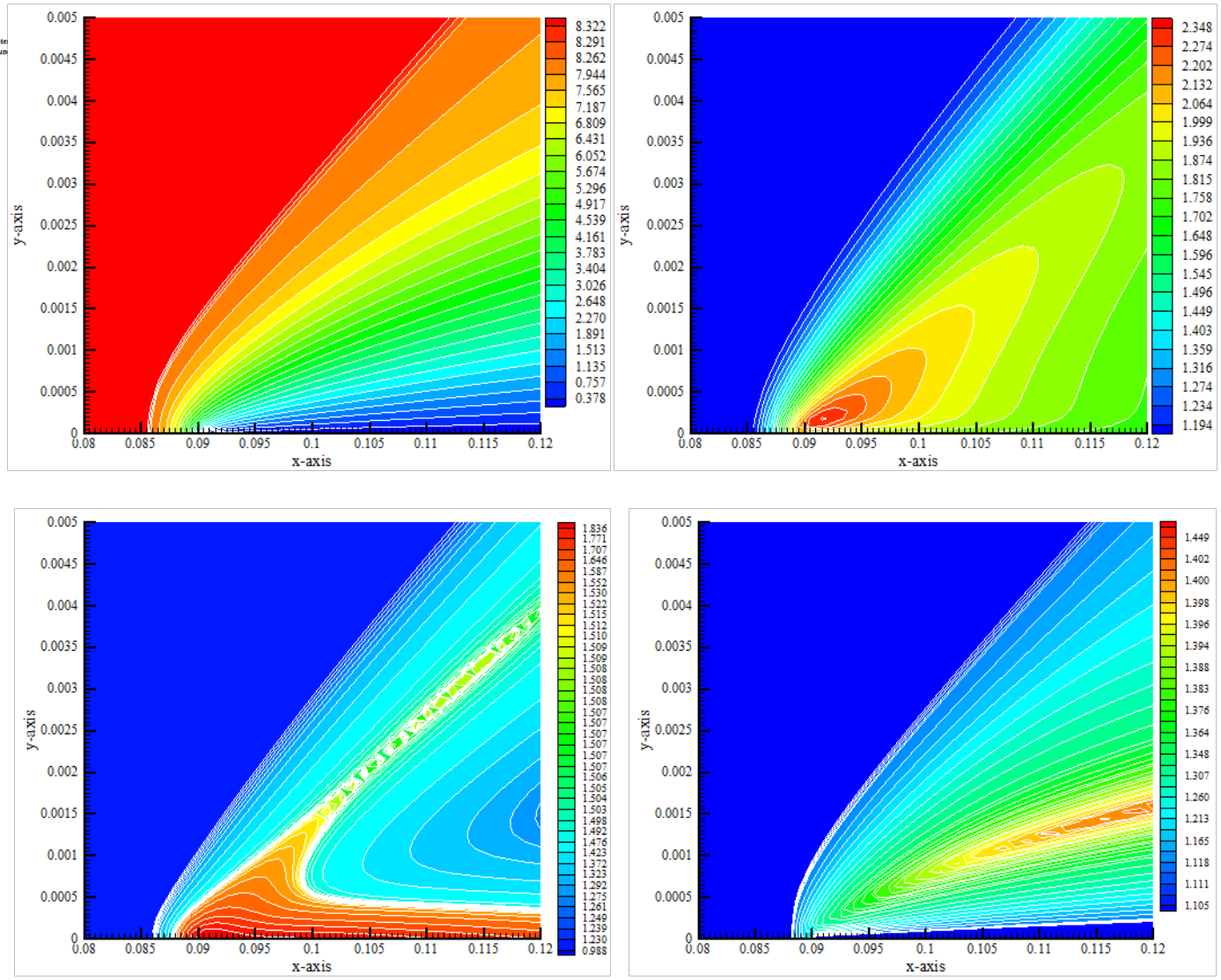
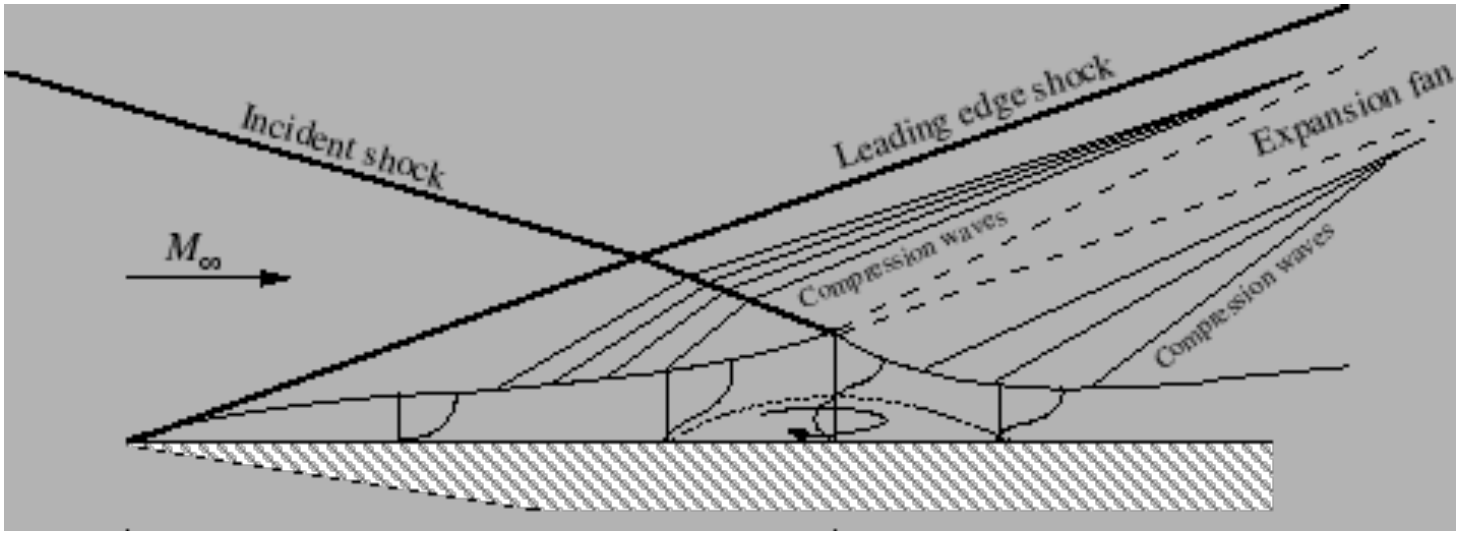


