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OVERVIEW OF TURBULENCE MODEL DEVELOPMENT AND APPLICATIONS AT ROCKETDYNE

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A.H. Hadid, E.D. Lynch, and M.M. Sindir
Rocketdyne Division
Rockwell International
Canoga Park, California

TURBULENCE MODELING REQUIREMENTS, DEVELOPMENT PHILOSOPHY AND APPROACH

- **REQUIREMENTS**
  - TURBULENCE MODELING IS A KEY ENABLING TECHNOLOGY FOR ALL PROPULSION RELATED CFD ACTIVITIES
  - FACTORS TO CONSIDER INCLUDE ACCURACY, CONSISTENCY, COMPUTATIONAL COST, AND EASE OF USE
  - TURBULENCE MODELS THAT CAN NOT BE INCLUDED IN PRODUCTION GRADE CFD CODES ARE OF LIMITED VALUE TO INDUSTRY
- **PHILOSOPHY**
  - BASIC MODEL DEVELOPMENT IS BEST LEFT TO SPECIALIZED "CENTERS OF EXCELLENCE"
  - VARIOUS CLASSES OF MODELS NEED TO BE SUPPORTED SINCE NO SINGLE UNIVERSAL MODEL IS SHOWN TO EXIST
  - ESTABLISHING THE RANGE OF APPLICABILITY, ACCURACY, AND THE COMPUTATIONAL COST OF THE MODELS IS ESSENTIAL

TURBULENCE MODELING REQUIREMENTS, DEVELOPMENT PHILOSOPHY AND APPROACH (Cont.)

- **APPROACH**
  - IDENTIFY KEY "CENTERS OF EXCELLENCE" AND ESTABLISH COLLABORATIVE RELATIONSHIP
  - ACQUIRE MODELS AND ASSESS PERFORMANCE FOR THE INTENDED CLASS OF APPLICATIONS
  - DELINEATE MODEL DEFICIENCIES AND INITIATE EFFORT TO REDUCE THEM
  - DEVELOP MODELS INTO STAND-ALONE MODULES
  - INCLUDE MODULES IN PRODUCTION CODES AND ESTABLISH BASELINE FOR APPLICATIONS

TWO MAJOR AREAS OF CONCENTRATION

- **HIGH SPEED TURBULENCE MODELING (LEAD DR. DOUG LYNCH)**
  - FOCUSED ON HIGH SPEED (M>1) PROPULSION (ROCKET AND AIRBREATHING) AND AERODYNAMICS
  - EMPHASIS ON 2-EQUATION PHENOMENOLOGICAL MODELS WITH NASA ARC AND LARC AS KEY TECHNOLOGY PARTNERS
  - LES WORK IN PLANNING STAGES WITH CTR
- **LOW SPEED TURBULENCE MODELING (LEAD DR. ALI HADID)**
  - FOCUSED ON LOW SPEED (M<1) AND ROTATING FLOW APPLICATIONS
  - EMPHASIS ON REYNOLDS STRESS PHENOMENOLOGICAL MODELS IN COLLABORATION WITH UMIST, ICOMP, CTR, AND UAH
  - LES WORK INITIATED WITH CTR

HIGH SPEED TURBULENCE MODELING

- **EMPHASIS IS ON THE DEVELOPMENT OF ENGINEERING TURBULENCE MODELS FOR**
  - HIGH SPEED AIRBREATHING PROPULSION SYSTEMS
  - THRUST CHAMBERS
  - VEHICLE AERODYNAMICS
- **APPROACH TAKEN IS BASED ON 2-EQUATION MODELS**
  - DIFFERENT CLASSES OF 2-EQUATION MODELS STUDIED
    - k-ε
    - k-ω
    - POINTWISE R_t
  - COMPRESSIBILITY EFFECTS AND TURBULENCE-CHEMISTRY INTERACTIONS MAJOR MODEL UPGRADE THRUSTS
    - COMPRESSIBILITY MODIFICATIONS FROM ARC
    - TURBULENCE-CHEMISTRY INTERACTION MODELS FROM LARC
  - **USA** AND **GASP** SERVE AS NUMERICAL PLATFORM
    - **GASP** - CHIEN, LAM-BREMHORST k-ε, k-ω
    - **USA** - VARIETY OF k-ε, k-ω

