Workshop on Engineering Turbulence Modeling

Proceedings of the Workshop on Engineering Turbulence Modeling sponsored by the Institute for Computational Mechanics in Propulsion and Center for Modeling of Turbulence and Transition
NASA Lewis Research Center
Cleveland, Ohio
August 21-22, 1991
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Proceedings of the Workshop on Engineering Turbulence Modeling sponsored by the Institute for Computational Mechanics in Propulsion and Center for Modeling of Turbulence and Transition
NASA Lewis Research Center
Cleveland, Ohio
August 21-22, 1991
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The proceedings are edited by

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1. OBJECTIVES

The purpose of this meeting is to discuss the present status and the future direction of various levels of engineering turbulence modeling related to CFD computations for propulsion. For each level of complication, there are a few turbulence models which represent the state of the art for that level. However, it is important to know their capabilities as well as their deficiencies in CFD computations in order to help engineers select and implement the appropriate models in their real world engineering calculations. This will also help turbulence modelers perceive the future directions for improving turbulence models.

The focus of this meeting will be one-point closure models (i.e. from algebraic models to higher order moment closure schemes and pdf methods) which can be applied to CFD computations. However, other schemes helpful in developing one-point closure models, such as RNG, DIA, LES and DNS, will be also discussed to some extent.

2. FORMAT

This meeting will consist of three sessions and will last about one and half days.

Each session will have three or five position presentations. In the first two sessions each position presentation (40 minutes) will be followed by a comment presentation (10 minutes) and a discussion. In session III, there are five position presentations (30 minutes) and one discussion. The presentations will be made by invited speakers and the discussions will be led by the session chairman (see outline of the workshop for details).

The viewgraphs of the presentations will be collected to be distributed later.

3. ORGANIZING COMMITTEE

T.-H. Shih (Chairman)
J. L. Lumley (Honorary Chairman)
P. Moin
M. Goldstein
L. A. Povinelli
E. Reshotko
J. M. Barton
4. OUTLINE OF THE WORKSHOP

August 21, 1991 (Wednesday)

08:00-08:15 am Registration

08:15-08:30 am Welcome by L. Povinelli

Session I: Turbulence Modeling in CFD and Algebraic Closure models.
Chairman: E. Reshotko

08:30-09:10 am B.E. Launder, “The current status of turbulence modeling in CFD and its future prospects.”
09:10-09:20 am D.M. Bushnell, “Comment paper.”
09:20-09:40 am Discussion
09:40-10:20 am D. Wilcox, “The present state and the future direction of eddy viscosity models.”
10:20-10:30 am P. Spalart, “Comment paper.”
10:30-10:40 am T. Coakley, “Comment paper.”
10:40-11:00 am Discussion
11:00-11:40 am D. Taulbee, “The present state and future direction of algebraic Reynolds stress models.”
11:40-11:50 am A.O. Demuren, “Comment paper.”
11:50-12:00 am Discussion
12:00-01:30 pm Lunch Break

Session II: Second Order Closure and PDF Method.
Chairman: J.L. Lumley

1:30-2:10 pm T.-H. Shih, “The present state and the future direction of second order closure models for incompressible flows.”
2:10-2:20 pm J.R. Ristorcelli, Jr., “Comment paper.”
2:20-2:30 pm C.G. Speziale, “Comment paper.”
2:30-2:50 pm Discussion
2:50-3:30 pm T.B. Gatski, “The present state and the future direction of second order closure models for compressible flows.”
3:30-3:40 pm J. Viegas, “Comment paper.”
3:40-3:50 pm G. Huang, “Comment paper.”
3:50-4:10 pm Discussion
4:10-4:50 pm S. Pope, “The present state and the future direction of pdf methods.”
4:50-5:00 pm E.E. O’Brien, “Comment paper.”
5:00-5:10 pm J.Y. Chen, “Comment paper.”
5:10-5:20 pm Discussion
6:30-9:00 pm Banquet (Pierre Radisson Inn, Great Northern Blvd.)
Session I

Turbulence Modeling in CFD and Algebraic Closure Models
August 22, 1991 (Thursday)

Session III: Unconventional Turbulence Modeling.
Chairman: J.H. Ferziger

08:30-09:00 am A. Yoshizawa, “The present state of DIA models and their impact on one point closures.”

09:00-09:30 am J. Weinstock, “The present state of two-point closure schemes and their impact on one point closures.”

09:30-10:00 am S. Orszag, “The present state of RNG and its impact on one point closure.”

10:00-10:30 am R.R. Mankbadi, “The present state of application of RDT to unsteady turbulent flows.”

10:30-11:20 am W.K. George, J.H. Ferziger “The role of experiments and DNS & LES in supporting turbulence modeling efforts.”

11:20-11:40 am Discussion

11:40-12:00 Concluding Remarks.

5. INVITED PARTICIPANTS

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| F. Simon             | C. Steffen           | W.M. To                   |
| C. Towne             | T. VanOverbeke       | C. Wang                   |
| Z. Yang              | S.T. Yu              |                           |
Turbulence modelling in CFD: Present status, future prospects

by

Brian Launder
UMIST, Manchester, UK

- To provide a (personal) view of the status of turbulence modelling for use with the fully averaged equations of motion, energy, etc.
- To give concrete examples of what types of problem can/should be tackled with different levels of closure model
- Particular emphasis on applications in turbomachinery and near-wall treatments
- Models considered:
  - (Isotropic) Eddy Viscosity Models (EVM)
  - Algebraic Second-Moment Closures (ASM)
  - Differential Second-Moment Closures (DSM)
- No space to consider numerical strategies needed for non-EVM treatments

- Can be interpreted as an implication of the turbulent kinetic energy ($k$) equation for a simple shear flow ($U_1(x,2)$; $U_2$, $U_3 = 0$) when production and dissipation of $k$ are effectively in balance ($P_k = e$)
- Main industrial interest is in applying turbulence models in conditions where these conditions are not satisfied!
- Seem to perform worst in 2D curved flows and where body forces act in direction of primary velocity gradient
- Compressibility effects on turbulence not adequately accounted for with an eddy-viscosity stress-strain relation
- Nevertheless models of this type are relatively easy to use and will be replaced only where demonstrably superior alternatives are available
Eddy viscosity models – II: Choice

- Available in versions requiring solution of 0-4 turbulent transport equations, of which one is (usually) that for $k$
- No extensive testing beyond 2-equation level
- Generalized statement of 2-equation model

\[
\begin{align*}
\frac{\partial \nu_t}{\partial t} &= c_\mu \frac{k^3}{\ell^2} \\
\frac{\partial k}{\partial t} &= \frac{\partial}{\partial z} \left( \frac{\partial k}{\partial z} \right) + P_k - \epsilon \\
\frac{\partial z}{\partial t} &= \frac{c_z - 1}{k} \frac{P_k}{k} - \frac{2c_z}{k} \frac{z^2}{\nu_t} + S_z \\
\end{align*}
\]

- Most popular strategy takes $\epsilon = k^{1/2} \ell^2$ as second dependent variable mainly because $S_\epsilon$ can be taken as zero in many simple flows
- Need for non-zero $S_\epsilon$ becomes evident in separated and impinging flows to prevent excessive near-wall length scales developing

Eddy viscosity models – III: Near-Wall Strategy

- EVM's rarely give satisfactory levels of $\bar{u}_i \bar{u}_j$ away from wall vicinity: if Reynolds stresses are important there, second-moment closure is needed
- More difficult to devise suitable ASM's/DSM's for near-wall sublayer
- Hence most current research on EVM's concerned with treatment of this "low-Reynolds-number" region
- Log laws are generally inadequate .
- ..... even a mixing-length scheme is better
- One-equation models for sublayer currently seem a good compromise, especially if used with a "floating" $k$ (the length-scale gradient)

Eddy viscosity models – IV: Low-Re $k-\epsilon$ models

- Devised by reference to 2-dimensional flows parallel to plane walls
- Fairly satisfactory in predicting laminarization and diffusion-controlled transition
- Return results of uncertain accuracy when used in 3D, separated or impinging flows or on curved walls
- Need for about 40 nodes across sublayer means that computations at this level for 3D flows are only just feasible
- Further development work still required, guided by DNS data banks (Rodi, Mansour)
- At present it is often better to use a one-equation EVM across sublayer blended to a two-equation model in fully turbulent region
Problem: Flow through square duct rotating in orthogonal mode

Relevant to: Internal cooling of turbine blades

Importance of both Coriolis and buoyancy forces

Experimental data of Wagner et al (1989); computations Bo, Iacovides, Launder (1991)

3D parabolic code with 35 x 67 x 200 grid covering half cross section and 20 hydraulic diameters

Standard $k-\epsilon$ model in core matched to one-equation low-Re treatment across sublayer; $\sigma_\delta = 0.9$ in both regions

Satisfactory results for this very complex flow due to weak influence of force fields in turbulence equations and to predominant importance of sublayer region

Standard two-equation low-Re model gives far worse results than one-equation model

Modelling level based on approximated set of rate equations for Reynolds stresses and any other influential second moments (e.g. heat fluxes)

Convective transport of $\overline{u_i u_j}$ together with stress generation due to shear, buoyancy, Coriolis forces etc. all handled exactly at this level

A modelling level intrinsically better able to cope with complex flows than EVM's

Approximations needed for

- Pressure-strain correlation, $\psi_{ij}$
- Dissipation, $\epsilon_{ij}$ (and hence $\epsilon$)
- Diffusion, $d_{ij}$
LeRC Status of SMC - I The Basic Model

- A simple closure based on:
  - Rotta's linear return-to-isotropy concept for non-linear part of $\varphi_{ij}$.
  - "Isotropization-of-production" concept for linear ("rapid") parts of $\varphi_{ij}$.
  - Daly-Harlow generalized gradient diffusion hypothesis for $\delta_{ij}$.
  - Local isotropy for $\epsilon_{ij}$.
  - $\epsilon$ equation used in $k-\epsilon$ model

has been extensively applied in 2-D and 3-D subsonic flows

- Performance nearly always superior to $k-\epsilon$ EVM - often markedly so

- Scheme now becoming available in many commercial codes (FLUENT, FLOW3D, PHOENICS, etc.)

LeRC Status of SMC - II The Basic Model (cont'd)

- Empirical extension of model to low-Re sublayer has been extensively applied by Shima (1989) and colleagues to laminarizing flows

- This model apparently does not do well in high M boundary layers, however (Huang, personal communication)

- "Wall echo" part of $\varphi_{ij}$ performs quite incorrectly in impinging flows

- Performs rather poorly in free flows (round/plane jet "anomaly"; strong/weak shear flow "paradox")

LeRC Application of Basic Model - I The Fairied Annular Diffuser (Jones & Manners, 1989)
Because secondary flows are absent, Coriolis effects on stress components is only agency provoking asymmetric flow.
• By suitably approximating transport (convection and diffusion) of $u_i u_j$ in terms of $k$ transport, the closure becomes one where:
  * algebraic equations are solved for $u_i u_j$'s
  * a differential equation is solved for $k$
• This is what we mean by an ASM closure
• Technique is most powerful where transport terms are small ... i.e. in wall flows
• Most widely used ASTH's not coordinate frame invariant
• Properly invariant versions have been proposed (Ahmadi, ICASE) but do not so far seem to have been extensively tested in crucial flows


- Status of ASM's
  * When transport is small, useful reduction in computational effort achieved while retaining virtually same results as DSM
  * Nature of ASTH is then unimportant
  * System of equations is stiffer than when DSM is used: convergence is often more difficult
  * ASM's are on their way out; not worth developing new software for this level of model
Approximation of $\varphi_{ij}$ (and other processes) designed to comply with extreme states of turbulence; e.g. isotropic turbulence, 2-component turbulence.

Proper frame indifference

Extensive use made of stress anisotropy invariants:

$$A_2 = a_{ij}a_{ij} \ ; \ A_3 = a_{ijk}a_{ijd}$$

$$a_{ij} = (\bar{u}_i \bar{u}_j - \frac{1}{2} \delta_{ij} \bar{u}_k^2)/k$$

Extensive use made of results of direct numerical simulations

Algebraically far more complex than basic model but greater numerical stability can lead to a reduction in overall computer time

Extensive testing in homogeneous flows (ICASE, Stanford, Cornell, LeRC, UMIST)

Moderate testing in 2D free shear flows

UMIST model tested in 2D recirculating and colliding flows

Far greater width of applicability demonstrated than with basic model

Only known test for swirling recirculating flows not fully successful

<table>
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<tr>
<th>Flow</th>
<th>Expt</th>
<th>Basic Model</th>
<th>New Model</th>
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<tbody>
<tr>
<td>Plane jet</td>
<td>0.105-0.110</td>
<td>0.100</td>
<td>0.110</td>
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<tr>
<td>Round jet</td>
<td>0.095</td>
<td>0.105</td>
<td>0.098</td>
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<tr>
<td>Plane wake</td>
<td>0.098</td>
<td>0.078</td>
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<tr>
<td>Plane plume</td>
<td>0.12</td>
<td>0.078</td>
<td>0.118</td>
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<tr>
<td>Mixing layer</td>
<td>0.16-0.20</td>
<td>0.16</td>
<td>0.176</td>
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Dimensionless rates of spread of equilibrium free shear flows

Colliding Round Jets

$V_C / V_{in}$ vs $r_C / D$
LeRC 8/91 | Key elements in UMIST model
---|---
• More intricate interconnection among stress and strain components in mean-strain (rapid) part of $\sigma_{ij}$
• Weakening of return-to-isotropy coefficient as stress field becomes more isotropic and also as it approaches 2-component limit
• Diminished effect of mean strain on evolution of $\epsilon$

$$\frac{D\epsilon}{Dt} - d_\epsilon + \left\{ \frac{c_{\epsilon_1}}{2} \left[ \frac{P_k}{\epsilon} + \frac{\epsilon}{\epsilon} \left( \frac{\partial U_i}{\partial x_j} \right)^2 \right] - c_{\epsilon_2} \right\} \epsilon^2$$

where $c_{\epsilon_1} = 0.7$ (versus 1.44)

$c_{\epsilon_2} = 1.92/(1 + 1.65A_2/A)$ (versus 1.92)

$A = 1 - \frac{9}{8} (A_2 - A_3)$

---

LeRC 8/91 | Issues in modelling near-wall turbulence
---|---
• DNS data bank suggest $\epsilon_{ij}$ far less isotropic than usually presumed; behaviour of $\epsilon_{1,2}$ especially strange
• Peak level of $\epsilon$ at wall
• Bradshaw et al (1987) have shown inhomogeneous effects on $\sigma_{ij}$ very important in buffer layer
• "Wall-reflection" models of $\sigma_{ij}$ need to consider different constraints imposed by parallel and impinging wall flows and free-surface flows

---

LeRC 8/91 | Some features of UMIST’s approach to near-wall turbulence
---|---
• $\epsilon_{ij}$ modelled to satisfy exact component ratios at wall
• Inhomogeneous effects on mean-strain part of $\sigma_{ij}$ accommodated through use of effective velocity gradient

$$\frac{\partial U_i}{\partial x_j} + c_1 \rho \frac{\partial U_i}{\partial x_k} \frac{\partial U_k}{\partial x_j} \frac{\partial U_j}{\partial x_m} , \text{ Launder & Tselepidakis (1991)}$$

• New wall-reflection model designed to handle impinging and parallel shear flows (but, alas, not free surface effects), Launder and Craft (1991)
• Best way of placing $\epsilon$ maximum at wall is to solve transport equation for

$$\overline{\epsilon} = \epsilon - 2r \left( \frac{\partial U_i}{\partial x_j} \right)^2 \text{ Kawamura (1991)}$$
Application to plane channel flow
Launder & Tselepidakis (1991)

$c_1 = 0.3; \text{'wall-echo' effect retained}$

$c_1 = 0.4; \text{'wall-echo' effect dropped}$

Application to turbulent impinging jet
Craft & Launder (1991)

Present status of new generation DSM's

- Substantial advances demonstrated over earlier models for free shear flows
- Significant unresolved (or incompletely resolved) problems remain in modelling near-wall turbulence that limit range of applicability of available models
- Much remains to be done in high-speed flows: present suggestions for modelling extra terms and/or physical processes seem generally to be "quick fixes"
- Many improvements foreseen over next 3-5 years
- New-generation closures now being incorporated into general purpose 3D solvers
- EVM's, ASM's and DSM's will remain in use though with steady decline in importance of EVM's and ASM's in favour of DSM's
- Improved versions of low-Re two-equation EVM's should lead to more reliable predictions of separated flows than at present
- New-generation DSM closures will soon (2–3 years) replace basic model even in commercial codes
- Further refinement of sub-models in second moment closures can be expected throughout this decade
- Increasing attention to interfacing SMC with higher order approaches such as LES
- Increasing use of two-time-scale schemes providing distinct time scales for large and (fairly) small eddies

- Extensive collaborative testing/assessment of turbulence models currently underway – coordinated/organized by Professor P. Bradshaw (Stanford) (with a little help from JLL and BEL)
- Outcome of that exercise will offer a more complete and objective view of state of turbulence modelling than is currently available
Comment on:
The current status of turbulence modeling in CFD and its future prospects

by

D. M. Bushnell

NASA Langley Research Center
FUNDAMENTAL PROBLEM WITH CONVENTIONAL TURBULENCE MODELING

- Phase/Spectral information lost ("averaged out")
  — implicit assumption of Similar Spectra

However (Kline, 1981)

"Contrary to earlier ideas, turbulence is not a single or even a simple set of states; it is a very complex and variable set of states that react in sometimes unanticipated ways to a great variety of circumstances"

"The Quasi-Coherent parts of the turbulent flows, what we call the large or medium eddy structures, are not the same in different kinds of turbulent flows"

- zonal modeling is an attempt to include this dynamic richness
FUNDAMENTAL PROBLEMS WITH THE "STATE OF THE ART" TURBULENCE MODELING APPROACH OF "EDDY VISCOSITY"

- Mixing length, Cebeci-Smith, Baldwin-Lomax, K-E etc.
  - relate turbulence stress directly to mean field, however, turbulence field cannot track rapid, inviscidly-induced, mean flow alterations
  - lack innate capability to generate turbulence-induced secondary flows, handle curvature/rotation effects
- Various "Fixes" have been proferred including Johnson-King and ASM.
THE MAJOR PROBLEMS WITH RSE CLOSURES

• Numerical/computer efficiency
  — Numerics/computers barely capable of good resolution for 2-D separated flows, a major reason why RSE closures are relatively unevaluated/unoptimized, esp. at high speeds ("stiffness" problem)

• Length Scale Equations
  — usual dissipation rate eq. is mainly Adhoc, anisotropic and/or split spectral equations may be required

• Wall Region Treatments
  — wall functions not suitable for separated/3-D flows, must compute to wall
- Pressure-strain and pressure-dilatation modeling
  - High-Speed flows may be different due to hyperbolic nature of pressure field
RSE CHALLENGES PROBABLY ADDRESSABLE WITHIN THE CONTEXT OF REYNOLDS AVERAGING

- Compressibility
  - simplex mean density/temperature variation
  - baroclinic torque/mean dilatation effects
  - alteration of eddy-eddy interaction at high $M^1, M_c$
  - energy radiation via acoustic waves ($M>>1$?)
  - bulk viscosity ($M>>1$?)

- Curvature
  - longitudinal and in-plane streamline curvature
  - induced by pressure gradients and organized vorticity as well as geometry
  - stationary curvature-induced Gortler vortices probably computable with good numerics
  - included to first order in RSE approaches
- Low Reynolds Number
  - transitional flow artifacts require $O(100\delta)$ for relaxation, both free and bound flows, especially important at high Mach No
  - wall regions, especially for unsteady, separated 3-D, flows and complex wall boundary conditions
RSE CHALLENGES WHICH MAY REQUIRE THEORETICAL/NUMERICAL SPECTRAL ADJUNCTS FOR SATISFACTORY SOLUTIONS

- Shock Interaction
  
  — Both direct and indirect amplification of incident disturbance fields
  
  — Direct amplification accompanied by intermodal energy transfer
  
  — Shock motions/oscillations convert mean flow energy into fluctuation field
  
  — Often accompanied by pressure gradient/bulk dilatation and streamline curvature which further amplify turbulence levels
  
  — Produces spectral alteration, with production of large scale structures
SHOCK OSCILLATIONS

- **Ideal Gas Shock Waves are, by themselves, stable (but shock perturbations can decay slowly and shock waves in reacting flows can be unstable)**

- **Shock oscillations produced by**
  
  — **Innately unstable flow fields** (e.g., separation (shear layer, bubble modes), transonic edge tones/Helmholtz resonator, Hartmann tube)

  — **Bifurcation between stable shock patterns** (e.g., "borderline operation" between Edney patterns, regular vs. Mach reflection etc.)

  — **Interaction with/reflection from/production by turbulent fields**

  — **Possibility of shock instability in reacting flows**
— Overall amplifications of factors of 2 to 3 not uncommon
RSE CHALLENGES WHICH MAY REQUIRE THEORETICAL NUMERICAL SPECTRAL ADJUNCTS FOR SATISFACTORY SOLUTIONS

- Intermittency
  - Transitional Flow Regions
  - Shear Flow "free boundary" regions
  - Chemically reacting flows
  - Function of pressure gradient, Mach number, roughness,

- Discrete Spectral Entities — initial/boundary conditions and embedded instabilities
  - example of discrete B.C.'s — stator/rotor wake interaction in rotating machinery
  - examples of imbedded instabilities (in turbulent flows)
    a. Gortler (dynamic)
    b. Karman shedding
    c. Intersection region horseshoe vortex interactions.
TOOLS AVAILABLE TO AID RSE MODELING

• Experimental
  — Quantitative Flow Visualization, direct (3 space and time!) measurements of terms/influences (e.g. Holographic velocimeter)
  — Mean and Second order (average and spectra) data to check validity of predictions, develop postdictions, determine presence of "new physics" (from discrepancies, discrete spectral peaks), provide initial boundary conditions.
  — Structure/visualization/physics experiments.

• Numerical Simulations
  — Only source of detailed/complete data
  — Historically limited to simple geometry/low ReN°, but both boundaries are expanding
• Theory
  — Rapid distortion theory
  — 3rd order and 2–pt. eqs

• Restrictions/Requirements
  — Realizability
  — Symmetry
  — Frame Indifference
  — Behavior at end conditions such as infinite ReN^0, 2–D Turb., homogenous shear
  — 2nd law of thermodynamics

• Dimensional Analysis
CONCLUDING REMARKS

- Currently there are only 2 ways to “make numbers” in Turbulent Engineering Flows
  — Numerical Simulations
  — Modeling

and for the usual complex flows simulation is not feasible; therefore we must model

- Simplex (Eddy viscosity) approaches such as mixing length/K-E etc. Provide reasonable estimates for simplex (quasi-parallel, near-equilibrium etc.) flows. Complex flows require second order (RSE) closures.

— 18 years of experience with K-E has resulted in numerous “fixes” which (tenuously) can extend its range of applicability
• RSE closures are in their infancy, due (historically) primarily to numerical difficulties and computer limitations. **WE DO NOT YET KNOW HOW GOOD (OR BAD) THE RSE CLOSURES ARE OR CAN BE.**

• Launder's group(s) have pioneered the low speed engineering applications of RSE closure, with Lumley's group providing many of the advanced concepts.

• RSE research frontiers include
  — Numerical efficiency improvements for the stiff eq sets
  — Length scale equation(s) (Anisotropic, Split Spectrum)
  — Pressure strain modeling
  — Wall region treatments
  — Compressibility
• Several applications may require theoretical/numerical spectral adjuncts
  — Shock interaction/oscillation
  — Discrete dynamical flow elements as initial/boundary conditions
  — Discrete dynamic instabilities of turbulent flows
  — Combustion/intermittency
SIMPLEX VIEW OF STATUS - TURBULENCE MODELING

Flow Phenomena

Design Problem:
- Attached B.L.
- 3-D, Vortical/
  Separated Flow
- Unsteady Flow, Discrete
  Spectral Inputs/Instabilities

CRUISE
- External Aero
  Inlets, Tips,
  Intersections
- Mixing Length, etc.
- K-e or Similar
- EDDY VISCOSITY

MANEUVER, TAKE OFF/
LANDING/OFF DESIGN
- Rotating Machinery /
  Combustor Propulsion
- K-e with "fixes," ASM
- RSE w/Split Spectrum,
  Anisotropic Len. Scale
- LES

SPECTRAL APPROACHES
- PDF
- 2ND ORDER CLOSURE
- DS

INCREASING
COMPLEXITY
- Also: Lower Re No., Higher Speed;
  Shock Waves, Multi-phase,
  Multiple Body Forces
COMPLICATING FEATURES — TURBULENT FLOWS

• 3–D:
  — Boundary Layers
  — Separated Flows
  — Vortical Flows
  — Free Mixing Layers

• Possibly Influenced By:
  — Complex 3–D Geometry (Corners/Intersections, roughness, etc)
  — Pressure Gradients, Curvature(s)
  — Compressibility
  — Low Reynolds Number (transition, walls, edges)
  — Discrete Organized Vorticity (instability, B. C.)
— Shock Wave Interaction(s)
— Combustion/Chemistry
— Multiple Phase/Phase Change
— Buoyancy/Stratified Media
— Plasma/Relativistic/Radiation Effects
— Non-Newtonian Fluids
DISCUSSION

J. Bardina (to B.E. Launder)

I just have a question for Prof. Launder. You dismissed the algebraic Reynolds stress models real fast. To me a natural way to go from two equation models to higher models is to go through algebraic relations first. Do you think that the poor predictions are only due to the poor models and not related to the numerical instability issues.

B.E. Launder (reply)

It’s a matter of taste and depends on the problem you are looking at. It’s true that if one is thinking of it in that relation, the idea of using just the same two equation $k - \epsilon$ or $k - \omega$ or more complicated stress-strain relation got some appeal. But nobody would suggest ASM is an improvement of physics over $k - \epsilon$. The problem you encounter in stiffer equations make it an unattractive level to fall to. It’s beginning to pass. It could be that for a particular discrete set of problems it would make a lot of sense. On the overall if you can not use an eddy viscosity model, you should just bite the bullet and use the Reynolds stress model.

A.K. Singhal

I would like to make a comment about the use of nomenclature. You can notice that even the names used for the Reynolds stress models by the invited speakers were different. It would be very helpful for industry if modelers could use the same nomenclature.
THE PRESENT STATE AND THE FUTURE DIRECTION
OF EDDY VISCOSITY MODELS

by

David C. Wilcox

Workshop on Engineering Turbulence Modeling
August 21, 1991

DCW Industries, Inc.
5354 Palm Drive, La Canada, CA 91011
TALK OUTLINE

- Evolution of eddy-viscosity models
- The eddy-viscosity dilemma
- Two-equation models
- Free shear flows
- Attached wall-bounded flows
- Separated flows
- The past (where we've been)
- The future (where we should be going)
EVOLUTION OF EDDY VISCOSITY MODELS

Eddy Viscosity Hypothesis
Boussinesq (1877)

Mixing-Length Hypothesis
Prandtl (1925)
Cebeci-Smith (1967)
Baldwin-Lomax (1978)

Two-Equation Models
Kolmogorov (1942)

One-Equation Models
Prandtl (1945)
Bradshaw (1967)
Baldwin-Barth (1990)

k-ε Models
Chou (1945)
Davidov (1961)
Harlow-Nakayama (1968)
Jones-Laurendeau (1972)

k-ω Models
Spalding (1969)
Saffman (1969)
Saffman-Wilcox (1974)
Wilcox (1984)

Other Models
k-λ: Rotta (1951)
k-kl: Rotta (1968)
k-τ: Zelerman-Wolfshtein (1986)
k-τ: Speziale (1991)
THE EDDY VISCOSITY DILEMMA

- The Boussinesq approximation is based upon making an analogy with molecular transport of momentum

\[ -\overline{u\nabla} = \nu_{\text{mix}} \left[ \ell_{\text{mix}} \frac{\partial u}{\partial y} + \frac{1}{2} \ell_{\text{mix}}^2 \frac{\partial^2 u}{\partial y^2} + \ldots \right] \approx \nu_T \frac{\partial u}{\partial y} \]

\[ \nu_T = \nu_{\text{mix}} \ell_{\text{mix}} \]

For this to work, we require

\[ Kn = \ell_{\text{mix}} / L \quad \text{where} \quad L = \frac{|\partial u / \partial y|}{|\partial^2 u / \partial y^2|} \quad \text{and} \quad \ell_{\text{mix}} / \nu_{\text{mix}} < < |\partial u / \partial y|^{-1} \]

- Neither condition is satisfied in a typical turbulent shear flow
- "SOLVE NOW, WORRY LATER" (J. Cole)
TWO EQUATION MODELS

- Models that fail to provide sufficient information to determine both a turbulence velocity scale and a turbulence length scale are **incomplete**

- A two-equation model is the simplest **complete** model of turbulence

- Virtually all two-equation models begin with the turbulence kinetic energy equation - the differences appear in the choice of a second dependent variable...
  
  \( \varepsilon \) - Dissipation Rate  
  \( \omega \) - Specific Dissipation Rate  
  \( \tau \) - Dissipation Time Scale  
  \( \ell \) - Dissipation Length Scale
EQUATIONS OF MOTION

- Two-equation models use the Boussinesq approximation so that

\[ \tau_{ij} = -u_i' u_j' = 2 \nu_T S_{ij} - \frac{1}{3} k \delta_{ij} \]

- The turbulence kinetic energy equation is

\[ \frac{dk}{dt} = \tau_{ij} \frac{\partial u_i}{\partial x_j} - \epsilon + \frac{\partial}{\partial x_j} \left[ (\nu + \nu_T/\sigma_k) \frac{\partial k}{\partial x_j} \right] \]

- For the \( k-\epsilon \) model...

\[ \frac{d\epsilon}{dt} = C_{e1} \frac{\epsilon}{k} \tau_{ij} \frac{\partial u_i}{\partial x_j} - C_{e2} \frac{\epsilon^2}{k} + \frac{\partial}{\partial x_j} \left[ (\nu + \nu_T/\sigma_\epsilon) \frac{\partial \epsilon}{\partial x_j} \right] \]

\[ \nu_T = C_\mu f_\mu k^2 / \epsilon \]

- For the \( k-\omega \) model...

\[ \frac{d\omega}{dt} = \alpha \frac{\omega}{k} \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta \omega^2 + \frac{\partial}{\partial x_j} \left[ (\nu + \nu_T/\sigma_\omega) \frac{\partial \omega}{\partial x_j} \right] \]

\[ \nu_T = k / \omega \quad \text{and} \quad \epsilon = C_\mu \omega k \]
RELATIONSHIP BETWEEN $\varepsilon$ AND $\omega$

- If we use $\varepsilon = C_\mu \omega k$ as the definition of $\omega$, transforming the $\varepsilon$ equation (with $\sigma_k = \sigma_w$ for simplicity) yields

$$\frac{d\omega}{dt} = \frac{\omega}{k \tau_{ji}} \frac{\partial u_j}{\partial x_j} - \beta \omega^2 + \frac{\partial}{\partial x_j} \left[ (\nu + \nu_t/\sigma_w) \frac{\partial \omega}{\partial x_j} \right] + 2 \frac{(\nu + \nu_t/\sigma_k) \partial k}{k \partial x_j} \frac{\partial \omega}{\partial x_j}$$

The cross-diffusion term does the following things:

1. Yields an excellent prediction for the plane jet
2. Disrupts defect-layer response to pressure gradient
3. Makes $k-\varepsilon$ model very stiff in the sublayer and dictates the need for viscous damping terms
Free Shear Flows

- $k-\omega$ models are sensitive to the freestream value of $\omega$ when applied to free shear flows

<table>
<thead>
<tr>
<th>Flow</th>
<th>Wilcox</th>
<th>$k-\varepsilon$</th>
<th>Speziale</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixing Layer</td>
<td>.100-.141</td>
<td>.099</td>
<td>.115</td>
<td>.116</td>
</tr>
<tr>
<td>Plane Jet</td>
<td>.090-.133</td>
<td>.108</td>
<td>.130</td>
<td>.100-.110</td>
</tr>
<tr>
<td>Round Jet</td>
<td>.115-.175</td>
<td>.120</td>
<td>.155</td>
<td>.086</td>
</tr>
<tr>
<td>Radial Jet</td>
<td>.088-.186</td>
<td>.095</td>
<td>.112</td>
<td>.096-.110</td>
</tr>
<tr>
<td>Plane Wake</td>
<td>.221-.498</td>
<td>.257</td>
<td>.285</td>
<td>.365</td>
</tr>
</tbody>
</table>

- Like the $k-\varepsilon$ model, the $k-\omega$ model suffers from the so-called round-jet/plane-jet anomaly
INCOMPRESSIBLE FREE SHEAR FLOWS

Plane Wake

Round Jet

Mixing Layer

Plane Jet
MODEL–PREDICTED BOUNDARY LAYER STRUCTURE

- Turbulence transport equations rarely have closed-form solutions
- Perturbation methods are invaluable for analyzing turbulence models
- Five distinct layers have been identified for the k-ω model...

Freestream

Superlayer \[ y - \delta \sim v/v \]

Defect Layer/Wake Region \[ y \sim \delta \]

Wall Layer \[
\begin{align*}
\frac{u_T y}{v} & >> 1 \\
\frac{v}{\delta} & << 1
\end{align*}
\]

Sublayer \[ y \sim v/u_T \]

Roughness Layer \[ y \sim k_0 \]
DEFECT-LAYER ANALYSIS

- Using perturbation methods, can simplify equations to similarity form

\[
\begin{align*}
(u_e - u)/u_\tau &= f(\eta) \\
\eta &= y/\Delta \\
\Delta &= u_e \delta^*/u_\tau
\end{align*}
\]

- Pressure gradient comes in through the equilibrium parameter

\[\beta_T = \frac{\delta^* \frac{dp}{dx}}{\tau_w} \quad \text{(Bradshaw } A = -0.255 \Rightarrow \beta_T = 5)\]

- The analysis shows that

\[(U_c - u)/u_\tau \sim -\kappa^* \log(y/\Delta) + A - C\beta_T(y/\Delta) \log(y/\Delta) \quad \text{as } y/\Delta \to 0\]

<table>
<thead>
<tr>
<th>Model</th>
<th>Type</th>
<th>A</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wilcox</td>
<td>k-\omega</td>
<td>13.1</td>
<td>1.18</td>
</tr>
<tr>
<td>Wilcox-Ruhesin</td>
<td>k-\omega^2</td>
<td>9.8</td>
<td>2.60</td>
</tr>
<tr>
<td>Kolmogorov</td>
<td>k-\omega</td>
<td>10.0</td>
<td>1.14</td>
</tr>
<tr>
<td>Launder</td>
<td>k-\epsilon</td>
<td>5.2</td>
<td>6.09</td>
</tr>
<tr>
<td>Speziale</td>
<td>k-\omega</td>
<td>5.1</td>
<td>4.96</td>
</tr>
</tbody>
</table>
Effects of Pressure Gradient

- Perturbation analysis results show that Kolmogorov did remarkably well without the aid of a computer!

![Graphs showing velocity profiles and wake strength variation](image)

(a) Velocity profiles, $\beta_T=0$  
(b) Velocity profiles, $\beta_T=8.7$

<table>
<thead>
<tr>
<th>Model</th>
<th>$\overline{\Pi}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wilcox</td>
<td>4.05</td>
</tr>
<tr>
<td>Wilcox–Rubesin</td>
<td>3.26</td>
</tr>
<tr>
<td>Kolmogorov</td>
<td>3.21</td>
</tr>
<tr>
<td>Launder</td>
<td>2.27</td>
</tr>
<tr>
<td>Speziale, et al</td>
<td>2.23</td>
</tr>
</tbody>
</table>

Figure 1. Comparison of computed and measured defect-layer properties: — Wilcox k-ω model; —— Wilcox-Rubesin k-ω$^2$ model; —— Launder k-ε model.

