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EXPERIENCES WITH TWO-EQUATION TURBULENCE MODELS

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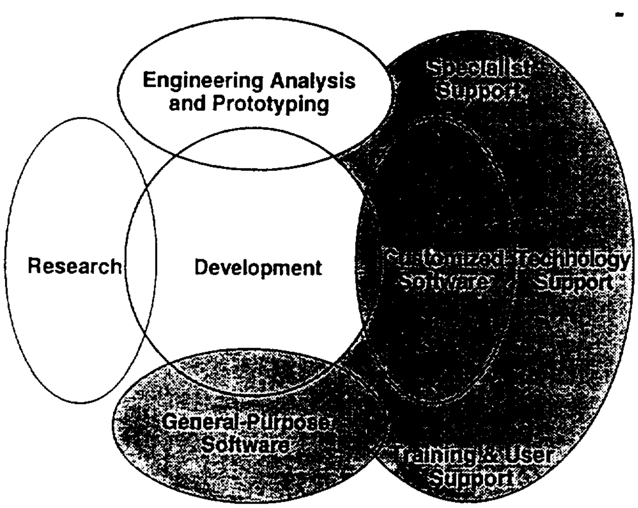
OUTLINE

- Introduction to CFDRC
- Experiences with 2-Equation Models
  - Models Used
  - Numerical Difficulties
  - Validation and Applications
  - Strengths & Weaknesses
- Answers to Three Questions (Posed by Workshop Organizing Committee)
  1. What Are Your Customers Telling You?
  2. What Are You Doing In-House?
  3. How Can NASA-CMOTT Help?

INTRODUCTION TO CFDRC

- Young and Energetic (Turbulent) Organization, Dedicated to the Continuous Process of Advancement and Effective Transfer of CFD Technology
- TWO TYPES OF COMPLEMENTARY ACTIVITIES:
  - PROJECTS
  - SOFTWARE



INTRODUCTION TO CFDRC (Continued)

- Objective User of Turbulence Models (0, 1, and 2 Equation Models, RSM and LES)
- Humble Developer, e.g. Monte Carlo Joint Scalar PDF
- Active Participant in Recent Small Eddies of Turbulence, e.g.
  - Stanford Endeavor: "Collaborative Testing of Turbulence Models" 1989-1993
  - National Workshops at: NASA MSFC, LeRC/CMOTT, etc. 1987-1994
  - ASME/Fluids Engineering Division, Biathlon, Lake Tahoe, June 1994

TWO-EQUATION MODELS USED

- Standard k-ε Model (Launder & Spalding, 1974)
- Low-Re k-ε Model (Chien, 1982)
- Extended k-ε Model (Chen & Kim, 1987)
- Multiscale k-ε Model (Kim & Chen, 1988)
- RNG-Based k-ε Model (Yakhot et. al. 1993)
- 2-Layer k-ε Model (Rodi, 1991)
- k~ε^{++} Models
- k-ω Model (Wilcox, 1991)

++ Models with Corrections for: Curvature, Rotation, Buoyancy, Compressibility, etc.

NUMERICAL DIFFICULTIES

- Positivity of k & ε (or ω) Is Not Guaranteed in Iterative Algorithms
- Strong Nonlinearity of Source Terms and Coupling Causes Numerical Difficulties
- Inappropriate Specifications of ε (or ω) at Boundaries or in Initial Conditions May Also Cause Divergence
- Non-orthogonaltiy of Grids Adds to Difficulties
- Non-smooth Change Over for Two-Layer Model Hinders Convergence

VALIDATIONS PERFORMED

- Channel and Pipe Flows
- Backward-Facing Step
- Turnaround Duct
- Swirl-Flow Combustor
- Rotating Disk Cavities
- Boundary Layers
- Jets, Wakes, and Mixing Layers
- Periodic Wakes Behind Bluff Bodies