Fig. 7.3 Illustration of strong and weak viscous interactions.

M =8.6, Re=4.37861*10.0E+5, Pr=0.70, γ= 1.4

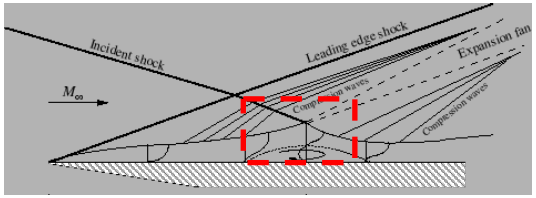


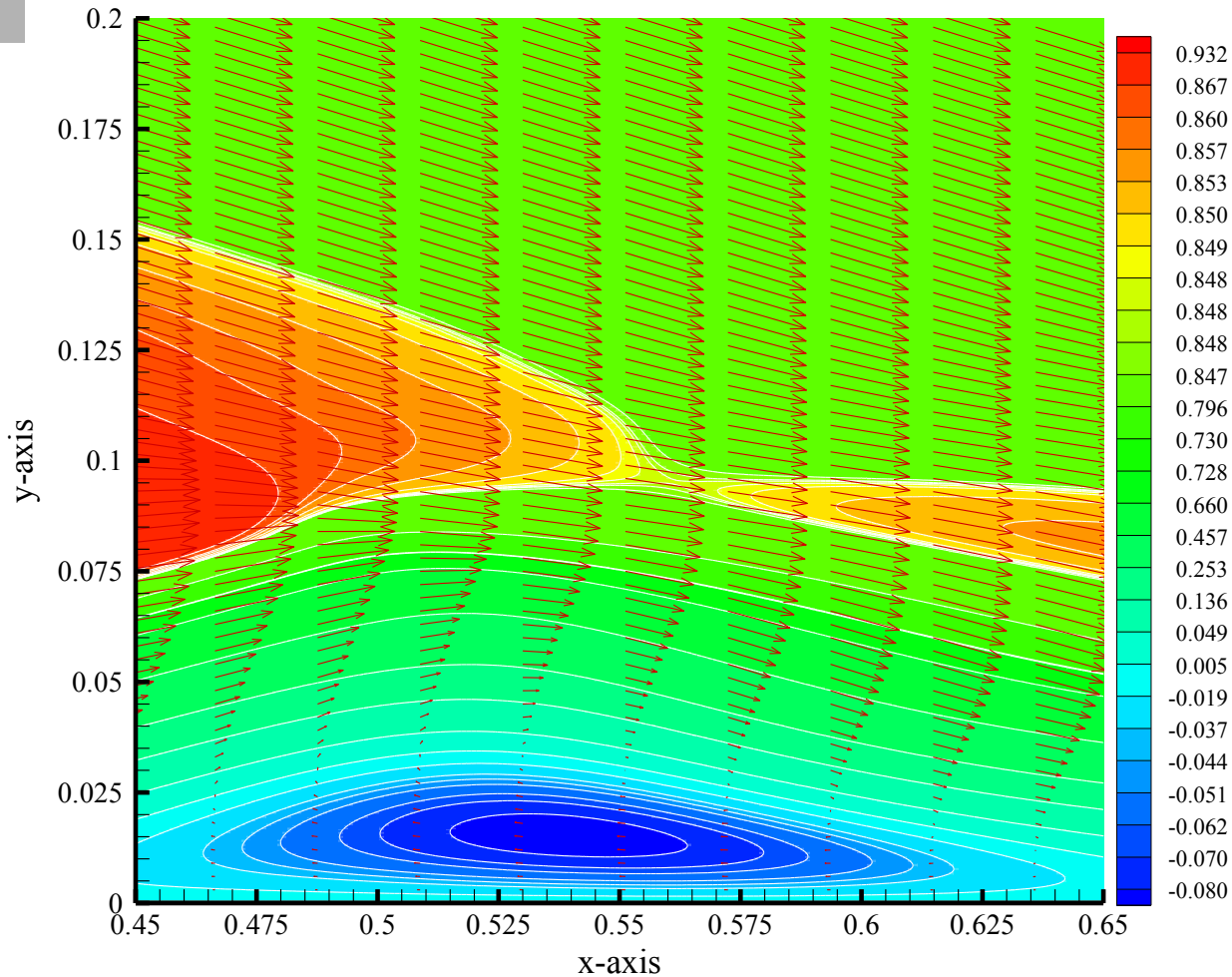
Test Case 2: Shock Boundary Layer Interaction: General Physics of the flow