COMPRESSIBILITY EFFECTS

- **MIXING LAYER SPREADING REDUCED AT HIGH MACH NUMBERS**
  - INCREASE DISSIPATION RATE OF k
    - DEFINE C_{k2} AS A FUNCTION OF TURBULENT MACH NUMBER $\sqrt{\rho k/\gamma p}$
    - ZEMAN MODIFICATION (1990)
    - SARKAR (1990, 1991) AND WILCOX (1991) PROPOSALS
  - MODIFICATIONS OF ZEMAN AND SARKAR NOT RECOMMENDED
- **HEAT TRANSFER OVER PREDICTED NEAR SHOCK WAVES**
  - LIMIT TURBULENT LENGTH SCALE L_t TO $\mathrm{MIN}\left(\frac{k^{3/2}}{\varepsilon}, \frac{Ky}{C_\mu^{3/4}}\right)$ (VUONG AND COAKLEY, 1987)
- **SEPARATION UNDERPREDICTED IN RAPID COMPRESSION OR STRAIN REGIONS**
  - INCREASE α_ε OR α_ω UNDER RAPID COMPRESSION (VUONG AND COAKLEY)
- **HEAT TRANSFER OVER PREDICTED FOR VERY COLD WALLS $T_w/T_{aw}<0.1$ (COAKLEY)**
  - CEBECI-SMITH ~ 60%, k-ω ~ 40%, q-ω ~ 10%, k-ε ~ 30%

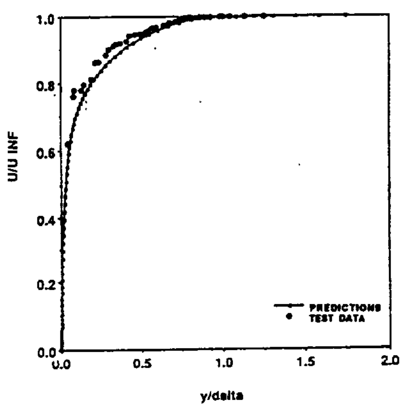
TURBULENCE MODELS ADAPTED TO USA CODE

ALGEBRAIC	DAMPING WALL	DAMPING LOCAL	BOUNDARY CONDITIONS	TRANSITION MODEL: HIGH ORDER POLYNOMINAL	TRANSITION MODEL: ARNAL	COMPRESSIBILITY EFFECTS: MIXING LAYER SPREADING	COMPRESSIBILITY EFFECTS: SEPARATION EXTENT	COMPRESSIBILITY EFFECTS: REATTACHMENT HEAT TRANSFER
Baldwin-Lomax	X	3 Versions		X	X			
k-ε								
1. Myong-Kasagi	X	X	$k=0$, $\varepsilon = \nu_t u^2/18y^2$	X		1. Sarkar (1991) 2. Zeman (1990) 3. Wilcox (1991)	4. Yuong & Coakley (1987)	5. Vuong & Coakley (1987)
2. Chien (1982)	X	X	$k=0$, $\varepsilon=0$	X		1., 2., 3.	4.	5.
3. Jones-Launder (1972)	X	X	$k=0$, $\varepsilon=0$	X		1., 2., 3.	4.	5.
4. Launder-Sharma (1974)	X	X	$k=0$, $\varepsilon=0$	X		1., 2., 3.	4.	5.
5. Huang-Coakley (1992)	X	X	$k=0$, $\varepsilon = 2\nu_t k_1/y^2$	X		1., 2., 3.	4.	5.
6. Speziale-So-Zhang (1993)	X	X	$k=0$, $\varepsilon = 2\nu_t k_1/y^2$	X		1., 2., 3.	4.	5.
7. Lam-Bremhorst (1981)	X	X	$k=0$, $\varepsilon_y=0$	X		1., 2., 3.	4.	5.
8. High Re	X	X	Wall Function	X				
k-ω								
1. High Re Wilcox (1991a)	–	–	$k=0$, $\omega_0 = 10\omega_1$	X		1., 2., 3.	4.	5.
2. Low Re Wilcox (1991b)	–	–	$k=0$, $\omega = 7.2\nu_t/y^2$	X		1., 2., 3.	4.	5.
q-ω								
Coakley (1987)			$k=0$, $\omega_y=0$	X				
One-Equation (Goldberg, Two-Time Scale 1992)	–		$k=0$					
One-Equation R_T (Goldberg 1993, 1994)		X	$\frac{d(\frac{k^2}{\varepsilon})}{dy} = \frac{d(\nu_t R_t)}{dy} = 0$	X				