- The unmodified "cross-diffusion" term distorts predicted defect-layer structure
$k-\omega$ LOVES SAMUEL-JOUBERT!
AND SO DOES $k-\tau$
Viscous Sublayer Structure

- If we simply add molecular viscosity to the $k$, $\omega$ and the mean-flow equations, we find

\[ k \rightarrow y^+ \text{ as } y \rightarrow 0 \quad \text{and} \quad u' - \kappa \text{log} y' \rightarrow B \text{ for } y \gg 1 \]

- Most $k-\omega$ models predict $3 < n < 4$ and $3 < B < 7$

  Kolmogorov: \hspace{0.5cm} n = 3.62 and $B = 3.1$

  Speziale and $k-\varepsilon$: \hspace{0.5cm} n = 1.39 and $B = -2.2$

- The Wilcox model predicts $n = 3.23$, $B = 5.1$ and pretty good overall agreement with measured sublayer properties
WALL FUNCTIONS AND VISCOUS DAMPING

- Any model that fails to predict $B = 5.0$ must have either wall functions or viscous damping to achieve accurate boundary-layer results - even mixing length needs the van Driest modification

- A great deal of effort has been devoted by Viegas, Rubesin, et al toward perfecting wall functions - robust, but solutions usually are sensitive to $y$

- A great deal of effort has gone into devising viscous damping functions for $k-\varepsilon$ - asymptotic consistency at the expense of stiffness

- Almost all of this effort needed because $k-\varepsilon$ says $B = -2.2$

- Yet, there is a path of far less resistance...$k-\omega$ says $B = 5.1$ and requires no damping!
VISCOUS DAMPING FOR $k-\omega$

- If you want asymptotic consistency with $k-\omega$, using simple damping functions similar to those of Glushko...
EFFECTS OF COMPRESSIBILITY

- Morkovin’s Original Hypothesis works well for boundary layers all the way up to Mach 10 (Speziale)

- For the mixing layer, Sarkar and Zeman postulate that dissipation is the sum of solenoidal and dilatational components

\[
\begin{align*}
\rho \frac{dk}{dt} &= -\rho (\varepsilon + \varepsilon_d) + \ldots \\
\rho \frac{d\varepsilon}{dt} &= -C_{\varepsilon2} \rho \varepsilon^2/k + \ldots \\
\varepsilon_d &= \xi^* F(M_\tau) \varepsilon \\
M_\tau^2 &= 2k/a^2
\end{align*}
\]

\textit{Sarkar’s Model}

- \( \xi^* = 1 \)
- \( F(M_\tau) = M_\tau^2 \)

\textit{Zeman’s Model}

- \( \xi^* = 3/4 \)
- \( F(M_\tau) = \left[ 1 - \exp\left\{ - (M_\tau - M_{\tau_0})^2/\Lambda^2 \right\} \right] H(M_\tau - M_{\tau_0}) \)

- Sarkar and Zeman modifications fix something that wasn’t broken...flat-plate boundary layer

- Perturbation analysis explains why
Applications

Compressible Mixing Layer

Adiabatic Wall Boundary Layer

C_{0}/C_{\delta_0}

M_c

C_{f}/C_{f_0}

M_\infty

- Langley Curve
- Unmodified k-\omega
- Zeman, \xi^*=3/4
- Sarkar, \xi^*=1

- Van Driest II
- Unmodified k-\omega
- Zeman, \xi^*=3/4
- Sarkar, \xi^*=1
Perturbation Analysis of the Wall Layer

• For the $k-\omega$ model...

The perturbation expansion proceeds in powers of $M_r = u_r/a_w$, and the velocity follows the Van Driest scaling, i.e.,

$$
\frac{u^*}{U_\infty} = \frac{1}{A} \sin^{-1} \left( \frac{2A^2v - B}{\sqrt{B^2 + 4A^2}} \right), \quad v = u/u_r
$$

$$
\frac{u^*}{u_r} \sim \frac{1}{K} \log(u_r y/v_w) + \left[ \text{constant} + \frac{1}{K} \log \left( \rho/\rho_w \right)^{1/4} \right]
$$

where

$$
K^2 \sim \kappa^2 \left[ 1 - (40.27 \xi^* - 0.89)M_r^2 + \ldots \right]
$$

• For the $k-\varepsilon$ model...

$$
\frac{u^*}{u_r} \sim \frac{1}{K_r} \log(u_r y/v_w) + \left[ \text{constant} + \frac{1}{K_r} \log \left( \rho/\rho_w \right)^{5/4} \right]
$$

where

$$
K_r^2 \sim \kappa^2 \left[ 1 - (10.23 \xi^* + 2.34)M_r^2 + \ldots \right]
$$
An Alternative Compressibility Term

- Turbulence Mach number is about twice as large in a mixing layer as it is in a boundary layer

Maximum Turbulence Mach Number, $(M_t)_{\text{max}}$

<table>
<thead>
<tr>
<th>$M_t$</th>
<th>Boundary Layer $\xi^* = 0$</th>
<th>$\xi^* = 1$</th>
<th>Mixing Layer $\xi^* = 0$</th>
<th>$\xi^* = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>.061</td>
<td>.061</td>
<td>.180</td>
<td>.159</td>
</tr>
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<td>2</td>
<td>.114</td>
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<td>3</td>
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<tr>
<td>4</td>
<td>.174</td>
<td>.154</td>
<td>.424</td>
<td>.254</td>
</tr>
<tr>
<td>5</td>
<td>.191</td>
<td>.171</td>
<td>.453</td>
<td>.266</td>
</tr>
</tbody>
</table>

- The following model for dilatational dissipation improves predictions for both the mixing layer and the boundary layer

$$\varepsilon_d = \xi^* F(M_t) \epsilon$$

$$F(M_t) = [M_t^2 - M_{iw}^2] H(M_t-M_{iw})$$

$$\xi^* = 3/2, \ M_{iw} = 1/4$$
Applications
New Compressibility Term

Compressible Mixing Layer

Adiabatic Wall Boundary Layer
UNSTEADY BOUNDARY LAYERS

- The k-ω model does remarkably well for unsteady boundary layers even when periodic separation and reattachment occurs as in the experiments by Jayaraman, Parikh and Reynolds.
UNSTEADY BOUNDARY LAYERS HIGH AMPLITUDE

Mean Velocity

Amplitude of 1st Harmonic

Phase Shift

High Amplitude \( x'=0.94 \)

\[ \text{Graphs showing mean velocity, amplitude of 1st harmonic, and phase shift for high amplitude } x'=0.94. \]
INCOMPRESSIBLE SEPARATION

- Flow past a backward-facing step has been a popular test case

- Thangam and Speziale have shown that a 200x100 grid is necessary for grid independence

- $k-\varepsilon$ does very well for this flow predicting reattachment at $x/H = 6.25$ (experiments say 7.1)
BACKSTEP RESULTS

Speziale: Standard $k-\varepsilon$
(Eaton-Johnston Experiment)

Mentor: $k-\omega$
(Driver Experiment)
COMPRESSIBLE SEPARATION

- Shock-induced boundary-layer separation is a more difficult problem.

- Horstman has run many shock-separated flows with the $k-\varepsilon$ model - separation region generally too small, q and $c_f$ too high at reattachment - "$k-\varepsilon$ is a totally unreliable model for design purposes in 2-D and axisymmetric compressible flows with separation."

- A few cases have been done with the $k-\omega$ model with similar results - skin friction tends to be closer to measurements.

- 2-D shock-separated flows can be routinely done on a $3,000$ desktop computer - $3500$ grid points $\rightarrow 3$ to $4$ hours.
Fig. 17 Comparison of computations based on wall functions with the k-ε model of turbulence, of a calculation based on the Jones-Launer near-wall terms in this k-ε model, and of measurements for the two-dimensional, supersonic, 24° compression corner experiment: \( M = 2.84 \). (a) Surface-pressure distribution; (b) Skin-friction coefficient distribution.
20° Planar Corner

24° Planar Corner
THE PRESENT STATE OF EDDY VISCOSITY MODELS

- At Stanford Olympics II, k-ε and k-ω² did very poorly for incompressible attached boundary layers in adverse pressure gradient. Since that time:
  - k-ε: No universally accepted fix has evolved
  - k=ω: Changing from k-ω² to k-ω fixes the problem
  - k-τ: Does well for Samuel-Joubert

- Integration to the wall continues to plague k-ε
  - k-ε and k-τ say B = -2.2 and must have viscous damping
  - k-ω says B = 5.1 and requires no damping

- Current status of two-equation models is as follows:

<table>
<thead>
<tr>
<th>Type of Flow</th>
<th>k-ω</th>
<th>k-ε</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free Shear Flows</td>
<td>C</td>
<td>C</td>
<td>C-</td>
</tr>
<tr>
<td>Boundary Layer in V_p</td>
<td>A</td>
<td>C-</td>
<td>B</td>
</tr>
<tr>
<td>Low Reynolds Number Effects</td>
<td>A-</td>
<td>C+</td>
<td>C+</td>
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<tr>
<td>Compressibility Effects</td>
<td>A-</td>
<td>C</td>
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<tr>
<td>Unsteady Boundary Layers</td>
<td>A</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>Backward Facing Step</td>
<td>A</td>
<td>B+</td>
<td>B+</td>
</tr>
<tr>
<td>Compressible Separation</td>
<td>D+</td>
<td>D</td>
<td>I</td>
</tr>
</tbody>
</table>
THE FUTURE DIRECTION OF EDDY VISCOSITY MODELS

- It is unlikely that a UNIVERSAL model will be of the two-equation variety - Boussinesq approximation isn’t good enough.

NEVERTHELESS...

- Development of the second equation (ε, ω, etc.) should continue - it is part of the foundation for second-order closure models and it is easier to work with in the two-equation model context

- Perturbation methods and similarity solutions should be used more to weed out inferior formulations - the back of the envelope is still a good place to solve problems!

- Using k-ω removes the pressure gradient and integration-to-wall problems - difficulties remain for free shear flows and turbulent/nonturbulent interfaces that should be resolved

- The k-ω model warrents more attention from the turbulence community - it does many things well with the same 5 closure coefficients!
Comment paper,

Workshop on engineering turbulence modeling

NASA Lewis, August 21, 1991

P. R. Spalart,

Boeing Commercial Airplane Group
Comments on position presentation

- What is a complete model?

- The emphasis on adverse pressure gradient is very laudable. We need to be cautious with "equilibrium boundary layers". They may be solutions of the modeled equations (which contain the same assumptions regarding the Reynolds-number dependence), and not of the full equations! Clauser's concept is not the only one around.

- This speaker is not shocked by, e.g., $k \propto y^{3.23}$ near the wall (as long as $k$ is at most $O(y^2)$). The near-wall behavior is no guide for fundamental choices such as that between $\epsilon$ and $\omega$. We see nothing wrong with damping functions.

- The $k-\omega$ results in the Samuel-Joubert flow are inconsistent ($\delta$ at different heights in $U$ and in $u'u'$).
Samuel-Joubert flow, computed with $k-\omega$

$x = 3.40 \text{ m.}$

$x = 3.39 \text{ m.}$
Boeing (commercial) position

• The push is towards complex geometries, unstructured or at least very distorted and multi-block grids, separation, and we must have high Reynolds number.

• We have experience with Mellor-Herring and derivatives, Baldwin-Lomax, Johnson-King, RNG, Baldwin-Barth, and one shot at \( k-\varepsilon \). Johnson-King has the best press in Navier-Stokes codes.

• Viscous-inviscid coupling and algebraic models are endangered (at least on the research side), but we are very unlikely to give up eddy viscosity for years.

• We find that a correct first \( y^+ \) (say \( \approx 5 \)) does not ensure grid convergence at Reynolds numbers of interest, because of artificial dissipation.

• The range of flow types is not as wide as in mechanical engineering ("industrial flows"). For instance we have not jets (except when on the ground!) and certainly no homogeneous turbulence. Boundary layers under numerous influences (shock, sweep, curvature) and approaching separation are everything.
Speaker's position

- The true $k$ and $\epsilon$ not very reliable: $f(y^+, R_\theta, PG)$. There is no proof that the asymptote as $R_\theta \to \infty$ is a finite function of $y^+$.

- $k$-$\epsilon$ requires $k^+ = C_{\mu}^{-1/2}$ in the log layer, which is not confirmed by ANY experiment nor DNS.

- The $k$ problem can be hidden by viscous damping functions ($f(y^+)$) and DNS Reynolds numbers are too low to clearly expose it.

- In some models $k$ is "not really" $k$, but then why does it get the whole benefit of the production term? (which is the only exact one!)

- The problem with using $y^+$ is not $y$. It's $u_\tau$. See new model.

- Because of the Reynolds number we use DNS results for guidance, but not for calibration.

- Five DNS's are cooking (slowly): 2D APG (Watmuff experiment); 3D APG (Sendstad); 2D bubble (Coleman); 2D with suction (Mariani); 2D with heat transfer (Bell). The Reynolds numbers are no higher but the physics are more interesting.
New one-equation model

- Accepted for Reno '92. Preprints available. Closer to Nee-Kovasznay and Secundov than to Baldwin-Barth.

- A one-equation model, transporting \( \tilde{\nu} \approx \nu_t \), has been developed from scratch.

\[
\frac{D\tilde{\nu}}{Dt} = c_{b1}[1 - f_t 2] \tilde{\sigma} \tilde{\nu} + \frac{1}{\sigma} \left[ \nabla \cdot \left( (\nu + \tilde{\nu}) \nabla \tilde{\nu} \right) + c_{b2}(\nabla \tilde{\nu})^2 \right] - \left[ c_{w1} f_w - \frac{c_{b1}}{\kappa^2} f_t 2 \right] \left[ \frac{\tilde{\nu}}{d} \right]^2 + \Delta U^2 f_t 1
\]

- "Rate of change = production + diffusion - destruction + trip".

- It is "semi-local": it uses the distance from the wall, \( d \), but not \( u_r, \delta^* \), nor \( F_{max} \). It is compatible with unstructured grids. The \( d \)-dependent term is a destruction of \( \nu_t \). It involves a finely-tuned function \( f_w \).

- The goal is not a universal model, but one that is useful in aerodynamics.

- The model was calibrated to give the right stress in the 2D mixing layer, the 2D wake, and the flat-plate boundary layer. It matches the classical log layer.

- The transported quantity is linear (\( \kappa u_r y \)) from the log layer all the way to the wall, making it easier to resolve than \( U \).

- The results are insensitive to the freestream value of \( \tilde{\nu} \) (0 is best).

- The model does better than CS, BL and \( k-\epsilon \) in adverse pressure gradient (lower \( C_f \), higher \( H \)). On Samuel-Joubert the \( C_f \) is fine, but \( H \) is low (how did they get \( H = 1.39 \) with \( R_\theta \approx 5000 \) and almost no PG?). In transonic flow the model seems to place the shock slightly in front of the experimental shock.
Samuel-Joubert flow, computed with the new model
Comment on: The Present State and Future Direction of Eddy Viscosity Models

T. J. Coakley
NASA-Ames Research Center
Moffett Field, CA 94035

Workshop on Engineering Turbulence Modeling
August 21-22, 1991
Summary and Comments

Wall bounded flows: The $k - \omega$ model is probably best

- Adverse pressure gradient flows
- Compressible flat plate flows, esp. with heat transfer
- Roughness – blowing – transition
- Simplicity – no damping functions
- Numerical stability – eg leading edge start

But: Separation and reattachment still are problems (all models)

Free Shear Flows: The $k - \varepsilon$ is probably best

- $k - \omega$ solutions depend on free stream $\omega$
- $k - \varepsilon$ more corrections and improvements available

This presentation: Compressible-hypersonic flows (NASP)

- General discussion of $k - \omega$ model with corrections
- Comparison of model prediction for flat plate flows ($k - \varepsilon$, $k - \omega$, $q - \omega$)
- Comparison of model predictions for a separated ramp flow
Generalizations of the $k-\omega$ Model

\[
\rho \frac{dk}{dt} = \mu_t S - \frac{2}{3} \rho k D - \beta^* \rho \omega k + \left[(\mu + \sigma_k \mu_T)k_{i,j}\right]_{i,j}
\]

\[
\rho \frac{d\omega}{dt} = \alpha \frac{\omega}{k} (\mu_t S - C_1 \rho k D) - \beta \rho \omega^2 + \left[(\sigma_L \mu + \sigma_\omega \mu_T)\omega_{i,j}\right]_{i,j}
\]

\[\mu_T = \alpha^* \rho k / \omega, \quad S = (u_{i,j} + u_{j,i} - \frac{2}{3} \delta_{ij} u_{k,k})u_{i,j}, \quad D = u_{k,k}\]

**Baseline Model**

\[\beta^* = 9/100, \quad \beta = 3/40, \quad \alpha = 5/9, \quad \alpha^* = 1,\]

\[\sigma_L = 1, \quad \sigma_k = \sigma_\omega = \frac{1}{2}, \quad C_1 = \frac{2}{3}\]

**Low Re Model** (Transition)

\[\alpha, \quad \alpha^* = \text{fn}(\frac{k}{nu}), \quad \sigma_L = 5/18\]

**Compressible Dissip.** (Compressible free shear layers)

\[\beta, \quad \beta^* = \text{fn}(\sqrt{k}/c)\]

**Compression Mod.** (Compressible separation)

\[C_1 = 2.4, \quad (d\rho L/dt = 0, \quad L = \sqrt{k}/\omega)\]

**Algebraic length scale** (Reattachment heat transfer)

\[\mu_T = \alpha^* \rho \sqrt{k} L, \quad L = \text{min}(\sqrt{k}/\omega, .225y)\]

**Vorticity length scale** (Incompressible separation)

\[\mu_T = \alpha^* \rho \sqrt{k} L, \quad L = \text{min}(\sqrt{k}/\omega, .3\sqrt{k}/|\omega|)\]
SKIN FRICTION ON INSULATED AND COOLED PLATES

COMpared with the Van DrisT Correlation

\[ q_a = 10 \text{ for } \Delta = 0.005 \text{ and } M = 5 \text{, } Re = 10^4 \]

\[ T_a / T_{	ext{in}} \]

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COMPARISON OF VELOCITY PROFILES
WITH THE COMPRESSIBLE
LAW OF THE WALL

EXPERIMENT: KEENER AND HOPKINS, M = 6.5
COMPUTATION: M = 5, TH/TAW = 0.2, 1.0
Hypersonic Cylinder-Flare

$35^\circ$ flare angle $M = 7.05$

- experiments
- J-L k-ε model

- baseline
- L-mod
- L-mod + C-mod
- L-mod + S-mod

(surface pressure)

(surface heat transfer)

$P_{\text{w}}/P_{\text{w,exp}}$

$Q_{\text{w}}/Q_{\text{w,exp}}$

$s$ (cm)
Hypersonic Cylinder-Flare

35° flare angle M = 7.05

- Experiments
- k-ω model
- Baseline
- L-mod
- L-mod + C-mod
- L-mod + S-mod

Surface pressure

Surface heat transfer

210-14
Hypersonic Cylinder-Flare

35° flare angle M = 7.05

P_s/P_{s,exp}

experiments
q-ω model

baseline
L-mod
L-mod + C-mod
L-mod + S-mod

s (cm)

Q_s/Q_{s,exp}

experiments
q-ω model

baseline
L-mod
L-mod + C-mod
L-mod + S-mod

s (cm)
COMMENT ON TWO-EQUATION MODELS

N. Lang and T. Chitsomboon

Center for Modeling of Turbulence and Transition
ICOMP/NASA Lewis Research Center

- SEVERAL NEAR-WALL TWO-EQUATION MODELS WERE STUDIED:
  - k-ε (9 models)
  - k-ω
  - q-ω
  - k-τ
FLAT PLATE BOUNDARY LAYER: $Re_\theta = 1410$

- DNS
- $k-\varepsilon$ (Chien)
- $k-\varepsilon$ (Yang-Shih)
- $k-\omega$ (Wilcox)
- $k-\tau$ (Speziale et al)
- $q-\omega$ (Coakley)
FLAT PLATE BOUNDARY LAYER: $Re_\theta = 1410$

- DNS
- $k-\varepsilon$ (Chien)
- $k-\varepsilon$ (Yang-Shih)
- $k-\omega$ (Wilcox)
- $k-\tau$ (Speziale et al)
- $q-\omega$ (Coakley)
FLAT PLATE BOUNDARY LAYER: \( \text{Re}_\theta = 1410 \)

- DNS (Chien)
- \( k-\varepsilon \) (Yang-Shih)
- \( k-\omega \) (Wilcox)
- \( k-\tau \) (Speziale et al)
- \( q-\omega \) (Coakley)
CHANNEL FLOW: $Re_\tau = 395$

- DNS
- $k-\varepsilon$ (Chien)
- $k-\varepsilon$ (Yang-Shih)
- $k-\omega$ (Wilcox)
- $k-\tau$ (Speziale et al)
- $q-\omega$ (Coakley)
SUMMARY

- STUDIED SEVERAL MODELS WITH SIMPLE FLOWS.
- COMPARED RESULTS WITH DNS.
- ALL MODELS PREDICTED GOOD TURBULENT SHEAR STRESSES.
- THEY DIFFERED IN COMPARISONS OF 'k' AND 'u'.
- A GOOD $k-\varepsilon$ MODEL IS AS GOOD AS ANY MODEL.
- A MODEL SHOULD BE ABLE TO HANDLE A SIMPLE FLOW IF IT WOULD HAVE A CHANCE FOR A MORE COMPLEX FLOW
DISCUSSION

D.M. Bushnell

I would like to make a comment pertaining to the problem of numerical resolution and numerical fidelity. People are showing all kinds of results with various models without keeping track of how well they are doing numerically. There should be, at some stage, in turbulence modeling community some agreement of some calculation with some standard code and then stick with that kind of quality and fidelity the whole way through. Without this I am not sure what I am looking at quite honestly.

R. Mankabadi (to D. Wilcox)

I noticed Wilcox in his talk gave $k - \epsilon$ an incomplete grade for the case of unsteady boundary layers. You may like to know that Howell (1980) and Ramaprian (1983) used $k - \epsilon$ model to calculate unsteady boundary layer and found that $k - \epsilon$ model could not predict this if the amplitude of oscillation or frequency is high.

D. Wilcox (to T. Chitsomboom)

I have a comment about the T. Chitsomboom’s slide we just saw for $Re = 1410$. I have grid independent solutions for that so I’ll be very suspec of these results.

T. Chitsomboom (reply)

I didn’t mention, and you didn’t either, that $k - \omega$ model is quite sensitive to $\omega$ boundary condition. Difficulty we encounter is how to specify $\omega$ at the wall. Solutions we have shown are about in the middle range; we can get some better results than this and also some worse.
D. Wilcox (to T. Chitsomboom)

You have to be careful with the $\omega$ boundary condition because if this is messed up then the boundary layer is all whacked up and I am sure that that is the case in this computation.

M.S. Anand (to D. Wilcox)

I like to preface my question by mentioning that we do pdf methods and for this purpose we need the time scale information. For this purpose we solve $\omega$ equation (either a mean $\omega$ equation or a stochastic $\omega$ equation). In the limited calculations I have done, I have not noticed the sensitivity to free stream $\omega$ you talked about. I have done calculations of single axial jets with or without co-flow; non-turbulent and very low turbulence co-flow. If there is sensitivity could you clarify what the sensitivity is due to and shouldn't there be sensitivity to $k - \epsilon$ models too?

D. Wilcox (reply)

No sensitivity in $k - \epsilon$ because it's just not there. You can vary freestream dissipation all over the place and get the same answer. In $k - \omega$ model I am cheating a little in one regard. I am always doing the similarity solutions and not marching. There are only two values of $\omega$ which satisfy this. I vary these a little bit in calculations. Neither of these values gives good spreading rate but these more or less bracket it. You are not seeing the sensitivity because you are calculating the free stream $\omega$. If you change the initial value of $\omega$ to start your calculation you'll see it.

M.S. Anand (to D. Wilcox)

That's what I am doing.
D. Wilcox (reply)

I'll look into numerics. I believe my similarity solutions are really good.

W.K. George

I would like to focus our attention away from the nitty gritty of solutions and focus on when should we expect eddy viscosity models to work. Tennekes and Lumely remind you that it was included in their book to show why eddy viscosity has problems. The fact that you have a local model, it can not handle separation or flow pass separation. Although Reynolds stress models are a straightforward increase in complexity but it's a quantum leap in adding physics.

B.E. Launder (to D. Wilcox and T. Gatski)

I would like to clarify a thing on Dave's and Tom's talk. Last time I saw the $k - \omega$ model it seemed to me that the second equation had in it a supplementary source term. I see Dave nodding and Tom saying no.

D. Wilcox (to B.E. Launder)

There ain't none.

B.E. Launder (to D. Wilcox)

So it's cleaned up in the current marketed version. It is very interesting step. As I indicated in my talk if for separated flows one wants accurate results we need to use an extra source term in dissipation equation which will remove difficulty with adverse pressure gradients. It's not a problem of high Mach number. It is intrinsically a problem of separated flow; we get too big of a length scale near the wall and too high of heat transfer coefficient. And
if separation is provoked by a shock wave, the separated flow could be a zero Mach number or a seven Mach number. Survey shows when one shifted attention from adverse to favorable pressure gradients $k - \omega$ did better in the adverse pressure gradient, and $k - \epsilon$ predicted much better transition and re-laminarization. Tom Coakley said if you want to predict transition using $k - \omega^2$ model you have to put $Re$ effects which are absent.

D. Wilcox (to Spalart)

Several points were made that I should answer to. First, a complete model refers to terminology used by ?? a few years ago. It simply means you can use it with out knowing anything whatsoever about the flow, like an appropriate mixing length. Thus a two equation model is about as simple of a model as you can get.

P. Spalart

Why then isn’t a one equation model complete?

D. Wilcox (to Spalart)

Because you still need to specify a length scale.

You also seemed alarmed that I was using Clauser’s data to tune the $k - \omega$ model. The perturbation method solution yields a similarity solution that demands that $\beta_T$ be constant. You must compare with data where $\beta_T$ is constant. Whether or not this is a limited data set, it is the only way that is formally consistent with the perturbation solution. When I go to a non-similar solution, the perturbation solution results are certainly bourn out. That is why I use Clauser’s data. It’s dictated by a mathematical necessity.
P. Spalart

How many of the moments of the turbulence satisfy this right kind of scaling? Scaling which is $U_r$ equals a constant?

D. Wilcox

Well, I don't know but this shouldn't invalidate the analysis.

You were worried about whether the velocity profiles and the shear stress data came from the same calculation- absolutely! You're only talking about one data point out near the edge.

C. Speziale (to Spalart)

Are you saying that there is no destruction term if there's no wall? Essentially the destruction term disappears?

P. Spalart (reply)

Yes.

C. Speziale (to Spalart)

How then would you do in a non-equilibrium shear flow? According to this, the only thing that the eddy viscosity term can do is grow. I was thinking specifically of a situation where diffusion effects are small.

P. Spalart (reply)

It wouldn't work there.
The Present Status
and Future Direction of
Algebraic Reynolds Stress Models

Workshop on Engineering Turbulence Modeling
ICOMP, NASA Lewis Research Center
August 21-22, 1991

Dale B. Taulbee
University at Buffalo
OUTLINE

• The need for algebraic stress models – deficiencies of the linear gradient model.

• Classical algebraic Reynolds stress models.

• Nonlinear stress-strain relations.

• Critique of the models and some new developments.
LINEAR GRADIENT MODEL

\[ u_i u_j = \frac{2}{3} k \delta_{ij} - 2 \nu_t S_{ij} \]

\[ S_{ij} = \frac{1}{2} \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \]

\[ \nu_t = C_\nu k l = C_\mu k^2 / \epsilon \]

\[ C_\mu = 0.09 \]

- Works reasonably well for near-parallel shear flows, however, \( C_\mu \) is not a constant.

- Poor representation of the normal stresses and, hence, does not work well for many multidimensional flows.
Shear Stress in the Axisymmetric Jet

- LDA Date Fit, — Gradient Hypothesis
Normal Reynolds Stress - Round Jet

\[ \frac{\overline{u^2}}{U_c^2} \]

- LDA Data fit
- \[ u^2 = -2\nu \frac{\partial U}{\partial x} + \frac{2}{3}k \]

\[ r/X \]
VARIATION OF $C_\mu$

MODEL PARAMETERS SHOULD NOT BE TAKEN AS UNIVERSAL CONSTANTS

$$\nu_t = C_\mu \frac{k^2}{\epsilon} = -\frac{\overline{u'v'}}{\partial U/\partial y}$$

$y/a$ FOR PIPE, $y/y_{1/2}$ FOR JETS AND WAKES

RODI (1975)
DEFICIENCIES OF LINEAR GRADIENT MODEL FOR $u_i u_j$

- Poor Representation of Normal Stresses
  - Homogeneous Shear Flow, $U = U(y)$
    \[
    \overline{u^2} = \overline{v^2} = \overline{w^2} = \frac{2}{3} k
    \]
    \[
    \overline{uv} = -\nu_t \frac{dU}{dy}
    \]

- Secondary Flow in a Non-Circular Duct

Driven by $(\overline{w^2} - \overline{v^2})$

- Linear Gradient Model:
  \[\overline{v^2} = \overline{w^2} = \frac{2k}{3}\]
\[ U = U_\infty \left( 1 - \frac{R^2}{x^2} \right) \]

\[ \frac{dU}{dx} = P - \epsilon \]

\[ \frac{d\epsilon}{dx} = \frac{\epsilon}{k} \left( C_{\epsilon_1} P - C_{\epsilon_2} \epsilon \right) \]

where: \( P = \overline{u^2} \frac{\partial U}{\partial x} - \overline{v^2} \frac{\partial V}{\partial y} = - \left( \overline{u^2} - \overline{v^2} \right) \frac{\partial U}{\partial x} \)

\( k - \epsilon \) model:

\[ \overline{u^2} = \frac{2k}{3} - \nu_t \frac{\partial u}{\partial x} \]

\[ \overline{v^2} = \frac{2k}{3} - \nu_t \frac{\partial v}{\partial y} \]

\[ P = \nu_t \left( \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \right) \frac{\partial u}{\partial x} = 2\nu_t \left( \frac{\partial u}{\partial x} \right)^2 \]
Stagnation Streamline Flow
ALGEBRAIC REYNOLDS STRESS MODELS

\[ f (\bar{u}_i \bar{u}_j ; k, \epsilon, S_{ij} ) = 0 \]

More accurately describes the anisotropy of the turbulence.

Account for the effects of:

- Longitudinal surface curvature
- Corner Geometry
- Swirl
- Buoyancy
- Rotation

Maintains the simplicity of a two-equation \((k - \epsilon)\) model calculation

Basic Assumption = Local Formulation:

Reynolds stress depends only on local conditions – turbulence is anisotropic only if maintained by velocity gradient.

\[ \bar{u}_i \bar{u}_j = \frac{2}{3} k \delta_{ij} \quad \text{if} \quad S_{ij} = 0 \]
DERIVATION OF

ALGEBRAIC STRESS MODELS

Classical ASM

- Derived from modeled Reynolds stress equation

Nonlinear stress-strain models

- Derived from:
  - Two-point closure theories
  - Continuum mechanics
  - Expansion of classical ASM formulation
CLASSICAL ASM

Algebraic Stress Model formulated from Modeled Reynolds Stress Equation (Rodi, 1972)

\[
\frac{D\overline{u_i u_j}}{Dt} = -\frac{\partial T_{ijk}}{\partial x_l} + P_{ij} + \Phi_{ij} + \epsilon_{ij}
\]

1) Convection and Diffusion Neglected

2) Convection – Diffusion proportioned to that of the kinetic energy equation

\[
\frac{D\overline{u_i u_j}}{Dt} - \frac{\partial T_{ijl}}{\partial x_l} = \frac{\overline{u_i u_j}}{k} \left( \frac{Dk}{Dt} - \frac{\partial T_l}{\partial x_l} \right)
\]

\[
= \frac{\overline{u_i u_j}}{k} (P - \epsilon)
\]

\[
\frac{\overline{u_i u_j}}{k} (P - \epsilon) = P_{ij} + \Phi_{ij} + \epsilon_{ij}
\]
Algebraic Stress Model Continued

\[
\frac{Du_iu_j}{Dt} = \frac{\partial T_{ij}}{\partial x_l} + P_{ij} + \Phi_{ij} + \epsilon_{ij}
\]

\[
\frac{u_iu_j}{k}(P - \epsilon) = P_{ij} + \Phi_{ij} + \epsilon_{ij}
\]

Rodi (1976)

\[
\Phi_{ij} = -C_1 \frac{\epsilon}{k} (u_iu_j - \frac{2}{3}k\delta_{ij}) - C_2 (P_{ij} - \frac{2}{3}P\delta_{ij})
\]

\[
u = \frac{2}{3}k\delta_{ij} + \frac{1 - C_2}{C_1} \left( \frac{P_{ij}/\epsilon - \frac{2}{3}P/\epsilon\delta_{ij}}{1 + \frac{1}{C_1} (P/\epsilon - 1)} \right) k
\]

Shear Flow

\[
\overline{u^2} = \frac{2}{3}k + \frac{4}{3} (1 - C_2) \frac{C_\mu}{P/\epsilon + C_1/2 - 1} \frac{k^3}{\epsilon^2} \left( \frac{\partial U}{\partial y} \right)^2
\]

\[
\overline{v^2} = \frac{2}{3}k - \frac{2}{3} (1 - C_2) \frac{C_\mu}{P/\epsilon + C_1/2 - 1} \frac{k^3}{\epsilon^2} \left( \frac{\partial U}{\partial y} \right)^2
\]

\[
\overline{w^2} = \frac{2}{3}k - \frac{2}{3} (1 - C_2) \frac{C_\mu}{P/\epsilon + C_1/2 - 1} \frac{k^3}{\epsilon^2} \left( \frac{\partial U}{\partial y} \right)^2
\]

\[
-\overline{uv} = C_\mu \frac{k^2}{\epsilon} \frac{\partial U}{\partial y}
\]

\[
C_\mu = \frac{2}{3} (1 - C_2) \frac{C_1/2 - 1 + C_2 P/\epsilon}{(P/\epsilon + C_1/2 - 1)^2}
\]

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ALGEBRAIC STRESS MODEL CONTINUED

\[ \Phi_{ij} = -C_1 \frac{\epsilon}{k} (u_i u_j - \frac{2}{3} k \delta_{ij}) - C_2 (P_{ij} - \frac{2}{3} P \delta_{ij}) \]

\[ - C_3 (D_{ij} - \frac{2}{3} P \delta_{ij}) - C_4 k \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \]

\[ C_2 \frac{C_2' + 8}{11} \quad C_3 = \frac{8C_2' - 2}{11} \quad C_4 = \frac{30C_2' - 2}{55} \]

Shear Flow

\[ \overline{u^2} = \frac{2}{3} k - \frac{2}{3} \frac{4C}{P/\epsilon + C_1/2 - 1} \frac{k^3}{\epsilon^2} \left( \frac{\partial U}{\partial y} \right)^2 \]

\[ \overline{v^2} = \frac{2}{3} k + \frac{2}{3} \frac{10C + 1}{P/\epsilon + C_1/2 - 1} \frac{k^3}{\epsilon^2} \left( \frac{\partial U}{\partial y} \right)^2 \]

\[ \overline{w^2} = \frac{2}{3} k - \frac{2}{3} \frac{6C + 1}{P/\epsilon + C_1/2 - 1} \frac{k^3}{\epsilon^2} \left( \frac{\partial U}{\partial y} \right)^2 \]

\[ \overline{uv} = -C_\mu \frac{k^2}{\epsilon} \frac{\partial U}{\partial y} \]

\[ C_\mu = \frac{C_1/2 - 1 - \frac{5}{6} \left( 11C^2 - 4C - 1 \right) P/\epsilon}{(P/\epsilon + C_1/2 - 1)^2} \]

\[ C = -\frac{1}{11} \left( 1 + \frac{3}{2} C_2' \right) \]

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ALGEBRAIC STRESS MODEL

Comparison with data for Homogeneous Shear Flow

Data from Harris, Graham, and Corrsin (1977)

Neglect Diffusion:

\[ \frac{D u_i u_j}{Dt} = \frac{u_i u_j Dk}{k \, Dt} \]

<table>
<thead>
<tr>
<th></th>
<th>( U \frac{d u_i u_j}{dx} )</th>
<th>( \frac{u_i u_j U}{k} \frac{dk}{dx} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u^2 )</td>
<td>1.96</td>
<td>2.09</td>
</tr>
<tr>
<td>( v^2 )</td>
<td>0.88</td>
<td>0.83</td>
</tr>
<tr>
<td>( w^2 )</td>
<td>1.32</td>
<td>1.24</td>
</tr>
<tr>
<td>( uv )</td>
<td>0.62</td>
<td>0.62</td>
</tr>
</tbody>
</table>

Stress Values:

\[ C_1 = 1.8 \quad C_1 = 1.5 \quad C_1 = 1.8 \]
\[ C_2 = 0.6 \quad C'_2 = 0.4 \quad C'_2 = 0.54 \quad \text{Exp.} \]

<table>
<thead>
<tr>
<th></th>
<th>( u^2 / k )</th>
<th>( v^2 / k )</th>
<th>( w^2 / k )</th>
<th>( -uv / k )</th>
<th>( C_\mu )</th>
</tr>
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<tr>
<td></td>
<td>1.195</td>
<td>0.402</td>
<td>0.402</td>
<td>0.356</td>
<td>0.068</td>
</tr>
<tr>
<td>Exp.</td>
<td>1.004</td>
<td>0.398</td>
<td>0.598</td>
<td>0.298</td>
<td>0.057</td>
</tr>
</tbody>
</table>
CONVECTION-DIFFUSION ASSUMPTION

\[
\frac{D u_i u_j}{D t} + \frac{\partial T_{ijk}}{\partial x_l} = k \frac{D a_{ij}}{D t} + \frac{\partial T_{ijl}}{\partial x_l} - \frac{u_i u_j}{k} \frac{\partial T_l}{\partial x_l} + \frac{u_i u_j}{k} (p - \epsilon)
\]

where: \( a_{ij} = \frac{u_i u_j}{k} - \frac{2}{3} \delta_{ij} \)

1) \( \frac{\partial T_{ijk}}{\partial x_l} - \frac{u_i u_j}{k} \frac{\partial T_l}{\partial x_l} \approx 0 \)

2) \( \frac{D a_{ij}}{D t} = 0 \)

Then the ASM represents the asymptotic solution of the modeled Reynolds stress equation. However, \( \tau = k/\epsilon \) is the local flow value as determined from the \( k \) and \( \epsilon \) transport equation.
ASM Prediction for Homogeneous Shear Flow:

\[ a_{ij0} = 0, \quad \left( \frac{k}{\epsilon} \frac{dU}{dy} \right)_0 = 0 \]
ASM Prediction for Homogeneous Shear Flow:

\[ a_{ij_0} = 0, \left( \frac{k}{\epsilon} \frac{dU}{dy} \right)_0 = 2.5 \]
SOLUTION WITH ASM FOR
MULTIDIMENSIONAL PROBLEMS

- Solve set of nonlinear algebraic equations as part of the solution – causes numerical problems.