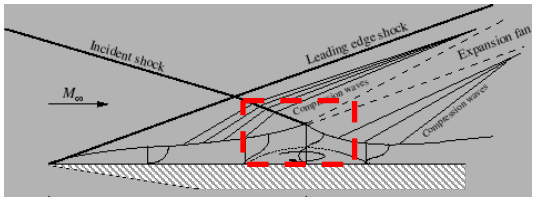
http://archives.limsi.fr/RS2005/meca/aero/aero3/

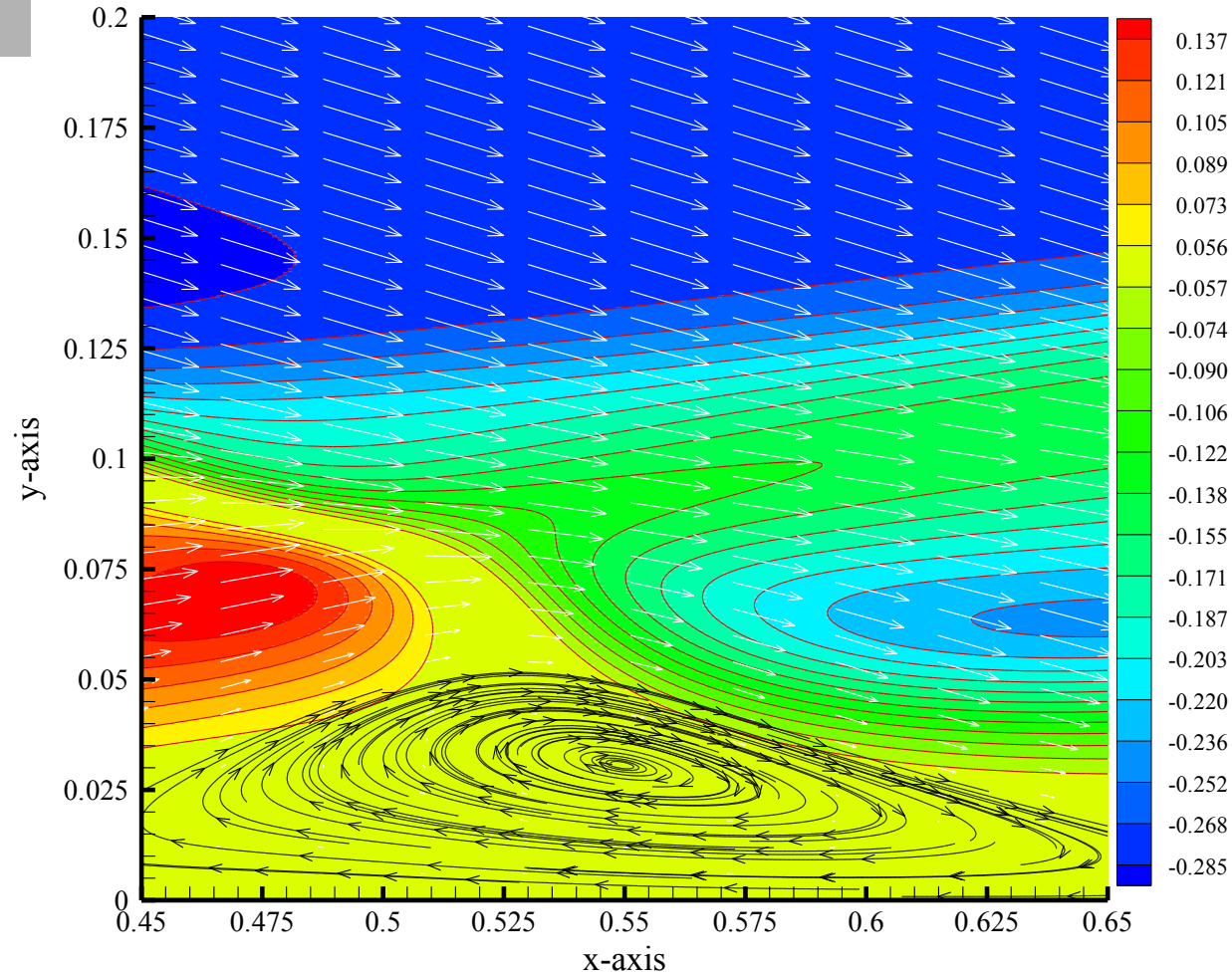
Test Case 2: Shock Boundary Layer Interaction: IDS Numerical Results u- Velocity