Examples of Successes and Failures

1) Flow Around a Square Cylinder; 2) 180° Square Duct; 3) S-Shaped Annular Diffuser; 4) Dump Combustor; 5) Backward Facing Step

FLOW AROUND A SQUARE CYLINDER

Strouhal Number

Strouhal Number = $\frac{fH}{U_o}$

f = Frequency of Vortex Shedding

H = Obstacle Height

U_o = Freestream Velocity

Model/Expt.	Time Period	Strouhal Number
Expt.	7.25	0.138
Standard k-ε	7.1	0.141
2-Layer k-ε	7.1	0.141
RNG k-ε	7.6	0.132

Notes:

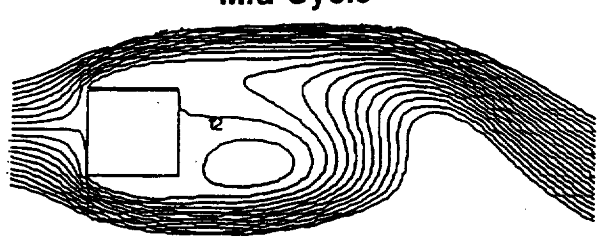
1. Experiments By Durao, Heitor, and Pereira (1988)
2. Computations with CFD-ACE
   Inlet: 78H Upstream; Outlet: 22H Downstream
   Grid: 120 x 80
   Time Steps: Over 70 Per Time Period

Ref.: Avva, R.K., Singhal, A.K., Lai, Y.G., "Numerical Simulation Of Periodic and 3-Dimensional, Turbulent Flows With CFD-ACE," ASME Fluid Dynamics Conference, Lake Tahoe, NV, June 19-23, 1994.