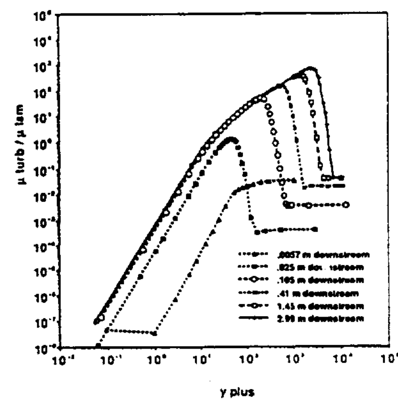
M = 9.2 FLAT PLATE FLOW

- CHIEN k-ε MODEL WITH RAPID COMPRESSION AND LENGTH SCALE COMPRESSIBILITY MODIFICATIONS

VELOCITY PROFILE



TURBULENT VISCOSITY

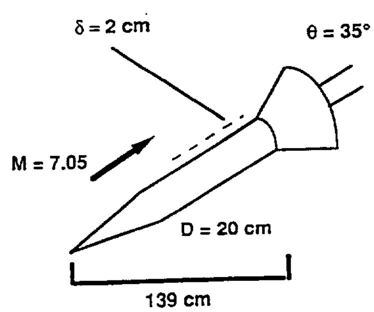


REF: G.T. COLEMAN AND J.L. STOLLERY, JFM 56: 741, "HEAT-TRANSFER FROM A HYPERSONIC TURBULENT FLOW AT A WEDGE COMPRESSION CORNER"

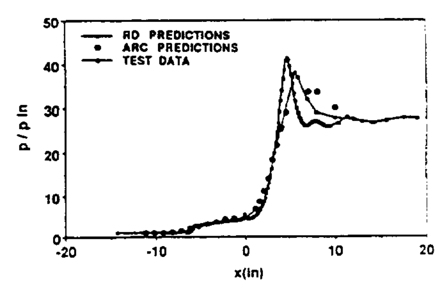
MACH 7.05 FLOW OVER AXISYMMETRIC FLARE

CHIEN k-ω MODEL WITH RAPID COMPRESSION AND LENGTH SCALE COMPRESSIBILITY MODIFICATIONS

AXISYMMETRIC FLARE



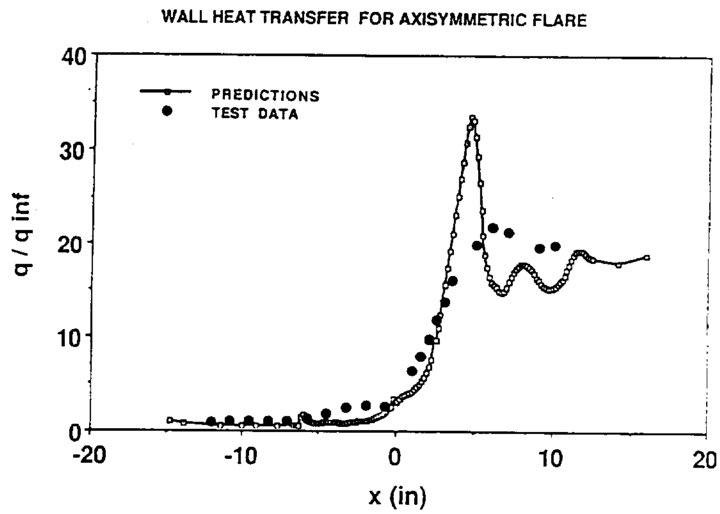
WALL PRESSURE FOR AXISYMMETRIC FLARE



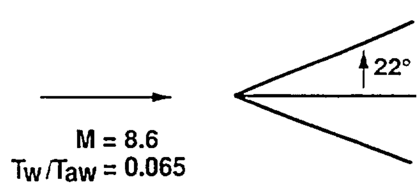
REF: M.I. KUSSOY AND C.C. HORSTMAN, "DOCUMENTATION OF TWO- AND THREE-DIMENSIONAL HYPERSONIC SHOCK-WAVE TURBULENT BOUNDARY LAYER INTERACTION FLOW," NASA TM 1-01075.