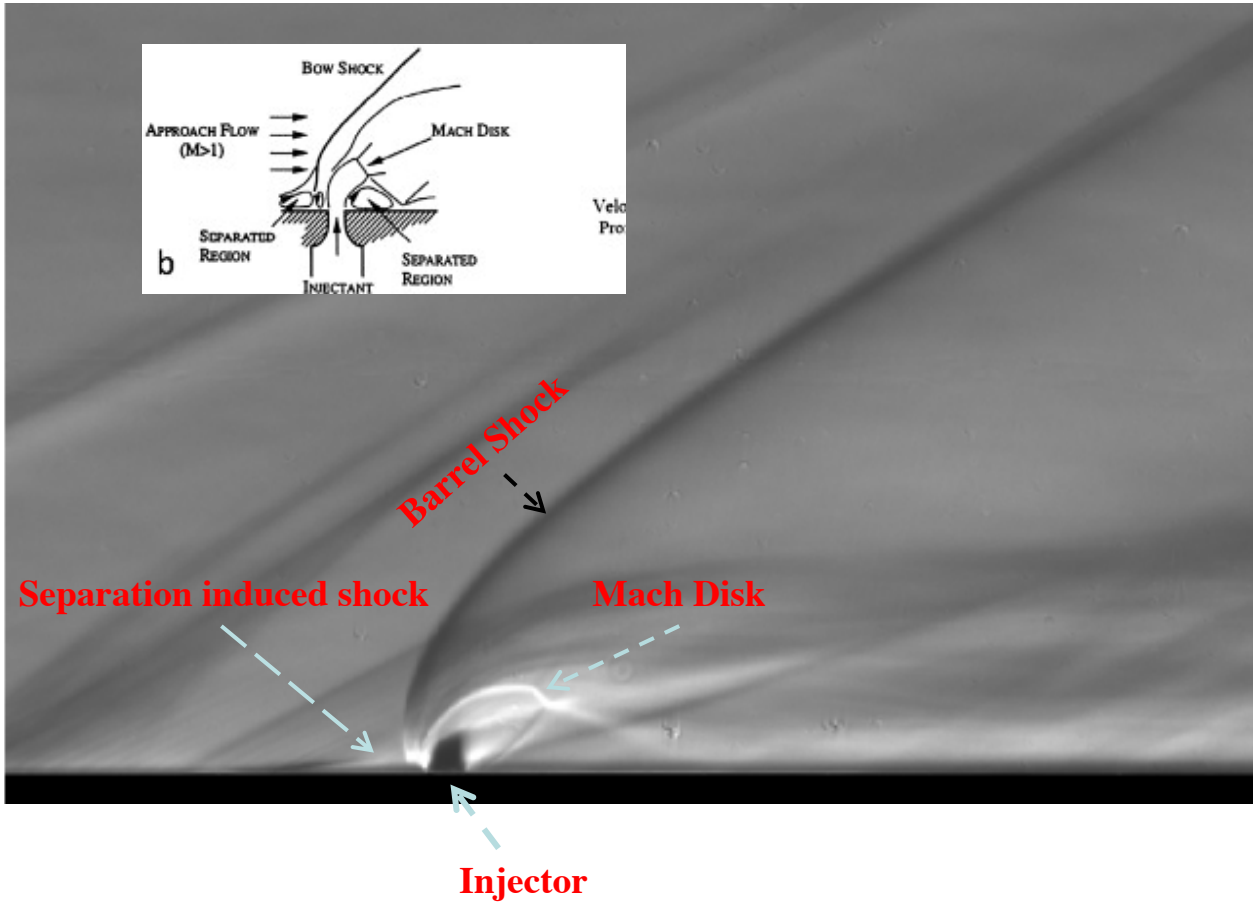


Test Case 2: Shock Boundary Layer Interaction: IDS Numerical Results u- Velocity





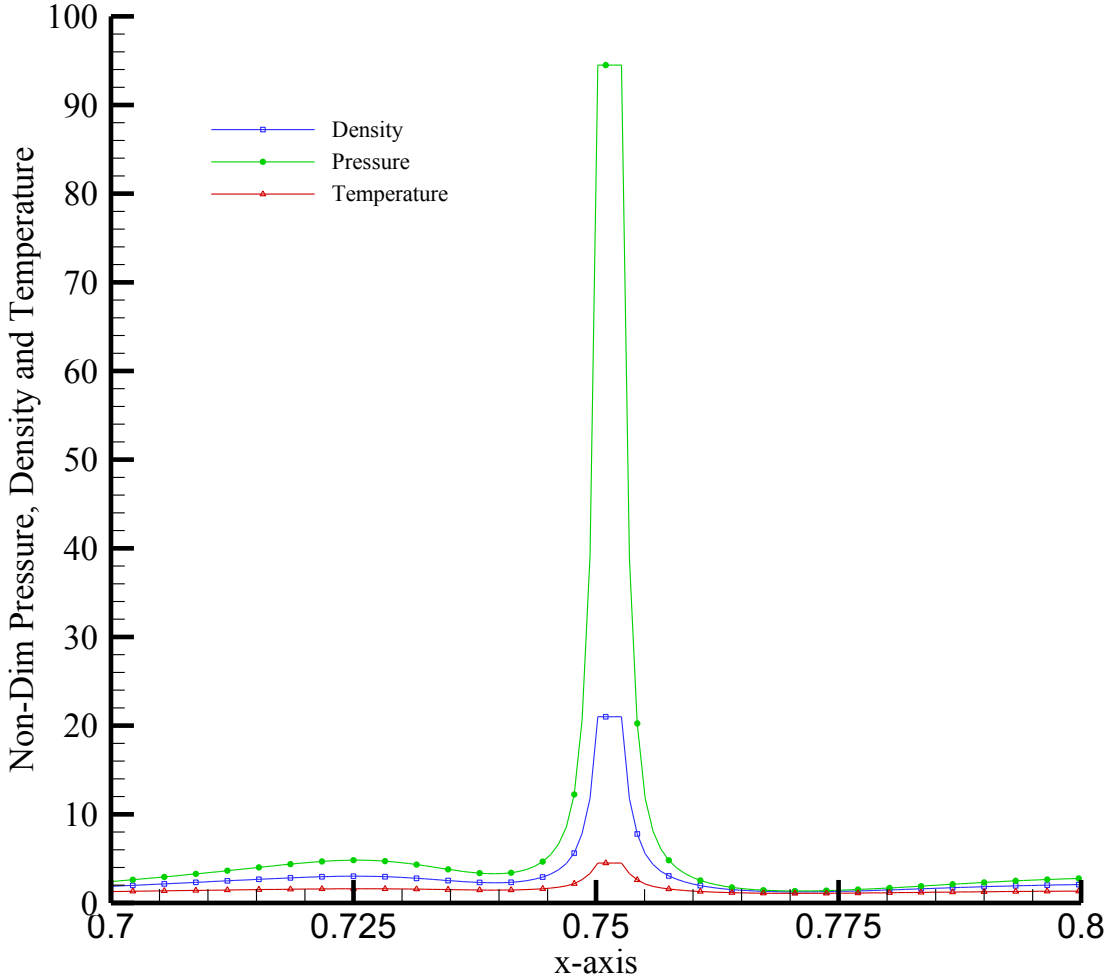
Test Case 3: The Mach Jet Flow Interaction Problem/ Stanford Experimental Result



[14] http://www.stanford.edu/group/psaap/heat_release_modeling/Jet_cross-flow.html.

