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PROGRESS IN SIMULATING INDUSTRIAL FLOWS USING TWO-EQUATION MODELS: CAN MORE BE ACHIEVED WITH FURTHER RESEARCH?

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Vahé Haroutunian
Fluid Dynamics International, Inc.
Evanston, Illinois

BACKGROUND AND OBJECTIVES

- ► Two-equation eddy-viscosity models (TEM's) are the most cost effective for the purposes of applied CFD. Give best accuracy vs. cost balance.
- ► There is a lot of confusion about true strengths and limitations of TEM's especially that of standard k-ε model.
- ► We have embarked on extensive study of TEM's over wide range of flows:
  - ▹ Identify true strengths and limitations of standard k-ε model.
  - ▹ Evaluate other TEM's.
  - ▹ Assess emerging models and novel modeling trends.
  - ▹ Identify key areas requiring further research.
- ► This talk provides brief review of TEM's from perspective of applied CFD.
  - ▹ It provides objective assessment of both well-known and newer models.
  - ▹ It compares model predictions from various TEM's with experiments.
  - ▹ It identifies sources of modeling error and gives historical perspective of their effects on model performance and assessment.
  - ▹ It recommends directions for future research on TEM's.

REMARK:

- ► Many reported poor predictions of TEM's are primarily due to combination of improper choice of near-wall model and over-diffuse numerics.
- ► TEM performance can be much improved form further research in:
  - ▹ Length scale determining equation.
  - ▹ Advanced (Anisotropic/Nonlinear) Eddy-viscosity models.

O About FDI

- ► Over 10 years in business.
- ► Primary product FIDAP (FluId Dynamics Analysis Package).

O About FIDAP

- ► First commercial general-purpose finite element CFD program.
- ► Models wide range of flows.
- ► Over 700 FIDAP licenses worldwide.

O FIDAP Turbulence Modeling Capabilities

- ► Based on two-equation eddy-viscosity models:
  - ▷ Standard k-ε model (Launder and Spalding).
  - ▷ Extended k-ε model (Chen and Kim).
  - ▷ RNG k-ε model (Yakhot, Orszag, Thangam, Gatski and Speziale).

- ► Low-Re near-wall modeling based on two-layer approach:
  - ▷ Viscous sublayers spanned by single layer of specialized elements.
  - ▷ van Driest's model used in viscous sublayers.
  - ▷ Interpolation functions based on universal flow profiles.

- ► Latest turbulence modeling enhancements (to appear soon):
  - ▷ Anisotropic eddy-viscosity models.
  - ▷ Wilcox's k-ω model.
  - ▷ Anisotropic version of the standard k-ε model.

O Typical Industrial User

- ► Design engineer.
- ► Trained in fluid mechanics and heat/mass transfer.
- ► Familiar with range of flows of interest to his/her organization.
- ► NOT CFD expert.
- ► Little or no background in turbulence modeling.

O Turbulence Modeling Requirements of Applied CFD Codes

- ► Optimal balance of cost and accuracy:
  - ▷ Turbulence modeling overhead of critical concern.
  - ▷ Overall accuracy of ± 15% adequate for most cases.
- ► Consistent performance over wide range of flows:
  - ▷ Heat/mass transfer
  - ▷ 2-D and 3-D (Cartesian, axisymmetric)
  - ▷ Complex geometries
  - ▷ Transient flows
- ► Adaptable to a wide range of complex flow physics:
  - ▷ Low-Re effects
  - ▷ Variable density/compressibility effects
  - ▷ Combustion
  - ▷ Two-phase
- ► Minimum level of user input/intervention:
  - ▷ No fine tuning model coefficients and/or solution parameters.
  - ▷ No physical input other than boundary and/or initial conditions.
- ► No geometry dependence:
  - ▷ Distance to wall and/or y^+ dependence.
- ► Stable numerical characteristics.

TURBULENCE MODELING CONSIDERATIONS

○ Key Modeling Issues

1- Accurate modeling of mechanisms governing $\rho\overline{u_i'u_j'}, \rho\overline{u_i'\theta'}, \rho\overline{u_i'c_\alpha'}$.
  a) Pressure-scrambling
  b) Body forces
  c) Transport effects
  d) Dissipation
2- Accurate modeling of characteristic turbulent length scales.
3- Accurate modeling of low-Re near-wall phenomena.

○ Optimal Level of Turbulence Model for Applied CFD

► **Second-Moment Closures (DSMC's) and (ASMC's)**
(+) DSMC's ideally suited to modeling aspects **1-a,b,c** above, however,
(–) DSMC's costly, especially in 3-D in presence of heat/mass transfer.
(–) Geometry dependence in current pressure-scrambling models.
(–) ASMC's perform erratically (1-c above not well modeled).
(–) ASMC's numerically less stable (stiff equations).

► **Two-Equation Eddy-Viscosity/Diffusivity Models (TEM's)**
(+) Least costly.
(+) No geometry dependence (except some low-Re TEM's).
(+) Numerically more stable.
(–) Conventional TEM's not suitable for modeling effects **1-a,1-b,&1-c.**
(+) Room for significant improvement in predicting effects of complex strain and anisotropy through the combined use of improved length scale equations and advanced eddy-viscosity models.
(–) Transport effects (1-c), however, cannot be directly predicted.