- Simplify the ASM formulation
  - \( P/\varepsilon = 1 \)
  - Neglect certain terms
  - Neglect certain gradient terms for specific problems

- Expand into an explicit nonlinear stress-strain form (NLM)

\[
\frac{u_i u_j}{k} = f(\tau S_{ij}, \tau^2 S_{ij}^2, \cdots)
\]
EXPLICIT STRESS-STRAIN RELATION
FROM ALGEBRAIC STRESS MODEL

\[
\frac{u_i u_j}{k} (P - \epsilon) = P_{ij} + \Phi_{ij} - \frac{2}{3} \delta_{ij}
\]

\[
\Phi_{ij} = -C_1 \frac{\epsilon}{k} (\frac{u_i u_j}{k} - \frac{2}{3} k \delta_{ij}) - C_2 (P_{ij} - \frac{2}{3} P \delta_{ij}) - \cdots
\]

\[
P = \frac{u_i u_j}{\epsilon} \frac{\partial U_i}{\partial x_i} = \frac{u_i u_j}{\epsilon} \frac{k}{\epsilon} \frac{\partial U_i}{\partial x_j}
\]

Expansion:
\[
\frac{u_i u_j}{k} = \frac{2}{3} \delta_{ij} + a_{ij}^{(1)} \tau + a_{ij}^{(2)} \tau^2 + \cdots
\]


\[
\frac{u_i u_j}{k} = \frac{2}{3} \delta_{ij} - 2C_\mu \frac{k}{\epsilon} S_{ij}
\]

\[
+ \alpha \frac{k^2 \epsilon^2}{\epsilon^2} \left[ S_{ij} \frac{\partial U_j}{\partial x_l} + S_{jl} \frac{\partial U_i}{\partial x_l} - \frac{2}{3} S_{lm} \frac{\partial U_l}{\partial x_m} \delta_{ij} \right]
\]

\[
- \beta \frac{k^2 \epsilon^2}{\epsilon^2} \left[ S_{il} \frac{\partial U_l}{\partial x_j} + S_{jl} \frac{\partial U_l}{\partial x_i} - \frac{2}{3} S_{lm} \frac{\partial U_l}{\partial x_m} \delta_{ij} \right]
\]

\(\alpha\) and \(\beta\) are directly determined from the constants of the RSM. However, if only terms through second order are retained, the expanded formulation does not accurately represent the original ASM.
NONLINEAR STRESS-STRESS MODELS

General form (Speziale, 1991)

\[ a_{ij} = -2 C_\mu \tau S_{ij} \]

\[ -4 \alpha_1 \tau^2 (S_{il} S_{lj} - \frac{1}{3} S^2 \delta_{ij}) \]

\[ -4 \alpha_2 \tau^2 (S_{il} \Omega_{lj} + S_{jl} \Omega_{li}) \]

\[ -4 \alpha_3 \tau^2 (\Omega_{il} \Omega_{lj} - \frac{1}{3} \Omega^2 \delta_{ij}) \]

\[ -2 \alpha_4 \tau^2 D S_{ij}/Dt \]

\[ \tau = \text{time scale} \ (\tau = k/\epsilon) \]

Lumley (1969)
Saffman (1974)
Yoshizawa (1984) DIA two-point closure theory
Speziale (1987) continuum mechanics
Ahmadi (1988) expansion of ASM
Rubinstein & Barten (1990) RNG theory
NLM COEFFICIENT VALUES

<table>
<thead>
<tr>
<th></th>
<th>$C_\mu$</th>
<th>$\alpha_1$</th>
<th>$\alpha_2$</th>
<th>$\alpha_3$</th>
</tr>
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<tbody>
<tr>
<td>Nisiziwa/Yoshizawa</td>
<td>0.090</td>
<td>0.0709</td>
<td>0.0159</td>
<td>0.0960</td>
</tr>
<tr>
<td>(Channel Flow)</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Speziale</td>
<td>0.090</td>
<td>-0.0138</td>
<td>0.0138</td>
<td>0</td>
</tr>
<tr>
<td>(Channel Flow)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Rubinstein &amp; Barten</td>
<td>0.0845</td>
<td>-0.0570</td>
<td>0.0120</td>
<td>-0.047</td>
</tr>
<tr>
<td>(RNG Theory)</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rubinstein &amp; Barten</td>
<td>0.090</td>
<td>-0.0523</td>
<td>0.0198</td>
<td>0</td>
</tr>
<tr>
<td>(ASM Expansion)</td>
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<td></td>
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<tr>
<td>Comparison with RSM</td>
<td>0.090</td>
<td>-0.0015</td>
<td>0.012</td>
<td>0</td>
</tr>
</tbody>
</table>

Homogeneous shear flow:

\[ C_\mu = -a_{12}/(\tau \frac{dU}{dy}) \]

\[ \alpha_1 - \alpha_3 = -\frac{3}{2} (a_{11} + a_{22})/(\tau \frac{dU}{dy})^2 \]

\[ \alpha_2 = -\frac{1}{4} (a_{11} - a_{22})/(\tau \frac{dU}{dy})^2 \]

Irrotational strain flow:

\[ C_\mu = \frac{1}{4} (a_{22} - a_{11})/(\tau \frac{dU}{dx}) \]

\[ \alpha_1 = -\frac{3}{8} (a_{11} + a_{22})/ (\tau \frac{dU}{dx})^2 \]
Stress-Strain Model Constants from RSM Solution
NLM Coefficients from RSM Solution

\[ \alpha_1, \alpha_2, \alpha_3 \]

Stress-Strain Model Constants from RSM Solution
Nonlinear Stress-Strain Model Solution for Homogeneous Shear Flow:

\[ C_\mu = 0.09, \quad \alpha_1 = -0.0015, \quad \alpha_2 = 0.012, \quad \alpha_3 = 0 \]
Nonlinear Stress-Strain Model Solution for Irrotational Strain Flow:

\[ C_\mu = 0.09, \ \alpha_1 = -0.0015, \ \alpha_2 = 0.012, \ \alpha_3 = 0 \]
STRESS-STRAIN RELATION FROM EXPANSION OF REYNOLDS STRESS MODEL

Reynolds Stress Equation:

\[
\frac{D u_i u_j}{Dt} = - \frac{\partial T_{ijk}}{\partial x_l} + P_{ij} + \Phi_{ij} - \frac{2}{3} \epsilon \delta_{ij}
\]

\[
\Phi_{ij} = - C_1 \frac{\epsilon}{k} \left( \frac{u_i u_j}{k} - \frac{2}{3} k \delta_{ij} \right) - \alpha \left( P_{ij} - \frac{2}{3} P \delta_{ij} \right) - \beta \left( P_{ij} - \frac{2}{3} P \delta_{ij} \right) - 2 \gamma k S_{ij}
\]

\[
\alpha = \frac{C_2 + 8}{11}, \quad \beta = \frac{8C_2 - 2}{11}, \quad \gamma = \frac{30C_2 - 2}{55}
\]

Dissipation equation:

\[
\frac{D \epsilon}{Dt} = - \frac{\partial \overline{u_l} \epsilon'}{\partial x_l} + C_{\epsilon_1} \frac{k}{\epsilon} P - C_{\epsilon_2} \frac{k^2}{\epsilon}
\]
EXPANSION Continued

\[ a_{ij} = \frac{u_i u_j}{k} - \frac{2}{3} \delta_{ij} \quad \Rightarrow \quad \tau = \frac{k}{\epsilon} \]

\[ \dot{a}_{ij} = -\frac{1}{k} \left[ \frac{\partial T_{ijl}}{\partial x_l} - (a_{ij} + \frac{2}{3} \delta_{ij}) \frac{\partial T_l}{\partial x_l} \right] \]

\[ - \frac{P a_{ij}}{\epsilon \tau} - (C_1 - 1) \frac{a_{ij}}{\tau} - \frac{8}{15} S_{ij} \]

\[ - (1 - \alpha - \beta) (a_{il} S_{lj} + a_{jl} S_{li} - \frac{2}{3} a_{kl} S_{lk} \delta_{ij}) \]

\[ - (1 - \alpha + \beta) (a_{il} \Omega_{lj} + a_{jl} \Omega_{li}) \]

\[ \dot{\tau} = -\tau \left[ \frac{1}{k} \frac{\partial u_i k'}{\partial x_l} - \frac{1}{\epsilon} \frac{\partial u_i \epsilon'}{\partial x_l} \right] + (C_{\epsilon_2} - 1) - (C_{\epsilon_1} - 1) \frac{P}{\epsilon} \]

Expansion: \[ a_{ij} = a_{ij}^{(1)} \tau + a_{ij}^{(2)} \tau^2 + \cdots \]

Requires \[ \tau (S_{kl} S_{lk})^{1/2} \] be small

Transport terms lead to small second order contributions and are neglected.
EXPANSION Continued

\[
\dot{a}_{ij} = a_{ij}^{(1)} \dot{\tau} + a_{ij}^{(1)} \tau + 2a_{ij}^{(2)} \tau \dot{\tau} + \cdots
\]

where \( \dot{\tau} = (C_{\varepsilon_2} - 1) - (C_{\varepsilon_1} - 1) \frac{P}{\varepsilon} \)

\[
a_{ij} = -2C_\mu \tau S_{ij} - 4\alpha_1 \tau^2 (S_{ik}S_{kj} - \frac{1}{3} S^2 \delta_{ij})
\]

\[
- 4\alpha_2 \tau^2 (S_{ik}\Omega_{kj} + S_{jk}\Omega_{ki}) - 2\alpha_4 \tau^2 \dot{S}_{ij}
\]

\[
C_\mu = \frac{4/15}{C_1 + C_{\varepsilon_2} - 2 + (2 - C_{\varepsilon_1})P/\varepsilon}
\]

\[
\alpha_1 = -\frac{(1 - \alpha - \beta) C_\mu}{C_1 + 2C_{\varepsilon_3} - 3 + (3 - 2C_{\varepsilon_1})P/\varepsilon}
\]

\[
\alpha_2 = \frac{(1 - \alpha + \beta) C_\mu}{2(C_1 + 2C_{\varepsilon_3} - 3 + (3 - 2C_{\varepsilon_1})P/\varepsilon)}
\]

\[
\alpha_4 = -\frac{C_\mu}{2(C_1 + 2C_{\varepsilon_3} - 3 + (3 - 2C_{\varepsilon_1})P/\varepsilon)}
\]
EXPANSION Continued

• Same general form as nonlinear stress-strain relation.

• Model coefficients are determined from Reynolds-stress model parameters.

• There is no \((\Omega_{il}\Omega_{lj} - \frac{1}{3}\Omega^2\delta_{ij})\) term. Possibly the model for the rapid part of the pressure strain term in the RSM is incomplete. Stress-strain models derived from DIA or RNG theory contain this term.

• Series is valid for small \(\tau S\). Solution with this model, even with more terms, does not give good results near the asymptotic state in homogeneous shear or irrotational strain flows.
SOLUTION VALID FOR
SMALL AND LARGE $kS/\epsilon$

\[
\tau \frac{D}{D\tau} \left( \frac{a_{ij}}{\tau} \right) = - (2 - C_{\epsilon_1}) \frac{P a_{ij}}{\epsilon \tau} - (C_1 + C_{\epsilon_1} - 2) \frac{a_{ij}}{\tau} - \frac{8}{15} S_{ij}
\]

\[
- (1 - \alpha - \beta) (a_{il} S_{lj} + a_{jl} S_{li} - \frac{2}{3} a_{kl} S_{lk} \delta_{ij})
\]

\[
- (1 - \alpha + \beta) (a_{il} \Omega_{lj} + a_{jl} \Omega_{li})
\]

For \( \frac{D}{D\tau} \left( \frac{a_{ij}}{\tau} \right) = 0 \):

- Correct form for small $\tau S$

\[
\frac{a_{ij}}{\tau} = a_{ij}^{(1)} + \cdots
\]

- Right side closely represents the asymptotic solution to the Reynolds stress equation, $Da_{ij}/Dt = 0$

Linear algebraic equations ($P/\epsilon$ retained implicitly) solved by the method given by Pope (1975).
ALGEBRAIC STRESS MODEL

IMPROVED:

\[
\left[ C_1 + C_{\epsilon_1} - 2 + \left( 2 - C_{\epsilon_1} \right) \frac{P}{\epsilon} \right] a_{ij} = -\frac{8}{15} \tau S_{ij} - (1 - \alpha - \beta) \left( a_{il} S_{lj} + a_{jl} S_{li} - \frac{2}{3} a_{kl} S_{lk} \delta_{ij} \right) \tau \\
+ (1 - \alpha + \beta) \left( a_{il} \Omega_{lj} + a_{jl} \Omega_{li} \right) \tau
\]

STANDARD:

\[
\left[ C_1 - 1 + \frac{P}{\epsilon} \right] a_{ij} = -\frac{8}{15} \tau S_{ij} - (1 - \alpha - \beta) \left( a_{il} S_{lj} + a_{jl} S_{li} - \frac{2}{3} a_{kl} S_{lk} \delta_{ij} \right) \tau \\
+ (1 - \alpha + \beta) \left( a_{il} \Omega_{lj} + a_{jl} \Omega_{li} \right) \tau
\]
NEW EXPLICIT ALGEBRAIC STRESS MODEL

For Two Dimensions

\[ a_{ij} = - 2C_{\mu} \tau S_{ij} \]

\[ - 2C_{\mu}(1 - \alpha - \beta) g \tau^2 S^2 \left( \frac{2}{3} \delta_{ij}^{(3)} - \delta_{ij}^{(2)} \right) \]

\[ - 2C_{\mu}(1 - \alpha + \beta) g \tau^2 (S_{i1}\Omega_{lj} + S_{jl}\Omega_{li}) \]

\[ C_{\mu} = \frac{4g/15}{1 - \frac{2}{3}(1 - \alpha - \beta)^2 g^2 S^2 - 2(1 - \alpha + \beta)^2 g^2 \Omega^2} \]

\[ g = \frac{1}{C_1 + C_{\epsilon_2} - 2 + (2 - C_{\epsilon_1}) P/\epsilon} \]

Model coefficients are determined in terms of the Reynolds-stress Model parameters.
New Algebraic Stress Model Solution for Homogeneous Shear Flow
New Algebraic Stress Model Solution for Irrotational Strain Flow
Axisymmetric Jet – Kinetic Energy
Axisymmetric Jet – Shear Stress
Axisymmetric Jet - Eddy Viscosity Coefficient
Stagnation Streamline Flow
CONVECTIVE EFFECTS

WRITE EQUATIONS IN TERMS OF $\tau S$

where, $\tau = k/\epsilon$ and $S = (S_{kl}S_{lk})^{1/2}$

$$\frac{\tau Da_{ij}}{Dt} = \tau^2 S \frac{D}{Dt} \left( \frac{a_{ij}}{\tau S} \right) + \frac{1}{S} \frac{D\tau S}{Dt} a_{ij}$$

$$\frac{1}{S} \frac{D\tau S}{Dt} = \tau \frac{DS}{S Dt} + (C_{c2} - 1) - (C_{c1} - 1) \frac{P}{\epsilon}$$

$$\tau^2 S \frac{D}{Dt} \left( \frac{a_{ij}}{\tau S} \right) = - \left[ C_1 + C_{c2} - 2 + (2 - C_{c1}) \frac{P}{\epsilon} + \tau \frac{DS}{S Dt} \right] a_{ij}$$

$$- \frac{8}{15} \tau S_{ij}$$

$$+ (1 - \alpha + \beta) \tau (a_{il} \Omega_{lj} + a_{jl} \Omega_{li})$$

$$C_{\mu} \sim \frac{4/15}{C_1 + C_{c2} - 2 + (2 - C_{c1}) \frac{P}{\epsilon} + \tau \frac{DS}{S Dt}}$$

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Stagnation Streamline Flow

\[
\frac{k}{k_0}
\]

- RSM
- New ARSM with Convective Term

\[
\frac{\bar{u}^2}{(2k_0)}
\]

\[
\frac{\bar{v}^2}{(2k_0)}
\]
SOLUTION FOR THREE DIMENSIONS

Pope (1975), Spencer & Rivlin (1959, 1960)

For \( a_{ij} = a_{ij}(S_{ij}, \Omega_{ij}) = a(S, \Omega) \)

There are Ten Independent Symmetric Tensors.

\[
\begin{align*}
T^{(1)} &= S \\
T^{(2)} &= S\Omega - \Omega S \\
T^{(3)} &= S^2 - I\{S^2\}/3 \\
T^{(4)} &= \Omega^2 - I\{\Omega^2\}/3 \\
T^{(5)} &= \Omega S^2 - S^2\Omega \\
T^{(6)} &= \Omega^2S - S\Omega^2 - 2I\{S\Omega^2\}/3 \\
T^{(7)} &= \Omega S\Omega^2 - \Omega^2S\Omega \\
T^{(8)} &= S\Omega S^2 - S^2\Omega S \\
T^{(9)} &= \Omega^2S^2 + S^2\Omega^2 - 2I\{S^2\Omega^2\}/3 \\
T^{(10)} &= \Omega S^2\Omega^2 - \Omega^2S^2\Omega
\end{align*}
\]

Then: \( a_{ij} = \sum_{n=1}^{10} G^{(n)} T^{(n)}_{ij} \)

Where \( G^{(n)} \) can be functions of the invariants:

\( \{S^2\}, \{\Omega^2\}, \{S^3\}, \{\Omega^2S\}, \{\Omega^2S^2\} \)
3-D SOLUTION Continued

\[
\begin{align*}
\left[ C_1 + C_{\varepsilon_2} - 2 + (2 - C_{\varepsilon_1}) \frac{P}{\varepsilon} \right] a_{ij} &= -\frac{8}{15} \frac{k}{\varepsilon} S_{ij} \\
&+ (1 - \alpha + \beta) \frac{k}{\varepsilon} (a_{il} \Omega_{lj} + a_{jl} \Omega_{li}) \\
&- (1 - \alpha - \beta) \frac{k}{\varepsilon} (a_{il} S_{lj} + a_{jl} S_{li} - \frac{2}{3} a_{kl} S_{lk} \delta_{ij})
\end{align*}
\]

\[1 - \alpha + \beta = \frac{1 + 7C'_2}{11}\]

\[1 - \alpha - \beta = \frac{5 - 9C'_2}{11} \rightarrow \text{small, neglect term}\]

\[
a_{ij} = \sum_{n=1}^{10} G^{(n)} T^{(n)}_{ij}
\]

\[
= -2 C_{\mu} \frac{k}{\varepsilon} S_{ij} - \alpha_2 g^2 \frac{k^2}{\varepsilon^2} \left( S_{ik} \Omega_{kj} - \Omega_{ik} S_{kj} \right)
\]

\[
- \alpha_6 g^3 \frac{k^3}{\varepsilon^3} \left( \Omega_{ik} \Omega_{kl} S_{lj} + S_{ik} \Omega_{kl} \Omega_{lj} - \frac{2}{3} S \Omega^2 \delta_{ij} \right)
\]

\[
- \alpha_7 g^4 \frac{k^4}{\varepsilon^4} \left( \Omega_{ik} S_{kl} \Omega_{lm} \Omega_{mj} - \Omega_{ik} \Omega_{kl} S_{lm} \Omega_{mj} \right)
\]

\[
C_{\mu} = \frac{4g}{15} \frac{1 - \frac{1}{2} \left[ (1 - \alpha + \beta) g \frac{k}{\varepsilon} \right]^2 \Omega^2}{1 + \frac{1}{2} \left[ (1 - \alpha + \beta) g \frac{k}{\varepsilon} \right]^2 \Omega^2 + \left[ (1 - \alpha + \beta) g \frac{k}{\varepsilon} \right]^4 \Omega^4}
\]

\[
\alpha_2 = \frac{8}{15} \frac{(1 - \alpha + \beta) \left\{ 1 - 2 \left[ (1 - \alpha + \beta) g \frac{k}{\varepsilon} \right]^2 \Omega^2 \right\}}{1 + \frac{1}{2} \left[ (1 - \alpha + \beta) g \frac{k}{\varepsilon} \right]^2 \Omega^2 + \left[ (1 - \alpha + \beta) g \frac{k}{\varepsilon} \right]^4 \Omega^4}
\]

\[
g = \left[ C_1 + 2C_{\varepsilon_2} - 2 + (2 - C_{\varepsilon_1}) \frac{P}{\varepsilon} \right]^{-1}
\]
CONCLUDING REMARKS

For simplicity and numerical solution purposes, explicit forms are highly desirable.

An Algebraic Reynolds Stress Model and its corresponding Nonlinear Stress Model can be formulated which closely reproduces the Reynolds Stress Model solution as long as:

1) The mean velocity field is not rapidly changing.

2) There are no boundary conditions or imposed flow conditions which give rise to strong non-local effects.

Coefficients in the stress-strain models are not in general constant but depend on the strain field and the time parameter of the turbulence.

A good explicit stress-strain relation which represents the anisotropy of the turbulence should replace the linear relation now used in the $k-\epsilon$ model for practical applications.
THE PRESENT STATUS AND FUTURE DIRECTION OF ALGEBRAIC REYNOLDS STRESS MODELS

—COMMENT ON—

A. O. DEMUREN
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NORFOLK, VIRGINIA 23529
INTRODUCTION

- AS EXPLAINED IN THE POSITION PAPER OF TAULBEE, ALGEBRAIC STRESS MODELS (ASM) ARE "QUICK" FIXES FOR DEFICIENCIES IN BOUSSINESQ EDDY VISCOSITY MODEL (BEVM).
- BEVM WAS PERHAPS NEVER INTENDED AS A GENERAL CONSTITUTIVE MODEL FOR COMPLEX TURBULENT FLOWS
- RIVLIN (1957) SUGGESTED MORE APPROPRIATE ANALOGY
  - TURBULENT "NEWTONIAN FLUID" FLOW ~ NON-NEWTONIAN FLUID
  - NOT. TURBULENT FLUCTUATION ≈ MOLECULAR VIBRATION
- LUMLEY (1970) & POPE (1975) DISCUSSED POSSIBILITIES FOR PROPER CONSTITUTIVE RELATIONS — BUT NO PRACTICAL ANSWER FOR COMPLEX/ENGINEERING FLOWS
- 0-, 1-, & 2-EQ. MODELS CONTINUE TO USE BEVM → k - ε MODELS BECAME VERY POPULAR
- DEFICIENCIES IN THE PRESENCE OF
  - CURVATURE
  - ROTATION/SWIRL
  - GRAVITATION/BODY FORCES
  - STREAMWISE CORNERS
REYNOLDS STRESS MODELS (RSM) APPEARED NOT TO SUFFER THESE DEFICIENCIES

ASM TO THE RESCUE — CONTAIN ESSENTIAL ELEMENTS OF RSM

LIMITED GOAL OF ASM — ASPIRE TO RSM RESULTS WITHIN 2 EQ. FRAMEWORK

RELATIVELY SUCCESSFUL IN MANY CASES — HELPED TO BUILD REPUTATION OF MODELS

TO COMPLEMENT Taulbee'S PRESENTATION SUCCESS AND LIMITATIONS IN APPLICATION TO COMPLEX FLOWS ARE ADDRESSED
TYPES OF ASM

□ DESIRABLE:-

- EVM $\frac{u_i u_j}{k} = \frac{2}{3} \partial_{ij} - 2c_\mu \tau S_{ij} + O(\tau^2, S^2, \Omega^2, \ldots)$
where $\tau = \frac{k}{\epsilon}$

□ STANDARD:-

- BEVM $O(\tau^2, S^2, \Omega^2, \ldots) = 0$
- $k - \epsilon \rightarrow C_\mu = 0.09 = \text{constant}$
- EDDY DIFFUSIVITY $\frac{\bar{u}_i \overline{\varphi}}{k} = -\frac{c_\mu}{\sigma_\phi} \tau \Phi_i$
where Prandtl/Schmidt No. $\sigma_\phi = \text{constant}$

□ CORRECTIONS

- (i) $C_\mu \neq \text{constant}$
  $\rightarrow$ Easiest form to apply
  $\rightarrow f^n$ of $P/\epsilon$, Ri, Curvature, Rotation, etc.
  $\rightarrow$ Multiple scale $k - \epsilon$ models fall somewhat in this category by making $C_\mu = f^n \frac{\tau_s}{\tau}$ ( $\tau_s =$ time scale of large eddies)
- (ii) $\sigma_\phi \neq \text{constant} ; \sigma_{\phi_x} \neq \sigma_{\phi_y}$
- (iii) $O(\tau^2, S^2, \Omega^2, \ldots) \neq 0$
  $\rightarrow$ Most Primitive form of ASM
→ Applicable to 3D Flows
→ Explicit Relations difficult for 3D
→ Non-linear Stress-Strain Relations (Speziale 1987, Yoshizawa 1984, Barton and Rubinstein 1990) fall in this category
SOME SUCCESSES

☐ CASE(I)
  • LESCHZINER & RODI (1981)

☐ CASE(II)
  • HOSSAIN & RODI (1982)
  • DEMUREN, SCHOENUNG & RODI (1987)

☐ CASE(III)
  • GIBSON & LAUNDER (1976), GIBSON (1979)
  • DEMUREN & RODI (1984, 1987)
Fig. 7. Annular jet with wake behind disk.
Fig. 8 Centre-plane velocity and temperature decay in plane vertical buoyant jets (from 32)
Fig. 7  
Curved mixing layer;  --- stress-equation model\textsuperscript{[20]},  ----- standard $k-\varepsilon$ model\textsuperscript{[20]},  --- algebraic stress model\textsuperscript{[21]},  ○ ● experiments\textsuperscript{[23]}

a) growth of layer width $\delta$

b) variation of maximum $k$ and $\bar{uv}$
Fig. 1  Developing flow in a square duct with non-uniform inlet conditions (from 6, 7):

a) Flow configuration
b) Shear stress along cruciform wall
c) Longitudinal velocity along corner bisector
d) Secondary velocity along corner bisector
LIMITATIONS

- ASM SUFFERS FROM AT LEAST ANY SHORTCOMINGS OF CORRESPONDING RSM

- AS SHOWN IN THE POSITION PAPER
  \[ \frac{D u_i u_j}{Dt} \neq \frac{u_i u_j}{k} \frac{D k}{Dt} \] in Homogeneous Shear Flows
  Ditto \[ C u_i u_j - D u_i u_j \neq \frac{u_i u_j}{k} (C_k - D_k) \]
  - Will certainly not be true in Complex Flows.
  - e.g. Round Jet with or without Swirl

- PROBLEMS WITH CORIOLIS/CENTRIFUGAL TERMS

- TRANSPORT OF $u_i u_j$ IMPORTANT IN COMPLEX FLOWS

- ASM CANNOT PREDICT COUNTER-GRADIENT DIFFUSION

- RSM MORE STABLE (MORE FORGIVING) THAN ASM

- BITE THE BULLET — USE RSM?

  - 2 DIFFULTIES
    - (i) Stiff Momentum Equations.
    - (ii) Computational Cost

  - REMEDIES
    - (i) Split $u_i u_j$ in momentum equations into Implicit/Explicit parts following non-linear stress-strain ideas.

Fig. 3 Ratio of ASM-to-DSM stress transport evaluated for fully developed round jet
(ii) Use Multigrid Acceleration for rapid convergence
  e.g. 3D Opposed Jets in Crossflow
DISCUSSION

A. Demuren

I just want to comment on the $k - \epsilon$ model. It appears the reason it performs so poorly is the value of epsilon at the wall. A very simple fix is to eliminate epsilon at the wall and use a simple mixing length. This works very well, and gives the right behavior in adverse pressure gradient, back facing step and separated flow, etc. It is quite an easy fix for the $k - \epsilon$ model and yields decent results.

Ronald So

A comment about the compressible calculation with a $k - \epsilon$ model. What we have found is that if you do the analysis correctly, you can actually predict compressible flow very well up to Mach 10. What Dave has shown up there about $C_f$ vs. Mach number is not quite correct. You can get the prediction of the adiabatic and cool wall cases very well. We have used the baseline model and Sarkar’s correction.

D.C. Wilcox (to B.E. Launder)

When you gave your talk this morning, you said that ASM suffered “frame-invariance”. Could you comment on this?

B.E. Launder (reply)

It depends on what hypothesis you use to relate the convective transport of stress to the convective transport of strain. Work attributed to Rodi shows that you get a different answer if your frame of reference is at rest or rotating at a constant angular velocity. You can devise a scheme, Ahmadi and Speziale have done so, that is frame invariant and Dale Taulbee was talking about these things. At the end of it though, you aren’t going to get
a better model out of it.

D.C. Wilcox (to B.E. Launder)

Are you saying that if I have flow over a curved wall, if you forget to include the Coriolis and centrifugal forces as you go over it, that this is what messes it up?

B.E. Launder (reply)

Yes.

Something that Dale said towards the end of his talk he just slipped in there. You guessed that if you have important diffusive transport, then ASM won't work. There are many free flows where diffusive transport is very important. I just don't know of a good algebraic representation of it. My feeling is that if you haven't already got the software in place for ASM, then you should look beyond ASM for better answers.

D.B. Taulbee (reply)

How about all the people who have $k - \epsilon$ programs sitting there. You can easily upgrade them by changing the explicit stress-strain relations. Not everyone has access to RSM's. They just can't buy them because they're too expensive. G. Huang (comment to D. Taulbee) ASM's are just as complicated to code as RSM's.

D. Bushnell

Brian Launder said it very well: if you have a situation that the physics is such that this ASM is fine then it may work. Under the NASP contract, we had a similar workshop about turbulence modelling about two and a half
years ago. What we asked was, "do you want the wrong answer very easily or the right answer?" In the NASP project, inside the scramjet combustors the flows are such that we need to go to RSM's to get the proper physics.

W. K. George

Since Dennis was free to paraphrase Brian, I feel free to paraphrase my colleague Dale Taulbee. If, for some reason, you don't have the resources to go to RSM and the physics is bad for ASM, then things will be a hell of a lot worse for a $k - \epsilon$ model and you shouldn't be using that either.

Also let me add that there is a lot of beating to death about the difference between 0.98 and 0.95 for the spreading rate of jets. It is probably absolutely impossible to determine this experimentally.

Let me comment on the emphasis on getting the constants in the Milliken formulation. If one goes back and looks at the original data and the compromises made in putting those constants there, numbers like 5.1 are an average of numbers that go from (0.5-20.0)! In fact the experiments just aren't that good. And the theory used to interpret them is not that good either.
Session II

Second Order Closure and PDF Method
THE PRESENT STATUS AND THE FUTURE DIRECTION OF
SECOND ORDER CLOSURE MODELS FOR
INCOMPRESSIBLE FLOWS

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ICOMP, NASA Lewis Research Center
OUTLINE

- Basic equations and model terms
- Model constraints and assumptions
- Present state of various closure models
- Future direction
Basic Equations and Model Terms for Incompressible Flows

Equations for the mean quantities:

\[ U_{i,i} = 0 \]

\[ \frac{D}{Dt} U_i = -\frac{1}{\rho} P_{,i} - (\bar{u_i u_j})_{,j} + \beta_i \Theta + \nu U_{i,jj} \]

\[ \frac{D}{Dt} \Theta = -(\bar{\theta u_j})_{,i} + \gamma \Theta_{,jj} \]

We need models for \( \bar{u_i u_j}, \bar{\theta u_i} \) — second moments.
Equations for the second moments:

Reynolds stress equation:

\[
\frac{D}{Dt} \overline{u_i u_j} = D_{ij} + P_{ij} + F_{ij} + T_{ij} + \Pi_{ij} - \varepsilon_{ij}
\]

\[
D_{ij} = \nu \overline{u_i u_j, k k}
\]

\[
P_{ij} = -\overline{u_i u_k U_j, k} - \overline{u_j u_k U_i, k}
\]

\[
F_{ij} = \beta_i \overline{\theta u_j} + \beta_j \overline{\theta u_i}
\]

\[
T_{ij} = -[\overline{u_i u_j u_k} + \frac{1}{\rho}(\overline{u_i p \delta_{j k}} + \overline{u_j p \delta_{i k}})], k
\]

\[
\Pi_{ij} = \frac{1}{\rho} \overline{p(u_{i,j} + u_{j,i})}
\]

\[
\varepsilon_{ij} = 2 \nu \overline{u_i, k u_j, k}
\]

\(T_{ij}, \Pi_{ij}\) and \(\varepsilon_{ij}\) must be modeled.
Heat flux equation:

\[
\frac{D}{Dt} \overline{\theta u_i} = D_{i\theta} + P_{i\theta} + F_{i\theta} + T_{i\theta} + \Pi_{i\theta} - \varepsilon_{i\theta}
\]

\[
D_{i\theta} = \gamma (u_i \overline{\theta, k})_k + \nu (u_i \overline{u, k})_k
\]

\[
P_{i\theta} = -\theta u_k U_i, k - \overline{u_i u_k \Theta, k}
\]

\[
F_{i\theta} = \beta_i \overline{\theta^2}
\]

\[
T_{i\theta} = -[\overline{\theta u_i u_k} + \frac{1}{\rho} \overline{p \theta \delta_{ik}}], k
\]

\[
\Pi_{i\theta} = \frac{1}{\rho} \overline{p \theta, i}
\]

\[
\varepsilon_{i\theta} = (\nu + \gamma) \overline{\theta, k u_i, k}
\]

\(T_{i\theta}, \Pi_{i\theta}\) and \(\varepsilon_{i\theta}\) must be modeled.

\[
\frac{D}{Dt} \overline{\theta^2} = \gamma (\overline{\theta^2})_k, k - 2 \overline{\theta u_k \Theta, k} - (\overline{\theta^2 u_k}, k) - 2 \gamma \overline{\theta, k} \overline{\theta, k}
\]
1. Invariant — independent of coordinate rotation.

2. Symmetry in various indices.

3. Correct behavior at large and small Reynolds numbers and incompressibility.

   - Non-negative variance of all turbulent quantities (Realizability).
   - Schwarz's inequality for all turbulent quantities (Joint Realizability).

5. Material frame indifference at 2D-2C turbulence.


7. ...
Assumptions

Turbulence can be characterized by energy containing scales.