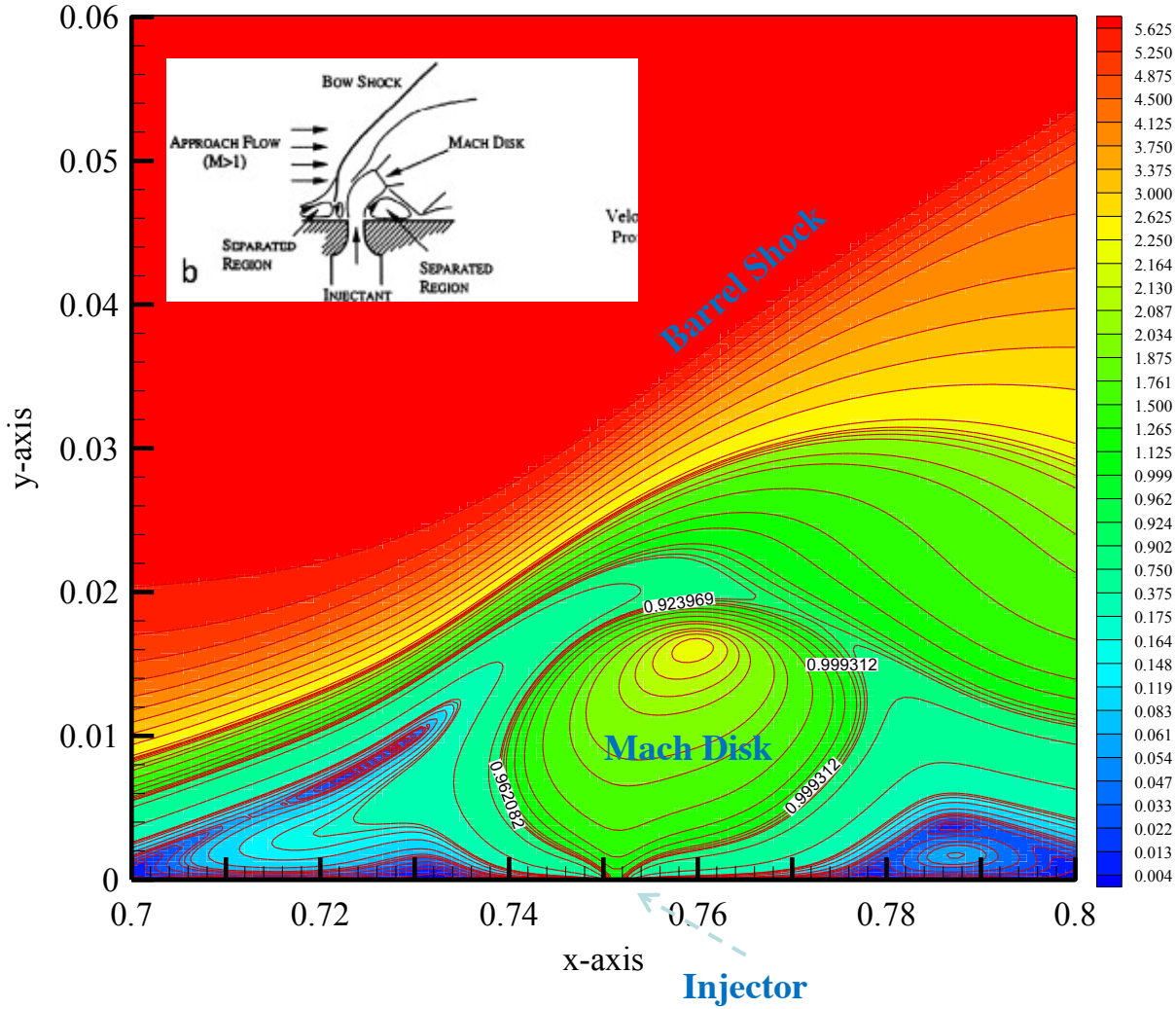
[15] R. S. Amano and D Sun, 'Numerical Simulation of Supersonic Flowfield with Secondary Injection', 24th International Congress of the Aeronautical Sciences, ICAS 2004 MR Gruber, AS Nejad, JC Dutton, An experimental investigation of transverse injection from circular and elliptical nozzles into supersonic crossflow. wright lab technical report, WL-TR (1996), pp. 96–2102

Test Case 3: The Mach Jet Flow Interaction Problem: Input Values for Jet Injection



Test Case 3: The Mach Jet Flow Interaction Problem: IDS Numerical Result: Mach Contours