LENGTH SCALE DETERMINING EQUATION

○ THE STANDARD k-ε MODEL

$$\rho\frac{D\varepsilon}{Dt}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+c_1\frac{\varepsilon}{k}G-c_2\rho\frac{\varepsilon^2}{k}$$

where,

$$G=-\rho\overline{u_i'u_j'}\frac{\partial u_i}{\partial x_j}\approx\mu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j}$$

and,

$$c_\mu=0.09,\ c_1=1.44,\ c_2=1.92,\ \sigma_k=1.0,\ \sigma_\varepsilon=1.3$$

► **Remarks on standard k-ε model:**

▷ Use is made of Boussinesq's "isotropic" viscosity model.
▷ Fine scale isotropy is assumed in modeling ε equation.
▷ Is high-Re model. Must be used with suitable near-wall sub-model.
▷ Many reported poor predictions are due to improper choice of near-wall model, mesh density, discretization scheme and boundary conditions.
▷ Model predicts much better than commonly believed, if used properly.
▷ It does however have its shortcomings in predicting difficult flows involving strong anisotropy and/or non-equilibrium effects - it tends to be over-diffuse. It predicts flatter flow profiles, shorter recirculating zones, and occasionally does not predict subtle separation bubbles.

LENGTH SCALE DETERMINING EQUATION

O THE EXTENDED k-ε MODEL OF CHEN AND KIM

- ► Employs modified ε equation containing extra generation term.
- ► Rationale is that in addition to turbulence time scale k/ε, there is further time scale $\rho k/G$ characterizing response of ε to mean strain.

$$\rho \frac{D\varepsilon}{Dt} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + c_1 \frac{\varepsilon}{k} G + c_3 \frac{G^2}{\rho k} - c_2 \rho \frac{\varepsilon^2}{k}$$

$$c_\mu = 0.09, c_1 = 1.15, c_2 = 1.9, c_3 = 0.25, \sigma_k = 0.75, \sigma_\varepsilon = 1.15$$

► Remarks on extended k- ε model of Chen and Kim:

- ▹ Is high-Re turbulence model. Needs near-wall model.
- ▹ Gives similar predictions to standard model in equilibrium flows.
- ▹ We find Chen and Kim's (1987) recommended model produce predictions that are too under-diffuse in confined flows.
- ▹ We have tuned constants $c_1 = 1.35$ and $c_3 = 0.05$ to improve performance
- ▹ Revised model gives better results for some well-known benchmark flows, but improved predictions over standard model are not realized consistently. More experience and possibly fine tuning is needed.

LENGTH SCALE DETERMINING EQUATION

O THE RNG k-ε MODEL

- ► RNG k-ε model has undergone two major revisions.
- ► Latest version due to Yakhot, Orszag, Thangam, Gatski, and Speziale

$$\rho \frac{D\varepsilon}{Dt} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + c_1 \frac{\varepsilon}{k} G - R - c_2 \rho \frac{\varepsilon^2}{k}$$

where

$$R = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\overline{\frac{\partial u_k'}{\partial x_i}\frac{\partial u_k'}{\partial x_j}} \approx \frac{c_\mu \eta^3 (1 - \eta/\eta_0)}{1 + \beta\eta^3}\frac{\varepsilon^2}{k}$$

$$\eta \equiv s\frac{k}{\varepsilon}; \quad s = \sqrt{G/\mu_t}$$

and

$$c_\mu = 0.085, c_1 = 1.42, c_2 = 1.68, \sigma_k = \sigma_\varepsilon = 0.7179, \eta_0 = 4.38, \beta = 0.015$$

- ► Above version is high-Re turbulence model. Needs near-wall model.
- ► Most testing of model has been done with simple near-wall model.
- ► Our testing of model with more accurate near-wall model indicates that RNG model is often under-diffusive in internal flows and can be very over-diffusive in some external flows.
- ► We have tuned model constants and obtained better overall predictions.
  $c_\mu = 0.0865, c_1 = 1.45, c_2 = 1.83, \sigma_k = 0.8, \sigma_\varepsilon = 1.15, \eta_0 = 4.618, \beta = 0.17$
- ► Revised model gives better results for some well-known benchmark flows, but improved predictions over standard model are not realized consistently. More experience and possibly fine tuning is needed.

LENGTH SCALE DETERMINING EQUATION

○ **Additional Remarks on RNG k-ε Model:**

- Interesting development though no major breakthrough.
- Most model constants are predicted from RNG theory.
- In applying RNG theory it is assumed that turbulence field has very wide spectrum and that inertial sub-range is isotropic.
- Values of model constants predicted by RNG theory are **approximate** owing to simplifying assumptions made in applying RNG method.
- Model predictions critically dependent on additional term R.
- The R term reflects proposed contributions from fine scale anisotropy .
- The R term is not derived and modeled using RNG theory.
- The R term has essential similarities with extra term in ε eq'n of extended k-ε model of Chen and Kim.
- Latest model does not predict von Karman constant.

- **The most notable fact about the RNG k-ε model of YOTGS is that it challenges the notion of fine scale isotropy of turbulence**
    - Thus ε (and consequently the characteristic turbulent length scale) is assumed to be significantly influenced by the fine scale structure. These effects are heuristically modeled via the time scale ratio η.
    - It is interesting to note that the assumption of fine scale anisotropy used in modeling R conflicts with notion of a wide and isotropic turbulent spectrum used in applying RNG theory to rest of model.
    - It is more likely that the turbulent length scale is influenced strongly by **large scale anisotropy** as characterized by the anisotropy tensor a_{ij}
    - Anisotropic eddy-viscosity models can provide estimates of a_{ij} which can be used to design improved length scale determining eqn's.