......
The Present State of Various Closure Models

Pressure strain (and temperature gradient) correlation terms:

\[ \Pi_{ij}, \quad \Pi_{i\theta} \]

Molecular dissipation terms:

\[ \varepsilon_{ij}, \quad \varepsilon_{i\theta} \]

Turbulent diffusion terms (triple correlation plus pressure transport):

\[ -[\overline{u_i u_j u_k} + \frac{1}{\rho} (\overline{u_i \rho \delta_j k} + \overline{u_j \rho \delta_i k})],_k \]

\[ -[\overline{\theta u_i u_k} + \frac{1}{\rho} \overline{p \theta \delta_i k}],_k \]

\[ \overline{\theta^2 u_i} \]

Mechanical and scalar dissipation rates: \( \varepsilon, \quad \varepsilon_{\theta} \)
Modeling of pressure correlation terms:

$$-\frac{1}{\rho} p_{,ij} = 2 U_{,ij} u_{,i} + u_{,ij} u_{,i} - \beta_i \theta_i - \overline{u_{,ij} u_{,i}}$$

Based on the linearity of $p$,

$$-\frac{1}{\rho} p_{,ij}^{(1)} = 2 U_{,ij} u_{,i} \quad \text{rapid part}$$

$$-\frac{1}{\rho} p_{,ij}^{(2)} = u_{,ij} u_{,i} \quad \text{slow part}$$

$$-\frac{1}{\rho} p_{,ij}^{(3)} = -\beta_i \theta_i \quad \text{buoyancy part}$$

one writes

$$\Pi_{i,j} = \Pi_{i,j}^{(1)} + \Pi_{i,j}^{(2)} + \Pi_{i,j}^{(3)}$$

$$\Pi_{i,\theta} = \Pi_{i,\theta}^{(1)} + \Pi_{i,\theta}^{(2)} + \Pi_{i,\theta}^{(3)}$$
Using the solutions of above equations, we obtain (for hom. flows) for the rapid terms:

\[
\Pi_{ij}^{(1)} = -2U_{p,q} \frac{1}{4\pi} \int_V \left[ (u_q(r)u_i(r'),p_j + (u_q(r)u_j(r'),p_i) \right] \frac{dv}{|r - r'|} \\
= 2U_{p,q} (X_{pjqi} + X_{pijq})
\]

\[
\Pi_{i\theta}^{(1)} = -2U_{j,k} \frac{1}{4\pi} \int_V \left[ u_k(r)f(r'),i_j \right] \frac{dv}{|r - r'|} \\
= 2U_{j,k} X_{ij\theta}
\]
for buoyancy terms:

\[
\Pi^{(3)}_{ij} = \beta_k \frac{1}{4\pi} \int_{V} \left[ (\theta(r)u_i(r'))_{,kj} + (\theta(r)u_j(r'))_{,ki} \right] \frac{dv}{|r - r'|}
\]

\[= -\beta_k (Y_{kij} + Y_{kji})\]

\[
\Pi^{(3)}_{i\theta} = \beta_k \frac{1}{4\pi} \int_{V} \left[ \theta(r)\theta(r') \right]_{,ik} \frac{dv}{|r - r'|}
\]

\[= -\beta_k Y_{ik}\]
For slow term, following Lumley (1978):

\[-\Phi_{ij}\varepsilon = \Pi_{ij}^{(2)} - \varepsilon_{ij} + \frac{2}{3}\varepsilon\delta_{ij}\]
\[-\Phi_{i\theta}\frac{\varepsilon}{q^2} = \Pi_{i\theta}^{(2)} - \varepsilon_{i\theta}\]

To model the pressure related terms, we need to model the following tensors:

\[X_{pjqi}, \quad X_{ijk}\]
\[Y_{kij}, \quad Y_{ik}\]
\[\Phi_{ij}, \quad \Phi_{i}\]

Note that the dissipation tensors \(\varepsilon_{ij}\) and \(\varepsilon_{i\theta}\) have been combined into the slow terms.
Models for the rapid terms:

\[ \Pi_{ij}^{(1)} = \frac{1}{\rho} p^{(1)} (u_{i,j} + u_{j,i}) \]

Based on \( \overline{u_i u_j} \) only:

Naot, Shavit & Wolfshtein (1970)
Launer, Reece & Rodi (1975)
Speziale, Sarkar and Gatski (1990)

---

\[ \Pi_{i0}^{(1)} = \frac{1}{\rho} p^{(1)} \theta_{i} \]

Based on \( \overline{u_i u_j} \) and \( \overline{\theta u_i} \):

Launer (1975)
Zeman and Lumley (1976)
Lumley (1978)

---

\[ \text{Realizability} \]

Shih & Lumley (1985)
Fu & Lauder (1987)
Ristorcelli & Lumley (1988)

Reynolds (1988)

Based on \( \overline{u_i u_j} \) & eddy structure tensors \( D_{ij} \):

Reynolds (1990)
Reynolds eddy structure model:

Basic idea:

\[ \Pi_{iq}^{(1)} = 2U_{p,j} (X_{ijpq} + X_{qjpi}) \]

\[ X_{ijpq} = \int_{K} \frac{k_PK_q}{k^2} E_{ij}(k) d^3 k \]

\[ X_{ijpp} = \overline{u_i u_j} \]

\[ X_{iipq} = \int_{K} \frac{k_PK_q}{k^2} \overline{E_{ii}(k)} d^3 k = D_{pq} \text{ orientation tensor} \]

\[ \Pi_{ij}^{(1)} = F(\overline{u_i u_j}, D_{ij}) \]

In addition to Reynolds stress equations, we need to solve six extra modeled equations for \( D_{ij} \).
\[
\frac{\Pi^{(1)}_{ij}}{4k} = 0.2S_{ij} + C_1(b_{ik}S_{jk} + b_{jk}S_{ik} - \frac{2}{3}\delta_{ij}b_{kl}S_{kl})
\]
\[+ C_2(b_{ik}\Omega_{jk} + b_{jk}\Omega_{ik}) \]
\[+ 0.2(b_{lk}b_{ik}S_{jl} + b_{lk}b_{jk}S_{il} - 2b_{kj}b_{li}S_{kl} - 3b_{ij}b_{kl}S_{kl})
\]
\[+ 0.2(b_{ik}b_{lk}\Omega_{jl} + b_{jk}b_{lk}\Omega_{il}) \]
\[+ r(4b_{nl}b_{ln}b_{im}\Omega_{jm} + 4b_{nm}b_{mn}b_{jl}\Omega_{il})
\]
\[+ 12b_{mi}b_{nj}b_{ml}\Omega_{nl} + 12b_{mi}b_{nj}b_{nl}\Omega_{ml}) \]
\[= \frac{1}{2}(U_{i,j} + U_{j,i}),
\]
\[= \frac{1}{2}(U_{i,j} - U_{j,i}) \]
\[
\Pi_{\theta}^{(1)} = 0.8\theta w_k U_{i,k} - 0.2\theta w_k U_{i,k} + 2CD_1 \theta w_k b_{ij} U_{i,k} + 2CD_2 (\theta u_j b_{ik}) U_{j,k} + 2CD_3 \theta w_k b_{kl} U_{i,k} + 2 \varepsilon \theta w_k (\theta u_i \theta w_k + 2b_{im} P_{im}) 
\]

Craft & Launder:

\[
\Pi_{\theta}^{(1)} = 0.8\theta w_k U_{i,k} - 0.2\theta w_k U_{i,k} + 2CD_1 \theta w_k b_{ij} U_{i,k} + 2CD_2 (\theta u_j b_{ik}) U_{j,k} + 2CD_3 \theta w_k b_{kl} U_{i,k} - 1.6\theta w_u S_{kl} + 0.8\theta w_u b_{im} S_{ml} - 0.2\theta w_k (\theta u_i \theta w_k + 2b_{im} P_{im}) 
\]

Shih & Lumley:
Difference between models of LRR and SSG:

- Model coefficients.
- If appropriate model constraints imposed, LRR and SSG should be exactly the same.

**Difference between models of UMIST and Cornell:**

- UMIST: Realizability on $\overline{u_i u_j}$.
- Cornell: Both Realizability and Joint Realizability on $\overline{u_i u_j}$, $\overline{\theta u_i}$.

Imposing joint realizability results in a simpler rapid pressure models (Lumley, 1983, Shih & Lumley, 1985).

If joint realizability is imposed, we expect that UMIST model will reduce to Cornell model.
Validation of the models:
Homogeneous Shear flow: Shear rate $S = 56.57$
Homogeneous Shear flow: Shear rate $S = 56.57$
Two-Dimensional Channel Flow: $Re_i = 180$
Models for the slow terms:

\[ \Pi^{(2)}_{ij} = \frac{1}{\rho} p^{(2)}(u_{i,j} + u_{j,i}) \]

Based on \( \overline{u_i u_j} \) only:

- Rotta (1951)
- Lumley (1978)
- Shih and Mansour (1988)
- Sakar and Speziale (1989)
- Craft and Launder (1989)

Based on two-point correlation:

- Weinstock (1987)

Based on \( \overline{u_i u_j} \) and eddy structure tensors:

- Reynolds (1990)

\[ \Pi^{(2)}_{i\theta} = \frac{1}{\rho} p^{(2)} \theta, i \]

Based on \( \overline{\theta u_i} \) only:

- Monin (1965)
- Lumley (1978)
- Shih and Lumley (1985)
- Shih and Shabbir (1990)
- Gibson et al (1987)

Based on \( \overline{\theta u_i} \) and \( \overline{u_i u_j} \):

- Craft and Launder (1989)
Lumley (1978):

\[ \Pi_{ij}^{(2)} = -\varepsilon [\beta b_{ij} + \gamma (b_{ij}^2 + 2II \delta_{ij} / 3)] \]

\[ \beta = \beta(II, III, Re), \quad \gamma = \gamma(II, III, Re), \quad Re = \frac{q^2}{9\varepsilon \nu} \]

Weinstock (1981):

\[ \Pi_{ij}^{(2)} = -\varepsilon C_{ij} b_{ij} \quad \text{(no summation on } i \text{ and } j) \]

\[ C_{ij} = F_{ij} \text{(Int. of } E_{ij}(k)) \]

Reynolds (1990):

\[ \Pi_{ij}^{(2)} = -0.3(d_{ik} u_k u_j + d_{jk} u_k u_i - 2d_{nm} R_{nm} d_{ij}) / \tau \]
Shih and Lumley (1985):

\[ \Pi_{i\theta}^{(2)} = -\frac{\varepsilon}{2k} (\phi_1 \theta u_i + \phi_2 b_{ik} \theta u_k) \]

Craft and Launder (1989):

\[ \Pi_{i\theta}^{(2)} = F(\theta u_i, b_{ik} \theta u_k, b_{ik} b_{kj} \theta u_j, b_{ij} \Theta, j) \]
Validation of the models:
Homogeneous Shear flow: Shear rate $S = 56.57$
Homogeneous Shear flow: Shear rate $S = 56.57$
Two-Dimensional Channel Flow: \( R_e \tau = 180 \)
Two-Dimensional Channel Flow: \( Re_\tau = 180 \)
Models for the buoyancy terms:

\[ \Pi_{ij}^{(3)} = \frac{1}{\rho} \frac{p^{(3)}(u_{i,j} + u_{j,i})}{x} \]

Launder (1975)

Zeman and Lumley (1976)

\[ \Pi_{i\theta}^{(3)} = \frac{1}{\rho} \frac{p^{(3)} \theta_{,i}}{x} \]

Launder (1975)

Zeman and Lumley (1976)

Shih and Lumley (1985)

Craft and Launder (1989)
Shih and Lumley (1985):

\[ \Pi_{ij}^{(3)} = -\beta_k (Y_{kij} + Y_{kji}) \]

\[ Y_{kij} = \beta_1 \delta_{ik} \theta u_j + \beta_2 (\delta_{ij} \theta u_k + \delta_{jk} \theta u_i) + \beta_3 b_{ik} \theta u_j \]
\[ + \beta_4 (b_{ij} \theta u_k + b_{jk} \theta u_i) + \beta_5 (\delta_{ij} b_{kp} + \delta_{jk} b_{ip}) \theta u_p \]
\[ + \beta_6 \delta_{ik} b_{jp} \theta u_p + \beta_7 b_{ik} b_{jp} \theta u_p + \beta_8 (b_{ij} b_{kp} + b_{jk} b_{ip}) \theta u_p \]
\[ + \beta_9 b_{ik}^2 \theta u_j + \beta_{10} (b_{ij} \theta u_k + b_{jk} \theta u_i) + \beta_{11} \delta_{ik} b_{jp}^2 \theta u_p \]
\[ + \beta_{12} (\delta_{ij} b_{kp}^2 + \delta_{jk} b_{ip}^2) \theta u_p \]


\[ \Pi_{ij}^{(3)} = -\left(\frac{4}{10} + \frac{3A_2}{80}\right) (G_{ij} - \frac{1}{3} \delta_{ij} G_{kk}) + \frac{1}{4} u_{ij} G_{kk} \]
\[ + \frac{3}{20} \left( \beta_i \frac{u_m u_j}{k} + \beta_j \frac{u_m u_i}{k} \right) u_m \theta - \frac{1}{10} \delta_{ij} \beta_k \frac{u_m u_k}{k} \frac{u_m \theta}{u_m} \]
\[ - \frac{1}{4} \beta_k \left( \frac{u_k u_i}{k} \frac{u_j \theta}{u_i} + \frac{u_k u_j}{k} \frac{u_i \theta}{u_j} \right) + \frac{1}{20} \delta_{ij} \beta_k \frac{u_m u_i}{k} \frac{u_m u_k}{k} \frac{u_m \theta}{u_n} \]
\[ - \frac{1}{8} \left[ \frac{u_m u_j}{k} \frac{u_i \theta}{u_j} + \frac{u_m u_i}{k} \frac{u_j \theta}{u_i} \right] \frac{u_m u_k}{k} \beta_k + \frac{1}{8} \left[ \frac{u_k u_i}{k^2} \frac{u_m u_j}{k^2} + \frac{u_k u_j}{k^2} \frac{u_m u_i}{k^2} \right] \beta_k \frac{u_m \theta}{u_m} \]
\[ - \frac{3}{40} \left( \beta_i \frac{u_m u_j}{k} + \beta_j \frac{u_m u_i}{k} \right) \frac{u_m u_n}{k} \frac{u_n \theta}{u_m} + \frac{1}{4} \beta_k \frac{u_m u_k}{k^2} \frac{u_i u_j}{u_m \theta}. \]
Shih and Lumley (1985):

$$\Pi_{i\theta}^{(3)} = -\beta_k Y_{ik}$$

$$Y_{ik} = \gamma_1 \theta^2 \delta_{ik} + \gamma_2 \theta^2 b_{ik} + \gamma_3 \theta u_i \theta u_k$$

$$+ \gamma_4 (\theta u_k b_{ip} \theta u_p + \theta u_i b_{kp} \theta u_p)$$

$$+ \gamma_5 \theta^2 b_{ik}^2 + \gamma_6 b_{ip} b_{kq} \theta u_p \theta u_q$$

$$+ \gamma_7 (b_{ip}^2 \theta u_p \theta u_K + b_{kp}^2 \theta u_p \theta u_i)$$


$$\Pi_{i\theta}^{(3)} = \frac{1}{3} \theta^2 \beta_i - 2\theta^2 b_{ik} \beta_k$$
Validation of the models:
Figure 7. Comparison between models for the pressure temperature-gradient correlation and the buoyant plume experiment. ---- Launder (1975) model; --- Zeman and Lumley model (1976); ---- Shih and Lumley (1985) model; — Craft et. al. (1990) model; — present model; • experiment of Shabbir and George (1990)
Models for turbulent diffusion terms:

\( u_i u_j u_k, \quad \theta u_i u_j, \quad \theta^2 u_i \)

Algebraic models:

Daly and Harlow (1970)

Hanjalic and Launder (1972)

Lumley (1978)

Dekeyser and Launder (1983)

Structural model:

Nagano and Tagawa (1990)
Lumley (1978):

\[
\overline{u_i u_j u_k} = -\frac{1}{3\beta} \frac{q^2}{\bar{\varepsilon}} \left[ \overline{u_k u_p (u_i u_j),p} 
+ \overline{u_j u_p (u_i u_k),p} + \overline{u_i u_p (u_j u_k),p} \right]
+ \frac{\beta - 2}{9\beta} \left[ \delta_{ij} q^2 \overline{u_k} + \delta_{ik} q^2 \overline{u_j} + \delta_{jk} q^2 \overline{u_i} \right]
\]

\[
\overline{q^2 u_k} = -\frac{3}{4\beta + 10} \frac{q^2}{\bar{\varepsilon}} \left[ \overline{u_k u_p q^2} + 2\overline{u_p u_q} \overline{u_k u_q},p \right]
\]

\[
\overline{\theta u_i u_j} = -\frac{q^2}{(\beta + 2\phi_1)\bar{\varepsilon}} \left[ (\overline{\theta u_i}),_k \overline{u_j u_k} 
+ (\overline{\theta u_j}),_k \overline{u_i u_k} +(\overline{u_i u_j}),_k \overline{\theta u_k} \right]
+ \frac{\beta - 2}{3(\beta + 2\phi_1)} \delta_{ij} \overline{q^2 \theta}
\]

\[
\overline{q^2 \theta} = -\frac{q^2}{(2 + 2\phi_1)\bar{\varepsilon}} \left[ 2\overline{u_p u_q} \left( \overline{\theta u_p},_q + \overline{\theta u_q} \overline{q^2},_q \right) \right]
\]

\[
\overline{\theta^2 u_k} = -\frac{\theta^2}{(2 + \phi_1)\bar{\varepsilon}_\theta} \left[ \overline{u_k u_p \theta^2},_p + \overline{\theta u_p} \overline{\theta u_k},p \right]
\]
Validation of the models:
Two-Dimensional Channel Flow: $R_e = 180$
Two-Dimensional Channel Flow: \( R_{er} = 180 \)
Two-Dimensional Channel Flow: $Re = 180$
Nagano and Tagawa (1990):

\[
\overline{vuv} = \frac{1}{3[(\pi/2)^2 - 1]} \left[ S(u) + \sigma_{uv} \frac{1}{2} \pi S(v) \right]
\]

\[
\overline{vuu} = \frac{1}{3[(\pi/2)^2 - 1]} \left[ S(v) + \sigma_{uv} \frac{1}{2} \pi S(u) \right]
\]

\[
\overline{vv\theta} = \frac{1}{3[(\pi/2)^2 - 1]} \left[ S(\theta) + \sigma_{uv} \frac{1}{2} \pi S(v) \right]
\]

\[
\overline{v\theta^2} = \frac{1}{3[(\pi/2)^2 - 1]} \left[ S(v) + \sigma_{uv} \frac{1}{2} \pi S(\theta) \right]
\]

\[
\overline{vu\theta} = \sigma_{uv} \frac{1}{4} \pi \overline{vuv\theta}
\]

\[
\sigma_x = 1 \quad x \geq 0, \quad \sigma_x = -1 \quad x \leq 0.
\]
Fig. 5 Comparison of model results for triple velocity correlations in wall turbulence.
BUOYANT PLUME

- Experiment of Shabbir & George (1987)
- Model of Nagano & Tagawa (1989)

Graphs showing the relationship between $v_r$ and $r/z$ and $a_0$ and $r/z$.
Fig. 2 Mean velocity profile in 2-D mixing layer. $U_{\text{max}}$, the free stream velocity, $Y_5$: the position where $U = \frac{1}{2}U_{\text{max}}$. ○: Bradshaw, et al[19], —: Present model.

Fig. 3 Shear stress profiles in 2-D mixing layer. Δ: Bradshaw, et al[19], △: Gutmark & Wygnanski[21], —: Present model.

Fig. 4 Normal stress profiles in 2-D mixing layer. O, △, ▽: Castro[20], ○, △, ▽: Gutmark & Wygnanski[21]. The lines represent the present model.
Fig. 5 Mean velocity profile in planar jet. \( U_s \): the center line mean velocity. O: Bradbury\({}^{[22]}\), \( \Delta \): Heskestad\({}^{[23]}\), X: Gutmark & Wygnanski\({}^{[25]}\), -: Present model.

Fig. 6 Shear stress profile in planar jet. Legend as in Fig.5.

Fig. 7 Normal stress \( \overline{u^2/U_s^2} \) profile in planar jet. Legend as in Fig.5.

Fig. 8 Normal stress \( \overline{v^2/U_s^2} \) profile in planar jet. Legend as in Fig.5.

Fig. 9 Normal stress \( \overline{w^2/U_s^2} \) profile in planar jet. Legend as in Fig.5.
Fig. 10 Mean velocity $U/U_s$ profile in axisymmetric jet. $U_s$: the centerline mean velocity. ○: Abbiss et al. [24], X: Wygnanski & Fiedler [25], ‘-‘: Present model.

Fig. 11 Shear stress $\overline{uv}/U_s^2$ profile in axisymmetric jet. ○: Rodi [26], X: Wygnanski & Fiedler [25], △: Abbiss et al. ‘-‘: Present model.

Fig. 12 Normal stress $\overline{u^2}/U_s^2$ profile in axisymmetric jet. Legend as in Fig. 11.

Fig. 13 Normal stress $\overline{v^2}/U_s^2$ profile in axisymmetric jet. Legend as in Fig. 11.

Fig. 14 Normal stress $\overline{w^2}/U_s^2$ profile in axisymmetric jet. Legend as in Fig. 11.
Fig. 1 Mean temperature in heated plane jet [Δ, Browne et al. (1984);
▽, Bashir & Uberoi (1975); △, Uberoi & Singh (1975); ○, Jenkins &
Goldschmidt (1973); —, present model].

Fig. 2 Heat flux \(\rho U_0^2\theta_0\) in heated plane jet [○, Jenkins (1976);
Δ, Antonia (1985); ▽, Browne et al. (1984); —, present model].

Fig. 5 Square-root of temperature variance in heated plane jet [○,
Antonia et al. (1983); ○, Bashir & Uberoi (1975); ▽, Uberoi & Singh
(1975); —, present model].
Fig. 6 Mean temperature in heated round jet [Δ, Lockwood & Moneib (1980); ○, Becker et al. (1967); —, present model].

Fig. 7 Square-root of temperature variance in heated round jet [Δ, Lockwood & Moneib (1980); ○, Becker et al. (1967); —, present model].
Future Direction

"Phenomenological Modeling: Present ... and Future?" by Launder (1989, Whither Turbulence? at Cornell)

- Application and Assessment
- Extension and Refinement
- New modeling Development

Above issues addressed in Launder’s paper are still very appropriate.
One of the weakest situations in second-order closure is Wall-bounded turbulent flows:

- General feature: Rapid variation near the wall and multiple scale problem.

- Models for the rapid pressure terms failed in modeling their near wall behavior, especially in buffer layer.

- Models for the turbulent transport terms also failed in the buffer layer.

- Models for the return terms (slow pressure + anisotropic dissipation tensor) seem ok from the comparison with the DNS data.

- The present treatment of the wall effect [Hanjalic and Lauder (1972), Launder and Tselepidakis (1991) Lai and So (1990), Shih and Mansour (1990)] have not resolved above model deficiencies.
Second order turbulence simulation of the rotating, buoyant, recirculating convection in the Czochralski crystal melt

1) PROBLEM STATEMENT

2OM for rotating turbulence

2) THE RAPID PRESSURE MODELS TESTED

LINEAR
1) The IP model
2) The SSG model

NONLINEAR
3) Launder's nonlinear
4) Shih & Lumley's model
5) The 2DMFI model

3) THE COMPUTATIONAL PROBLEM

4) SHORTCOMINGS AND FUTURE WORK
THE CZOCHRALSKI PROBLEM

\[ \text{Res} = \frac{\omega_s R_s^2}{\nu} \quad \text{Res} < 10^5 \]

\[ \text{Rec} = \frac{\omega_c R_c^2}{\nu} \quad \text{Rec} < 10^5 \]

\[ \text{Gr} = g \beta \Delta T R_c^3 / \nu^2 \quad \text{Gr} \leq 10^{12} \]

\[ \text{Re} = \text{Gr}^{1/2} \quad \text{Re} < 10^6 \]

\[ \text{Pr} = \frac{\nu}{\alpha} \quad \text{Pr} \sim .01 \]

\[ \text{Ar} = \frac{H}{R_c} \quad \text{Ar} \sim 1 \]

\[ \text{Bi} = \frac{\varepsilon \sigma T_m^4 R_c^4 k \Delta T}{\text{Bi}} \quad \text{Bi} \leq 4 \]

\[ \Delta = \frac{\Delta T}{T_m} \quad \Delta \sim .05 \]

\[ \text{Ma} = -\sigma_T \Delta T R_s \text{Pr} / \rho \nu^2 \quad \text{Ma} < 10^5 \]

\[ 1 \leq \text{Ro} = \frac{\text{Re}}{ \mid \text{Rec} \mid } \leq \infty \]

\[ \text{Sb} = \frac{\text{Re}_s^2}{\text{Gr}} \leq 10^2 \]
THE COMPUTATIONAL PROBLEM

17 NONLINEAR COUPLED PDE's

MEAN \[ [U, V, W, T] \]

\[
\begin{bmatrix}
<u_u> & r^2<u_{uv}> & <u_w>
\end{bmatrix}
\begin{bmatrix}
<r2><\theta_u>
\end{bmatrix}
\]

\[
\begin{bmatrix}
<r2><\theta_v>
\end{bmatrix}
\]

\[
\begin{bmatrix}
<r2><\theta_w>
\end{bmatrix}
\]

\[
[\varepsilon, \varepsilon_\theta] <\theta\theta> \]

24 NONLINEAR ALGEBRAIC EQUATIONS

\[
\begin{bmatrix}
<\theta\theta> \\
<\theta\theta_u> \\
<\theta_u_u> \\
<u_{iijd}>
\end{bmatrix}
\]

3OM

17 INEQUALITIES (at least)

\[ <u_{ij}>, <\theta\theta>, \text{ dij} = <u_{ij}><\theta\theta> - <\theta u_i><\theta u_j> \]

\[ <u_\alpha u_\gamma> / (u_{\gamma u_\gamma})^{1/2} <u_\alpha u_\alpha>^{1/2} ) \]

\[ <\theta u_\alpha> / (\theta <u_\alpha u_\alpha>^{1/2} ) \]
Figure 7.5: Temperature, streamfunction, vorticity and angular momentum; Solution with Ristorcelli and Lumley's rapid and buoyancy pressure models. $Gr = 10^9$, $Re = 3.16 \times 10^4$, $Re_s = 0.0$, $Re_c = 0.0$, $Ro = \infty$, $Ma = 10^3$, $Pr = 0.01$, $Bi = 2.5$, $R_s/R_c = 0.5$, $ar = 1.0$, $T = 80$. 
Figure 7.10: Twice turbulence energy, $q^2$, and scalar variance, $<\theta^2>$, second invariant, $\Pi$, and $(i,j=3,3)$ component of the anisotropy tensor, $b_{33}$; Solution with Ristorcelli and Lumley’s rapid and buoyancy pressure models. $Gr = 10^9$, $Re = 3.16 \times 10^4$, $Re_s = 0.0$, $Re_c = 0.0$, $Ro = \infty$, $Ma = 10^3$, $Pr = 0.01$, $Bi = 2.5$, $Rs/Rc = 0.5$, $ar = 1.0$, $T = 80$. 
Figure 7.7: Twice turbulence energy, \( q^2 \), and scalar variance, \( < q^2 > \), second invariant, \( II \), and (i,j=3,3) component of the anisotropy tensor, \( b_{33} \); Solution with the SSG linear rapid pressure model and Ristorcelli and Lumley's buoyancy pressure model. \( Gr = 10^9 \), \( Re = 3.16 \times 10^4 \), \( Re_s = 0.0 \), \( Re_c = 0.0 \), \( Ro = \infty \), \( Ma = 10^3 \), \( Pr = 0.01 \). \( Bi = 2.5 \), \( R_s/R_c = 0.5 \), \( ar = 1.0 \), \( T = 70 \).
FUTURE WORK / SHORTCOMINGS

1) WALL FUNCTIONS
   Physics: boundary layers and turbulence
   Computations: grid dependence
   resolution of flow field
   Low Re 2OM Models: too many nodes

2) RAPID ROTATION / STABLE STRATIFICATION
   inadequate parameterization of cascade

3) WHAT IS THE TIME DEPENDENCE ?
   Joint Realizability couples rapid models
   What does the averaging mean ?
   Long time scale "coherent" structures

4) COMPUTATIONAL STRATEGIES
   FDAs reflecting realizability
   Include mean quantities in 3OM eq's
   FDAs with accurate time evolution
   FDAs reflecting turbulent diffusion
CONTRIBUTIONS OF THE THESIS

EXPECTATIONS OF 2DMFI MODELS

1) Flows with strong body forces
   stable stratification
   rotation
   magnetic fields

2) Environmental shallow water flows
   industrial effluents
   mixing between bodies of water

3) Quasi two-dimensional geophysical flows
   large scale ocean mixing
   regional atmospheric modeling
   (mesoscale variability)

4) Unsteady flows
   time scales > integral time scale
   unsteady separation
   large scale "coherent structures" ??
CONTRIBUTIONS OF THE THESIS

0) THE 2DMFI MODEL

Models $X_{pri}$ & $X_{psir}$: $f(b, b^2, b^3), f(b, b^2, b^3, \langle u \rangle)$

Satisfies Realizability, Joint Realizability

Satisfies 2DMFI

Off-realizability corrections exact

Off-geostrophy corrections exact

Free parameters available
COMMENTS ON THE PRESENT STATE OF SECOND-ORDER CLOSURE MODELS FOR INCOMPRESSIBLE FLOWS

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Workshop on Engineering Turbulence Modeling

NASA Lewis Research Center

August 21 - 22, 1991
Second-order closure models account for history and nonlocal effects of the mean velocity gradients on the Reynolds stress tensor.

Turbulent flows involving:

- Body forces or curvature
- Reynolds stress relaxational effects
- Counter-gradient transport

are usually better described.
homogeneous turbulent shear flow in a rotating frame
Rotating Shear Flow

(a) $K-t$ Model

(b) LRR Model

(c) LES (Bardina et al. 1983)
REYNOLDS STRESS TRANSPORT EQUATION

\[ \frac{\partial \tau_{ij}}{\partial t} + \bar{u}_k \frac{\partial \tau_{ij}}{\partial x_k} = -\tau_{ik} \frac{\partial \bar{u}_j}{\partial x_k} - \tau_{jk} \frac{\partial \bar{u}_i}{\partial x_k} + \Pi_{ij} \]

\[ -\frac{2}{3} \varepsilon \delta_{ij} - \frac{\partial C_{ijk}}{\partial x_k} + \nu \nabla^2 \tau_{ij} \]

where

\[ \tau_{ij} = u'_i u'_j, \quad \varepsilon = \nu \frac{\partial u'_i}{\partial x_j} \frac{\partial u'_i}{\partial x_j} \]

\[ \Pi_{ij} = p' \left( \frac{\partial u'_i}{\partial x_j} + \frac{\partial u'_j}{\partial x_i} \right) - \varepsilon_{ij} \]

\[ \varepsilon_{ij} = 2\nu \frac{\partial u'_i}{\partial x_k} \frac{\partial u'_j}{\partial x_k} - \frac{2}{3} \varepsilon \delta_{ij} \]

\[ C_{ijk} = u'_i u'_j u'_k + p' u'_i \delta_{jk} + p' u'_j \delta_{ik} \]

\[ K = \frac{1}{2} \tau_{ii} \]
ISSUES IN SECOND-ORDER CLOSURE MODELING

Models for $\Pi_{ij}$:

Typically, it is assumed that

$$\Pi_{ij} = \varepsilon A_{ij}(b) + K M_{ijk\ell}(b) \frac{\partial \bar{u}_k}{\partial x_\ell}$$

where

$$b_{ij} = \frac{\tau_{ij} - \frac{1}{3} \tau_{kk} \delta_{ij}}{\tau_{\ell\ell}} \quad \text{(anisotropy tensor)}$$

These models have deficiencies in rotating homogeneous turbulent flows (Reynolds 1989 and Speziale, Sarkar and Gatski 1990).
For the return to isotropy problem in a rotating frame (with angular velocity $\Omega$), these models predict that the second and third invariants of $b_{ij}$ are independent of $\Omega$ in contradiction of DNS and RDT (Reynolds 1989).

Fig. 2 Typical RDT solution for the rotation of initially anisotropic homogeneous turbulence (by T.S. Shih).
For rotating homogeneous shear flow in the unstable flow regime, these models predict that the growth rate $\lambda$ of the flow defined by

$$K \sim e^{\lambda t}, \quad \varepsilon \sim e^{\lambda t}$$

is symmetric about its most energetic value (Speziale, Sarkar and Gatski 1990).
Consequently, if the most energetic state – where $\lambda = \lambda_{\text{max}}$ – is placed at $\Omega/S = 0.25$, the model will exhibit similarity with respect to the Richardson number $Ri \equiv -2\Omega/S(1 - 2\Omega/S)$. This is in violation of RDT and LES results (Speziale, Sarkar and Gatski 1990 and Speziale and Mac Giolla Mhuiris 1989).
Speziale, Sarkar and Gatski 1990 recently showed that the general model is topologically equivalent to the quadratic model

$$\Pi_{ij} = -C_1 \varepsilon b_{ij} + C_2 \varepsilon (b_{ik} b_{kj} - \frac{1}{3} II \delta_{ij})$$

$$+ C_3 K \overline{S}_{ij} + C_4 K (b_{ik} \overline{S}_{jk} + b_{jk} \overline{S}_{ik})$$

$$- \frac{2}{3} b_{mn} \overline{S}_{mn} \delta_{ij} + C_5 K (b_{ik} \overline{W}_{jk} + b_{jk} \overline{W}_{ik})$$

in plane homogeneous turbulent flows where

$$\overline{S}_{ij} = \frac{1}{2} (\partial \overline{u}_i / \partial x_j + \partial \overline{u}_j / \partial x_i)$$

and

$$\overline{W}_{ij} = \frac{1}{2} (\partial \overline{u}_i / \partial x_j - \partial \overline{u}_j / \partial x_i).$$

Based on these ideas, the SSG model was developed.
The SSG model yields only modest improvements on the Launder, Reece and Rodi model. Substantial improvements will only come if $\Pi_{ij}$ is taken to be a non-linear function of the mean velocity gradients.

Two possible approaches are:

(1) The eddy structure model of Reynolds (1990)

(2) Tensor dissipation models (Speziale, Raj and Gatski 1990).
NEAR WALL MODELS

We currently do not know how to properly integrate second-order closure models to a solid boundary! The major problem lies in the pressure strain correlation $\Pi_{ij}$. The commonly used near wall models for $\Pi_{ij}$ have two major deficiencies:

(1) The ad hoc dependence of $\Pi_{ij}$ on the unit normal $n_i$ to the wall. This does not allow for the proper treatment of wall bounded flows with corners.

(2) Asymptotic consistency is satisfied through singular differential equations; for example

$$\nu \frac{\partial^2 \tau_{12}}{\partial y^2} = C_1 \frac{\varepsilon}{K} \tau_{12} + \mathcal{O}(y^2)$$

for the near-wall behavior of $\tau_{12}$. This can cause problems in numerically recovering an asymptotically consistent solution.
Entirely new approaches are needed for the near wall modeling of $\Pi_{ij}$!

We are at the end of the road for models of the form

$$\Pi_{ij} = \varepsilon A_{ij}(b) + K M_{ijk\ell}(b) \frac{\partial u_k}{\partial x_\ell}$$

with ad hoc near wall fixes.
NEEDED IMPROVEMENTS

• Models for $\Pi_{ij}$ that are nonlinear in the mean velocity gradients.

• Entirely new methods for the integration of second-order closures to a solid boundary.

• Incorporation of directional information into the turbulence length scale (possibly via an integral tensor length scale).
DISCUSSION

S. Sarkar (to T.-H. Shih)

I have a question to Dr. Shih about the slow term pressure strain correlation comparisons he showed. It seemed to me that Rotta and our model gave the same results. That was little surprising because the linear term coefficients were different in the two models. On top of that our model had a nonlinear term.

T.-H. Shih (reply)

The nonlinear term is very small. Linear term coefficient for LRR model is 1.5 and for your model is 1.7.

S. Sarkar (to T.-H. Shih)

We have a paper in Physics of Fluids in which we compare the two models and they are completely different.

T.-H. Shih (reply)

Your nonlinear term can also have opposite sign to linear terms thus giving results similar to LRR.

C.G. Speziale (to T.-H. Shih)

You refered to SSG model as a linear model. There is a coefficient which goes as square root of second invariant and also a term which contains a production term multiplying the anisotropic tensor. In precise mathematical terms it is a quasi-linear model.
T.-H. Shih (reply)

If the coefficient is constant the model is linear. In SSG model the coefficient is a function of second invariant and a production term.

J.L. Lumley (to C.G. Speziale)

You refer to your models as being equivalent to all the other models but only in the equilibrium situation. These flows are never in equilibrium. Would you like to comment on that.

C.G. Speziale (reply)

Question is how drastic are the departures. Then there is this issue of calibrating the coefficients. My motivation for doing SSG model was that most of the calibration we do is from homogeneous plane flows near equilibrium state. Since all the models are collapsing to this degenerate form, my feeling was to calibrate the model at this state and see the differences. It seemed to be reasonable.

J.R. Ristorcelli (to C.G. Speziale)

I have been judging these models from the point of view of computability. SSG model doesn't compute very well. It does better in rotating situations then it does in the non-rotating situations. I imagine it would do well in in homogeneous shear flow situation from which it was calibrated. For me I built the principles of realizability in the computation and I can't compute the flow with SSG model.