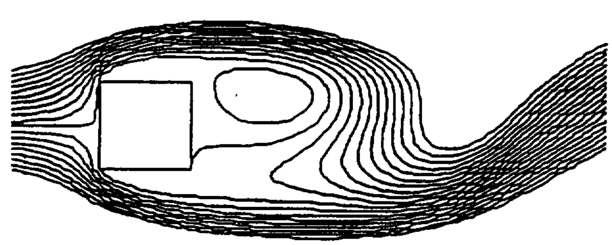
FLOW AROUND A SQUARE CYLINDER

Instantaneous Streamlines

Mid-Cycle

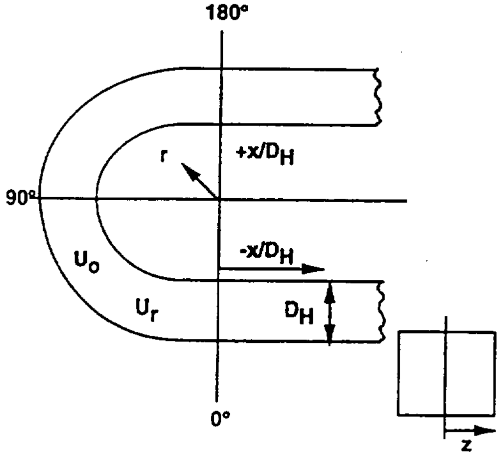


End of Cycle

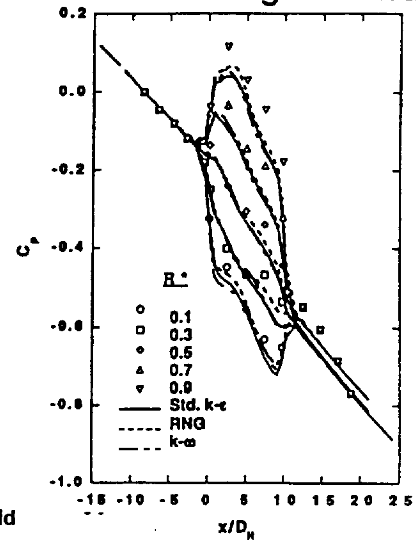


FLOW IN A 180° SQUARE DUCT

Computational Domain



Static Pressure Along Duct Walls

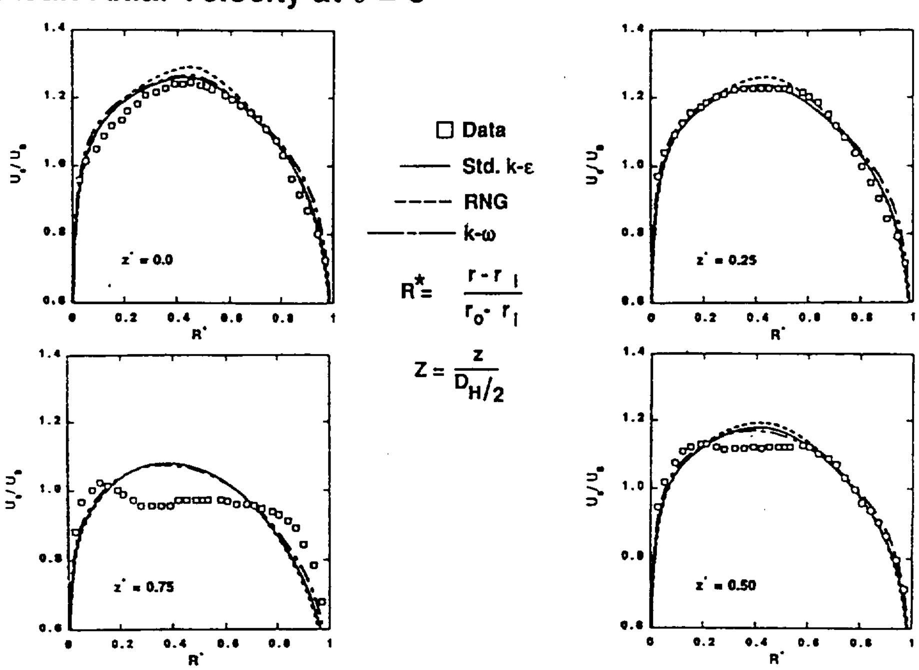


- Experiment by Chang, Humphrey and Modavi (1983)
- Computations Done with CFD-ACE on a 40x40x20 Grid

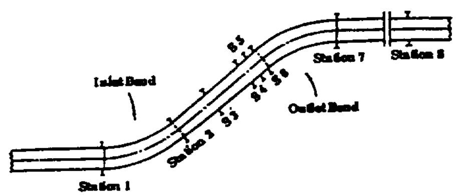
Ref.: Avva, R.K., Singhal, A.K., Lai, Y.G., "Numerical Simulation Of Periodic and 3-Dimensional, Turbulent Flows With CFD-ACE," ASME Fluid Dynamics Conference, Lake Tahoe, NV, June 19-23, 1994.