ADVANCED EDDY-VISCOSITY MODELS (Beyond Boussinesq)

○ **Anisotropic Eddy Viscosity Models (AEVM's)**

- There has been renewed emphasis in developing AEVM's.
- Lead to better approximations of the normal and shear stresses and therefore turbulence anisotropy effects.
- In addition to more accurate modeling of $\rho\overline{u_i'u_j'}$, AEVM's could potentially be used to improve modeling of:
    - Length scale determining eq'n.
    - Generation rate of turbulence energy.
- Examples of AEVM's are:
    - Lumely (1970)
    - Speziale (1987)
    - Yoshizawa (1984), DIA
    - Rubinstein and Baron (1990), RNG
    - Taulbee (1992) and Speziale (1993), derived from DSMC's
    - Launder (1993)

- **Remarks:**
    - Potential of models have been demonstrated using simple tests.
    - Improvements in accuracy often of second-order in magnitude.
    - Not been extensively tested especially for swirling flows.
    - Anisotropic models not yet extended to turbulent heat/mass fluxes.
    - We are presently investigating AEVM's of Speziale (1987) and Launder (1993).

THE LOW-RE NEAR-WALL MODEL

○ **Wall Function Models**

- ▸ Produce over-diffuse solutions in off-equilibrium boundary layers.
  - ▹ Often fail to predict separation or vortex shedding.
- ▸ Unfortunately still in extensive use in applied CFD codes.

○ **Specialized Finite Element Model (FIDAP)**

- ▸ Is essentially two-layer model.
- ▸ Avoids fine near-wall mesh via use of one layer of specialized elements.
- ▸ Employs van Driest's low-Re mixing-length model in near-wall layer.
- ▸ Combines low cost of wall function models with accuracy of two-layer models.
- ▸ y^+ dependence confined to single layer and transparent to user.

Remarks:

- ▸ Most of historical testing and verification of TEM's has been done using wall functions. The excess diffusion has lead to much confusion in assessing TEM's.
- ▸ Proper assessment of TEM's requires at least two-layer models.
- ▸ Wall function approach is simply unacceptable for applied CFD.

IMPACT OF DISCRETIZATION ERROR

○ **Sources of Discretization Error:**

- ▸ Grid refinement (grid convergence).
- ▸ Location of computational boundaries (e.g., outlet, inlet, entrainment).
- ▸ Choice of discretization scheme in space and time.

Remarks:

- ▸ Effect of discretization error has received less attention in turbulence model development and testing.
- ▸ Most serious source of error results from discretization of advection terms (i.e., the *upwinding scheme*).
- ▸ Common but dangerous upwinding strategy is used in many CFD codes:
  - ▹ Use <u>accurate</u> unbounded scheme in <u>mean flow equations</u>.
  - ▹ Use <u>inaccurate</u> numerically diffuse scheme in <u>turbulence equations</u>.
  - ▹ Overall scheme is stable but often highly diffusive.
  - ▹ Most of development and testing of turbulence models has been done using above upwinding strategy.
  - ▹ In our computations we employ the accurate **streamline upwind** (SU) scheme in both mean and turbulence equations.
  - ▹ Even more accurate schemes are available which are based on Petrov-Galerkin finite element formulations.

- ▸ <u>Accurate schemes must be used in both mean flow and turbulence eq's.</u>

NUMERICAL RESULTS

○ **Free Jets**
- ► Round jet
- ► Plane jet

○ **Internal Flows with Separation**
- ► Flow past backward facing step (Kim et. al)
- ► Flow past step in channel with diffuser wall (Driver and Seegmiller)
- ► Flow in pipe expansion (Szszepura)

○ **Transient Flow (Vortex Shedding)**
- ► Flow past square prism (Lyn)

○ **3-D Flow**
- ► Flow past passenger car models

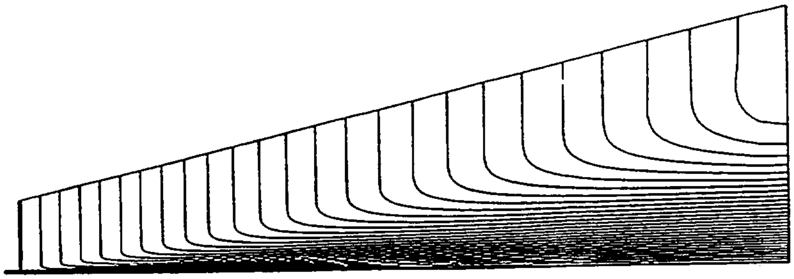
REMARKS:

- ► Five sets of model predictions are presented:
  - ▷ Standard k-ε model
  - ▷ Extended k-ε model (original)
  - ▷ Extended k-ε model (revised)
  - ▷ RNG k-ε model with (original)
  - ▷ RNG k-ε model with (revised)