C.G. Speziale (to J.R. Ristorcelli)

What happens?
J.R. Ristorcelli (reply)

I get correlation (coefficients) which are larger than unity or eigenvalues of matrices going to zero.

C.G. Speziale (to J.R. Ristorcelli)

But no problems with $k$ or $\epsilon$.

J.R. Ristorcelli (reply)

Well $k$ is the sum of these eigenvalues.

C.G. Speziale (to J.R. Ristorcelli)

SSG model satisfies limited realizability. It does guarantee positive $k$ and $\epsilon$.

T.B. Gatski (to J.R. Ristorcelli)

I did various calculations with homogeneous shear flows using some nonlinear models e.g. Shih-Lumley model. It was very difficult to use in homogeneous shear flow because it was very stiffening.

J.R. Ristorcelli (to T.B. Gatski)

What do you mean by stiffening?

T.B. Gatski (reply)

All the equations for these flows are ode's. You are using Runge Kutta
method and you need very very small steps. The only dilemma with making
assessments of turbulence models where you have pde’s is that you can not
be sure unambiguously that there are no problems with the algorithm.

E. Reshotko (to J.R. Ristorcelli)

How do you know that these flows are turbulent

J.R. Ristorcelli (reply)

A lot of experiments have been done to support this e.g. at AT&T. Also the
Gr = 10^{12} and Re = 10^6 for these flows.

E. Reshotko (to J.R. Ristorcelli)

Will your equations with all the turbulence terms would give a laminar so-
lution?

J.R. Ristorcelli (reply)

Turbulence would decay indicating a return toward a laminar state.

B.E. Launder (to T.-H. Shih)

Did the channel flow rapid term comparisons you showed include the inho-
mogeneous part of the rapid term or the wall reflection effects?

T.-H. Shih (reply)

No wall reflection or inhomogeneous effects were included. From the com-
parisons may be we can see how to include the inhomogeneous effects.
B.E. Launder (to J.R. Ristorcelli)

Regarding your choice of linear or nonlinear rapid term, it seems that the nature of inter-linkage between the stress and dissipation equations is crucial in determining if you get a steady state or a periodic behavior.

J.R. Ristorcelli (reply)

Everything was same and just the rapid term model was changed.

B.E. Launder (to J.R. Ristorcelli)

Since some of the $\epsilon$ equations you are using are not the ones advocated by the model originators so what you were seeing wasn't the effect of just a change in the rapid term.
THE PRESENT STATE AND FUTURE DIRECTION
OF SECOND ORDER CLOSURE MODELS
FOR COMPRESSIBLE FLOWS

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Reynolds Stress Closure Models

- The complexity of the turbulent flow fields associated with advanced aerodynamic vehicles requires turbulent closure models that are capable of handling phenomena such as shock-turbulence interactions, flow separation, and strong three-dimensional effects.

- The strong anisotropies associated with such effects cannot, in general, be handled by eddy viscosity type models. The next level of closure is required, that is, Reynolds stress closure models.

- Some areas where work needs to be focused in order to effectively close the Reynolds stress transport equations are:
  - Pressure-strain models capable of handling complex flows.
  - Pressure dilatation model for compressible flows.
  - Model for the compressible dissipation rate.
  - Near-wall stiffness problems.
  - Reynolds mas and heat flux terms

- In order to compute complex compressible turbulent flows, it is also necessary to develop efficient and accurate numerical algorithms whose characteristics are well documented.
Favre Averages and Governing Equations

- Any dependent flow variable $f$ can be decomposed using the usual Reynolds decomposition given by

$$f = \bar{f} + f',$$

where

$$\bar{f} = \lim_{\tau \to \infty} \frac{1}{\tau} \int_0^\tau f(x, t) \, dt$$

or a Favre average given by

$$f = \tilde{f} + f'',$$

where

$$\tilde{f} = \frac{\rho \bar{f}}{\rho}.$$
Favre Averages and Governing Equations (cont.)

- The mean conservation equations for mass, momentum and total energy can then be written as

**MASS**

\[ \partial_t \bar{\rho} + (\bar{\rho} \bar{u}_k)_k = 0, \]

**MOMENTUM**

\[ \partial_t (\bar{\rho} \bar{u}_i) + (\bar{\rho} \bar{u}_i \bar{u}_j)_{,j} = -\bar{p}_{,i} + \bar{\sigma}_{ij,j} - (\bar{\rho} \bar{\tau}_{ij})_{,j}, \]

where

\[ \bar{\sigma}_{ij} = -\frac{2}{3} \mu \bar{u}_{k,k} \delta_{ij} + \mu (u_{i,j} + u_{j,i}) \approx -\frac{2}{3} \mu \bar{u}_{k,k} \delta_{ij} + \bar{\mu} (\bar{u}_{i,j} + \bar{u}_{j,i}) \]

\[ \bar{\tau}_{ij} \equiv \bar{u}_i^\prime \bar{u}_j^\prime, \quad \bar{p} = \bar{\rho} \bar{R} \bar{T} \]
Favre Averages and Governing Equations  (cont.)

TOTAL ENERGY

\[ \partial_t (\rho \dot{E}) + (\rho \dot{u}_k \dot{E})_{,k} = (\sigma_{jk} \bar{u}_j - \rho \dot{u}_k - \bar{q})_{,k} + (\sigma'_{jk} \bar{u}'_j - \rho' \bar{u}'_k - \bar{E}'' \bar{u}''_k)_{,k} \]

where \( E = C_v T + \frac{1}{2} u_i u_i \),

\[ \bar{q}_k = -\kappa \bar{T}_{,k} \approx -\kappa \bar{T},_{k} \]

\[ \bar{E}'' \bar{u}''_k = C_v \bar{u}'' \bar{T}'' + \bar{u}_i \tau_{jk} + \frac{u''_i \bar{u}'_j \bar{u}'_k}{2} \]

\[ \approx -C_v C'_\mu \frac{k^2}{\epsilon \bar{T}} \bar{T}_{,k} + \bar{u}_i \tau_{jk} + \frac{u''_i \bar{u}'_j \bar{u}'_k}{2} \]

and \( \kappa \) is the thermal conductivity.

- The energy equation is written in terms of the total energy because this structure is necessary in order to effectively employ shock capturing techniques in the numerical solution algorithms.
Favre Averages and Governing Equations (cont.)

- The Favre-averaged Reynolds stress transport equation is given by

\[
\partial_t(\bar{\rho}\tau_{ij}) + (\bar{u}_k\bar{\rho}\tau_{ij})_k = P_{ij} + \Pi_{ij} - T_{ijk,k} - \epsilon_{ij} + \frac{2}{3}p'u'_{k,k}\delta_{ij} - \bar{u}''_{i}\bar{p}_j - \bar{u}''_{j}\bar{p}_i + (\sigma'_{ik}u'_j + \sigma'_{jk}u'_i)_k + \bar{u}''_{i}\bar{\sigma}_{jk,k} + \bar{u}''_{j}\bar{\sigma}_{ik,k}
\]

where

\[
P_{ij} = -\bar{\rho}\tau_{ik}\bar{u}_{j,k} - \bar{\rho}\tau_{jk}\bar{u}_{i,k}
\]

\[
\Pi_{ij} = \frac{p'u'_{i,j} + p'u'_{j,i}}{2} - \frac{2}{3}p'u'_{k,k}\delta_{ij}
\]

\[
\epsilon_{ij} = \frac{\sigma'_{ik}u'_{j,k} + \sigma'_{jk}u'_{i,k}}{k^2}
\]

\[
T_{ijk} = \frac{p'u''_{i}u''_{j}u''_{k}}{\bar{\rho}} + (p'u'_{i}\delta_{jk} + p'u'_{j}\delta_{ik})
\]

\[
\sim -C_s\bar{\rho}\frac{k^2}{\epsilon}[\tau_{ij,k} + \tau_{jk,i} + \tau_{ik,j}]
\]

and

\[
\sigma'_{ik}u'_{j} + \sigma'_{jk}u'_{i} \sim \bar{\mu}[\tau_{ij,k} + \tau_{jk,i} + \tau_{ik,j}]
\]
Model for the Deviatoric Part of the Pressure-Strain Rate Correlation

- An analysis of pressure-strain correlation models using a dynamical systems approach has led to the development of a new model for this correlation. This improved model is only weakly nonlinear in the anisotropy tensor.

- Based on an analysis of the bifurcation diagram for rotating shear flow, it has been shown that the deficiencies of many pressure-strain correlation models are intrinsic to this general hierarchy of models and cannot be eliminated by the addition of more complex terms.

- The model performs better, overall, in incompressible, homogeneous shear, with and without rotation than previously proposed models. In the case of homogeneous shear with curvature, the model performs as well as other models.

- This overall improvement is shown to carry over to the compressible regime where a simple variable density extension of the model is used.
The SSG Pressure-Strain Rate Correlation Model

\[ \Pi_{ij} = -\rho(C_1 \varepsilon + C_1^* \mathcal{P}) b_{ij} + C_2 \varepsilon (b_{ik}b_{kj} - \frac{1}{3} b_{mn} b_{mn} \delta_{ij}) + (C_3 - C_3^* II^\frac{1}{2}) k (\tilde{S}_{ij} - \frac{1}{3} \tilde{S}_{kk} \delta_{ij}) \]
\[ + C_4 k (b_{ik} \tilde{S}_{jk} + b_{jk} \tilde{S}_{ik} - \frac{2}{3} b_{mn} \tilde{S}_{mn} \delta_{ij}) + C_5 k (b_{ik} \tilde{W}_{jk} + b_{jk} \tilde{W}_{ik}) \]

where \( \mathcal{P} = -\tau_{ij} \tilde{u}_{i,j} \) is the turbulence production, \( \tilde{S}_{ij} \) and \( \tilde{W}_{ij} \) are the mean strain and vorticity tensors, respectively, and

\[ C_1 = 3.4, \ C_1^* = 1.80, \ C_2 = 4.2, \ C_3 = \frac{4}{5}, \]
\[ C_3^* = 1.30, \ C_4 = 1.25, \ C_5 = 0.40 \]
Comparison of the Speziale, Sarkar and Gatski (SSG) model and Fu, Launder and Tselepidakis (FLT) model with large-eddy simulations (LES) of rotating shear flow for different ratios of the rotation rate to shear ($\Omega/S$): (a) LES of Bardina, Ferziger and Reynolds, (b) FLT model, and (c) SSG model.
Variation of Kinetic Energy with Strain for Homogeneous Shear with Longitudinal Curvature (symbols are the experimental results of Holloway and Tavoularis, 1992): a) Craft, Fu, Launder and Tselepidakis (CFLT) Model, b) SSG Model.
Variation of Anisotropies with Strain for Homogeneous Shear with Longitudinal Curvature (symbols are the experimental results of Holloway and Tavoularis, 1992): a) Craft, Fu, Launder and Tselepidakis (CFLT) Model, b) SSG Model.
A Model for the Pressure-Dilatation $\overline{p'd'}$

- Decompose the pressure-dilatation into contributions from the incompressible pressure and the compressible pressure.

$$\overline{p'd'} = \overline{p'^{i}d'} + \overline{p^{C'}d'}$$

- The incompressible pressure satisfies the usual Poisson equation

$$\nabla^2 p'^{i} = -2\overline{\rho u'_{m,n}u'^{i}_{n,m}} - \overline{\rho u'_{m,n}u'^{i}_{n,m}}$$

and the remainder is the compressible pressure $p^{C'}$

- The time-integrated $\overline{p^{C'}d'} \approx 0$. Therefore only $\overline{p'^{i}d'}$ needs to be modeled.

- The Poisson equation for $p'^{i}$ is solved and the resulting exact expression for $\overline{p'^{i}d'}$ is used to obtain the following model

$$\overline{p'd'} = -\alpha_2\overline{\rho P M^2_i} + \alpha_3\overline{\rho \epsilon_s M^2_i}$$

where $P = -\overline{\epsilon_{ij}u''_{i}u''_{j}}$ is the production, and $\epsilon_s$ the solenoidal dissipation.

- DNS is used to verify the model for $\overline{p'd'}$ and to calibrate it.
Pressure-Dilatation as a Function of Nondimensional Time: a) Decaying Isotropic Turbulence, b) Homogeneous Shear Flow.
Compressible Turbulent Dissipation Rate Model

- For the present purposes, the turbulent dissipation rate is assumed to be isotropic, so that
  \[ \epsilon_{ij} = \frac{2}{3} \rho \epsilon \delta_{ij}, \]
  and
  \[ \overline{\rho \epsilon} = \sigma_{k1} u'_{k,1}. \]

- The compressible Navier-Stokes equations have been asymptotically analyzed at high Reynolds numbers. This leads to a decomposition of the dissipation rate \( \epsilon \) into a solenoidal part, \( \epsilon_s \), and a compressible part, \( \epsilon_c \),
  \[ \overline{\rho \epsilon} = \rho (\epsilon_s + \epsilon_c), \]
  where
  \[ \epsilon_s = \overline{\nu \omega'_i \omega'_i}, \quad \epsilon_c = \frac{4}{3} \overline{\nabla u'^2_{k,k}}, \]
  and \( \omega'_i \) is the fluctuating vorticity.
Compressible Turbulent Dissipation Rate Model (cont.)

- There is an equi-partition between the kinetic and potential energies in high turbulent Reynolds number and low turbulent Mach number flows. The analysis leads to a model for the compressible dissipation rate,

\[ \epsilon_c \simeq \alpha_1 \epsilon_s M_t^2, \]

where \( M_t \) is the turbulent Mach number based on the turbulent kinetic energy and local mean speed of sound, and the modeling coefficient \( \alpha_1 \) is taken as 0.5 based on comparison with direct simulations of the compressible, homogeneous turbulence.

- An extension of the incompressible form is adopted for \( \epsilon_s \),

\[ \partial_t(\bar{\rho}\epsilon_s) + (\bar{\rho}\bar{u}_k\epsilon_s)_k = - C_{\epsilon_1} \frac{\epsilon_s}{k} \bar{\rho} \tau_{ij}(\bar{u}_{i,j} - \frac{1}{3} \bar{u}_{k,k} \delta_{ij}) - \frac{4}{3} \bar{\rho} \epsilon_s \bar{u}_{i,i} \]
\[ - C_{\epsilon_2} \bar{\rho} \frac{\epsilon_s^2}{k} + C_{\epsilon} \left( \frac{\bar{\rho}_k}{\epsilon_s} \bar{u}_k \bar{u}_l \epsilon_s \epsilon_{s,l} \right)_k \]

where the model coefficients are given by

\[ C_{\epsilon_1} = 1.44, \quad C_{\epsilon_2} = 1.90, \quad C_{\epsilon} = 0.15 \]
Compressible Turbulent Dissipation Rate Model (cont.)

- This equation is applicable to moderate Mach number turbulence and may have to be modified for strongly supersonic or hypersonic flows.
Variation of Scaled Turbulent Dissipation Rate Ratio as a Function of Nondimensional Time (a) and Turbulent Mach Number (b).
Variable Viscosity Effects

- The transport equation for the fluctuating vorticity can be written in the form

\[ \frac{\partial \omega'_i}{\partial t} + \tilde{u}_j \frac{\partial \omega'_i}{\partial x_j} = F_i \]

- The solenoidal dissipation is defined as \( \epsilon_s = \nu \overline{\omega'_i \omega'_i} \). It can be obtained from the fluctuating vorticity transport equation by first using

\[ 2\tilde{\nu} \overline{\omega'_i} \left( \frac{\partial \omega'_i}{\partial t} + \tilde{u}_j \frac{\partial \omega'_i}{\partial x_j} \right) + \frac{D\overline{\nu}}{Dt} \overline{\omega'_i \omega'_i} = \frac{\partial (\tilde{\rho} \epsilon_s)}{\partial t} + \frac{\partial (\tilde{\rho} \tilde{u}_j \epsilon_s)}{\partial x_j} \]

- The transport equation for the solenoidal dissipation can then be written as

\[ \frac{\partial (\tilde{\rho} \epsilon_s)}{\partial t} + \frac{\partial (\tilde{\rho} \tilde{u}_j \epsilon_s)}{\partial x_j} = \frac{D\overline{\nu}}{Dt} \omega'_i \omega'_i - \frac{4}{3} \tilde{\rho} \epsilon_s \frac{\partial \tilde{u}_i}{\partial x_i} - C_{\epsilon_1} \frac{\epsilon_s}{k} \tilde{\rho} r_{ij} \left( \tilde{u}_{i,j} - \frac{1}{3} \tilde{u}_{k,k} \delta_{ij} \right) \]

\[ - C_{\epsilon_2} \tilde{\rho} \frac{\epsilon^2_s}{k} + C_{\epsilon} \left( \frac{\tilde{\rho} k}{\epsilon_s} \overline{\omega'_k \omega'_l} \epsilon_{s,l} \right)_{k} \]

- For simplicity, a power law dependence on the temperature can be used for the molecular viscosity

\[ \mu(T) = \mu(T_0) \left( \frac{T}{T_0} \right)^n \]

where \( n \approx 0.7 \).
Variable Viscosity Effects (cont.)

- This leads to the relation (using the isentropic compression assumption; see Coleman & Mansour, 1991)

\[
\frac{D\bar{\nu}}{D_t} \omega'_i \omega'_i = \bar{\rho} \epsilon_s \frac{1}{\bar{\nu}} \frac{D\bar{\nu}}{Dt} = [1 - n(\gamma - 1)] \frac{\partial \bar{u}_i}{\partial x_i} \bar{\rho} \epsilon_s
\]

where \( \gamma = c_p/c_v \).

- The solenoidal dissipation equation can then be written as

\[
\frac{\partial (\bar{\rho} \epsilon_s)}{\partial t} + \frac{\partial (\bar{\rho} \bar{u}_j \epsilon_s)}{\partial x_j} = - 0.6 \bar{\rho} \epsilon_s \frac{\partial \bar{u}_i}{\partial x_i} - C_{\epsilon 1} \frac{\epsilon_s}{k} \bar{\rho} \tau_{ij} (\bar{u}_{i,j} - \frac{1}{3} \bar{u}_{k,k} \delta_{ij})
\]

\[
- C_{\epsilon 2} \bar{\rho} \frac{\epsilon_s^2}{k} + C_{\epsilon} \left( \frac{\bar{\rho} k}{\epsilon_s} \bar{u}_k'' \bar{u}_l'' \epsilon_{s,l} \right)_{,k}
\]
Supersonic Shear Layer

- It is observed experimentally that the fully developed turbulent shear layer spreads as

\[
\frac{d \delta}{dx} = C_\delta \left( \frac{U_1 - U_2}{U_1 + U_2} \right)
\]

where \( C_\delta \) is approximately constant for the incompressible case.

- Experiments show that the spreading rate parameter \( C_\delta \) decreases dramatically when the convective Mach number \( M_c = \Delta/(a_1 + a_2) \) increases.
Variation of Normalized Growth Rate with Convective Mach Number for Supersonic Shear Layer.
Variation of Normalized Stress Distributions with Convective Mach Number for Supersonic Shear Layer: (a) Normalized Streamwise Stress, (b) Normalized Shear Stress.
Near-Wall Stiffness Problems

- It is becoming more desirable to integrate directly to the wall in solving wall-bounded turbulent flows because of the need to compute more complex flowfields.

- It is necessary to have the proper balance of terms in the near-wall region in order to insure the correct asymptotic behavior of the computed turbulent variables.

- An analysis of two-equation models has shown that there are two major deficiencies associated with the solution of the isotropic dissipation rate equation: (1) the lack of natural boundary conditions for the dissipation rate, $\epsilon$, and (2) the appearance of higher-order correlations in the balance of terms for the dissipation rate at the wall.

- This deficiency naturally carries over to the solution of the Reynolds stress transport equations.

- In order to achieve asymptotic consistency in the near-wall region, a modification of the solenoidal dissipation equation is required.

- Two damping functions need to be introduced into the equation: (1) a damping function associated with the eddy viscosity in order to insure the correct near-wall behavior for the modeled triple correlation term, (2) a damping function associated with the destruction of dissipation term.
Normalized Skin-Friction Distribution: a) as a function of Mach number for adiabatic wall, b) as a function of wall temperature.
Models for the Reynolds Mass and Heat Flux

- An examination of the total energy equation and the Reynolds stress transport equations how that models for both the heat flux $u_k''T_k''$ and the mass flux $u_i''$
  
- These quantities are also needed in the modeling of the pressure-velocity diffusion term $(p'u_i')_j$
  
\[
  p'u_i' = -\tilde{\rho}R\tilde{T}u_i'' + \tilde{\rho}Ru_i''\tilde{T}''
\]

- When gradient transport models are used in the model for the pressure-velocity diffusion term, stiffness problems arise.
  
\[
  \overline{u_i''} = \frac{C_\mu}{\rho\sigma_\rho} \frac{k^2}{\epsilon} \tilde{\rho},i
\]

\[
  u_i''\tilde{T}'' = -\frac{C_\mu}{\sigma_T} \frac{k^2}{\epsilon} \tilde{T},i
\]

- Improvements in the gradient transport hypothesis or an improved set of models for both the Reynolds heat and mass flux are probably needed.
Numerical Solution of Compressible Turbulent Transport Equations

- Discretization Requirements
  - Accuracy
  - Shock Capturing Ability
  - Artificial Dissipation Scheme Development

- Time Integration Requirements
  - Turbulent transport equations are stiff in near-wall region

- Geometric Complexity Requirements
  - Practical aerodynamic configurations are very complex

- The discretization requirement can be satisfied by developing an algorithm using a (upwind) Roe flux difference splitting scheme for the spatial differences.

- The time integration requirement can be satisfied by using an implicit time integration scheme.

- The extension to complex geometries can be accomplished in many configurations by using a multiblock, finite volume method.
Concluding Remarks

- As has been shown, compressibility corrections and modifications need to be introduced into a variety of terms in the energy and Reynolds stress transport equations in order to treat high speed flows.

- The more important the role of turbulent transport processes in the flow dynamics, the more desirable/necessary it is to use turbulent stress transport equations.

- At present there is a reluctance to generally utilize Reynolds stress transport equations relative to the simpler two-equation turbulence models. This is true in the incompressible regime and even more so in the compressible regime.

- Reynolds stress turbulent modeling will be utilized on a broader scale only after it is shown that it can be efficiently used with improved predictive capability.

- A generalized time accurate Navier-Stokes code is being adapted (LaRC) to run both two-equation and Reynolds stress models. This duality eliminates the numerical differences and the efficiency of the algorithm with the turbulent closure models can be effectively compared.
Comment on: The Present State and Future Direction of Second-order Closure Models for Compressible Flows

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Workshop on Engineering Turbulence Modeling
August 21-22, 1991
Outline

• Viegas
  • Opening comments
  • An alternative RSE model
    • Results from VHVRK (FRAME) and LS models
  • On shear layers — spread rate comparisons
    • Results of compressibility corrections

• Huang
  • General comments on RSE models
    • compressibility corrections
  • On the law of the wall
  • Concluding remarks
An alternative RSE model: FRAME model (VHVRK, 1983)

* Developed in collaboration with colleagues from France
  (A second-order closure model for compressible turbulent boundary layers which is capable of predicting shock boundary layer flows.)

* Builds upon pioneering incompressible second order model of LRR.

* Compressibility effects included by:
  * Introducing Favre Averaging
  * Reintroducing non-zero divergence terms that were eliminated in original models
  * Accounting for non-zero mass weighted fluctuating velocity - compressibility terms.

* Near wall effects included by using:
  * LRR near wall pressure-rate of strain terms
  * Wall damping of quadratic return to isotropy (slow) terms and in the dissipation terms
  * Using the Favre averaged form of the Hanjalic-Lauder dissipation rate equation with some coefficient modifications to the near wall terms and by using wall damping in the destruction part of this equation.

* Uses total energy equation (including $k$)
* Uses "total" turbulent dissipation rate equation

Successfully applied to:

* Adiabatic flat plate, $M=3$, to develop model
* Supersonic expansion at $M=1.76$ - Dussauge
* Transonic shock-boundary layer interaction at $M=1.36$ - Delery
* Corner flow at $M=3$ - Settles
* Oscillating boundary layer on flat plate at $M=0$ - Spalart -DNS
* Adiabatic and nonadiabatic flat plate to $M=8$ - Karman-Shoenherr
SKIN FRICTION ON AN ADIABATIC FLAT PLATE

KARMAHNSCHOENHERR LAW

\[ C_f \text{ and } \text{Re}_x \text{ directly measured, } M_* = 1.5 \rightarrow 5.8 \]

JONES-LAUNDER MODEL

LAUNDER-SHIMA MODEL

FRAME MODEL
SKIN FRICTION ON A NON-ADIABATIC FLAT PLATE AT MACH NO. = 5

KARMANN-SCHOENHERR LAW

○ TW/TAW = 1.0
○ TW/TAW = 0.8
△ TW/TAW = 0.6
+ TW/TAW = 0.4
X TW/TAW = 0.2

C_f directly measured; M_s = 2.8 → 7.4.

JONES-LAUDER MODEL

LAUNDER-SHIMA MODEL

FRAME MODEL
ALTERNATIVE CORRELATIONS OF SPREAD RATE

* IMPACT PRESSURE THICKNESS

\[ \delta'_{\text{pit}} = G(M_c) \frac{(1 - U_2/U_1) (1 + \sqrt{(\rho_2/\rho_1)} )}{1 + \sqrt{(\rho_2/\rho_1)} (U_2/U_1)} \]

\[ M_c = \frac{M_1 \sqrt{\rho_2/\rho_1} - M_2}{\sqrt{\rho_2/\rho_1} + 1.0} \]

\[ G(M_c)/G(0) \]

Papamoschou and Roshko

* VORTICITY THICKNESS

\[ \delta_\omega = (U_1 - U_2)/(\partial U/\partial y)_{\text{max}} \]

\[ \delta'_{\omega} = C_\omega(M_c) \frac{1 - U_2/U_1}{1 + U_2/U_1} \]

\[ C_\omega(M_c)/C_\omega(0) \]

Bagdanoff
TURBULENCE MODELS APPLIED

EDDY VISCOSITY (mass weighted variables)

\[ \mu_t = C_\mu \bar{\rho} \frac{\bar{k}^2}{\bar{\varepsilon}} \]

\[ C_\mu = 0.09 \]

TURBULENCE FIELD EQUATIONS

\[ (\bar{\rho} \bar{k}),_t + (\bar{\rho} \bar{u}_j \bar{k})_j = -(\bar{\rho} \bar{u}_i'' \bar{u}_j'' \bar{u}_i \bar{j}) - \bar{\rho} \bar{\varepsilon} + D_k + E_k \]

\[ (\bar{\rho} \bar{\varepsilon}),_t + (\bar{\rho} \bar{u}_j \bar{\varepsilon})_j = -C_{e1} \frac{\bar{\varepsilon}}{\bar{k}} (\bar{\rho} \bar{u}_i'' \bar{u}_j'') \bar{u}_i \bar{j} - C_{e2} \bar{\rho} \frac{\bar{\varepsilon}^2}{\bar{k}} + D_\varepsilon + E_\varepsilon \]

\[ E_k, E_\varepsilon = \text{Extra Compressibility Terms} \]

STANDARD k - \varepsilon MODEL \hspace{1cm} E_k = 0 \text{ and } E_\varepsilon = 0

SARKAR ET AL. (SEHK) k - \varepsilon MODEL \hspace{1cm} E_\varepsilon = 0

\[ E_k = -\alpha_1 M_t^2 \bar{\rho} \bar{\varepsilon} \]

\[ M_t = \frac{\sqrt{2k}}{a} \]

\[ a = \sqrt{\gamma RT} \]

\[ \alpha_1 = 1.0 \]

ZEMAN k - \varepsilon MODEL \hspace{1cm} E_\varepsilon = 0

\[ E_k = -C_d F(M_t) \bar{\rho} \bar{\varepsilon} \]

\[ F(M_t) = 1.0 - \exp \left[ - \left( \frac{(M_t - 0.1)}{0.6} \right)^2 \right] \]

and \[ F(M_t) = 0, \text{ if } M_t < 0.1, \]

\[ C_d = 0.75 \]

\[ M_t = \frac{\sqrt{2k}}{a^*} \]

\[ a^* = \sqrt{2\gamma RT/(1+\gamma)} \]

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EFFECT OF COMPRESSIBILITY CORRECTIONS ON PREDICTED FREE-SHEAR SPREAD RATES

[Graph showing Impact Pressure Thickness Growth Rate]

Matched free stream densities

\[ p_1 = p_2 = 2116.8 \text{ psf} \]
\[ T_1 = T_2 = 500 \degree R \]
\[ M_2 = 2.0 \]

[Graph showing Vorticity Thickness Growth Rate]

Model

- Standard \( k - \epsilon \)
- SEHK
- Zeman

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EFFECT OF COMPRESSION CORRECTIONS ON IMPACT-PRESSURE THICKNESS GROWTH RATE

Matched total temperatures

$T_{11} = T_{12} = 1500 \, ^\circ \text{R}$

$\rho_1 = \rho_2 = 2116.8 \, \text{psf}$

Model

☐ Standard $k - \varepsilon$

△ SEHK

◇ Zeman

Data

■ "Langley compilation"

◇ Chinzei et al.

▲ Papamoschou and Rashko

---

Lauder et al. $k - \varepsilon$ parabolic calc

$G/(G_0)$ vs. $M_e$
EFFECT OF COMPRESSIBILITY CORRECTIONS ON VORTICITY THICKNESS GROWTH RATE

Matched total temperatures

\( T_{11} = T_{12} = 1500 \, ^\circ\text{R} \)
\( p_1 = p_2 = 2116.8 \, \text{psf} \)

\[
\frac{C_{w}}{C_w(0)}
\]

\[
M_{1,2}
\]

2.8, 2

5.3, 2

4.9, 1

14, 2

4.5; 8.1; 16, 1.5

13, 5

Model

- Standard \( k - \varepsilon \)
- SEHK
- Zemon

Data

- Bogdanoff compilation
- Elliot and Sommny

\( M_e \)
Evolution of Turbulence Models

- Experiments
- Physical Intuition
- DNS & LES
- Math. Constrain

Incom. Models

\[ \frac{\partial \psi}{\partial t} = f(k, e, \ldots) \]

Include dilatation terms

Comp. Models

\[ \frac{d}{dx} \left( \frac{u^2 dp}{dx} \right) \]

\[ p' \frac{du}{dx} \]
Modeling

\[
\frac{D\rho u_i''u_j''}{Dt} = d_{ij} + P_{ij} + \Phi_{ij} - \rho \varepsilon_{ij} + \text{Compressibility terms}
\]

Incompressible Modeling

- Turbulence diffusion, \( d_{ij}^T \)
  
  \[
  \frac{\partial}{\partial x_k} \left[ c_s \rho \frac{k}{\varepsilon} \left( u_i''u_m'' \frac{\partial u_j''}{\partial x_m} + u_j''u_m'' \frac{\partial u_i''}{\partial x_m} + u_i''u_m'' \frac{\partial u_j''}{\partial x_m} \right) \right]
  \]
  
  \[
  \frac{\partial}{\partial x_k} \left[ \frac{2}{3} c_s \rho \frac{k}{\varepsilon} \left( \frac{\partial u_i''}{\partial x_m} + \frac{\partial u_j''}{\partial x_m} + \frac{\partial u_i''}{\partial x_m} \right) \right]
  \]

- Pressure Interaction, \( \Phi_{ij} = \Phi_{ij,1} + \Phi_{ij,2} + \Phi_{ij,w} \)

  - Slow Term, \( \Phi_{ij,1} \)
    
    \[
    -c_1 \rho \varepsilon b_{ij}
    \]
    
    \[
    -c_1 \rho \varepsilon b_{ij} + c'_1 \rho \varepsilon (b_{ik} b_{kj} - \frac{1}{3} II \delta_{ij})
    \]

  - Fast Term, \( \Phi_{ij,2} \)
    
    - Launder, Reece and Rodi, 1975
    
    - Fu, Launder and Tselepidakis, 1987
    
    - Craft, Fu, Launder and Tselepidakis, 1991
    
    - Shih and Lumley, 1985
    
    - Speziale, Sarkar and Gatski, 1990
Incompressible Modeling (continue)

- Wall-Reflection Term, $\Phi_{ij,w}$
  - Hanjalic and Launder, 1976
  - Gibson and Launder, 1978

- Dissipation rate, $\varepsilon_{ij}$
  - isotropic, $\varepsilon_{ij} = \frac{1}{3} \delta_{ij} \varepsilon$, with constants in $\Phi_{ij}$ functions of II and III (Launder and Shima, 1989 and Launder, 1990)
  - anisotropic
    - $\varepsilon_{ij} = [(1 - f) \frac{1}{3} \delta_{ij} + f u_i'' u_j' / k] \varepsilon$ [Hanjalic and Launder, 1976]
    - models satisfying asymptotic near-wall behavior [Launder and Reynolds, 1983; So, 1991 and Shih, 1991]
    - transport models model for $\varepsilon_{ij}$ [Kollman, 1991]

- Heat Fluxes, $u_i' \theta$
  - $u_i \theta = -\frac{2}{3} c_T \frac{k^2}{\varepsilon} \frac{\partial T}{\partial x_k}$
  - $u_i' \theta = -c_T \frac{k}{\varepsilon} u_i'' u_j' \frac{\partial T}{\partial x_k}$
  - ASM type heat-flux equation
  - Transport heat-flux equations
Compressible Modeling

- Pressure dilatation, $p'u''_{k,k}$
  - Gatski et al., 1991 ($f_1(M_t)P_k$ and $f_2(M_t)\epsilon$)
  - Zeman, 1991 ($\rho'^2$-equation)
  - Rubesin, 1990 ($\rho'^2$-equation + polytropic process)
  - Taulbee and VanOsdol, 1991 ($\rho'^2$-equation + modeled $p'u''_{k,k}$ Poisson solution)

- Fluctuation velocity average, $\bar{u}''_i$
  - Gatski et al., 1991 (density-gradient model)
  - Zeman, 1991 (transport equation for $\bar{u}''_i$)
  - Taulbee and VanOsdol, 1991 (transport equation for $\bar{u}''_i$)
  - Rubesin, 1991 (Constant total enthalpy + polytropic process)

- Dilatation dissipation
  - $\epsilon = \epsilon_s + \epsilon_d$ and $\epsilon_d = f(M_t)\epsilon_s$
    - Zeman, 1990
    - Sarkar et al., 1989
    - Rubesin, "total" $\epsilon$-transport equation.

- Rapid Compression Model, $\rho L^n = \text{Constant}$ (Reynolds, 1980; Morel and Mansour, 1982; Young and Coakley, 1987; Coakley and Huang, 1991; Rubesin, 1990 and Zeman, 1991)
Some Remarks

- There are more models than what has been presented in the position paper. Some have been tested in many "real" flows with success.

- Comparison of the models based only on simple homogenous-type flows may be misleading.

- Near-wall modeling is still a challenging problem for 2nd moment closure.

- Due to strong coupling among governing equations and the absence of numerical stabilizing turbulence viscosity in the mean-flow equations, the solution of Reynolds stress equations requires special attention.

- Currently, LRR, FRAME and Launder-Shima models have been implemented in a N-S code and comparison of models against real-flow experimental data is underway.

- The use the total energy is necessary for hypersonic flow calculations: \( E_T = E + k \), where \( E = c_v T + \frac{1}{2} u^2 \)

\[
\frac{D \rho E}{Dt} = \ldots - P_k + \rho \varepsilon
\]
Hypersonic Cylinder-Flare

$35^\circ$ flare angle $M = 7.05$

- Experiments
- $k-\omega$ model
- With $k$ in $E$
- Without $k$ in $E$

Surface pressure

Surface heat transfer

$s$ (cm)
Some Remarks (continue)

- \textit{Wall flows} — The law of the wall is independent of the Mach number if the comparison is made based on the Van Driest transformed variables.

- Models using $\epsilon$-equation produce lower Von Karman constant, $\kappa$.

- Model constants can be derived as functions of density gradients.

- $k - \omega$ model is less sensitive to Mach number effects (coincidence?) — only for wall flows.

- Need more turbulent energy !!

- Dilatation dissipation concepts make the flow more \textit{laminar} — wrong direction.

- The new pressure dilatation model shown in the position paper also lowers $\kappa$.

- Rubesin's total $\epsilon$-model approach goes into the right direction.