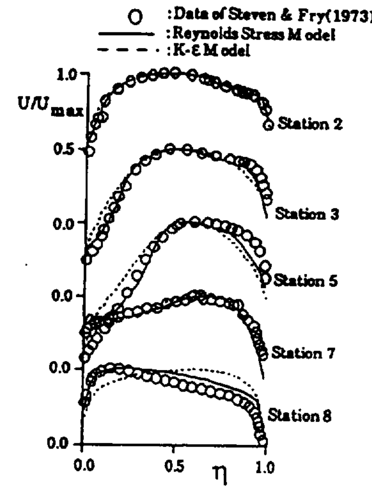
FLOW IN A 180° SQUARE DUCT

Mean Axial Velocity at θ = 3°



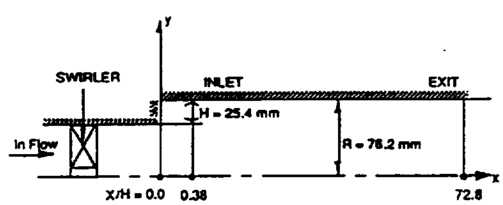
S-SHAPED ANNULAR DIFFUSER

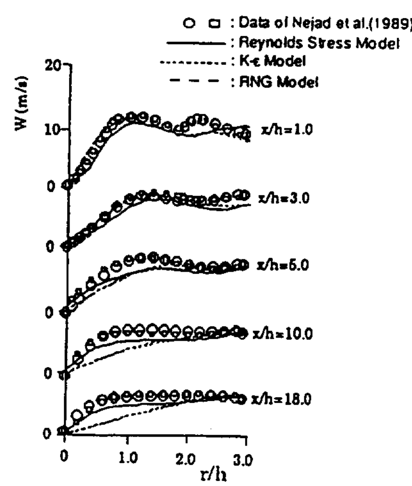




* k-ε Model and RNG Model Failed to Predict the Correct Location of the Maximum Velocity Downstream
* Computations with CFD-ACE; Publication Under Preparation

Confined Swirling Flow for a Dump Combustor

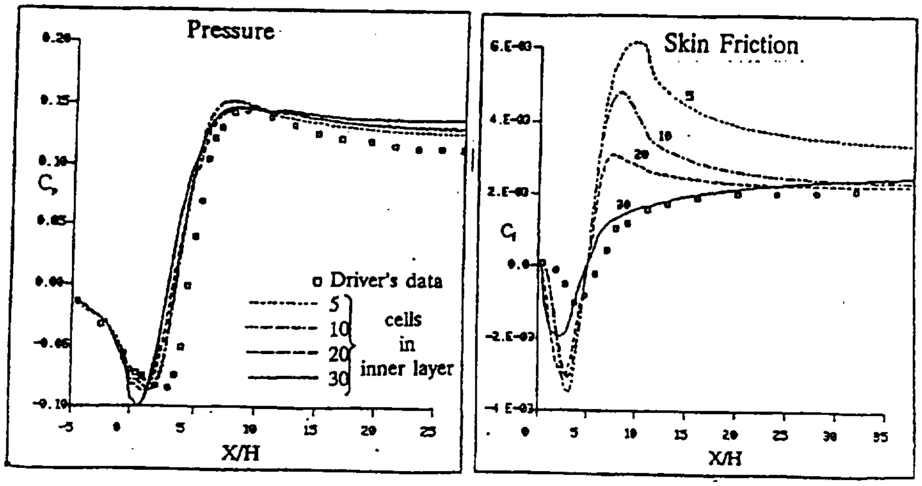




* K-ε model failed to preserve the vortex core strength near center (see x/h=10 & 18)
* Computational results to be presented at 1994 ASME Winter Annual Meeting (Chicago)

BACKWARD-FACING STEP

Sensitivitv to Grid Refinement



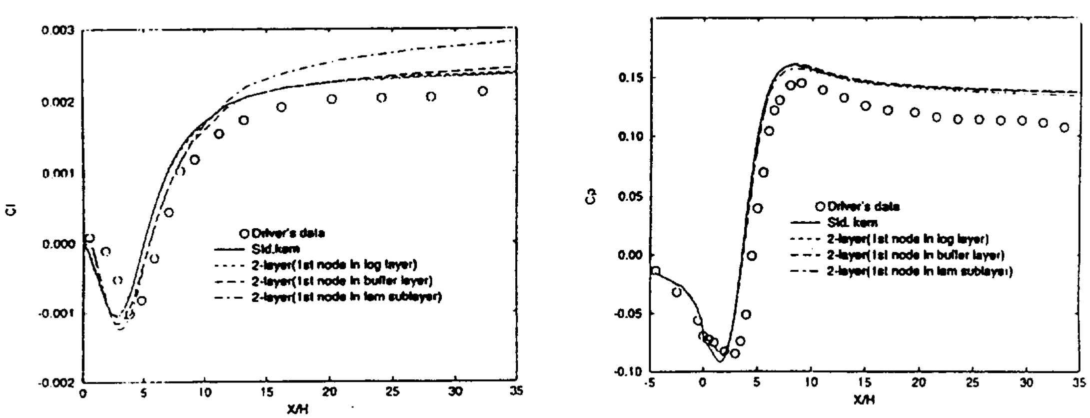
- **Low-Re Model Requires >30 Nodes in the Inter Layer**