FREE JETS

The Submerged Plane and Round Jets

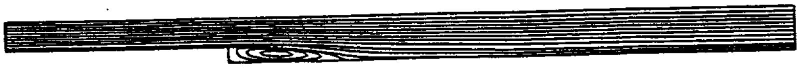
	Plane Jet		Round Jet	
	$d\delta/dx$	% error	$d\delta/dx$	% error
Experiment	≈0.105		≈0.095	
Standard k-ε model	0.104	−1	0.112	18
Extended k-ε model (original)	0.10	−5	0.10	5
Extended k-ε model (revised)	0.102	−3	0.104	9.5
RNG k-ε model (original)	0.131	25	0.157	65
RNG k-ε model (revised)	0.101	−4	0.113	19



TURBULENT FLOW OVER BACKWARD FACING STEP

Kim et al Test Case: Re = 45000

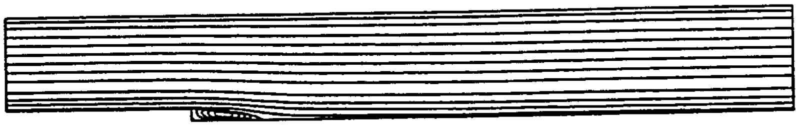
	X_R	% error
Experiment	7.0 ±0.5	
Standard k-ε model	6.5	–7.1
Extended k-ε model (original)	8.4	20.0
Extended k-ε model (revised)	7.1	1.4
RNG k-ε model (original)	7.5	7.1
RNG k-ε model (revised)	7.46	6.6

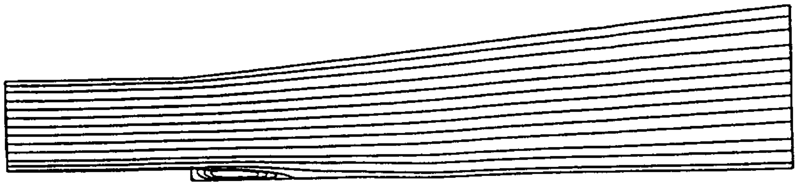


TURBULENT FLOW OVER STEP IN CHANNEL WITH DIFFUSER WALL

Driver and Seegmiller Test Case: Re = 36000

	Angle			
	0 degrees		6 degrees	
	X_R	% error	X_R	% error
Experiment	6.2		8.1	
Standard k-ε model	5.3	–14.5	6.6	–18.5
Extended k-ε model (original)	6.6	6.5	9.55	17.9
Extended k-ε model (revised)	5.76	–7.1	7.4	–8.6
RNG k-ε model (original)	6.17	–0.5	8.33	2.8
RNG k-ε model (revised)	6.11	–1.5	8.33	2.8





TURBULENT FLOW IN PIPE EXPANSION

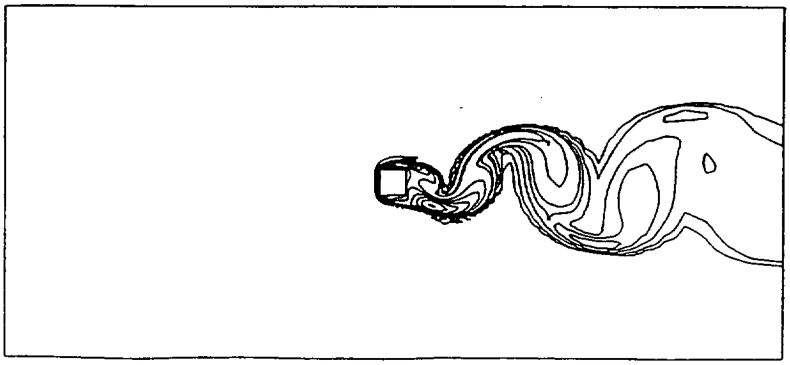
Szczepura Test Case: Re = 890,000

	X_R	% error
Experiment	9.51	
Standard k-ε model	9.59	0.9
Extended k-ε model (original)	12.44	30.8
Extended k-ε model (revised)	10.6	11.5
RNG k-ε model (original)	11.35	19.5
RNG k-ε model (revised)	11.39	20