MACH 7.05 FLOW OVER AXISYMMETRIC FLARE

CHIEN k-ω MODEL WITH RAPID COMPRESSION AND LENGTH SCALE COMPRESSIBILITY MODIFICATIONS



MACH 8.6 FLOW OVER COLD WALL WEDGE



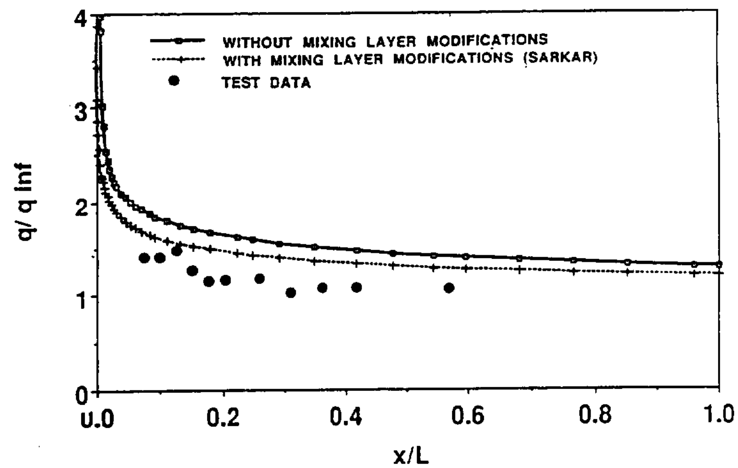
THREE STUDIES

1. CHIEN k-ε MODEL WITH RAPID COMPRESSION AND LENGTH SCALE CORRECTIONS AND WITH AND WITHOUT MIXING LAYER TREATMENT
2. HIGH-Re k-ω MODEL WITH VARIOUS AIR CHEMISTRY MODELS
3. BALDWIN-LOMAX TURBULENCE MODEL USING WALL AND LOCAL DAMPING