Ref.: "Comparative Study of High and Low Reynolds Number Versions of k-e Models," R.K. Avva, C.E. Smith, A.K. Singhal, AIAA-90-0246.

BACKWARD FACING STEP

2-Layer Model;

80 x 60 Grid, Central Differencing



Computations with CFD-ACE; To Be Published

EXAMPLE APPLICATIONS

- Gas Turbine Combustors
- Liquid Rocket Engines
- Seals and Bearing Cavities
- Impellers, Inducers, and Fans
- IC Engines
- CFD Reactors
- External Aerodynamic Flows
- Plus Many More

STRENGTHS & WEAKNESSES

Strengths of 2-Equation Models

- Numerically Economical
- Easy to Modify
- Reasonable Applicability Within Engineering Accuracy

Weaknesses

- Use of Wall Functions Requires First Grid Outside the Viscous Sublayer. This is Difficult to achieve, *a Priori*
- Low-Re Approach Does Not Offer Overall Advantage.
- Two-Layer Approach Needs More Work (e.g. Smoothing)
- Reynolds Analogy Inadequate for Heat-Transfer Applications.
- Effect of Surface Roughness on Turbulence.

CMOTT/CP QUESTIONS

1. What Are Your Customers Telling You?

2. What Are You Doing In-House?

3. How Can NASA-CMOTT Help?

WHAT ARE CUSTOMERS TELLING?

- PLEASE Don't Confuse Us,
  with Additional Models and False Hopes
- Conclusions (Confusion) Over Last 15-Years
  - Use k~ε Model, with Wall Functions
  - Wall Functions, Oh No!, Never!!
    Use Low-Re k~ε,.: Which One?, How?? (Good Questions)
  - k-ε Is No Good; Neglects Non-Isotropicity, etc., etc.
  - Jump on RSM Wagon, Now!
    It Can Take You Anywhere, Eventually!!
  - Look How Great is this k~ε++
    When and How to Use it? (Good Questions)
  - Look How Accurate is this Scheme, No Numerical Diffusion.
    Don't Contaminate the Solutions with Turbulence

WHAT IS CFDRC DOING?

- Using What is Available, in Best Possible Ways
- Listening to Both Sides (Model Developers and Users)
- Trying to Resist Peer Pressures
- Struggling to Find Resources for Mundane Goals Such as Developing Guidelines for Correct Use of Turbulence Models

HOW CAN CMOTT HELP?

- CMOTT Has Been Providing Commendable Service in the Very Difficult Subject: Turbulence
- "Turbulence Subprogram" Should Help Further
- Additional Effort is Needed in Many Areas, Such As:

- Near Wall Treatment
- Effect of Surface Roughness
- Economical Heat Transfer Model
- Documentation of Experiences in:
  a) Model Robustness(In Addition to Accuracy)
  b) Model Sensitivity to Grid Distribution and Boundary Conditions
- Transition Model (if Possible Suitable for $k \sim \varepsilon$ Framework)

HOW CAN CMOTT HELP? (Continued)

- NASA-CMOTT Is One of the Few Groups Sustaining Momentum for Turbulence Modeling.
- It Is In Unique (Privileged) Position for Embracing the Challenge of Developing Specific Recommendations (Guidelines) For:
  a) Selection of Adequate Models for Different Class of Problems
  b) Correct Use of Each Model
- The Task Is Difficult But Practical
- Select Fewer Roads, Post Milestones, and Go Further
- Move An Inch Closer to Users