TURBULENT FLOW PAST SQUARE PRISM

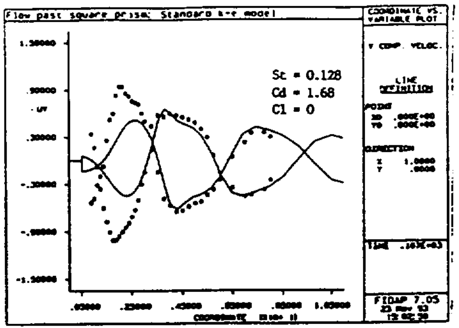
Lyn's Test Case: Re = 21400

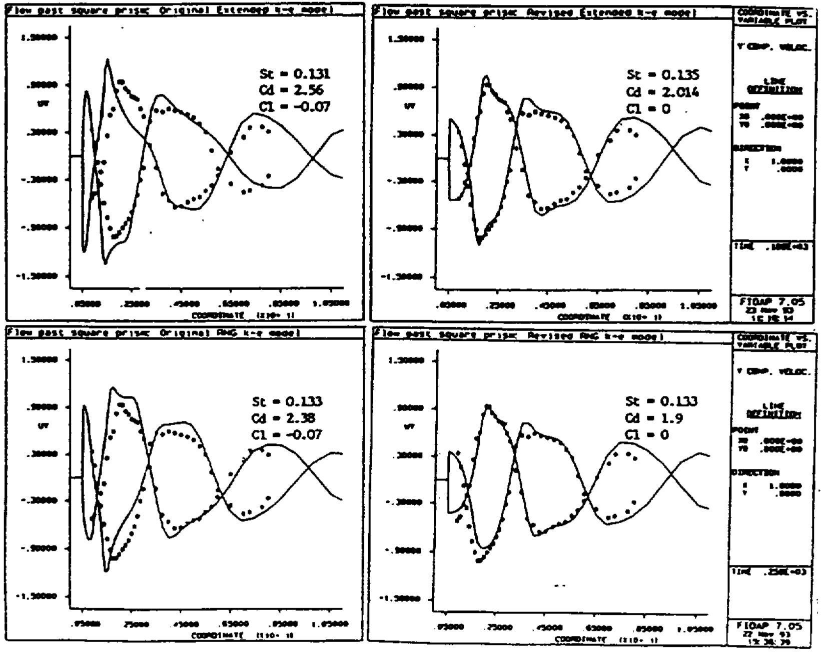
	Strouhal No.	C_d	C_l
Experiment	0.132 ± 0.035	= 2.0	N.A.
Standard k-ε model	0.128	1.68	0
Extended k-ε model (original)	0.131	2.56	–0.07
Extended k-ε model (revised)	0.135	2.014	0
RNG k-ε model (original)	0.133	2.38	–0.07
RNG k-ε model (revised)	0.133	1.9	0

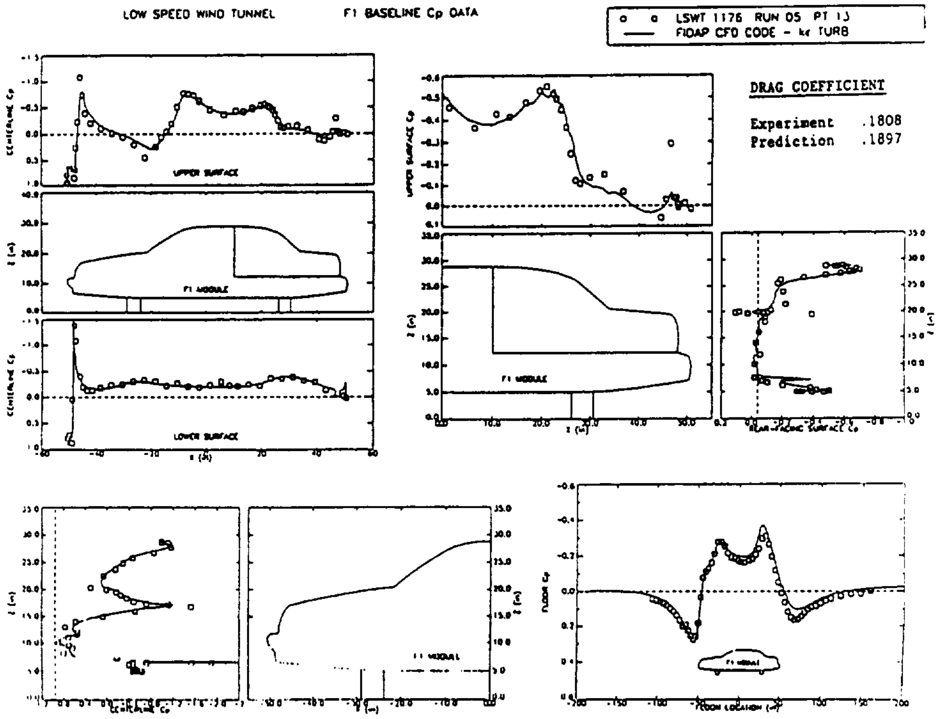


Experimental Data

St = 0.132 ±.035
Cd = 2.0
Cl = ...