- Zeman's new pressure dilation model does an excellent job.
$M = 10, \text{Re}^0 = 50000$

Adiabatic Wall, Boundary Layer Flow
Compressible Law of the Wall
Compressible law of the wall
Adiabatic wall, couette flow

\[ U_c^+ \]

- \( \kappa = 0.41 \)
- unmod. model
- Sarkar p dilatation
- Zeman p dilatation
- dissip. dilatation
- Rubesin

\[ M = 5, \text{Re}_\theta = 10000 \]
\[ \kappa-\varepsilon \text{ model} \]
Some Remarks (continue)

- Modeling of the $\epsilon$ equation is still a challenging problem — both for incompressible and compressible flows — Experience has shown that a 2-equation-level model can be used to improve the weakness of the $\epsilon$-equation.

- Two baseline test problems are recommended - one is the compressible mixing layer and the other is the compressible law of the wall. Experience has shown that these two flows display completely different behavior.
  
  - **Mixing layer** — As Mach number increases, the spreading rate decreases.
    
    - All unmodified turbulence models fail to predict this behavior.
    
    - This leads to models designed to increase the total dissipation rate as the turbulence Mach number increases.
Comment 1: Turbulent Dissipation Rate - $\bar{\rho} \varepsilon$

$$\bar{\rho} \varepsilon = \bar{\rho} \left( \varepsilon_s + \varepsilon_c \right), \quad \varepsilon_s = \bar{\nu} \omega_i^{''} \omega_i^{''}$$

$$\frac{D \varepsilon_s}{Dt} = \text{Incompressible Models} - 0.6 \bar{\rho} \varepsilon_s \bar{u}_{k,k} \text{ (in the position paper)}$$

$$- \bar{r}_{ij}^{'''} \bar{T}_{jj}^{'''} \bar{S}_{ii}^{'''} + ... \text{ (Liou and Shih (1991))}$$

- Preliminary analysis (Liou and Shih (1991)) has shown that the third order moments, $\bar{r}_{ij}^{'''} \bar{T}_{jj}^{'''} \bar{S}_{ii}^{'''}$, may be as important as the terms that being retained and may need to be modeled as well.

Comment 2: Turbulent Mass Flux - $\bar{u}_i^{'}$

Compressibility Effects: ..., reduced spreading rate, ...

entainment

- Turbulent mass flux terms in the Favre-averaged equations may have a fair amount of effect on the mean flow development if they are modeled more rigorously, especially for wall-bounded flows.
DISCUSSION

B. E. Launder (T.B. Gatski)

I must say that I feel preferably unpersuaded by the practice of adding, just multiplying the dissipation rate which comes out of the dissipation rate transport equation by a factor that is proportions to the Mach number. A concept of the dissipation equation is that it is really representing the spectral transfer rate of energy. It is looking at the large scales; the small scales are totally irrelevant. Admittedly, you won't get the right behavior with the so-called standard dissipation equation. But surely one must look at how to improve the transport equation rather than having a quick fix.

A comment on what John Viegas said earlier. He looks at two flows and believes you need a correction of different sign - wrong! I believe we need to look at twenty-two or on hundred and twenty-two. All we are looking at is the desperate sparsity of the compressible flow data base. That is why one can get away with these simplistic ideas. Just by having \( c_1 \) equal to the quantity one plus a function of Mach number, quantity times epsilon won't work.

S. Sarkar (reply)

First, this was not meant to be the only compressible fix. And, as far as you're saying that the compressible dissipation should not add to the solenoidal dissipation, because after all our conventional wisdom is that this is a fine scale thing, therefore it shouldn't affect epsilon. This does not violate that. What you are saying is that this has an extra irrotational component which has large scales and small scales. It is not as if the compressibility is just changing the small scale end of the spectrum; what it is doing is creating an irrotational component that is both small and large scales. We are just choosing to look at the small scales because it's is simpler to do it.
G. Huang (S. Sarkar)

You can compose that anyway you like, but only for homogeneous and constant property flow.

S. Sarkar (reply)

Yes, absolutely.
THE PRESENT STATE AND
FUTURE DIRECTIONS OF
PDF METHODS

S. B. Pope
Cornell University
WORKSHOP OBJECTIVE

- "To discuss the present status and the future direction of various levels of engineering turbulence modeling related to CFD computations for propulsion"

- Combustion is an essential part of propulsion

- Discuss PDF methods for turbulent combustion
TURBULENT COMBUSTION MODELS

• Essential to integrate the development of:
  - turbulence model
  - chemical kinetics
  - numerical method

• Turbulent/combustion interactions

• Tractable thermochemistry
TURBULENT COMBUSTION MODELS IN USE IN INDUSTRY

Typically:

- k-ε
- equilibrium/mixing-limited combustion
- finite-volume codes
IMPROVEMENTS SOUGHT

• Finite-rate kinetics — NO$_x$, CO, soot
  — extinction, ignition

• Generality — beyond idealized premixed and diffusion flames

• PDF Methods can provide these improvements
PDF METHODS

- Solve modelled evolution equation for a one-point joint pdf

- \( \phi(x,t) \) — compositions, \( \phi = \{ \phi_1, \phi_2, ..., \phi_\sigma \} \)
  mass fractions, enthalpy

U(x,t) — velocity

\( \omega(x,t) \) — turbulence frequency = \( \varepsilon/k \)

- Hierachy of PDF methods

  - \( \phi \)
  - U, \( \phi \)
  - U, \( \omega, \phi \)

- Non-linear reaction rates in closed form
COMPOSITION JPDF

- Need turbulence model
  \((k-\varepsilon' \text{ or } \langle u_i u_j \rangle - \varepsilon')\)

- Gradient-diffusion model of turbulent transport of \(\phi\)

- e.g. J.-Y. Chen et al.
  
  - \(\langle u_i u_j \rangle - \varepsilon\)
  - 4-step reduced scheme for methane
  - solve for jpdf of 5 compositions
  - Masri/Bilger/Dibble piloted diffusion flame
VELOCITY-COMPOSITION JPDF

- $<\mathbf{U}>$, $<u_iu_j>$ etc. obtained from jpdf
- Need $\varepsilon$ equation (or equivalent)
- All convective transport in closed form (no gradient-diffusion modelling)
- Connection to Reynolds-stress models
- e.g. Haworth & El Tahry (GM)
  Anand et al. (Allison GT)
FLOW OVER A BACKWARD-FACING STEP

\[ H = 0.0762 \text{ m} \quad W_3/(W_3-H) = 1.43 \]
\[ W_3 = 0.254 \text{ m} \quad U_{ref} = 0.196 \text{ m/s} \]

MEASUREMENTS: PRONCHICK & KLINE (1983)
PDF CALCULATIONS: ANAND, POPE & MONGIA (1990)
FLOW OVER A BACKWARD-FACING STEP
MEAN AXIAL VELOCITY

<\textit{U}/U_{\text{ref}}>

\begin{align*}
\text{\textbullet} & = -0.71 \\
\text{\textbullet} & = -0.26 \\
\text{\textbullet} & = -0.01 \\
\text{\textbullet} & = 0.47
\end{align*}

\begin{align*}
\frac{y}{H} & = 0.01 \\
\frac{y}{H} & = 0.25 \\
\frac{y}{H} & = 0.50 \\
\frac{y}{H} & = 1.00
\end{align*}
FLOW OVER A BACKWARD-FACING STEP
TRIPLE CORRELATIONS

$10^3 \frac{\langle u^2 v' \rangle}{U_{ref}^3}$
VELOCITY-FREQUENCY-COMPOSITION JPDF

- Single, self-contained model equation
- Describes distribution of $\varepsilon$.
- e.g. plane mixing layer
PLANE MIXING LAYER
MEAN VELOCITY PROFILE

Data of Lang (1985)
JPDF CALCULATION OF THE PLANE MIXING LAYER
SCATTER PLOT: AXIAL VELOCITY vs. LATERAL POSITION
JPDF CALCULATION OF THE PLANE MIXING LAYER
SCATTER PLOT: DISSIPATION vs. LATERAL POSITION

\[ \frac{\epsilon^+}{\langle \epsilon \rangle_{\text{max}}} \]

\[ y^+/x \]
PRESENT STATE OF PDF METHODS

- Much research and development work remains to be done, but:
  
  - Realistic finite-rate kinetics have been incorporated
  
  - Applications have been made to complex 2D and 3D flows
  
  - Accuracy—should be at least as good as a second-order closure
THE FUTURE OF PDF METHODS

- El Tahry & Haworth (General Motors):

"...in our opinion, the PDF method is the most appealing of the one-point statistical approaches for in-cylinder reacting flows. Applications to in-cylinder combustion can be expected within a few years."

- Correa (General Electric):

"The prevalent k-ε/assumed shape pdf closure model...must be improved upon or replaced before other quantities can be usefully predicted. An alternative is the Monte-Carlo/pdf approach; although well proven for fully-developed shear flows, this method needs to be adapted to pressure-dominated flow in complex geometries."

- From Proposal for PDF research and development by Rolls Royce, SNECMA, MTU.....to European Community:

...a joint velocity-composition pdf...method allows relatively complex chemistry to be simulated and also fully couples the turbulence with the chemistry. It seems the only way forward from the present position.
FUTURE DIRECTIONS OF PDF METHODS

1. Improvements and extensions

2. Applications to practical combustion devices
IMPROVEMENTS

1. Reduced kinetics — Maas & Pope (1991)

DECAY OF THE PDF OF A CONSERVED SCALAR

DIRECT NUMERICAL SIMULATIONS

MAPPING CLOSURE
EXTENSIONS

- Incorporate $\nabla \phi$ in jpdf

  Meyers & O'Brien 1981

- Represent coupling between reaction and mixing

- Contains information on:
  - jpdf of $\xi$ and $\chi$ (diffusion flames)
  - $<c>$ and $\Sigma$ (premixed flames)

- Reconciles flamelet and non-flamelet approaches
NUMERICAL DEVELOPMENT FOR APPLICATIONS (WORK AT CORNELL)

1. Reduced kinetics—automatic generation and tabulation procedures

2. Improved Monte Carlo/particle method
   - second-order accurate in space and time
   - low statistical error

3. General, robust pressure algorithm
TRANSITION FROM k-ε to PDF

- Industrial combustor codes:
  - complex geometry—grid generation
  - models for other processes—sprays, soot, radiation
  - post-processing/integration in design procedures

- Incorporate PDF methods within existing codes

- Numerical method fundamentally different (particle method vs. finite-volume method)
4 STAGE TRANSITION

0. Starting point: finite volume code for 
   \( <U>, <p>, k, \varepsilon, <\phi> \)

1. \text{ jpdf of } U, \phi; \text{ discard } U \text{ information}  
   (PDF method determines \( <\phi>, <p> \): incorporate reduced kinetics)

2. \text{ jpdf of } U, \phi  
   (finite-volume code determines \( <p> \) and \( \varepsilon \))

3. \text{ jpdf of } U, \omega, \phi  
   (finite-volume code determines \( <p> \))

4. \text{ jpdf of } U, \omega, \phi—self-contained particle method
FIRST STAGE

finite-volume code

Monte Carlo/particle method

- essentially jpdf of $\phi$

- but simple transition (2nd stage) to

  jpdf of $<U>$, $\phi$ (avoids gradient-diffusion modelling)

- reduced kinetics can be incorporated
CONCLUSIONS

- Turbulent combustion modelling:
  need to integrate
  - turbulence model
  - chemical kinetics
  - numerical method

- PDF methods
  - $\phi; U, \phi; U, \omega, \phi$
  - reaction and convective transport in closed form
  - finite-rate kinetic effects

- Future model development:
  - mapping closures
  - reduced kinetics
  - add $\nabla \phi$

- Future numerical developments:
  - more accurate particle methods
  - general pressure algorithm
  - incorporation in combustor codes

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COMMENTS ON
THE PRESENT STATE AND
FUTURE DIRECTIONS OF
PDF METHODS

E.E. O'Brien
SUNY at Stony Brook

My first comment on the presentation of S.B. Pope is to note that Professor Pope is almost single-handedly responsible for the development of the one-point PDF method to the state in which it can now be reasonably expected to address actual engineering problems.

My second comment is that I am in accord with virtually all of the points he has made including his first, which was to express surprise that a conference on "modeling related to CFD computations for propulsion" should be so thin on combustion modeling. The PDF method he reviewed is relatively complicated, but it appears to be the only format available to handle the non-linear stochastic difficulties caused by typical reaction kinetics. Turbulence modeling, if it is to play a central role in combustion modeling, as it must, has to be integrated with the chemistry in a way which produces accurate numerical solutions to combustion problems. It is questionable whether the development of turbulent models in isolation from the peculiar statistics of reactant concentrations is a fruitful line of development as far as propulsion is concerned.

There are three issues, two mentioned by S.B. Pope, for which I have prepared additional outlines which are appended to this note.

a. The one-point PDF method
b. The amplitude mapping closure
c. A hybrid strategy for replacing a full two-point PDF treatment of reacting flows by a single-point PDF and correlation (& cross-correlation) functions.

Finally, I would like to appeal for a concerted effort to obtain an adequate data base for compressible flow with reactions for Mach numbers of unity or higher. DNS results have played an important role in aiding the development of PDF models for incompressible flows. A similar role can be played in the efforts to elucidate the many interactions of pressure with other flow variables including species concentrations.
PDF Method Outline

From

1) N-S eqn.
2) Energy eqn.
3) Equation of State
4) Species conservation eqn.

• Generate an evolution equation for the 1-point PDF
  (T.S. Lundgren, 1957; C. Dopazo, 1990)

• Close the PDF equation where necessary by 'suitable' closures

• Use Monte Carlo/particle methods for numerical solution
  (S. Pope, 1981+)

Major advantage + linear increase of numerical effort with the number of dimensions
1-point PDF equation
\[
\frac{\partial \hat{\phi}}{\partial t} = -u \cdot \nabla \phi + D \nabla^2 \phi + \dot{\omega}(\phi)
\]

- \( DE(\nabla \phi)^2 | \phi \) is expected value of scalar dissipation conditioned by the scalar value.
General 1-Point PDF Equation

- Easily generated, and can include multispecies inhomogeneity, compressibility, etc.

\[ \rho \left( \theta, \phi, \ldots, \phi_N, \rho, \dot{\rho}; x, t \right) \quad \cdots \cdots \cdots \cdots \ (1) \]

- Closed terms: advection and reaction

- Unclosed terms: pressure, molecular diffusion of all quantities in (1)

- Closure strategies: Satisfy PDF realizability and
  
a) Reproduce second-order moment closures for physical space terms (Pope, 1985)
  
b) Approximate density effect by ignoring the coupling with pressure oscillation phenomena, i.e. \( \rho = \rho (\phi_1, \ldots, \phi_N, H_{\text{ref}}) \)
  
c) Represent molecular diffusion in velocity-composition-enthalpy space by models. Most recently mapping closures.
The Amplitude Mapping Closure

(Chen, Chen, Kraichnan 1989; Gao, 1991)

- Attractive for strongly non-Gaussian processes

- Simplest example: Non-reacting single scalar $\phi(x,t)$ in statistically homogeneous system.

- 1-Pt PDF

$$\frac{\partial P(\hat{\phi}, t)}{\partial t} = \frac{\partial^2}{\partial \hat{\phi}^2} \left[ DE\{(\nabla \phi)^2 | \phi, t, \phi(t, t)\} \right]$$

- Define $\theta(z)$ time-independent, homogeneous, isotropic, normalized Gaussian r.v. All statistics of $\theta(z)$ are known if $\bar{\theta} = 0, \theta^2 = 1$ and $f_{\theta}(r) = \theta(z) \theta(z + r)$ are given.

- Define a scalar field $\phi^s(x,t)$ generated from $\theta(z)$ from the mapping

$$x = z / J(t)$$

and $\phi^s(x, t) = X(\theta(z), t)$

- Demand $P(\hat{\phi}, t) = P(\hat{\phi}^s, t)$
Consequences of the Mapping

- Since statistics of $\theta(z)$ are completely known the statistics of $\phi^s(x,t)$ are also completely known if $J(t)$ and $X$ are specified.

- N & S condition for $P(\phi, t) = P(\phi^s, t)$

  is $E( (\nabla \phi)^2 | \phi, t) = E( (\nabla \phi^s)^2 | \phi^s, t)$

- It turns out that substitution of the mapping into the PDF equation produces a solvable equation for $X$

  $$\frac{\partial X}{\partial \tau} = -\phi \frac{\partial X}{\partial \phi} + \frac{\partial^2 X}{\partial \phi^2}$$

- $\tau$ is a normalized time scale $d\tau = \frac{DJ^2(t)}{\lambda^2_0} dt$.

Note: J(t) & $\lambda_0$ (the only parameter of $f_0$ that matters)

Appear only in the time scale

\[ \therefore \text{the shape of } P(\phi, \tau) \text{ depends only on the mapping } X(\theta, t). \]
Some Results of the Mapping

- Symmetric binary mixing (initial double delta PDF)
  \[ P(\phi, 0) = \frac{1}{2} \delta(\phi+1) + \frac{1}{2} \delta(\phi-1) \]
  \text{soln: } \mathbb{E}(\nabla \phi)^2|\phi, \tau}/F(\tau) = \exp\{-2 [\text{erf}^{-1}(\phi)]^2\}

- Unsymmetric binary mixing
  \[ P(\phi, 0 = a\delta(\phi+1) + (1-a) \delta(\phi-1), \ 0<a<1 \]
  Same mapping closure solution for \( \mathbb{E}(\nabla \phi)^2|\phi, \tau}/F(\tau) \)

- General soln. has been obtained (Gao, 1991)

- Current status: Formal solutions have been obtained for multispecies cases (Gao & O'Brien, 1991)
  But, no reported success in incorporating it in numerical codes for more than one species
  Also seems to misrepresent asymptotic behavior in time
2-Point PDF

**Advantages**

- Spatial structures explicitly included
- Self-contained time and length scales as in spectral description of turbulence and unlike 1-Point PDF & K-ε or other moment closures

**Disadvantages**

- Dimensions doubled
- Closures harder to construct
- Numerical work so far limited to isothermal reactions of type \( A + B \rightarrow P \).

**Closure approximations**

<table>
<thead>
<tr>
<th>Advection</th>
<th>EDQNM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffusion</td>
<td>Linear Mean Square Estimate</td>
</tr>
<tr>
<td>Reaction</td>
<td>None needed</td>
</tr>
</tbody>
</table>

**New Wrinkles**

- Use 1-point joint PDF of quantities and their gradients
  \[ P(\phi, \nabla \phi; x, t) \]
- Hybrid closures
Hybrid Strategy

- Aimed at more than 2 species, statistically homogeneous.

- Numerical method is fractional steps (Yanenko, 1971)

\[ P(t + \Delta t) = (I + O_A \Delta t)(I + O_B \Delta t)(I + O_R \Delta t) P(t) \]

* I is the identity operator

- Replaces the full 2-point PDF method by a correlation function - 1 point PDF approach.

In a cycle of computations in both composition & physical space

a) Advection has no effect on 1-point PDF but it modifies the correlation and cross-correlation functions \( f(r,t) \) [EDQNM]

b) Molecular diffusion modifies the 1-point PDF (LMSE or mapping closure, if workable and the correlation functions (known)

c) Chemical reaction effects the 1-point PDF (known) and, inadvertently, may alter the correlation functions (assume similarity)

- Reproduces full 2-point PDF results for

\[ A + B \rightarrow P \]
Workshop on Engineering Turbulence Modeling

Comments on Pdf Methods

J.-Y. Chen
Combustion Research Facility
Sandia National Labs
Livermore, CA
Grand Challenge of Combustion Engineering

Challenge: Significant Reduction of Combustion Generated Pollutants

Facts:

- Pollutant Formation Rate $<<$ Fuel Oxidation Rate
- Small Quantity
- Highly Sensitive to Interactions between Turbulence and Chemistry

Difficulty:

- Not Capable of Solving Navier-Stokes Equations with Detailed Chemistry

Approach:

- "Rational" Modeling
Research of PDF Methods at Sandia

- Simple Geometry (Parabolic Flow)

- Reduced Reaction Mechanisms:
  - Two-step H2 Flames
  - Three-step CO/H2 Flames
  - Four-step CH4 Flames
  - Five-step CH3OH Flames
  - up to six reactive scalars

- Thermal NO Formation in Turbulent Hydrogen Jet Flames

- Soot Formation in C2H4 flames
Experiments of Turbulent Jet Flames (Masri & Dibble, 1988)

(Fuel Jet: 45% CO/15% H2/40% N2)  
(Pilot Jet: 70% CO/30% H2)
Departures From Chemical Equilibrium

Hydrogen

Methanol

Carbon Monoxide

Methane
Modeling Turbulent Reacting Flows

Reynolds Stress Model for Velocity Field

\[ l_t, \tau_t \]

\[ \bar{\rho} \]

Stochastic Simulation of The Effects of Turbulence on Chemical Reactions

Reduced Reaction Mechanisms
Superequilibrium OH Radical Measurements Predictions

Case B, x/D=30

Case A, x/D=30

Case A, x/D=30

Case A, x/D=50

Case A, x/D=50
PDF Modeling of Turbulent Jet Flames

(Fuel Jet: 45% CO/15% H2/40% N2)
(Pilot Jet: 70% CO/30% H2)
Scatter Plot for CH4 and O2
(CH4 Turbulent Jet Flames)
Methanol Turbulent Jet Flames

Joint PDF of (f, CO2), (f, CO)

Predictions

Measurements

(f, CO)

(f, CO2)
Comparison Between Predictions and Experimental Data

Experimental Data for H₂ Turbulent Jet Flames
by Chen & Driscoll (1990)

\[ \left( \frac{U_{\text{coflow}}}{U_{\text{fuel}}} \right) \lessapprox 0.001 \]

---

**Graph:***

- **Y-axis:** g/kg-sec
- **X-axis:** STRAIN RATE \( \frac{U_F}{d_F} \) (1/sec) \( \sim \) Da⁻¹

- **Legend:**
  - ○ \( d_F = 0.16 \) cm
  - △ \( d_F = 0.26 \) cm
  - ◇ \( d_F = 0.37 \) cm

**Lines:**

-Prediction
-Experiment

**Notes:**

- SLOPE = 1/2

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Turbulent $C_2H_4$ Jet Flames

Fig. 2. Mean soot volume fraction $\Phi$ along the axis compared to measurements by Neill and Kennedy (1990) for a turbulent $C_2H_4$ flame with zero pressure gradient.
Needed Improvements of PDF Methods for Combustion Applications

- Computationally Expensive

- Direct Calculation of Detailed Chemical Kinetics - Not Feasible

— Capabilities of Reduced Reaction Mechanisms ??

- Primitative Status of Mixing Model

- Interactions between Turbulence and Chemical Reactions
Development of "Rational" Models

Development

Direct Numerical Simulation

Large Eddy Simulation

Turbulence Model

Reduced Mechanisms

Stochastic Simulation

Laminar Flames with Detailed Mechanisms

Practical Interests

Combustion in Compressible Turbulence

Soot in Turbulent Flames

Flame Extinction & Reignition

NOx in Turbulent Flames

Others... Coal...
SOME COMMENTS ON TURBULENCE MODELING
FROM AN INDUSTRIAL PERSPECTIVE

MUNIR M. SINDIR
21 AUGUST 1991
TURBULENCE MODELING IS ONE OF THE KEY PROBLEMS IN CFD USE

- IN PROPULSION INDUSTRY COMPUTATIONAL TECHNIQUES (NAMELY CFD) GRADUALLY BECOMING ENGINEERING DESIGN AND ANALYSIS TOOLS
  - HIGH PERFORMANCE AIRCRAFT ENGINES
  - HIGH SPEED AIR-BREATHING PROPULSION (e.g. NASP)
  - ROCKET PROPULSION (e.g. SSME, STME, NLS)
  - ADVANCED PROPULSION (e.g. NUCLEAR, ELECTRIC)

- THE KEY ISSUES IN ACCEPTANCE OF CFD ARE TURN-AROUND TIME, COST AND ACCURACY
  - TURN-AROUND TIME OF ANALYSIS HAS TO FIT PROGRAM SCHEDULE
  - COST IS THE BOTTOM LINE, THE VALUE OF CFD TO THE PROGRAM SHOULD AT LEAST BALANCE ITS COST (ASSUME $800 PER CRAY HOUR FOR COMPUTER COST IN ADDITION TO LABOR COST)
  - UNCERTAINTY IN PREDICTIONS HAVE TO BE QUANTIFIED. IS IT 20% OR 200%? THESE FIX THE SAFETY FACTORS AND MARGINS REQUIRED FOR DESIGN

- IF CFD CAN BE DIVIDED INTO 2 MAJOR PARTS - NUMERICS AND PHYSICAL MODELS
  - NUMERICS - RELATIVELY MATURE, INACCURACIES TRACTABLE, STEADY PROGRESS
  - PHYSICAL MODELS - CRITICAL PROBLEM, LIMITED DATABASE, FEW PRACTICAL NEW IDEAS
TURBULENCE MODELING FROM AN APPLICATIONS PERSPECTIVE

• CODE NUMERICS AND MODELS SHOULD BE VIEWED TOGETHER IN ASSESSING MODEL ACCURACY AND PERFORMANCE

• NUMERICAL ISSUES
  • SPATIAL ACCURACY (MOST CODES 1ST-3RD ORDER)
    • HOW NUMERICALLY DIFFUSIVE IS THE METHODOLOGY?
    • 1ST ORDER RESULTS CAN BE VASTLY DIFFERENT FROM 3RD ORDER FOR A GIVEN GRID
  • TEMPORAL ACCURACY (MOST CODES 1ST-2ND ORDER)
    • CAN NUMERICAL SCHEME RESOLVE TRANSIENTS?
  • GRID RESOLUTION
    • WHAT IS THE MINIMUM RESOLUTION REQUIRED?
    • WHAT I CAN AFFORD IS NOT THE ANSWER
  • CONVERGENCE
    • HOW DO YOU ASSESS CONVERGENCE?
    • WHAT DO YOU MONITOR IN COMPLEX FLOWS
    • RESIDUALS OFTEN MISLEADING
  • HOW SENSITIVE ARE RESULTS TO BOUNDARY CONDITION IMPLEMENTATION
    • e.g. PRESSURE b. c. ON A ROTATING SURFACE
TURBULENCE MODELING FROM AN APPLICATIONS PERSPECTIVE (CONT.)

• MODELING ISSUES

• TURBULENCE MODELS ARE VERY SENSITIVE TO GRID DISTRIBUTION AND SPACING ESPECIALLY IN REGIONS OF HIGH SHEAR (e.g. WALLS)

• REQUIRED GRID HOWEVER IS RARELY DISCUSSED (AT BEST ONLY $y^+$ IS GIVEN FOR THE FIRST POINT)

• EQUALLY IMPORTANT QUESTION FOR COMPLEX GEOMETRIES IS THE REQUIRED GRID FOR THE ENTIRE DOMAIN

• THERE ARE VERY FEW WELL ESTABLISHED ANSWERS TO THESE QUESTIONS. RESULTS ARE GENERALLY NOT UNIVERSAL BUT ARE

• PROBLEM DEPENDENT

• CODE DEPENDENT
FOR TURBULENCE MODEL EVALUATION IT IS DIFFICULT TO SEPARATE NUMERICAL INACCURACIES FROM MODEL LIMITATIONS

- UNLESS

  - SAME CODE EMPLOYED
  - RESOLUTION REQUIREMENTS FOR EACH MODEL DETERMINED AND USED (SAME GRID IS NOT APPROPRIATE FOR ALL MODELS)
  - EVALUATION DONE BY THIRD PARTY (LIMITED BIAS)

- EVALUATION SHOULD INCLUDE

  - MORE COMPLICATED TEST CASES TO CLEARLY DIFFERENTIATE BETWEEN MODELS (FLAT PLATES ARE LIMITED IN VALUE)
  - PERFORMANCE DATA
    - COMPUTATION TIME (ACTUAL CPU)
    - STABILITY CHARACTERISTICS
    - CONVERGENCE RATE
    - ACCURACY
    - EASE OF USE

- THERE IS A CRITICAL NEED FOR "WELL DEFINED" EXPERIMENTAL DATA TO SUPPORT MODEL EVALUATION TASKS
WHAT DOES INDUSTRY DO?
ROCKETDYNE PERSPECTIVE

- TURBULENCE MODELING DONE ON COMPONENT LEVEL
  - e.g. WHAT MODEL DO WE USE FOR HIGH SPEED INLETS?
    WHAT IS APPROPRIATE FOR COOLING CAVITIES IN TURBOPUMPS?

- CONCENTRATE ON FIVE CRITICAL COMPONENTS
  - INLETS
  - COMBUSTORS/INJECTORS
  - NOZZLES
  - TURBINES
  - PUMPS

- ACCEPT THAT FOR MOST APPLICATIONS TURBULENCE MODELS ARE "NON-UNIVERSAL"
  - SELECT 1 CFD CODE FOR EACH COMPONENT
  - IMPLEMENT ALL APPROPRIATE MODELS IN THAT CODE
  - IDENTIFY RELATIVE ACCURACY VS COST OF EACH MODEL THROUGH
    A SYSTEMATIC EVALUATION PROCESS AND ESTABLISH MODEL PERFORMANCE
    DATABASE
  - MATCH MODEL TO LEVEL OF ANALYSIS/ACCURACY REQUIRED IN APPLICATIONS
DISCUSSION

D. Wilcox (to Sindir)

I understand that there is some concerns with NASP contractors that RSM is too expensive. I find only a 20% increase in CPU time to compute a full RSM with the newer algorithms, relative to the two equation models.

M. Sindir (reply)

The model that you came up with is not a tool unless it gets into the methodology of established codes that contractors use for validation. And that is a major activity.

T. Gatski (to Sindir)

You describe an extremely complex situation and then use a Baldwin Lomax model; I have a confidence level of zero in that calculation!

M. Sindir (reply)

I know and agree, but that is what is being done in industry. But time constraints keep this problem from being handled properly.

A. Hsu

I feel that two items ought to be added to the list of tasks to pursue in PDF modeling. First, we have to examine PDF for high speed flows, like flows with shocks. Second, for the particle Monte Carlo method, problems involved in solution over a realistic geometry should be addressed.
A. Singhal (to S. Pope)

How do we transition this new and evolving technology into industry? In the first stage of transition, you introduced the joint PDF of velocity and composition, not just the first level of PDF which was shown in the hierarchy to be just composition. I'm curious why.

S. Pope (reply)

The reason for that is that the numerical algorithm for joint PDF of velocity and composition is really simple and more economical than just composition alone. It sounds strange, but the reason is that in the PDF for composition, the diffusion terms, turbulent transport,
Session III

Unconventional Turbulence Modeling
The Present State of DIA Models and Their Impact on One Point Closures

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I. Objectives

A. Outline of DIA

B. Outline of TSDIA (two-scale DIA) and some suggestions to turbulence modeling

C. Proposals:
   - Helicity for the study of the effects of swirling and cross flow
   - Density variance for the study of highly compressed flows
II. Basic Laws

Compressible fluid

\[
\frac{\partial}{\partial t} \rho + \nabla \cdot (\rho u) = 0
\]
\[
\frac{\partial}{\partial t} \rho u_i + \left( \frac{\partial}{\partial x_j} \right) (\rho u_j u_i) = - \left( \frac{\partial}{\partial x_i} \right) p
+ \left( \frac{\partial}{\partial x_j} \right) \mu s_{ij}
\]
\[
\frac{\partial}{\partial t} \rho e + \nabla \cdot (\rho e u) = - p \nabla \cdot u + \phi + \nabla \cdot (\lambda \nabla \theta)
\]

where

\( \rho \): Density; \( u \): Velocity; \( p \): Pressure;
\( e \): Internal energy; \( \theta \): Temperature;
\( \mu \): Viscosity; \( \lambda \): Heat conductivity;
\( s_{ij} = \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - (2/3) \nabla \cdot u \delta_{ij} \)
\( \phi = \mu \left[ (\frac{\partial u_j}{\partial x_i})^2 + \frac{1}{3} (\nabla \cdot u)^2 \right] \)
[Note] Thermodynamic relations for a perfect gas:

\[ p = \rho R \theta \quad (R: \text{Gas constant}) \]
\[ = (\gamma - 1) e \quad (\gamma: \text{Ratio of specific heats}) \]
\[ e = C_v \theta \quad (C_v: \text{Specific heat at constant volume}) \]

**Incompressible approximation**

\[ \nabla \cdot u = 0 \]

\[ (\partial / \partial t) u_i + (\partial / \partial x_j) (u_j u_i) = - (\partial / \partial x_i) p + \nu \Delta u_i \]

where

\[ p / \rho \rightarrow p \]

\[ \nu = \mu / \rho: \text{Kinematic viscosity} \]
III. Outline of DIA\textsuperscript{1}

Premise: Vanishing mean velocity

Homogeneity

$$\langle u_i(x; t) u_j(x'; t') \rangle = \langle u_i(x - x'; t) u_j(0; t') \rangle$$

Independence of the coordinate origin

\begin{itemize}
  \item Infinite or periodic region
  \item Fourier-integral or -series representation
\end{itemize}

Fourier integral

$$f(x; t) = \int f(k; t) \exp(-ik \cdot x) \, dk$$
Homogeneous turbulence

\[ k \cdot u (k; t) = 0 \]

\[ (\partial / \partial t) u_i (k; t) - i k_j \delta (k - p - q) dp dq \times u_j (p; t) u_i (q; t) = i k_i p (k; t) - \nu k^2 u_i (k; t) \]

[Note] Elimination of pressure:

\[ p (k; t) = - (k_i k_j / k^2) \delta (k - p - q) dp dq \times u_i (p; t) u_j (q; t) \]

[Note] Green's function:

\[ (\partial / \partial t) G_{i,j} (k; t, t') - i M_{i,m} (k) \delta (k - p - q) dp dq \times u_m (p; t) G_{n,j} (q; t, t') = D_{i,j} (k) \delta (t - t') \]

where

\[ D_{i,j} (k) = \delta_{i,j} - k_i k_j / k^2 \]

\[ M_{i,j,k} (k) = [k_j D_{i,k} (k) + k_k D_{i,j} (k)] / 2 \]
Fundamental variables

\[ Q_{ij}(k; t, t') = \frac{\langle u_i(k; t) u_j(k'; t') \rangle}{\delta(k + k')} \]
\[ G_{ij}(k; t, t') = \langle G_{ij}(k; t, t') \rangle \]

Difficulties in incorporating inhomogeneity

- Necessity of the orthogonal function satisfying the noslip condition

[Note] Dannevik's work

Turbulent Rayleigh-Benard convection between two parallel plates (no mean flow)

- Coexistence of slow modes (mean field) and fast modes (fluctuation)

→ Simultaneous treatment of different modes
IV. Outline of TSDIA (Two-Scale DIA)

Departure from a complete two-point scheme

- Passive: Difficulty in dealing with a boundary
- Positive: Difficulty of obtaining "formulae" applicable to general flows

Two scales

\[ \xi \ (= x), \ X \ (= \delta x); \ \tau \ (= t), \ T \ (= \delta t) \]

where

\[ \delta: \text{A small scale-expansion parameter} \]

Then

\[ f = F(X;T) + f'(\xi, X;\tau, T), \quad F = \langle f \rangle \]
Two-scale expressions

\[ \nabla_\xi \cdot u' = -\delta (\partial/\partial X_j) u_j', \quad \nabla_\xi = (\partial/\partial \xi_i) \]

\[ (\partial/\partial \tau) u_i' + (U \cdot \nabla_\xi) u_i' + (\partial/\partial \xi_i) p' - \nu \Delta_\xi u_i' \]

\[ = \delta [-u_j' (\partial/\partial X_j) U_i - (D/DT) u_i' - (\partial/\partial X_i) p' \]
\[ - (\partial/\partial X_j) u_j' u_i'] + \nu\text{-related terms} \]

[Note] The effects of slow modes:
Direct effects: Through \( U \)
Indirect effects: Through \( X \) and \( T \) in \( u' \)

Fourier representation of \( \xi \)

\[ f' (\xi, X; \tau, T) = \int f' (k, X; \tau, T) \exp [-ik \cdot (\xi - U\tau)] \, dk \]

Scale expansion

\[ f' (k, X; \tau, T) = \sum_{n=0}^{\infty} \delta^n f_n' (k, X; \tau, T) \]

[Note] Lowest-order or basic field \( u_0' \):
The same system of equations as for homogeneous turbulence, except the \( X \) and \( T \) dependence
Isotropic and helical field

\[
\langle u_{B_i'} (k, X; \tau, T) u_{B_j'} (k', X; \tau', T) \rangle / \delta (k + k') \n\]

\[
= D_{i,j} (k) Q_B (k, X; \tau, \tau', T) \n\]

\[
+ \frac{i}{2} (k_m / k^2) \epsilon_{i,j,m} H_B (k, k', X; \tau, \tau', T) \n\]

[Note]

\[
\langle u_{B'}^2 / 2 \rangle = \int Q_B (k, X; \tau, \tau, T) \, dk \n\]

\[
\langle u_{B'} \cdot \omega_{B'} \rangle = \int H_B (k, X; \tau, \tau, T) \, dk, \quad \omega_{B'} = \nabla \times u_{B'} \n\]

Important correlation functions

Calculation of the Reynolds stress etc. using DIA based on \( Q_B \) and \( G_B \)

\[ \rightarrow \] Extended eddy-viscosity representation for the Reynolds stress
V. Main Results from TSDIA: No Helicity

Reynolds stress

\[ - \langle u'_i u'_j \rangle = - \frac{2}{3} K \delta_{i,j} + \nu e S_{i,j} \]

\[ - \sum_{n=1}^{3} \tau_n \left[ T_{n i,j} - \frac{1}{3} T_{n m m} \delta_{i,j} \right] \]

\[ - \tau_4 (D/Dt) S_{i,j} + \cdots \]

where

\[ K = \langle u'^2 \rangle / 2 \]

\[ S_{i,j} = \partial U_j / \partial x_i + \partial U_i / \partial x_j \]

\[ T_{1 i,j} = \left( \partial U_i / \partial x_m \right) \left( \partial U_j / \partial x_m \right) \]

\[ T_{2 i,j} = \left[ \left( \partial U_i / \partial x_m \right) \left( \partial U_m / \partial x_j \right) \right] / 2 \]

\[ T_{3 i,j} = \left( \partial U_m / \partial x_i \right) \left( \partial U_m / \partial x_j \right) \]

[Note] See Speziale and Rubinstein and Barton
Turbulent scalar flux

\[ \langle u_i' \theta' \rangle = - \kappa_{i,j} \left( \partial / \partial x_j \right) \Theta \]

where

\[ \kappa_{i,j} = \kappa \delta_{i,j} - [\gamma_1 \left( \partial U_j / \partial x_i + \partial U_i / \partial x_j \right) \]
\[ - \gamma_2 \left( \partial U_j / \partial x_i - \partial U_i / \partial x_j \right) ] \]

[Note] See Rubinstein and Barton

Some other suggestions

- Triple correlations

\[ \langle (u'^2/2) u' \rangle = - \nu_k \nabla K + \nu_k' \nabla \epsilon \]

- Equations for the dissipation rates of energy and scalar variance (\( \epsilon \) and \( \epsilon_\theta \))

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VI. Proposal: Helicity

Motivation

Explanation of the generation of "white spot" in Saturn (the spiral vortical structures along the equator) 10

Fig. 1: Saturn's huge white spot (NASA Hubble Space Telescope)

What is the helicity?

\[
(\partial/\partial t) u = u \times \omega - \nabla (p + u^2/2) + \nu \Delta u
\]

\[u \parallel \omega \rightarrow u \times \omega = 0 \text{ (no energy cascade)}\]

Helicity \(u \cdot \omega\): A measure of the break of reflectional symmetry in flow

Fig. 2. Helicity
Importance of helicity

- A measure of "smallness" of energy cascade
- A "conserved" quantity in the absence of the injection and loss due to viscous effects

[Note] $\langle u \cdot \omega \rangle = U \cdot \Omega + \langle u' \cdot \omega' \rangle$

- No mean helicity: $U \cdot \Omega = 0$ ($U \perp \Omega$)
  Two-dimensional mean flow
  channel flow, jet, wake, mixing layer, etc.