MACH 8.6 FLOW OVER COLD WALL WEDGE

CHIEN k-ε MODEL WITH AND WITHOUT MIXING LAYER TREATMENT

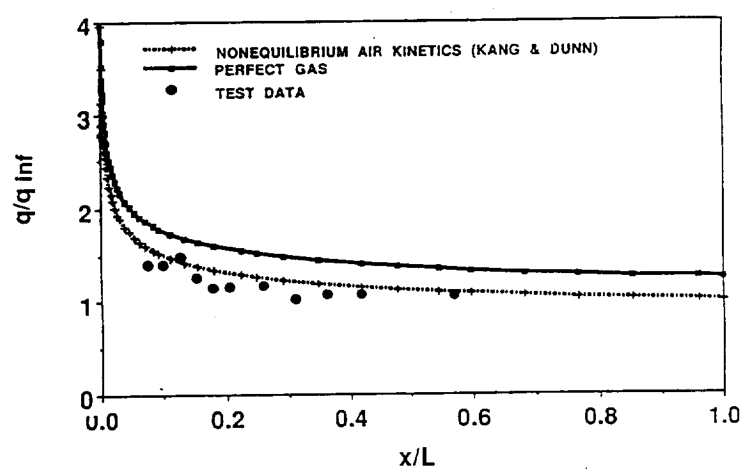
HEAT FLUX CALCULATIONS



MACH 8.6 FLOW OVER COLD WALL WEDGE

HIGH-Re k-ω MODEL WITH VARIOUS AIR CHEMISTRY MODELS

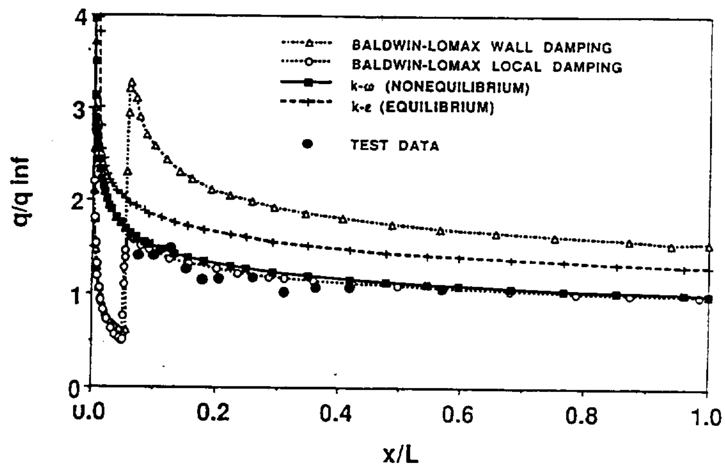
HEAT FLUX CALCULATIONS



MACH 8.6 FLOW OVER COLD WALL WEDGE

BALDWIN LOMAX, k-ε, k-ω MODEL COMPARISONS

HEAT FLUX CALCULATIONS

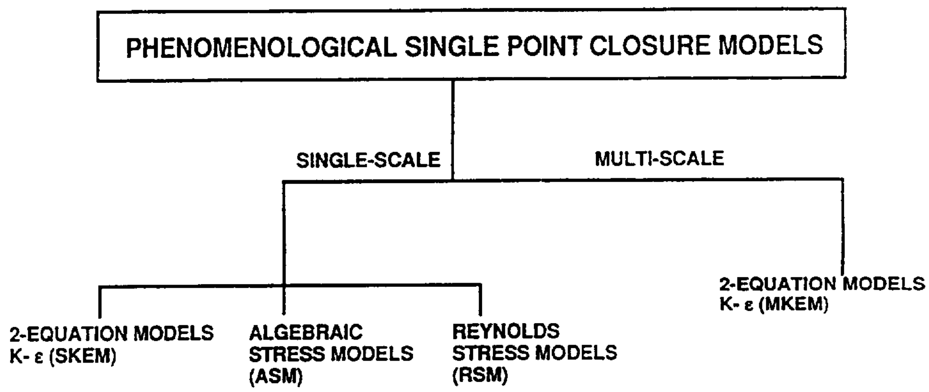


LOW SPEED TURBULENCE MODELING

- **EMPHASIS IS ON THE DEVELOPMENT OF ENGINEERING TURBULENCE MODELS FOR**
  - ROTATING MACHINERY
  - FLOW IN DUCTS AND MANIFOLDS
  - REACTING FLOWS
- **APPROACH TAKEN IS TO**

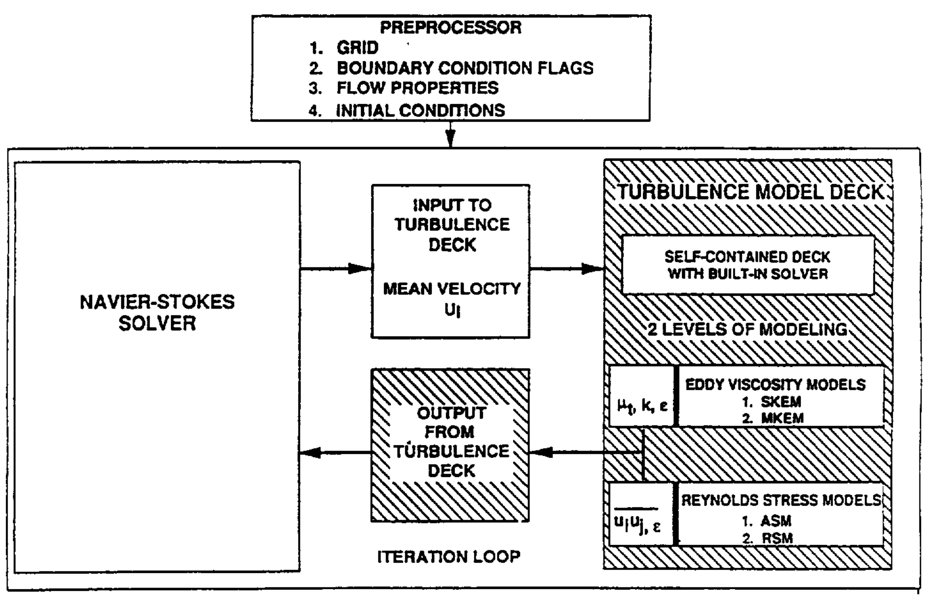
1. SYSTEMATICALLY ASSESS EXISTING PHENOMENOLOGICAL MODELS USING COMMON NAVIER-STOKES SOLVER
2. IDENTIFY, DEVELOP AND VALIDATE MODEL UPGRADES COMMENSURATE WITH OBSERVED FLOWPHYSICS
3. DEVELOP SELF-CONTAINED TURBULENCE MODEL DECKS (MODULES) THAT CAN BE INTEGRATED WITH NAVIER-STOKES SOLVERS
4. PROVIDE GUIDANCE TO EXPERIMENTAL AND THEORETICAL RESEARCH IN TURBULENCE MODELING FOR ENGINEERING APPLICATIONS