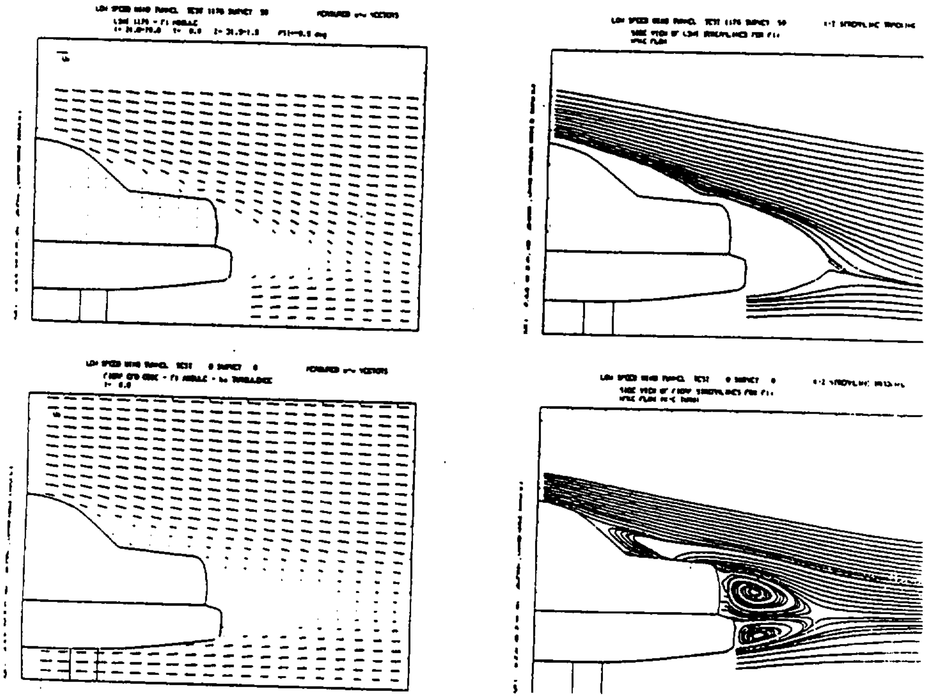


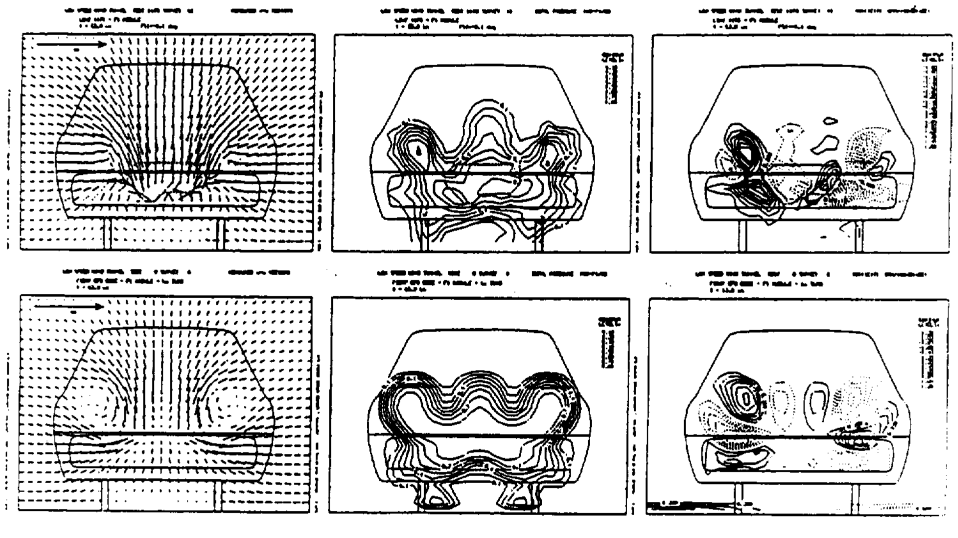


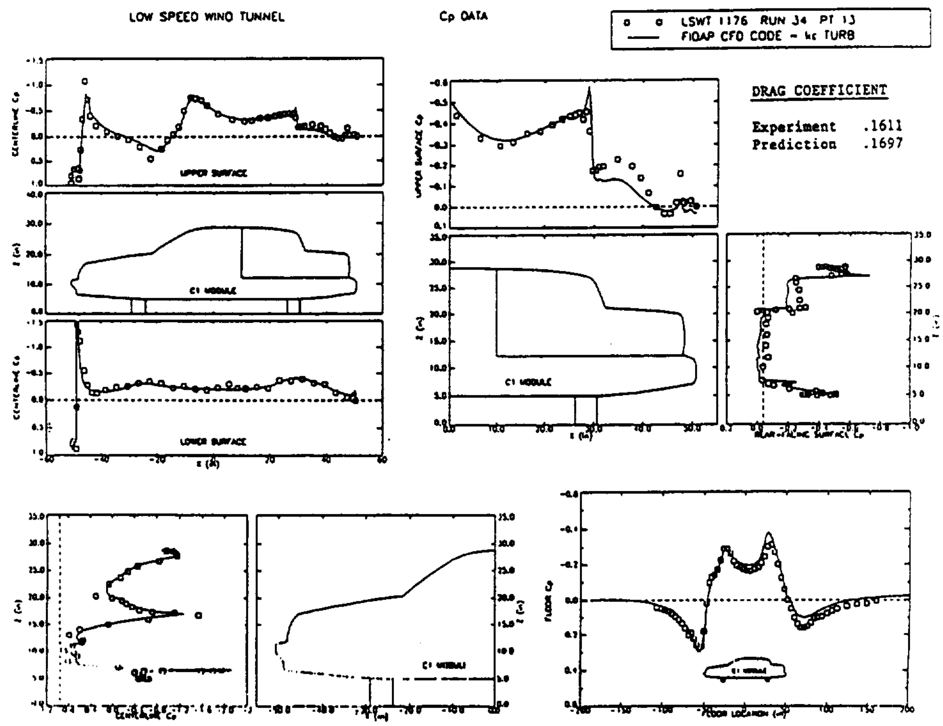


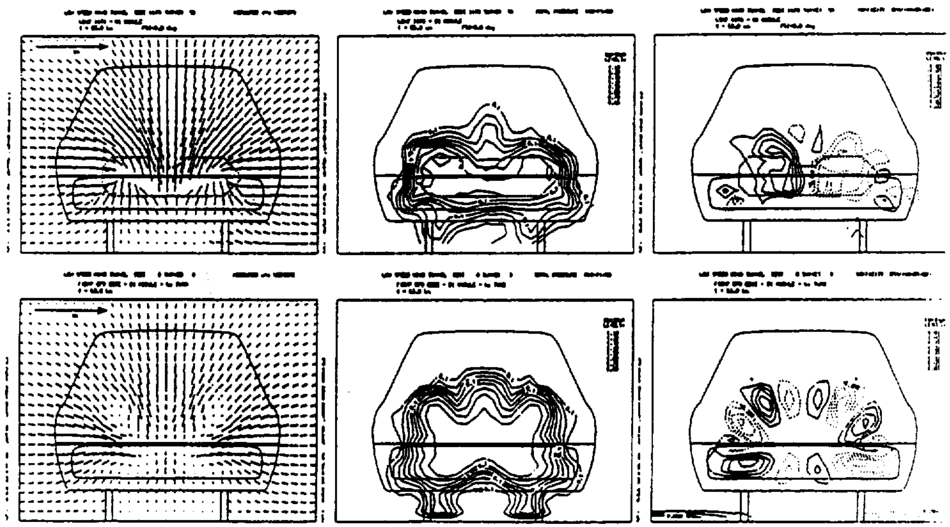
DRAG COEFFICIENT

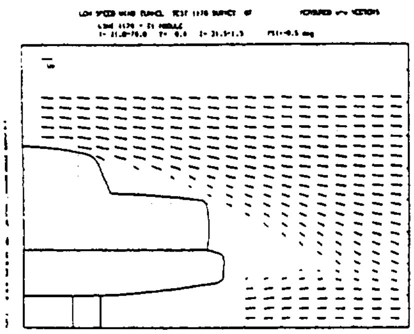
Experiment	.1808
Prediction	.1897

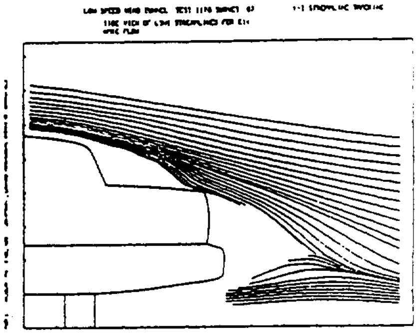