M =6.0, Re=1.086*10.0E+7, Pr=0.042, γ= 1.4

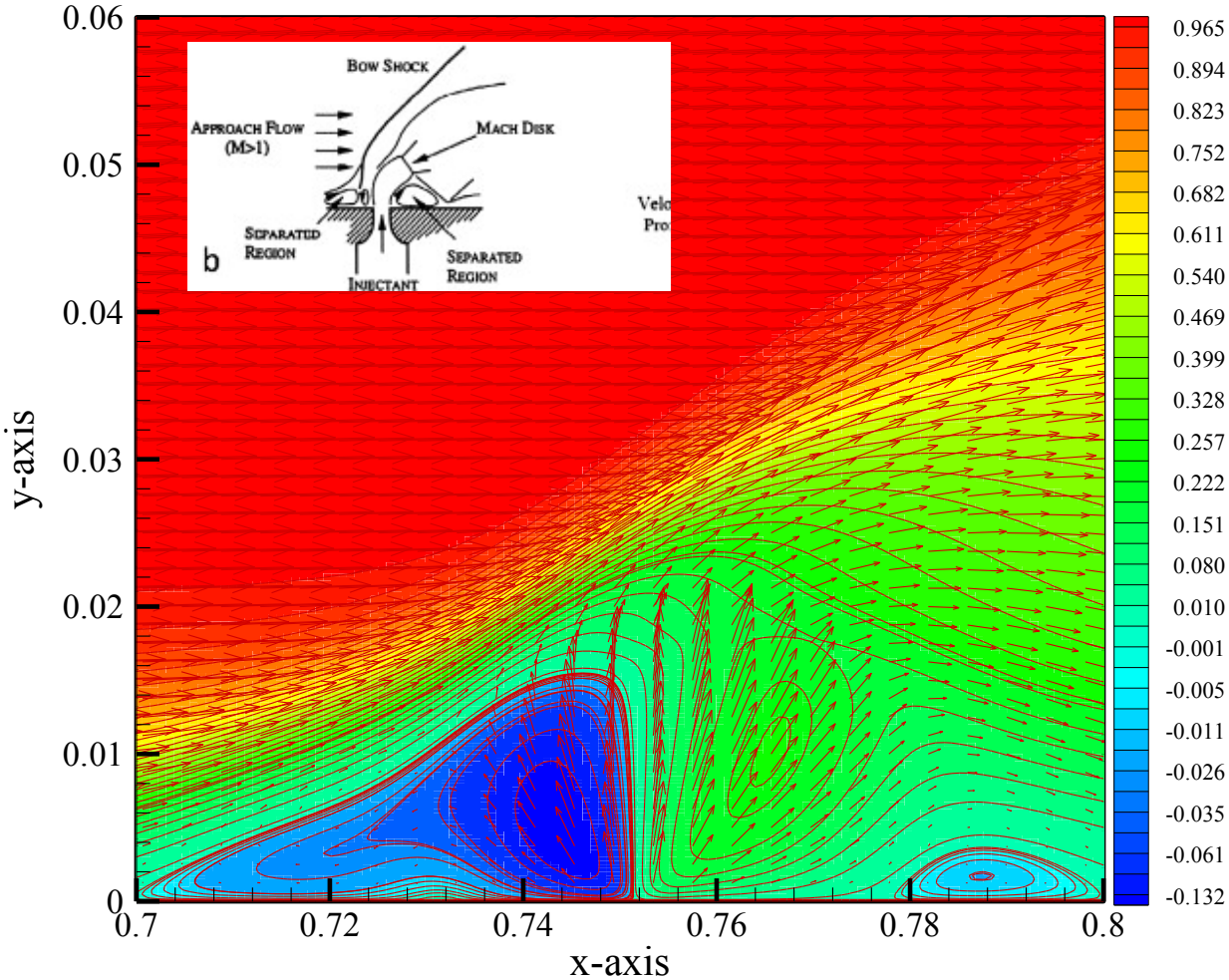


MR Gruber, AS Nejad, JC Dutton, An experimental investigation of transverse injection from circular and elliptical nozzles into supersonic crossflow. wright lab technical report, WL-TR (1996), pp. 96–2102

Test Case 3: The Mach Jet Flow Interaction Problem: IDS Numerical Result: u-Velocity