- Finite mean helicity: $U \cdot \Omega \neq 0$
  Swirling flow, Three-dimensional mean flow

[Note] Swirling flow:

Question: Why do the eddy-viscosity models break the swirling motion so fast?

Answer: No consideration of helicity or the decreasing effect of cascade (virtual decrease of eddy viscosity)
[Note] Cross-flow effects:

- Lag of the turbulent stresses in response to the cross-flow gradient (also important in aerodynamical flows\textsuperscript{11, 12})

**Fig. 2 Spinning cylinder\textsuperscript{12}**

- Curvature effects leading to secondary flows

Three-equation model\textsuperscript{13}

\[ K = \langle u'^2/2 \rangle : \text{Turbulent kinetic energy} \]

\[ \varepsilon : \text{Energy dissipation rate} \]

\[ H = \langle u' \cdot \omega' \rangle : \text{Turbulent helicity} \]

[Mean equation]

\[ \nabla \cdot \mathbf{U} = 0 \]

\[ \frac{D}{Dt} U_i = - \left( \frac{\partial}{\partial x_i} \right) P + \left( \frac{\partial}{\partial x_j} \right) R_{ji} \]
[Reynolds stress]

\[ R_{ij} = - \left< u_i' u_j' \right> \]
\[ = - \left( \frac{2}{3} \right) K \delta_{ij} + \nu_e \left( \frac{\partial U_j}{\partial x_i} + \frac{\partial U_i}{\partial x_j} \right) \]
\[ - \left[ \Omega_i \gamma_j + \Omega_j \gamma_i - \left( \frac{2}{3} \right) \Omega \cdot \gamma \delta_{ij} \right] \]

where

\[ \nu_e = C_1 K^2 / \epsilon, \quad \gamma = C_2 \left( K^4 / \epsilon^3 \right) \nabla H \]

[Note] Symmetry-breaking factor:

Reynolds stress: Reflectionally symmetric

→ Necessity of another symmetry-breaking factor, that is, inhomogeneity such as \( \nabla H \)
[K equation]

\[ \frac{\partial K}{\partial t} = P_K - \epsilon + \nabla \cdot [C_3 \left( \frac{K^2}{\epsilon} \right) \nabla K] \]

where

\[ P_K = R_{ij} \left( \frac{\partial U_j}{\partial x_i} \right) \]

[H equation]

\[ \frac{\partial H}{\partial t} = P_H - \epsilon_H + \nabla \cdot T_H \]

where

\[ P_H = R_{ij} \left( \frac{\partial U_j}{\partial x_i} \right) - Q_i \left( \frac{\partial / x_j}{\partial x_i} \right) R_{ji} \]

\[ \epsilon_H = C_4 \left( \frac{\epsilon}{K} \right) H \]

\[ T_H = KQ + C_5 \left( \frac{K^2}{\epsilon} \right) \nabla H \]

[\epsilon equation]

\[ \frac{\partial \epsilon}{\partial t} = C_6 \left( \frac{\epsilon}{K} \right) P_K - C_7 \left( \frac{\epsilon^2}{K} \right) + C_8 \left( \frac{K^2}{\epsilon} \right) Q \cdot \nabla H \]

\[ + \nabla \cdot [C_9 \left( \frac{K^2}{\epsilon} \right) \nabla \epsilon] \]
Swirling flow in a pipe \([(r, \theta, z); z: \text{axial}]\)

\[-<u_r' u_\theta'> = \nu_e r \left( \frac{\partial}{\partial r} \right) \left( \frac{U_\theta}{r} \right) - \eta \Omega_\theta \frac{\partial H}{\partial r} \]

\[-<u_r' u_z'> = \nu_e \left( \frac{\partial U_z}{\partial r} \right) - \eta \Omega_z \frac{\partial H}{\partial r} \]

\[-<u_\theta' u_z'> = \nu_e \left( \frac{\partial U_\theta}{\partial z} \right) - \eta \Omega_\theta \frac{\partial H}{\partial z} \]

where

\[\eta = C_1 K^4 / \varepsilon^3 > 0\]

Comparison with observation

Fig. 4. Mean velocity

(Fig. 5. \(-<u_r' u_\theta'>\)

(Broken lines: weak swirl region)

\[-<u_r' u_\theta'> = \nu_e r \left( \frac{\partial}{\partial r} \right) \left( \frac{U_\theta}{r} \right) - \eta \Omega_\theta \frac{\partial H}{\partial r} \]

Around \(r = 0.7\)

\[A > 0\]

\[B > 0 \quad (\Omega_\theta = - \frac{\partial U_z}{\partial r} < 0, \quad \frac{\partial H}{\partial r} < 0)\]

[Note] \(H = 0\) at the wall \(\rightarrow\) \(\frac{\partial H}{\partial r} < 0\) near it

\[C \leq \bar{5}\]
Application to SGS modeling

Appearance of streamwise vortices (streaks) dependent on the strength of shear

- Nonvanishing helicity on the SGS, but not on the ensemble or time mean

- Importance in the SGS modeling

- Incorporation of the helicity effect

- Virtual change of the Smagorinsky constant in channel flow, mixing layer, isotropic flow in accordance with the strength of shear
VII. Proposal: Density Variance

Prominent difference between incompressible and compressible turbulence

Decelerated streamwise velocity effects

- Compressible (shock wave):
  - Decrease in turbulence level
  - Increase in temperature etc.

- Incompressible:
  - Increase in turbulence level

Mass-weighted mean

\[ \hat{f} = \{f\} = \frac{\langle \rho f \rangle}{\bar{\rho}}, \quad \bar{\rho} = \langle \rho \rangle \]

\[ f' = f - \hat{f} \]
[Mean equation]

\[
\frac{\partial}{\partial t} \bar{\rho} + \nabla \cdot (\bar{\rho} \hat{u}) = 0
\]

\[
\frac{\partial}{\partial t} \bar{\rho} \hat{u}_i + \left( \frac{\partial}{\partial x_j} \bar{\rho} \hat{u}_j \hat{u}_i \right) = - \left( \frac{\partial}{\partial x_i} \right) [ (\gamma - 1) \bar{\rho} \hat{e} ] \\
+ \left( \frac{\partial}{\partial x_j} \right) R_{j,i}
\]

\[
\frac{\partial}{\partial t} \bar{\rho} \hat{e} + \nabla \cdot (\bar{\rho} \hat{u} \hat{e}) = - (\gamma - 1) \bar{\rho} \hat{e} \nabla \cdot \hat{u} + \bar{\rho} (\epsilon + \chi) \\
+ \nabla \cdot (-H)
\]

where

\[R_{i,j} = - \langle \rho u_i u_j' \rangle = - \bar{\rho} \{u_i u_j'\}\]

\[H = \langle \rho u' e' \rangle = \bar{\rho} \{u' e'\}\]

\[\chi = - (\gamma - 1) \langle \rho e' \nabla \cdot u' \rangle / \bar{\rho} = - (\gamma - 1) \{e' \nabla \cdot u'\}\]

- \textbf{R}_{i,j}: Reynolds stress
- H: Internal energy flux
- \chi: Fluctuating dilatation effect

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[Note] Importance of $\chi$:
Trace of the pressure-strain correlation
(no contribution in the incompressible case)

[Note] Inference of $\chi$:
Large positive in a highly compressed region

→ Virtual increase of energy dissipation

Three-equation model\textsuperscript{16, 17}

\[ K = \langle u'^2 / 2 \rangle, \quad \epsilon, \quad K_d = \langle \rho' \rangle : \text{Density variance} \]

[Reynolds stress]

\[ R_{i,j} = -(2/3) \bar{\rho} K \delta_{i,j} + \bar{\rho} v_e \hat{s}_{i,j}, \quad v_e = C_1 K^2 / \epsilon \]

[Internal energy flux]

\[ H = - \bar{\rho} \kappa_e \dot{\epsilon}, \quad \kappa_e = C_2 K^2 / \epsilon \]

[Fluctuating dilatation effect]

\[ \chi = C_3 (\epsilon / K) \left( K_d / \bar{\rho}^2 \right) \hat{\epsilon} \]
[**K equation**]

\[
(\partial/\partial t) K + \nabla \cdot (\bar{\rho} \hat{u} K) = P_K - \bar{\rho} (\varepsilon + \chi) + \nabla \cdot T_K
\]

[**ε equation**]

\[
(\partial/\partial t) \varepsilon + \nabla \cdot (\bar{\rho} \hat{u} \varepsilon) = C_4 (\varepsilon/K) P_K - C_5 \bar{\rho} (\varepsilon/K) (\varepsilon + \chi) + \nabla \cdot T_\varepsilon
\]

[**Kd equation**]

\[
(\partial/\partial t) K_d + \nabla \cdot (\hat{u} K_d) = - K_d \nabla \cdot \hat{u} - C_6 (\varepsilon/K) K_d + \nabla \cdot T_d
\]

exact!

Can the turbulence level decrease behind a shock wave?

\[\nabla \cdot \hat{u} < 0 \text{ near a shock wave}\]

\[\rightarrow \text{ Production of } K_d \text{ (Kd equation)}\]

\[\rightarrow \text{ Larger } \varepsilon, \text{ larger } \chi \text{ (than elsewhere)}\]

\[\rightarrow \text{ Decrease in } K \text{ and } \varepsilon \text{ (K and } \varepsilon \text{ equations)}\]
REFERENCES


Fig. 2
SPIN FLOW
Suction Slot
Adjustable Walls

U_r

Spinning Section

Stationary Section

3D Interaction Zone

Surface Skin-Friction Lines

Fig. 3
Fig. 4
\[-\langle u_r' u_\theta' \rangle\]
PRESENT STATE OF TWO-POINT CLOSURES AND THEIR
IMPACT ON SINGLE-POINT CLOSURES

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CONTENTS

MOTIVATION

BACKGROUND OF TWO-POINT CLOSURES, BRIEFLY

VERY RECENT SIMPLIFICATION

RESULTS

APPLICATION TO SINGLE-POINT CLOSURES

"COMPLEXITY" ISSUE AND SIMPLIFICATION

PRESSURE - STRAIN RATE

DIFFUSION

DISSIPATION

DIRECTION FOR FUTURE WORK
MOTIVATION, AND A VERY PERSONAL PERSPECTIVE

CARDINAL PRINCIPLE

\[ \langle u_i u_j \rangle = \int dk \ S_{ij}(k, t) \]

ALL SCALES INCLUDED -- NOT ALL NEEDED

POTENTIAL FOR HIGH SUCCESS OF SINGLE-POINT CLOSURES

PARTNERSHIP

GOAL TO "ELIMINATE" EMPIRICAL COEFFICIENTS

0 KEY = ANALYTICAL SOLUTION

ARBITRARY REYNOLDS NUMBER

DETAILS COMPLEX, BUT \rightarrow MINIMIZES UNCERTAINTY

SHAPE OF SPECTRUM NOT NECESSARILY IMPORTANT

SIMPLIFICATION IS POSSIBLE

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\[
\frac{\partial S_k}{\partial t} = -L_0 S_k - (1 + T_h) \left( \langle u_k^* (u_k u)_k \rangle + \langle i_k \frac{\partial u_k^*}{\partial x} \rangle \right) - 2\nu S_k
\]

**LINEAR**
(RDT)

**NONLINEAR**
ADVECTION

**NONLINEAR**
PRESSURE-STRAIN RATE

**DIST.**

\[
\begin{pmatrix}
L_0 S_k = (1 + T_h) S_k \cdot \nabla u_k \cdot (I - \mathbf{R}) - \langle \sigma_{\perp k} \rangle \cdot \frac{\partial S_k}{\partial t}
\end{pmatrix}
\]

**TWO TASKS**

**DERIVE CLOSURE EQUATIONS**

**SOLVE CLOSURE EQUATIONS**

- EDGNN, DIA
- COMPLICATED
  HAS NOT BEEN REDUCED
  TO QUADRATURES

**ANALYTICAL SOLUTION**

**RADICAL SIMPLIFICATION**

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\[
\begin{align*}
0 \begin{array}{c}
\text{NONLINEAR} \\
\text{P.S.R.}
\end{array} &= -0.32 \frac{k^{7/3}}{k_0^{1/3} u_0} E(k) \left( \frac{s_{z_k}}{s_{z_k}} - s_{z_k} \right) \\
\begin{array}{c}
\text{NONLINEAR} \\
\text{ADVECTION}
\end{array} &= -0.32 \frac{k^{7/3}}{k_0^{1/3} u_0} \int_{s_{z_k}} E(k) - \left[ \frac{(k \partial^2/\partial k^2) E(k)}{(10/3 + A)^2} \right] \\
\end{align*}
\]

\[
\begin{align*}
\frac{\partial s_{z_k}}{\partial t} &= -L_a s_{z_k} - 0.32 \frac{k^{7/3}}{k_0^{1/3} u_0} \left[ E(k) \frac{s_{z_k}}{s_{z_k}} - \left( \frac{(k \partial^2/\partial k^2) E(k)}{(10/3 + A)^2} \right) \frac{s_{z_k}}{s_{z_k}} \right]
\end{align*}
\]

Determines \( S_{ij}(k, t) \) all \( i, j, k, t \) -- any \( \nabla \cdot \vec{u} \) and \( \vec{R} \)
RESULTS - GROWTH OF TURBULENCE

\[ \frac{u_0^2(t)}{u_0^2(0)} \]

\( u_0^2(t) \) depends on \( t/t_0 \) \((1 + \frac{\partial u_0}{\partial x_2})\).

No distinction between weak & strong shear.
\[ k_0 = \frac{1}{1.8} u^{-1} \frac{\partial u_0}{\partial x_2} \]

\[ \epsilon = c(t) g^2 \frac{\partial u_0}{\partial x_2} \]

\[ \varepsilon_{ij} \text{ AND LOCAL ISOTROPY} \]
COMPARISON OF THEORETICAL PREDICTION WITH
NASA COMPUTER SIMULATION (AT AMEC RES. CENTER)

DIMENSIONLESS TIME - St

PRESSURE - STRAIN
CORRELATION

VERTICAL
TRANSVERSAL
LONGITUDINAL

THEORY 11
THEORY 22
THEORY 33
SIMULATION 11
SIMULATION 22
SIMULATION 33
COMPARISON OF P.S.R. THEORY WITH SIMULATIONS

\[ C_{ll}^{(i)} \equiv \text{ROTTA } \text{"CONSTANT" } \equiv \frac{\Phi_{ll}^{(i)}}{\langle u_i^2 \rangle - u_0^2} \]
APPLICATION TO SINGLE-POINT MODELING

\[
\frac{D\langle u_i u_j \rangle}{Dt} = p_{ij} + \phi_{ij} + \frac{\partial}{\partial x_m} d_{ijm} - \epsilon_{ij}
\]

PRESSURE
STRAIN
RATE
DIFFUSION
DISSIPATION

THEORY DETERMINES \( \phi_{ij}, d_{ijm}, \epsilon_{ij} \)

USE OF THEORY

TEST EXISTING MODELS

O DETERMINE COEFFICIENTS

VARIATION OF COEFFICIENTS

DERIVE MODELS FROM "FIRST PRINCIPLES"
COMPLEXITY ISSUE

TOO MANY DETAILS - YES & NO

A SIMPLE "PHILOSOPHY"

A PRACTICAL SOLUTION

EXAMPLE - P.S.R. SLOW TERM
\[ \phi_{ij}^{(s)} = -\log \sqrt{\frac{2\pi}{3}} \int_0^\infty \int_0^\infty \frac{k^2_a k^2_b}{(k^2_a + k^2_b)^{3/2}} \frac{E(h_a) [E_{ij}(k_a) - \frac{1}{2} E(h_a) \delta_{ij}]}{8} \]

**ONLY NEED** → \(k_1, k_2, k_3, k_\nu\)

**EMPIRICAL WITHOUT ALL \(k\)'S.**

**STILL COMPLICATED.**
DEFIES EMPIRICAL TREATMENT, BUT IS COMPLICATED:

C SIMPLIFICATION - $R_\nu$ VARIATION

FIFTH SCALE BECAUSE $E_{12} \propto k^{-5/3}; \quad C_{12} = 2\langle C'' \rangle_{\text{AVF}}$

\[ C_{12} = 1.7(1 - R_\nu^{-1/2}) \]

UNIVERSALITY:

INSENSITIVITY TO SMALL $k$ REGION OF $E(k)$; PRODUCTION REGION

\[ \nabla \tilde{U} \]
FAST TERM AND $\varepsilon_{ij}$

**NEAR**

**COMPLETED** FOR SIMPLE MEAN SHEAR:

**FUTURE** = ARBITRARY MEAN STRAINING:

CONFIRM OR IMPROVE EXISTING MODEL

CHIH AND LUMLEY, 1965

FU, LAUNDER & TSELEPIDAKIS, 1982

LOOK FOR UNIVERSALITY (GUIDED BY MODELS)

(RESOLVE HELP) QUESTIONS OF NONLINEARITY
INFLUENCE OF BUOYANCY: LUMLEY, ZEMAN, SEISS (1978)  
(WEINSTOCK, 1989)

INFLUENCE OF MEAN SHEAR: MANSOUR, KIM, MOIN (1989); WYNGAARD (1980)

\[
\langle u_z u_z \rangle = -7 \left[ \langle u_z^2 \rangle \frac{\partial}{\partial x_z} \langle uu \rangle + (1 + T) \langle u_z^2 \rangle \frac{\partial}{\partial x_z} \langle u_z^2 \rangle \right] + \frac{2\langle u_z u_z \rangle}{\nu} \nabla^2 u_z + 2 \langle u_z u_z \rangle \nabla \bar{U}
\]
INHOMOGENEITY AND NON-STATIONARITY

WEAK INHOMOGENEITY: DONE

\[ L \gg l_0 \]

STRONG INHOMOGENEITY \rightarrow FUTURE

CALCULATE \( \langle u(t_1)u(t_2)u(t_3) \rangle \) FOR \( d_{ijm} \) AND \( \Phi_{ij} \)

SPECULATED METHOD:

\[
\begin{align*}
\text{\textbf{u}}(t) &= \text{\textbf{u}}(0) - \int_0^t \left[ \text{\textbf{u}} \cdot \nabla \text{\textbf{u}} + \text{\textbf{u}} \cdot \nabla \text{\textbf{u}} + \frac{\partial \text{\textbf{u}}}{\partial t} + \frac{\partial \text{\textbf{u}}}{\partial t} + \nabla \rho \right] dt \\
\therefore \quad \langle \text{\textbf{u}}(t_1)\text{\textbf{u}}(t_2)\text{\textbf{u}}(t_3) \rangle &= -\int_0^t \langle \text{\textbf{u}}(t_1)\text{\textbf{u}}(t_2)\text{\textbf{u}}(t_3) \rangle dt + \cdots \\
&= -\int_0^t \langle G(t, t_1) \text{\textbf{u}}(t_1)\text{\textbf{u}}(t_2)\text{\textbf{u}}(t_3) \rangle dt + \cdots \\
&= -\int_0^t \langle G(t, t_1) \text{\textbf{u}}(t_1)\text{\textbf{u}}(t_2) \rangle \cdot \text{\textbf{G}} \langle \text{\textbf{u}}(t_3) \rangle dt + \cdots
\end{align*}
\]

\( \therefore \) FUTURE

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SUMMARY

RADICAL SIMPLIFICATION
SOLVES HOMOGENEOUS SHEAR FLOWS

PROVIDES $\phi_{ij}$, $d_{ij}$, $e_{ij}$
TEST AND/OR IMPROVE EXISTING MODELS.

GOAL $\Rightarrow$ AVOID EMPIRICAL COEFFICIENTS

FUTURE
INCORPORATE HOMOGENEOUS THEORY INTO 1-POINT MODELS
INFLUENCE OF VARIOUS STRAINING ON FAST TEAM

STRONG INHOMOGENEITY
The Present State of RNG

Its Impact on One Point Closure

- Introduction to renormalization group methods for one-point closure

- Strain rate expansion
  V. Yakhot, S. Thangam, T. Gatski, & C. Speziale

S. Orszag

Princeton University
DIRECT NUMERICAL SIMULATION

DNS

\[ \Delta \ll \frac{l_d}{Re^{3/4}} L \]

Grid size

Dissipation scale

Navier-Stokes Equations

Large Scale (eddy)

\[ Re^{3/4} \]
DIRECT NUMERICAL SIMULATION

DNS

Renormalization Group

\[ \frac{\partial u_l^l}{\partial t} + u_l^l \cdot \nabla u_l^l = - \nabla p_l^l + \nabla \omega(l) \nabla u_l^l + f_l^l \]

Navier-Stokes Equations

- Construct calculus of recursion relations to compute \( \omega(l), f_l^l, \ldots \)
Langevin Model

\[ \frac{\partial u'}{\partial t} = -\frac{\nu'(l)^2}{\nu'} + f' \]

Nonlocal convolution operator

Assume

\[ \frac{d\nu(l)}{dl} \propto E \quad \text{(rate of energy dissipation)} \]

Dimensional analysis \[\Rightarrow\]

\[ \frac{d\nu}{dl} = \frac{AE}{\nu'0} l^3, \quad \nu'(l_d) = \nu_0 \]

Solution:

\[ \nu(l) = \nu_0 \left[ 1 + \frac{3}{4} \frac{AE}{\nu_0^3} (l'' - l_d'') \right]^{1/3} \quad (l > l_d) \]

\[ \nu(l) \sim \left( \frac{3}{4} AE \right)^{1/3} l^{4/3} \quad (l \gg l_d) \]
Intrinsic Stirring Force in Turbulence and the $\varepsilon$-Expansion

Large-scale force to model the effects of initial and boundary conditions

\[
\left[-i\omega + v_0 k^2\right] u_a(k,t) = -\frac{1}{2} i P_{apg}(k) \int u_p(p,\Omega) u_r(k-p,\omega-\Omega) dpd\Omega + f_a(k,\omega)
\]

\[
\langle f_a(\vec{k}) f_b(\vec{k}') \rangle \propto D_{apg}(k) \delta(k) \delta(k+k') \delta(\omega+\omega')
\]

DIFFICULTY: Nonlinear solutions of the Navier-Stokes equations involve an 'infinity' of interacting 's to produce $u(k)$ [k finite]

Correspondence Principle (Yakhot & Orszag 1986)

\[
\langle f_a(\vec{k}) f_b(\vec{k}') \rangle \propto D_{apg}(k) k^{1-\varepsilon} \delta(k+k') \delta(\omega+\omega')
\]

\[
\delta(k) = \lim_{\varepsilon \to 4} \frac{(4 - \varepsilon) k^{1-\varepsilon}}{4\pi}
\]

Gel'fand
Additional Physics

Example: Stratified Shear Flow

$$\nu_{\text{eddy}} = \nu_0 \left[ 1 + \frac{3}{4} \frac{A}{\nu_0^3} (E - g \frac{\partial T}{\partial z}) (l^n - l_d^n) \right]^{1/3}$$
RNG CLOSURE FOR STRATIFIED TURBULENCE

\[ \frac{K}{u^*} \left[ \frac{u(x)}{\bar{u}} - \frac{u(x)}{\bar{u}} \right] \]

- x Theory \( \xi < 0 \)
- \( \bullet \) Theory \( \xi > 0 \)
- \( \Delta \) Experiment
- \( \square \) Experiment

\( \xi = y/L \)

I Stable Stratification
II Unstable Stratification
Renormalization Group Analysis of Compressible Turbulence

- $c(L) \sim L^{4/3}$: Effective sound speed is scale dependent
- $Ma_{\text{eff}} \sim \frac{1}{\sqrt{3}}$: Universal equation of state at large scales

- Equipartition of energy
  
  $E_{\text{incompressible}} \sim 3 E_{\text{compressible}}$

- As $Ma \to \infty$, $\text{Veddy} \propto \sqrt{\frac{e}{\delta y}}$
  
  not $\text{Veddy} \propto \left| \frac{\partial U}{\partial y} \right|$ as in Prandtl mixing length theory

  $\frac{\partial U}{\partial t} = \frac{\partial}{\partial y} \left[ \frac{1}{\delta y} \frac{\partial U}{\partial y} \right] = 0$ (Self-focusing of jets)
Turbulence Simulations

Filter Size $\lambda$

$\text{DNS} \leftarrow \text{LES} \rightarrow \text{RANS}$

Numerical Accuracy: $\Delta \ll \lambda$

$\text{DNS} \quad \Delta \ll l_d$

$\text{LES} \quad l_d \ll \Delta \ll \frac{1}{2} \lambda \ll L$

$\text{RANS} \quad l_d \ll \Delta \ll \lambda \ll L$

Robustness: $\lambda$-Independence!

$u_\lambda$ - $\lambda$-filtered velocity

$R_\lambda$ - $\lambda$-sub-grid model

$F_\lambda$ - $\lambda$ filter $\quad R_\lambda \approx u - F_\lambda u$

Test: If $\lambda < \mu$, is

$$\frac{\overline{F(u_\lambda)^2}}{\overline{F(u_\mu)}^2} \approx \overline{F(u_\mu)} + \left\{ \overline{F(R_\mu)} - \overline{F(R_\lambda)} \right\}$$
Renormalization Group Subgrid Model for LES

\[ K \propto \sqrt[3]{\Delta} \]

\[ \nu_{\text{eddy}} = \nu_{\text{mol}} \left[ 1 + \frac{3}{4} \frac{A E}{(2 m)^{\nu} \nu_{\text{mol}}^{3/2}} (\Delta^\nu - \eta_d^\nu) \right]^{\nu/3} \]

\[ E = \nu_{\text{eddy}} |\nabla \bar{U}|^2 \]

**High Turbulence Limit**

\[ \nu_{\text{eddy}} \sim \left[ \frac{3}{4} \frac{A}{(2 m)^{\nu}} \right]^{\nu/2} \Delta^2 |\nabla \bar{U}| \]

**Transitional Regimes**

\[ \nu_{\text{eddy}}^3 = \nu_{\text{mol}}^3 + \frac{3}{4} \frac{A}{(2 m)^{\nu}} (\Delta^\nu - \eta_d^\nu) \nu_{\text{eddy}} |\nabla \bar{U}|^2 \]

**Alternate Formulation**

Unphysical roots can be a problem.

\[ E = \frac{S^2}{\nu_{\text{eddy}}} \quad S = \nu_{\text{eddy}} |\nabla \bar{U}| \quad \text{[eddy SGS]} \]

\[ \nu_{\text{eddy}} = \nu_{\text{mol}}^{\nu} \nu_{\text{eddy}} + \frac{3}{4} \frac{A S^2}{(2 m)^{\nu}} (\Delta^\nu - \eta_d^\nu) \]

Only 1 real root with \( \nu_{\text{eddy}} \geq \nu_{\text{mol}} \)
RNG K-E Eddy Viscosity

\[ \nu(l) \sim \left( \frac{3}{4} A E \right)^{1/3} l^{1/3} \]

\[ K = \int_0^\infty C_{k_0} E^{2/3} k^{-5/3} \, dk \]
\[ = \frac{3}{2} C_{k_0} E^{1/3} l^{2/3} \]

\[ \nu = \frac{(3/4)^{1/3} \frac{K^2}{(3/2 C_{k_0})^2}}{E} \]

\[ C_m = \frac{(3/4)^{1/3} \frac{RNG}{E}}{(3/2 C_{k_0})^2} \approx 0.0845 \]

Actually -- \[ \nu = C_m \frac{K^2}{E} \text{ only if } \nu \gg \nu_0 \]

RNG Differential Relation

\[ \nu = \nu_0 \left[ 1 + \sqrt{\frac{C_m}{\nu_0}} \frac{K}{\nu_0 \sqrt{E}} \right]^2 \]
Practical Turbulence Theory

Navier-Stokes equations at large $R$ with complicated geometry

Correspondence Principle:
'Heat bath' - random force to model large scales - initial conditions + boundary conditions

$\frac{d\nu(K)}{dK} \sim -\frac{AE}{\nu^5 K^5}$

Renormalization group - generalized scaling theory of the inertial range

ENGINEERING TRANSPORT APPROXIMATIONS - Reynolds averaged equations & Large eddy simulations - RNG theory used to evaluate unknown - unclosed - terms
RNG K-E Modelling

\[ \frac{D\rho}{Dt} = -2\nu_0 \nabla \cdot \nabla \rho - 2\nu_0 (\nabla \rho \cdot \nabla \rho) - 2\nu_0 \nabla \cdot \nabla \rho \nabla p + \nu_0 D^2 \rho \]

\[ T_{1,2} = O(\sqrt{Re}) \quad \text{where } Re = \frac{U^2}{\nu} \]

but \[ T_1 + T_2 = C_{e2} \frac{\rho}{\rho_{ref}} = O(1) \quad \text{as } Re \to \infty \]

\[ C_{e2} = 1.68 \text{ by RNG (Smith+Reynolds 1991, Yakhot+Smith 1991)} \]

Final result (Yakhot+Smith 1991): \[ Re \to \infty \]

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot \rho \overline{v} \rho = -C_{e1} \frac{\rho}{\rho_{ref}} \overline{\nabla} \overline{S}_{ij} \overline{S}_{ij} - C_{e2} \frac{\rho}{\rho_{ref}} - R + \rho \alpha \overline{v} \overline{v} \]

High Re limit: \[ C_{e1} = 1.92 \quad C_{e2} = 1.68 \quad \alpha = 1.39 \]

\[ R = 2\nu_0 \overline{S}_{ij} \left[ \frac{\partial \overline{u}_i}{\partial x_j} \right] \]

\[ \text{R not yet evaluated by RNG methods} \]
\[ \frac{\partial \bar{U}}{\partial t} + \bar{U} \cdot \nabla \bar{U} = -\nabla p + \nabla \cdot [\mu(\nabla \bar{U} + \nabla \bar{U}^T)] \]

\[ \frac{\partial \bar{K}}{\partial t} + \bar{U} \cdot \nabla \bar{K} = -\bar{E} - \bar{\tau}_{ij} \hat{s}_{ij} + \nabla \cdot \alpha_K \nabla \bar{K} \]

\[ \alpha_K \rightarrow 1.39 \quad \text{as} \quad Re \rightarrow \infty \]

\[ \bar{\tau}_{ij} = -2 \, C_m K \bar{\eta}_{ij} \]

\[ \bar{\eta}_{ij} = \bar{s}_{ij} K/E \]
Generalized K-E RNG Model
Yakhot, Thangam, Gatski, Orszag, Spez \(1991\)

\[ R = 2 \nu \sigma \frac{\partial u_i}{\partial x_j} \frac{\partial u_j}{\partial x_i} \]

- \( R = 0 \) if \( \eta = \frac{5E}{\bar{E}} = 0 \)

- \( \eta = 0 \) Homogeneous turbulence
- \( \eta \neq 4 \) Homogeneous shear
- \( \eta = 3 \) Log layer (channel)

- \( \eta \to 0 \) \( R = 4 \tau S^3 \ll \frac{E}{K} \tau S^2 \) so \( R \) negligible

- \( \eta \to \infty \) \( R = O\left( \frac{E^*}{K} \eta \right) \)

Expansion in powers of \( \eta \):

\[ R = 4 \tau S^3 \left[ 1 + \tau \eta + \tau^2 \eta^2 + \ldots \right] \]

where \( \tau_n \) are constants.....

Truncations of this series after a finite \# of terms violate \( R = O(\eta) \) and realizability!
Evaluation of $\mathcal{R}$

- Consistency with weakly sheared turbulence $\eta \to 0$
  \[ \mathcal{R} \sim \nu S^3 \]

- Consistency with strongly sheared (rapid distortion) turbulence $\mathcal{R} = O(\eta) \eta \to \infty$

**Pade' Approximant**

\[ \mathcal{R} = \frac{12 S^3 (1 - \eta/\eta_0)}{1 + \beta \eta^3} \]

$(\sum \eta^n \eta''$ is a geometrical series)

I.e. \[ \mathcal{R} = \frac{C \eta^3 (1 - \eta/\eta_0)}{1 + \beta \eta^3} \frac{\ddot{\xi}}{\dot{\xi}} \]
Diffusion by Random Narrow-Band Velocity Field

Kraichnan 1970

\[ E(k) = \frac{3}{2} v_0^2 \delta(k - k_0) \text{ Not scale invariant} \]

**RNG (Differential model with \( \epsilon \)-expansion to lowest order)**

\[ \kappa_{\text{RNG}} = \frac{v_0}{k_0} \]

**RNG (To all orders in \( \epsilon \) with generalized Wilson rule)**

\[ \kappa_{\text{RNG}} = \sqrt{\frac{2}{\pi}} \frac{v_0}{k_0} \approx 0.80 \frac{v_0}{k_0} \]

**Direct-interaction approximation**

\[ \kappa_{\text{DIA}} \approx 1.1 \frac{v_0}{k_0} \]

**Numerical (Kraichnan)**

\[ \kappa_{\text{numerical}} \approx 0.95 \frac{v_0}{k_0} \]
Two Constants: $\eta_0$ and $\beta$ not yet determined

- Karman constant $K = 0.4$
- Growth rate of homogeneous shear turbulence

\[
\frac{K}{K_0} \propto e^{0.14 t^*}
\]

$\Rightarrow \eta_0 \approx 4.38 \quad \beta = 0.012$
Time evolution of the turbulent kinetic energy in homogeneous shear flow.

--- K-ε model; ○ Large-eddy simulation of Bardina et al.\textsuperscript{14} for $\varepsilon_0/SK_0 = 0.296$

Figure 1
Time evolution of the turbulent kinetic energy in homogeneous shear flow.