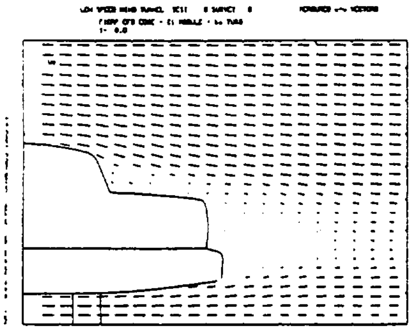


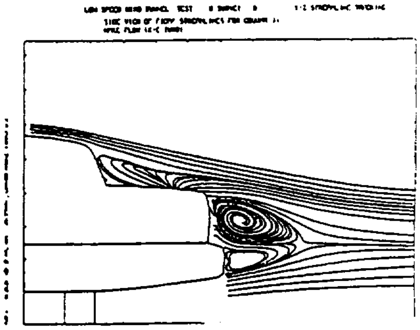

LOW SPEED WIND TUNNEL
Cp DATA
LSWT 1176 RUN 34 PT 13
FIDAP CFD CODE – kε TURB
DRAG COEFFICIENT
Experiment .1611
Prediction .1697
CENTERLINE Cp
UPPER SURFACE
C1 MODULE
LOWER SURFACE
UPPER SURFACE Cp
REAR-FACING SURFACE Cp
CENTERLINE Cp
FLOOR Cp
FLOOR LOCATION (in)