M =6.0, Re=1.086*10.0E+7, Pr=0.042, γ= 1.4

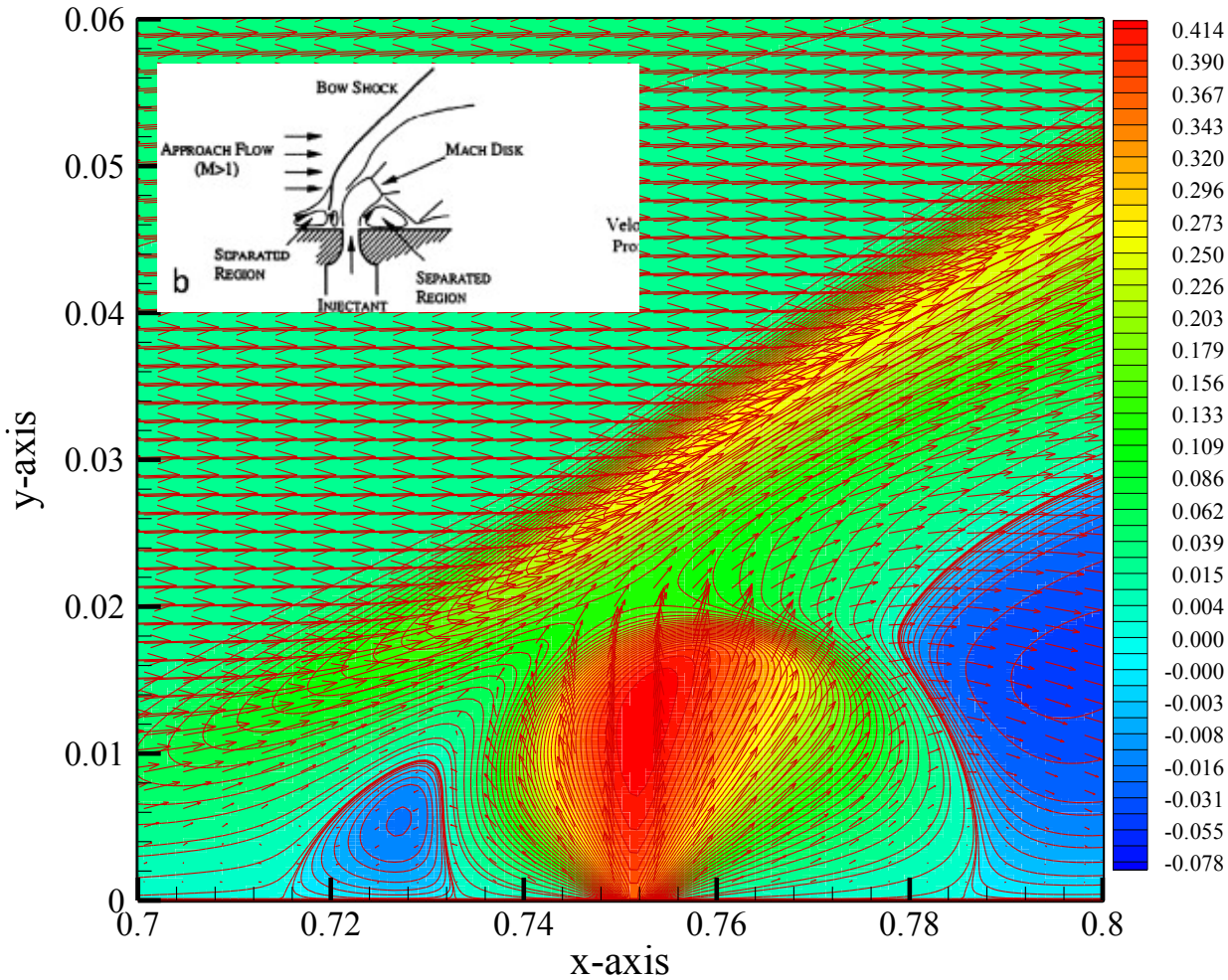
uVelocity Contours with Velocity-vector Overlayed



Test Case 3: The Mach Jet Flow Interaction Problem: IDS Numerical Result: v-Velocity

M =6.0, Re=1.086*10.0E+7, Pr=0.042, γ= 1.4

vVelocity Contours with Velocity-vector Overlayed



Conclusions

- A IDS for solving the Q1D/2D/3D forms of the system of the Navier-Stokes equations was developed and tested.
- The capability of the IDS with respects to predicting the flow physics for wide class of problems (Q1D flows, incompressible flows, compressible external flows and compressible internal flows) was evaluated.
- In all cases the results showed very good agreement with the physical expectation of the flow fields, and with available experimental data.
- The IDS 2D FORTRAN code is capable of running on multiple HPC platforms (with OpenMP and MPI capability).
- Extension of IDS to Arbitrary Geometries is currently being explored.
- The IDS 3D is being updated to run of HPC, with OpenMP & MPI capablilty.
- An Error Analysis of the IDS Concept is in progress.

Questions?