— Relaxation model; ○ Large-eddy simulation of Bardina et al.\textsuperscript{14} for $\varepsilon_0/SK_0 = 0.296$

Figure 2
BACKWARD-FACING STEP:

(a) Streamlines

(b) Dimensionless mean velocity profile

(— Computations with isotropic eddy viscosity; o Experiments of Kim et al., 1980; Eaton & Johnston, 1981)

Computed mean flowfield for the new RNG K-ε model

[E = 1:3; Re = 132,000; 200x100 mesh]

Figure 4

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BACKWARD-FACING STEP:

(a) Turbulence intensity

(b) Turbulence shear stress

Computed turbulence stresses for the new RNG K-ε model [E=1:3; Re = 132,000; 200x100 mesh; ---- computations with isotropic eddy viscosity; o experiments of Kim et al, 1980; Eaton & Johnston, 1981]

Figure 5
BACKWARD-FACING STEP:

(a) Streamlines

(b) Dimensionless mean velocity profile

(— Computations with anisotropic eddy viscosity; ○ Experiments of Kim et al, 1980; Eaton & Johnston, 1981)

Computed mean flowfield for the new RNG $K-\varepsilon$ model

$E = 1.3; Re = 132,000; 200 \times 100$ mesh

Figure 6
BACKWARD-FACING STEP:

(a) Turbulence Intensity

(b) Turbulence shear stress

Computed turbulence stresses for the new RNG $K-\varepsilon$ model [$E=1:3; \text{Re}=132,000; 200\times100$ mesh; —— computations with anisotropic eddy viscosity; o experiments of Kim et al., 1980; Eaton & Johnston, 1981]

Figure 7
THE PRESENT STATE OF USING RDT IN TURBULENCE MODELLING OF UNSTEADY FLOWS

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OUTLINE

1. TURBULENCE RESPONSE TO OSCILLATORY DISTURBANCE IN THE BASIC (MEAN) FLOW

2. QUASI-STEADY APPROACH TO TURBULENCE MODELLING

3. RAPID-DISTORTION THEORY

4. OSCILLATORY TURBULENT BOUNDARY LAYER

5. OPEN QUESTIONS, ONGOING ACTIVITIES
THE DISSIPATION TRANSPORT EQUATION SHOULD NOT BE BASED ON LOCAL-EQUILIBRIUM HYPOTHESIS BUT ON RAPID-DISTORTION HYPOTHESIS. NO SUCH DIFFERENTIAL EQUATION IS CURRENTLY AVAILABLE. BUT HUNT ET AL. 1986 AND NEWLEY (1985), BASED ON RAPID-DISTORTION ARGUMENTS, PROPOSED AN ALGEBRAIC EXPRESSION FOR THE DISSIPATION LENGTH SCALE:

\[ 1/l_e = (1/0.09) + 1/\kappa y + \beta \left( \frac{\partial U/\partial z}{k^{1/2}} - \left\langle \frac{\partial U/\partial z}{k^{1/2}} \right\rangle \right) + 1/L_0, \]

WHERE \(< >\) DENOTES A STREAMWISE AVERAGE. THE FIRST PART OF THIS EQUATION RELATES \(L-e\) TO THE MIXING LENGTH VIA A SMOOTHED VERSION OF THE NORMAL RAMP FUNCTION, WHEREAS THE SECOND PART REPRESENTS THE INFLUENCE OF THE MEAN-STRAIN-RATE DEVELOPMENT ON \(L-e\) AND THE THIRD ACCOUNTS FOR ANY IMPOSED LENGTH SCALE.
TURBULENCE RESPONSE TO IMPOSED
OSCILLATORY DISTURBANCES

* SEVERAL EXPERIMENTS ON TURBULENT BOUNDARY LAYERS,
CHANNEL, OR PIPE FLOW SUBJECT TO PERIODIC
DISTURBANCES:

ACHARYA & REYNOLDS 1975
BRERETON, REYNOLDS & JAYARAMAN 1990,
BINDER ET AL. 1981, 1991,
COUSTEI & HOUDERVILLE 1977, 1985
HANARATY ET AL. 1986, 1988
KARLSON 1959, RAMAPRAN & TU 1983
REYNOLDS ET AL. 1982, 1987
RONNEBERGER ET AL. 1977, 1985
* THESE EXPERIMENTS INDICATE THAT:

1. **TIME-AVERAGED QUANTITIES ARE PRACTICALLY NOT INFLUENCED BY UNSTEADINESS**

2. **OSCILLATING QUANTITIES BEHAVE EITHER IN A QUASI-STeadY MANNER OR IN A TRULy UNSTeadY MANNER, DEPENDING ON THE FREQUENCY OF IMPOSED OSCILLATIONS.**
\[ \frac{\bar{\tau}_{\text{unsteady}}}{\bar{\tau}_{\text{steady}}} \]

Ratio of unsteady to steady time mean wall shear stress.

\[ \omega^+ = \frac{\omega \sqrt{x}}{ \nu^*} \]

(Tradu et al. 1991)
Effect of Frequency on Turbulence Intensity - From Mizushima et al. (1973)
Modulation of wall shear stress

pipe:
- Ronneberger/Ahrens (1977)
channel:
- Höhler (1978)
- Ramaprian/Tu (1983)
- Binder/Tardu/Blackwelder (1985)
- Finnicum/Hanratty (1988)

true quasisteady (pipe) \( R e_D = 10^4 \)

\[
\frac{a_{\tau'}}{A\overline{u}^+}
\]

\( 10^{-5} \)
\( 10^5 \)

\( 10^{-4} \)
\( 10^{-3} \)
\( 10^{-2} \)
\( 10^{-1} \)

\( \phi_{\tau'} - \phi\overline{u}_m \)

(Ronneberger & Binder 1991)
QUASI-STEADY APPROACH TO MODELLING

EXTENDS STEADY-FLOW MODELS TO THE UNSTEADY CASE BY ACCOUNTING FOR ONLY THE UNSTEADY DERIVATIVES IN THE TRANSPORT EQUATIONS.


The Calculated Cycle-Variations in the Reynolds Shear Stress at Re = 50,000 in Comparison with Tu and Ramaprian's (1983) Data for a Pipe Flow at y/R = 0.035
QUASI-STEADY MODELS ARE:

* SUCCESSFUL AT THE QUASI-STEADY DOMAIN (LOW-FREQUENCY, OSCILLATIONS).

* FAIL AT THE HIGHLY UNSTEADY DOMAIN (HIGH-FREQUENCY OSCILLATIONS).
* REYNOLDS-STRESS TRANSPORT MODELS ARE VALID WHEN LOCAL EQUILIBRIUM HOLDS \((T_e > T_0)\). MAY NOT RESPOND PROPERLY WHEN THEY ARE USED TO PREDICT MORE COMPLEX STRAIN FIELDS.

* EDDY-VISCOSITY MODELS MAY NOT BE SUITABLE FOR UNSTEADY FLOWS SINCE THEY ASSUME THE ALIGNMENT OF REYNOLDS STRESSES WITH THEIR GENERATING RATES OF STRAIN (NO MEMORY EFFECTS).
* RAPID-DISTORTION THEORY IS ONLY VALID ON THE LIMIT
T_d << T_L, BUT IT IS NOT RESTRICTED BY LOCAL APPROXIMATIONS AND
DEScribes THE CONTINuum INFLUENCE OF STRAIN HISTORY.

SINCE IT DOES NOT ASSUME LOCAL TIME DEPENDENCE, IT MAY BE
PARTICULARLY SUITED FOR OSCILLATING TURBULENT FLOWS WHERE AT
HIGHER FREQUENCIES THE OSCILLATION PERIOD IS OF SIMILAR
MAGNITUDE AS THE LARGE-EDDY TIME SCALE.
RAPID-DISTORTION THEORY (RDT)

* BASIC DEVELOPMENT BY BACHELOR & PROUDMAN (1954),

* RECENT APPLICATIONS BY:
  BALAKUMAR & WIDNALL (1986)
  GARSHORE ET AL. (1983)
  GATSKI (1987)
  GOLDSTEIN & ATTASI (1976)
  GOLDSTEIN & DURBIN (1980)
  MANSOUR, SHIH & REYNOLDS (1994)
  STRECHER & BRITTER (1985)
BASIC RDT

* TURBULENCE MOTION ARE MADE UP OF MANY INDIVIDUAL STRUCTURES. FOURIER SERIES IS DEFINED FOR THE VELOCITY FLUCTUATION AND SUBSTITUTED IN THE EQUATIONS OF MOTION.

* THE RESULTING EQUATIONS ARE LINEARIZED ASSUMING THAT THE TURBULENCE IS WEAK.

* THE TURBULENT-REYNOLDS-NUMBER IS CONSIDERED TO BE HIGH AND THE FLOW IS LOCALLY HOMOGENEOUS.
* It follows that the variation of time of a single component of the fluctuation field is described by an equation for its amplitude $a_i(k)$

$$\frac{da_i(k)}{dt} = -\frac{\partial U_t}{\partial x_i} a_i(k) + 2k_i k_l \frac{\partial U_t}{k^2} \frac{\partial}{\partial x_m} a_m(k)$$

And by an equation for the rate of change of the wavenumber $k$ of the component

$$\frac{dk_i}{dt} = -\frac{\partial U_t}{\partial x_i} k_i,$$

which describes the rotation and distortion of the velocity pattern by mean-flow gradient.
* TO OBTAIN DEFINITE PREDICTIONS IT IS NECESSARY TO ASSUME THE INITIAL STATE OF THE TURBULENCE BEFORE DISTORTION. USUALLY AN INITIALLY ISOTROPIC TURBULENCE IS ASSUMED.

* BUT MAXEY (1982) HAVE SHOWN THAT ASSUMING THE FLOW TO BE INITIAL AXISYMMETRIC INSTEAD OF ISOTROPIC PRODUCES RESULTS IN BETTER AGREEMENT WITH EXPERIMENTAL DATA FOR SHEAR FLOWS.

\[ \alpha = \int_0^t dt' \frac{\partial U_1}{\partial z}, \]
* Mathieu (1971) and Hunt & Maxey (1978) have pointed out that the effective strain is limited by the finite distortion time. Thus at larger times there will also be an equilibrium value of strain

\[ \alpha = T_d \frac{\partial U_1}{\partial z}. \]

Where \( T_d \) is some eddy time scale.
THE TWO LIMITS OF RAPIDLY EVOLVING FLOWS AND EQUILIBRIUM FLOWS ARE RELATED THROUGH

\[ \frac{\partial \alpha_{\text{eff}}}{\partial t} = \frac{\partial U_1}{\partial x_3} \frac{\alpha_{\text{eff}}}{T_D}. \]
RDT AS AN AID IN MODELLING:

WORK IN TERMS OF STRUCTURAL PARAMETERS $a_{ij}$. MATHIEU (1971) PROPOSED THAT:

$$\frac{\dot{u}v}{k} = F(\text{ACCUMULATED STRAIN RATE ALONG A STREAMLINE})$$
SIMPLE MODEL FOR OSCILLATORY TURBULENT BOUNDARY LAYERS: (MANKBAIDI & LIU, 1991, JFM)

SIMPLIFICATIONS:

1. THE OSCILLATIONS ARE OF SMALL AMPLITUDE AND REMAINS HARMONIC SUCH THAT THE GOVERNING EQUATION CAN BE LINEARIZED.

2. THE MEAN FLOW IS ASSUMED TO BE GIVEN AND NOT INFLUENCED BY THE UNSTEADINESS.

3. THE DISSIPATION IS ESTIMATED BASED ON LOCAL EQUILIBRIUM HYPOTHESIS.

4. NO DIFFUSION TERM IN THE EFFECTIVE STRAIN EQUATION.
Computed phase-averaged streamwise velocity compared with data of Binder & Kueny (1981), in terms of magnitude of $u'$ and phase angle $\phi_u$, relative to their respective imposed values. $\omega' = 0.0637\left(\tau_* = 5.6\right)$. 
Computed phase-averaged wall shear stress compared with data of Mao & Hanratty (1986), ○, and Ramaprian & Tu (1983), □. (a) Amplitude
\[ \left( \frac{|\tau_w|}{\overline{\tau_w}} \right) / (A/U_\tau) \]. (b) Phase angle.
Ratio of modulated Reynolds shear stress to modulated turbulent kinetic energy. (a) Amplitude $|r_{xy}^*/\|K^*\|$. (b) Phase difference.
ONGOING WORK

THE EFFECTIVE STRAIN EQUATION FOR INHOMOGENEOUS FLOW SHOULD BE MODIFIED TO ALLOW FOR THE TRANSPORT OF EFFECTIVE STRAIN BY THE ADVECTION OF TURBULENT EDDIES BY THE TURBULENCE ITSELF (TOWNSEND 1970, MAXEY 1982).

\[ \frac{\partial \alpha_{\text{eff}}}{\partial t} = \frac{\partial u_1}{\partial x_3} + \frac{\partial}{\partial x_3} \left( R_{1D} \frac{\partial \alpha_{\text{eff}}}{\partial x_3} \right) - \frac{\alpha_{\text{eff}}}{T_{1D}}. \]
THE ROLE OF EXPERIMENTS
IN
TURBULENCE MODELLING

by

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1. W. K. George

"Governing Equations, Experiments, and the Experimentalist"
Experimental Fluid Thermal Science - 1990

2. W. K. George & D. B. Taulbee

"Designing Experiments to Test Closure Hypothesis"
to appear Experimental Fluid Thermal Science - 1992
(Also Proceedings Symposium on Turbulence Modelling
Dubrovnik 1990).

Some Experimental Dilemmas -- just a few of many
- the Round Jet - what is its growth rate?
- the Turbulent Boundary Layer
- the Plane Wake
- the Dissipation

THE ROUND JET

\[ \delta^{1/2} = 0.095 X \]
\[ \text{not} \quad 0.085 X \]

Illustrates one of the biggest problems for modeller - Who to believe?
- Problem for experimentalists is
  - How to overturn old results?
    - unpublished since disagree with earlier results
    - unaccepted since unpublished
    - unused since unknown
- Problem for everyone - Isn't there better way
  - to get results out
  - to purge old results
LOCAL ISOTROPY ???

- Local Axisymmetry?
- Equi-partition of Dissipation?
Axisymmetric Jet \( (Re_0 = 10^5) \)
With the exception of all greater departures from of validating (3).

The results of large and the reasonableness of the same experimental differences between correlation [cs] to [9] of (4). Both the expected and the important terms in (4), these are shown in the estimates of Lees and of the centreline to absolute.

Lees (1954) derivatives with
THE PLANE WAKE

- there is no wake which is independent of generator
Figure 5. Variation centerline velocity deficit and half-width with distance for three wake generators; □, airfoil; Δ, 70% solidity screen; ○, solid strip (from Wygnanski et al. 1986).

Figure 6. Reynolds stress normalized by centerline velocity deficit for the solid strip and airfoil (Wygnanski et al. 1986).
Figure 7. Normalized turbulence intensity profiles for the three generators of Figure 5 (Kienzler et al. 1986).

**The Axisymmetric Wake: A Flow Which Does Not Evolve at Constant Reynolds Number**

The axisymmetric wake presents an interesting contrast to the axisymmetric jet and plane wake flows described above in that it does not evolve at constant Reynolds number (as will be seen). As a consequence, the nature of the assumptions regarding the dissipation will be seen to predict two quite different asymptotic developments. There appears to be experimental evidence for both forms in different experiments, which raises an interesting question as to how the flow chooses one form or another. An interesting possibility is that the flow evolves from one state to another as the Reynolds number changes. These possibilities will be discussed in more detail below following the analysis.

The equations of motion describing the axisymmetric wake to first order can be shown to reduce to,

\[ \frac{\partial}{\partial r} \left( \frac{1}{2} \rho r^2 \right) = -\frac{1}{r} \frac{\partial}{\partial r} \rho \bar{v} \]

where \( \bar{v} \) is the undisturbed speed of the free stream. This can be integrated across the flow to yield the integral constraint,

\[ 2\pi \int_0^\infty \rho U_o (U-U_o) r dr = \pi U_0^2 \theta^2 - M/\rho \]

where \( \theta \) is defined to be the momentum thickness.
This persistent effect of initial conditions may be widespread!
Theory also predicts that spectral shape is determined by initial conditions. Note different shapes of 1" and 2" grid spectra.
The 'Well-established' Turbulent Boundary Layer

. Is there really a log layer?

. Should comparisons be made with these correlations?
Fig. 1.1.1 On the determination of the friction coefficient
from KLINE et al. (1967).

**Bottom line:** If you assume log layer
and use it to calculate \( u^* \), you get log
layer — not very comforting.
Fig. 1.1.2 On the determination of the friction coefficient:
from KLINE et al. (1967).

Figure 9b. $u^-$-$y^-$ profiles using $u_1$ (note shifted origin).
Fig. 2.1.2.1.1 Velocity in inner variables with log law.

Puntell et al., $R_{th} = 465, 498, 700, 1000, 1340, 1370, 1840, 2840, 3480, 4090, 5100$. 

Inferred $T_w$
Fig. 1.4.1 Velocity profiles obtained with a wall slope determined shear stress:

Purcell et al., $R_{th} = 465, 498, 700, 1000, 1240, 1370, 1840, 2840, 3480, 4090, 5100$.

$Y_+ = (Y \cdot U_{\tau})/\nu$
Fig. 1.2 Velocity derivative from Direct Simulation:
from SPALART (1988)

Figure 5. Mean velocity profile and its derivative. \( R_e = 300; \quad R_e = 670; \quad R_e = 1410; \quad \cdots \). Log law \( U^+ = \log (y^+)/0.41 + 5 \): \( + \). \( R_e = 617 \) (Erm et al. 1985): \( O \). \( R_e = 1368 \) (Murlis et al. 1982). (a) \( U^+ \); (b) \( y^+ \frac{dU^+}{dy^+} \).
Fig. 3.1.2.2.11 *Outer variables:*

Purcell et al., $R_th = 5100$. 

$R_th = 5100$. 

$\frac{y}{\delta} \cdot \frac{D(u/u_{INF})}{D(y/\delta)}$ (3 points)

$u/u_{INF}$
Fig. 4.4.3.1.1 Shape factor.

Smith and Walker. $x = 15.75$ in, 27.75 in, 39.75 in, 51.75 in.

George and Bower (1984) Perforated theory

$$H \to \frac{1 - I_0}{I_0 - J_0} \quad \text{as } Re \to \infty$$

$$> 1 \sim 1.23$$

$x = 15.75$ in

$x = 27.75$ in

$x = 39.75$ in

$x = 51.75$ in
Fig. 4.2.2.1.1 Momentum thickness:

Smith and Walker. $x = 15.75$ in, 27.75 in, 39.75 in, 51.75 in.
Fig. 4.4.2.1.1 *Momentum thickness:*

Smith and Walker. \( x = 15.75 \text{ in}, 27.75 \text{ in}, 39.75 \text{ in}, 51.75 \text{ in} \)

\[ (U_{\text{INF}} - \Delta) / \nu \]

\[ ^{\circ} \theta^\circ \]

\[ 0.600E+05 \]

\[ 0.450E+05 \]

\[ 0.300E+05 \]

\[ 0.150E+05 \]

\[ 0.000E+00 \]

\[ 0.000E+00 \]

\[ 0.125E+06 \]

\[ 0.250E+06 \]

\[ 0.375E+06 \]

\[ 0.500E+06 \]

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\( x = 15.75 \text{ in} \)

\( x = 27.75 \text{ in} \)

\( x = 39.75 \text{ in} \)

\( x = 51.75 \text{ in} \)

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Fig. 4.4.6.1.1 Friction coefficient as a function of $x$.
Smith and Walker (53 points).
The Past

Without experiments, there would be no single-point turbulence models.

DNS, LES, etc. have helped augment data base in recent years. Contributions have been important, but relatively minor when taken as part of the whole.

The Future

Question: Is this balance likely to change?

No question simulations will play increasingly important role

- ability to produce difficult quantities (for expts) (pv, pressure strainrate, dissipation, etc.)
- increasing Reynolds number (still small)
- National economic agenda of U.S. - we will do what is necessary to maintain market position
- indirect subsidy of CFD

What role will this leave for expts?

Experiments of value to modelling community are very difficult to do

Most efforts, however well-intended, do not measure up!

Reasons complicated but... high on the list....

- Inexperience of investigator.
- Ignorance of goals.
- Money usually runs out before experimenter learns to do it right.

These will be increasing problems in next decade.

Biggest Problem for Experimentalist:

- Few sponsors have patience to see an experiment through to its completion - none in my experience!
- As complexity of flows to be investigated increases (Bushnell comment), this problem will be exacerbated!
FINAL THOUGHT

However successful our closure efforts may be, we are not solving the turbulence problem – we are only being responsible engineers!

We must therefore be careful not to demean the efforts of those who are trying to grapple with the real turbulence problem – there may be an underlying physical principle which will very much affect what we do!
TWO TYPES OF NUMERICAL SIMULATION

Direct Numerical Simulation (DNS)

  Exact realizations
  Good for studying physics
  Limits: Low Re, Simple geometry

Large Eddy Simulation (LES)

  Small scales modeled
  More complex flows
  Less accurate
FLOWS SIMULATED

Homogeneous turbulence

Isotropic

Strained (various)

Sheared

Compressed

Compressible

Rotating

Combinations
Homogeneous Incompressible Turbulence

Isotropic decay  Strain  Relaxation from strain

Shear  Rotation  Compression

\[ \Omega \]
MODEL EQUATIONS

\[ k - \varepsilon: \]

\[ \partial_y (\nu + \nu_T/\sigma_k) \partial_y k = \varepsilon - \nu_T (\partial_y U)^2 \]

\[ \partial_y (\nu + \nu_T/\sigma_{\varepsilon}) \partial_y \varepsilon = \frac{[C_{\varepsilon_2} \varepsilon - C_{\varepsilon_1} \nu_T (\partial_y U)^2]}{T} \]

\[ \overline{v^2} - \varphi_{22}: \]

\[ \partial_y (\nu + \nu_T/\sigma_k) \partial_y \overline{v^2} = \frac{\overline{v^2}}{k} \varepsilon - \varphi_{22} \]

\[ L^2 \partial_y^2 f_{22} - f_{22} = -\Pi_{22} \]

\[ \varphi_{22} = k f_{22} \]

\[ \Pi_{22} = \frac{C_1}{T} \left[ \frac{2}{3} - \frac{\overline{v^2}}{k} \right] + C_2 \nu_T (\partial_y U)^2 \]
Fig. 1b. k (solid line) and v2 (dashed line) from the model compared to DNS data (symbols).
COMPRESSIBLE TURBULENCE

New Physics:
  Faster decay at high Mach number
  Mixing layer growth rate reduced
  Eddy shocklets

Model by Zeman
  Introduced dilation dissipation concept
  Model based on concept

Isotropic turbulence decay—well predicted
Growth of mixing layer—well predicted
Boundary layer questionable
Fig. 1 Pressure dilatation during 1D rapid compression
STOCHASTIC SHOCKLET DISSIPATION MODEL.

Figure 1. (a) Sketch of shock-like structure in a turbulent eddy; (b) normal shock relations.

Average dilatation dissipation:

\[ \epsilon_d \propto \frac{q^2}{L} \left[ \frac{1}{M_t^{*4}} \int_1^\infty \left( \frac{m^2 - 1}{m} \right)^3 p(m, K) \, dm \right] \]

and

\[ \epsilon_d = \epsilon_s c_d F(M_t, K) \]

Total dissipation (for given kurtosis \( K \) of \( m \))

\[ \epsilon_{tot} = \epsilon_s \{1 + c_d F_k(M_t)\} \]
Normalized Mixing Layer Growth Rate

\[ M_c \]

\[ \frac{\partial}{\partial t} \]

\[ \frac{Q}{Q} \]
Centerline Turbulence Intensities in Mixing Layer

\[
\left( \frac{-\bar{uv}}{\Delta U} \right)^{1/2} \frac{A_{\Delta U}}{\Delta U}
\]

- Model \( \frac{u'}{\Delta U} \)
- Model \( \frac{v'}{\Delta U} \)
- Model \( \frac{-\bar{uv}^{1/2}}{\Delta U} \)
- Data \( \frac{u'}{\Delta U} \)
- Data \( \frac{v'}{\Delta U} \)
- Data \( \frac{-\bar{uv}^{1/2}}{\Delta U} \)

\( M_c \)
Fig. 3 Response of turbulent energy to the normal shock
CONCLUSIONS

DIRECT SIMULATION

Useful for studying detailed physics
Understanding leads to new/improved models
Wide range of examples
Building block flows
Further examples:
  Compressed turbulence
  Strained turbulence
  Reacting flows–flamelet models
  Stratified flows
  Atmosphere
FUTURE

DIRECT SIMULATION

More complex flows
Wider range of applications
Wide range of examples
Building block flows

LARGE EDDY SIMULATION

Complex flows
Interaction between LES/RANS
Possible engineering applications
FLOWS SIMULATED—CONTINUED

Free shear flows

Mixing layers

Wakes, jets

Wall bounded flows

Channel

Boundary layer

Couette flow
Inhomogeneous Incompressible Turbulence

Wall-bounded flows

Channel  Curved channel  Boundary Layer

Free shear flows

Mixing Layer  Plane Jets
USES OF SIMULATIONS

Study physics of turbulence

Test validity of models

Gain insights for new models
EXAMPLES—MODEL TESTING/VALIDATION

Boundary layers

Mixing layers

Atmospheric models

Stratified turbulence
EXAMPLES-MODEL DEVELOPMENT

Rotating turbulence
Compressed turbulence
Compressible turbulence
Wall layers
Flamelet models
ROTATING TURBULENCE

Isotropic turbulence subject to rotation

Important building block flow

History:

Several experiments—disagree

Simulations:

Bardina & Ferziger

Aupoix & Cousteix

Mansour & Coleman
RESULTS–ROTATING TURBULENCE

Turbulence decay reduced

Reduced transfer to small scales

Anisotropy only at moderate Ro

Several models developed
ANISOTROPY MEASURE

\[ A = \frac{2(t-t_0)\varepsilon_0}{q_0^2} \]

- \( R_0 = \infty \)
- \( R_0 = 0.4 \)
- \( R_0 = 0.008 \)
- \( R_0 = 0.04 \)
ENERGY SPECTRUM

\[ E(k, t_0) \sim \nu k^2 (t, t_0) \]

\[ 2(t - t_0) \frac{\delta}{\varepsilon^2} = 8.35 \]
WALL BOUNDED FLOWS

Near-wall turbulence difficult

Existing models not totally satisfactory

Mansour & coworkers:
  
  Tested approximations to pressure-strain
  
  Computed dissipation equation budget
  
  Found scaling laws for various terms

Durbin:

  New model based on equation for $\nu^2$
  
  No need for special low-Re model
  
  Good predictions of boundary layers
Summary

Have modelled blocking effect with new $k - \varepsilon - \nu$ model.

Elliptic relaxation model for $\varphi_{22}$ accounts for strong non-homogeneity and introduces homogeneous solutions in the $\nu^2$ part of the model.

This is able to describe near-wall transport in channel flow; holds promise for non-equilibrium flow—which is where models are most needed.
DISCUSSION

B.E. Launder (to S. Orszag)

You showed us values of $C_1$ and $C_2$ which would give too high a decay rate of grid turbulence.

S. Orszag (reply)

There is some question about what the decay rate really is.

B.E. Launder (to S. Orszag)

You talked about $C_2$ but you didn’t say how $C_1$ emerged.

S. Orszag (reply)

That’s the same calculation.

S. Pope (to S. Orszag)

Calculations you did with backward facing step, what boundary conditions did you use?

S. Orszag (reply)

That was not a full RNG calculation. It should have been done using interpolation formulation for the various constants all the way to the wall. Instead it was done using the a fit right to the log layer.
T. Gatski (to W.K. George)

Two things modelers are looking for validation and calibration. Bill referred to the kind of experiments we use for validation. The kind of work you (J.H. Ferziger) do with DNS has been building block for calibration. Do you want to design the experiments to validate our model or calibrate?

W.K. George (reply)

I would like to design experiments which would invalidate your models.

T. Gatski (to W.K. George)

But that would be destructive for both of us.

P. Spalart (to J.H. Ferziger)

I differ with your description of DNS as exact solution. I would like to say that my solution are not exact. I spend quite a lot of time thinking how I can keep the error small. If I can double the number of the grid points in each direction I would sleep better but it would take fifty years instead of two years to finish the simulation.

J.H. Ferziger (reply)

I should have said that in my talk that any numerical calculation is approximate and I hope we work hard to keep them small. There are errors due to numerical methods and errors due to the fact that we have limited computer time.
P. Spalart (to W.K. George)

A comment on Bill's theory that it's a power law instead of log law. I think in your original APS abstract you make it sound like it's just a matter of taste if you use defect law or your theory.

W.K. George (reply)

In the original APS abstract I wasn't clear why the theory comes apart asymptotically and I feel much confident now that the existing theory is wrong.

P. Spalart (to W.K. George)

There is very different Galelian invariance to those two theories and its not a matter of test. Defect law says we are coming from the free stream and we don't know how fast the wall is moving; it may be a moving belt. Your theory doesn't do that.

W.K. George (reply)

That's right. There is no question that there is a lot of sorting out to be done.

B.E. Launder (to W.K. George)

It's very interesting that he (or it) brings out into question the universality. If you got flows to decrease rapidly with distance from the wall as you do in low Re channel flows there is data going back to fifties that your log-log constant goes up. So logically you would expect log-log constant would go down in adverse pressure gradients. The implicit faith shown in sectors of fluid community in the universality of the log law I think is misplaced.
There is now emerged which I think an excellent paper by Nagano (at the upcoming SFC in Munich) showing what seems to me a clear dependence of log-log constant on shear stress gradient. In adverse pressure gradients lower log-log constants than you find in zero pressure gradients. Bill gets unhappy at unacknowledged as his private discoveries as all of us do, I suggested this in a paper about eight years ago.

W.K. George (reply)

I presented this in 1978.

P. Spalart (to B.E. Launder)

I have results that show that in moderate pressure gradients log-log going down. At \( y^+ = 50 \) it goes down by almost one wall unit at \( \beta = 2 \) which is not very strong at all.

S. Pope (to P. Spalart)

You very quickly mentioned that you use DNS data for guidance and not calibration. Could you expand on that?

P. Spalart (reply)

If I calibrate turbulence model for boundary layer based on flat plate results I'll get too high \( Re \), so I don't have DNS results which I'll trust within 10% to extrapolate to high \( Re \).

G. Hwang (to J.H. Ferziger)

You talked about P. Durbin model that uses \( \overline{v^2} \) as damping function. But
problem is we want to use this model in multi-dimensions. Then you are
talking about $k - \nu^2$ and $\epsilon$ equation which is as complicated as Reynolds
stress models. I am not disputing the model there are some good points to
it.

A. Yoshizawa (to J.H. Ferziger)

You pointed out the possibility of LES as engineering tool but our experience
shows we can not perform LES with Smorginsky constant fixed. LES criti-
cally depends on Smorginsky constant e.g. we perform LES of channel flow
using $C_s = 3.1$ but using this constant we can not simulate e.g. backward
facing step. My opinion is without overcoming this difficulty LES can not
become engineering tool.

J.H. Ferziger (reply)

I agree with you. There is a new model which does overcome some of these
difficulties. I don't want to say that all the difficulties are overcome but we
have hope.

J. Bardina (to A. Yoshizawa)

We have investigated DIA, RDT and LES. LES is much simpler than DIA.
You have difficulty with Smorginsky constant but we know that this constant
is not right. It's not universal for all flows because only thing it's doing more
is dissipating more energy; that's all. At high $Re$ you are putting more
energy at small scales and there are many other effects which you have to
put there.
E. Reshotko

Bill brought up many of the problems in looking at experiments. There are many more which try to fulfill some of the desires and expectations that have been brought up here at the workshop. First any self-respecting experimentalist is not there to design experiments to validate or calibrate a theory. First of all he is there to discover new physics. May be a theoretician wants to see if the physics is reproduced by the model.

But when it comes to doing that particularly in measuring turbulence we come up with the problem of how to measure at a point. We have all these wonderful things at a point when we have probes which are not a point. Recently we had experience with multiple wire probe that showed our probe was not measuring at a point although our probe was less than 0.1mm in overall size. And this problem becomes worse if one goes to high speeds. I understood just a few years ago why all good turbulence measurers were working in large facilities and in low speeds because only in that way you can feel reasonably secure that in terms of wall units you are operating at a point. We tried running some experiments at 100 ft/sec and found that our probe was 100 wall units which typically a spanwise streak size. In compressible flows, aside from increased speeds and increased probe dimensions in wall units, we also have the problem of calibration in transonic regimes. It's not that we don't know how a hot-wire works in transonic regimes. It's so sensitive to Mach number in transonic regime that there is not a way of saying it's reliable. I am worried about the double and triple correlations in boundary layers with the present probes. One of the things H. Nagib is doing is looking at probe miniaturization and I encourage this but until then I think prospects of getting detailed compressible flow measurements are dim.
J.H. Ferziger (to all participants)

I thought it would be interesting to throw out at the modelers that what do they think is missing in the experiments, simulations and theory?

B.E. Launder

I ponder from time to time about these nice homogeneous flows which people use to come up with constants in dissipation equation as Steve Orszag was talking about. Question comes to my mind that its the variation in inhomogeniety which we are interested in looking at. The variation in spatial length scales ought to enter in our closures in ways other than the diffusive like terms. That is to say perhaps if we are thinking of dissipation equation having adjacent to one another layers of different length scales are going to be promoting spectral transport of energy removed more readily than you'll find in homogeneous flows. So I ask myself if DNS can help clarify this.

J.H. Ferziger (to B.E. Launder)

Are those relatively simple inhomogeneous flows in that regard.

B.E. Launder (reply)

I think simpler inhomogeneous flow you are talking about is channel flow where everything is so dominated by the fascinating structure of the near wall sublayer. If you could do simulation away from wall where low Re dissipation issues are dominated.

J.H. Ferziger (to B.E. Launder)

Then there are mixing layers.
B.E. Launder (reply)

Maybe mixing layer results will be valuable. I don't think they ought to belong to this question. That is your dissipation equation needs to be different in inhomogeneous from that in homogeneous.

J.H. Ferziger (to B.E. Launder)

We tried doing flow simulation of experiments of Warhaft. May be we can collaborate.

B.E. Launder (reply)

Maybe those experiments themselves will answer. There are no mean velocity gradients in that experiment John (to J.L. Lumley).

J.L. Lumley (to B.E. Launder)

No mean velocity gradients - just a gradient of scale. I was just going to draw attention to that.

J. Bardina (to B.E. Launder)

Brian are you suggesting that homogeneous flows are not a valid test for $k-\epsilon$ model since it would not account for inhomogeneous part in shear flows.
B.E. Launder (reply)

We should look at homogeneous flows as building blocks and may be we shouldn't say going from homogeneous to inhomogeneous flows just adds a diffusion like transport term but may be adds other as well.

J. Bardina (to B.E. Launder)

The $k - \epsilon$ model worked good for homogeneous flows we tested and it wasn't tuned for these. We looked at homogeneous shear, and plane strain flows and it did very well. It didn't do well for rotational flows because effect of rotation isn't accounted for.

W.K. George (to B.E. Launder)

I think you are right Brian. If you look at Antonio's dissipation results all but one derivative is way out of line. I have come to believe that it associated with inhomogeneity. And if you look at each term in the equation, if the flow is truly locally homogeneous you can not produce any of those. This question is best resolved by DNS of inhomogeneous situation at low Re.

J. Weinstock (to B.E. Launder)

I wouldn't have any doubt that inhomogeniety would cause changes other then diffusive transport. Nature of the change is such that we can not tell until we do it. I did a calculation where I accounted for strong time variation where the turbulence energy is changing at times of order of eddy circulation time and a simple result came out of that. It wasn't diffusive transport. Eddy circulation becomes function of turbulence time scale. So the coefficients involving damping become function of rate of change of turbulence. I think if we put spatial inhomogeniety we would come up with something related to that. It's obviously not diffusive.
Workshop on Engineering Turbulence Modeling

The purpose of this meeting is to discuss the present status and the future direction of various levels of engineering turbulence modeling related to CFD computations for propulsion. For each level of complication, there are a few turbulence models which represent the state of the art for that level. However, it is important to know their capabilities as well as their deficiencies in CFD computations in order to help engineers select and implement the appropriate models in their real world engineering calculations. This will also help turbulence modelers perceive the future directions for improving turbulence models. The focus of this meeting will be one-point closure models (i.e. from algebraic models to higher order moment closure schemes and pdf methods) which can be applied to CFD computations. However, other schemes helpful in developing one-point closure models, such as RNG, DIA, LES and DNS, will be also discussed to some extent.