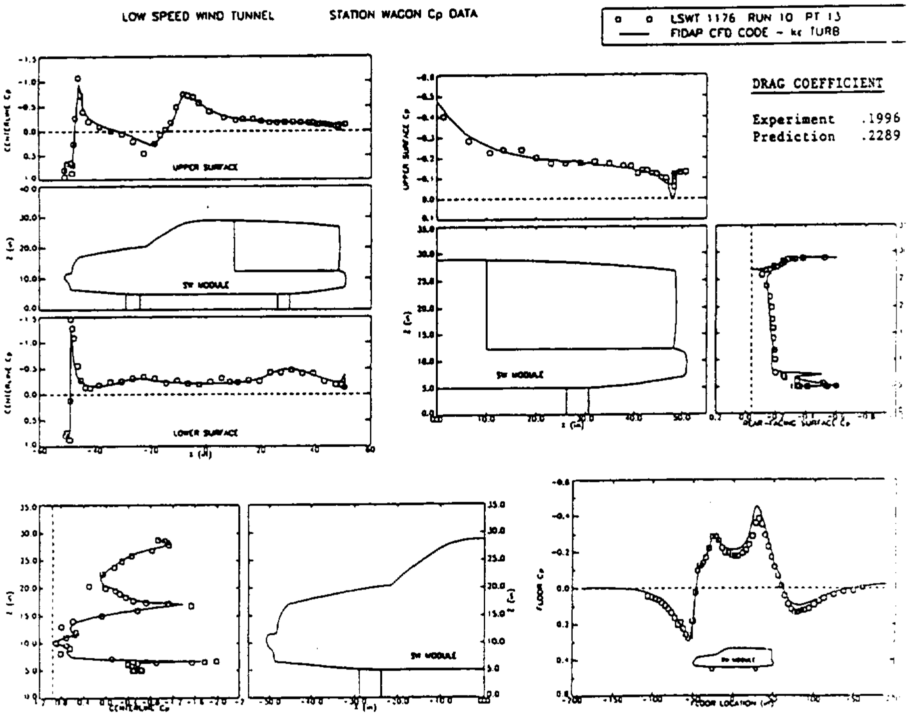


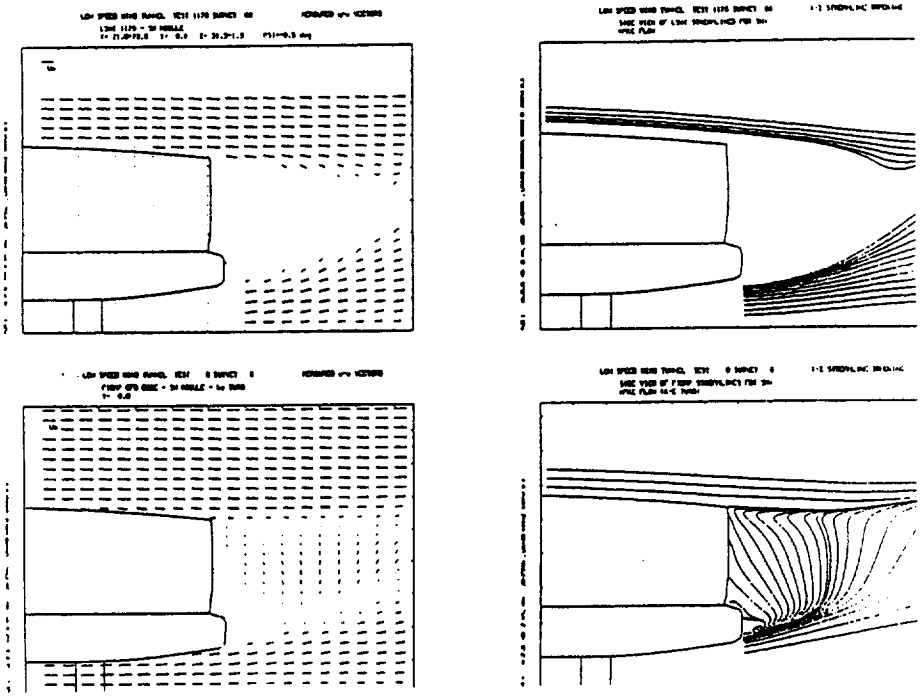


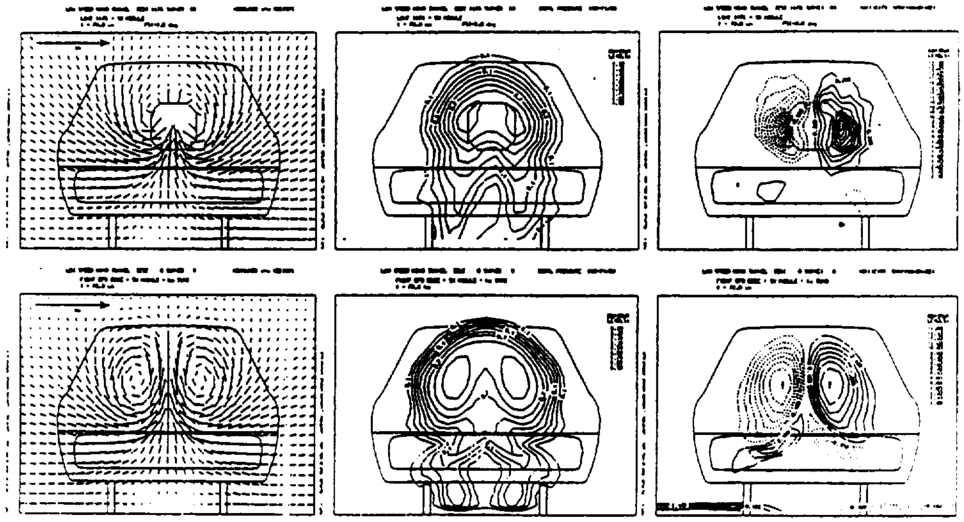







LOW SPEED WIND TUNNEL
STATION WAGON Cp DATA
LSWT 1176 RUN 10 PT 13
FIDAP CFD CODE - kε TURB
DRAG COEFFICIENT
Experiment .1996
Prediction .2289
UPPER SURFACE
SW MODULE
LOWER SURFACE
CENTERLINE Cp
UPPER SURFACE Cp
REAR-FACING SURFACE Cp
FLOOR Cp
FLOOR LOCATION (in)
z (in)
x (in)
y (in)





CONCLUSIONS AND DIRECTIONS FOR FURTHER RESEARCH

- For applied CFD, TEM's strike balance between accuracy and efficiency.

- The use of inadequate near-wall models and over-diffuse numerical schemes obscures true performance characteristics of TEM's. And this has lead to much confusion in evaluation of TEM's.

- Consequences of using better near-wall model and accurate numerics are:
  - Standard k-ε model performs much better than commonly believed.
  - Extended k-ε model with **original** set of model constants produces under-diffuse predictions.
  - RNG k-ε model with **original** set of model constants gives predictions that can be both under-diffusive or over-diffusive depending on flow.
  - The extended and RNG models with **revised** set of model constants perform better than with **original** set of model constants.

- Newer models are quite promising, but do not yet perform consistently better than standard k-ε model.

- Significant advances in TEM capabilities may potentially result from further research in two key areas:

  - Advanced constitutive-type laws for the Reynolds stresses:
    - AEVM's appear to be best candidates.
  - Improved length scale determining equation:
    - Better modeling of off-equilibrium effects.
    - Better modeling of large-scale anisotropy effects.