TURBULENCE MODELS BEING ASSESSED



NEAR-WALL TREATMENTS INCLUDE (WHERE APPROPRIATE) WALL FUNCTIONS, MULTILAYER MODELS, AND LOW-REYNOLDS NUMBER APPROXIMATIONS

TURBULENCE MODEL DECK STRUCTURE AND INTEGRATION WITH NAVIER-STOKES SOLVER



PROJECT WELL UNDERWAY

- **TEAM**
  - MODELS PROVIDED BY UMIST, LERC/ICOMP, ARC/CTR
  - MODULE DEVELOPMENT BY ROCKETDYNE
  - MODULE TESTING BY ROCKETDYNE (**REACT**, **USA**) AND UAH (**MAST**)
  - MODEL UPGRADES BY ROCKETDYNE, UMIST, ARC/CTR
  - APPLICATION BY ROCKETDYNE TO TURBOPUMP COMPONENT (E.G. IMPELLER) ANALYSIS

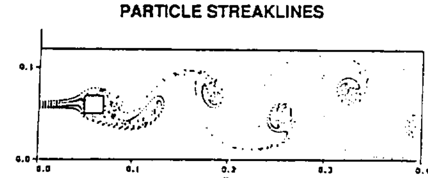
- **2-D MODULES COMPLETED, TESTED, AND RELEASED**
  - SINGLE SCALE k-ε
  - MULTI SCALE k-ε
  - ASM
  - RSM

- **3-D MODULE DEVELOPMENT IN PROGRESS**

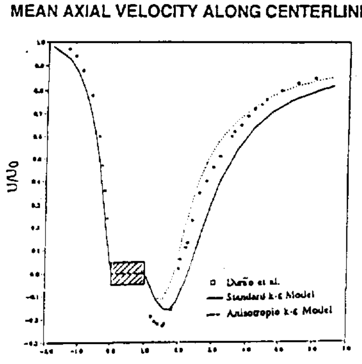
NONLINEAR ALGEBRAIC-STRESS MODEL

VORTEX SHEDDING FROM RECTANGULAR CYLINDERS (DURAO, et al)

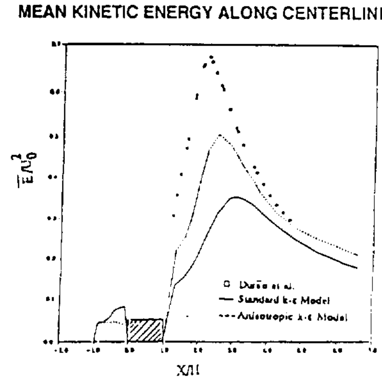
PARTICLE STREAKLINES



MEAN AXIAL VELOCITY ALONG CENTERLINE



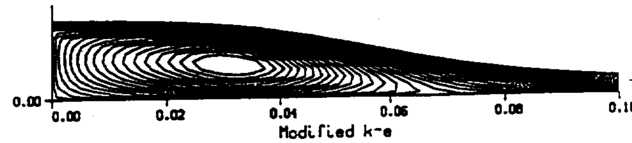
MEAN KINETIC ENERGY ALONG CENTERLINE



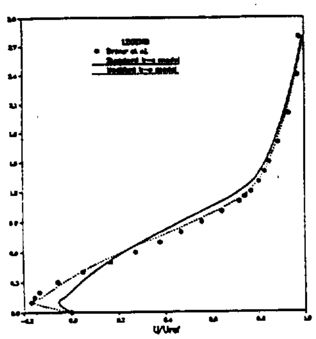
ROTATION MODIFIED k-ε MODEL

BACKWARD FACING STEP (DRIVER AND SEEGMILLER)

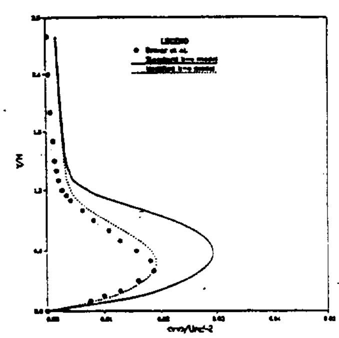
STREAMLINE CONTOURS



MEAN AXIAL VELOCITY AT X/M=4



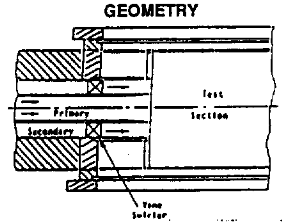
RADIAL TURBULENT INTENSITY ($\overline{vv}/u^2_{ref}$)



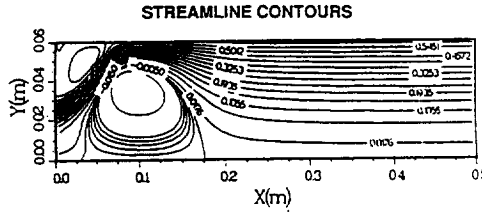
ALGEBRAIC STRESS MODEL

CONFINED COAXIAL SWIRLING JET FLOW (ROBACK AND JOHNSON)

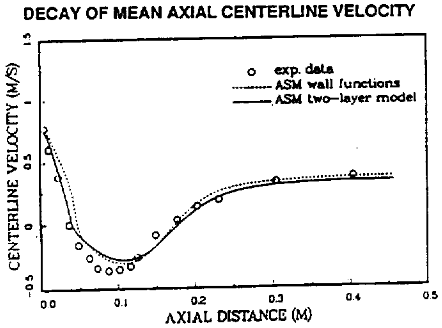
GEOMETRY



STREAMLINE CONTOURS

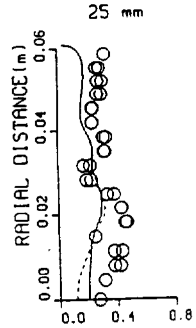


DECAY OF MEAN AXIAL CENTERLINE VELOCITY



RADIAL PROFILES OF $\overline{uu}$

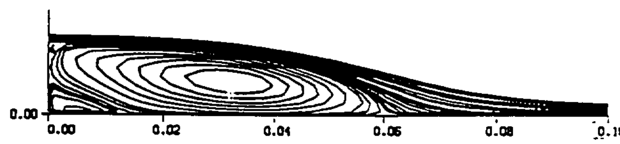
25 mm



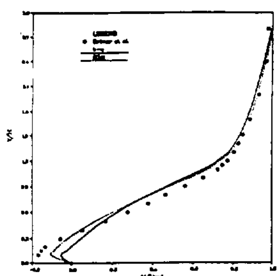
REYNOLDS STRESS MODEL (LRR – MODEL)

BACKWARD FACING STEP (DRIVER AND SEEGMILLER)

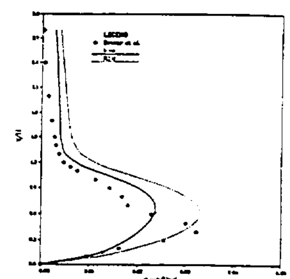
STREAMLINE CONTOURS



MEAN AXIAL VELOCITY AT X/H=4



AXIAL TURBULENT INTENSITY AT X/H=4



CONCLUDING REMARKS

- PROGRAMS (BOTH COMMERCIAL AND GOVERNMENT) EMPLOY NEW TECHNOLOGY ONLY WHEN IT PROVIDES "ADDED VALUE"
  - REDUCED DEVELOPMENT COST
  - INCREASED RELIABILITY AND PERFORMANCE
  - ENHANCED MANUFACTURABILITY
- THE NEW TECHNOLOGY WE OFFER IS THE COMPUTATIONAL ENGINEERING TOOLS FOR PRODUCT DESIGN AND ANALYSIS
- THESE TOOLS ARE THE END PRODUCT FOR ALL ENABLING TECHNOLOGY DEVELOPMENT
  - PRE- AND POST PROCESSING
  - ALGORITHMS AND NUMERICAL PLATFORMS
  - PHYSICAL MODELS (E.G. TURBULENCE AND CHEMISTRY)
- FAILURE OF ANY ENABLING TECHNOLOGY JEOPARDIZES THE PERFORMANCE (VALUE) OF THE TOOL

NOW MORE THAN EVER, THERE IS A NEED FOR CLOSER COLLABORATION AND COOPERATION BETWEEN GOVERNMENT, INDUSTRY, AND RESEARCH INSTITUTIONS TO ENSURE MAINTENANCE OF COUNTRY'S TECHNOLOGY BASE