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ADVANCED TURBULENCE MODELS FOR TURBOMACHINERY

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1995117023

ABSTRACT

Development and assessment of the single-time-scale k-ε turbulence model with different near-wall treatments and the multi-scale k-ε turbulence model for rotating flows are presented. These turbulence models are coded as self-contained module decks that can be interfaced with a number of CFD main flow solvers. For each model, a stand-alone module deck with its own formulation, discretization scheme, solver and boundary condition implementations is presented. These satellite decks will take as input (from a main flow solver) the velocity field, grid, boundary condition specifications and will deliver turbulent quantities as output. These modules were tested as a separate entities and although many logical and programming problems were overcome only wider use and further testing can render the modules sufficiently "fool proof".

DEVELOPMENT OF A MODULAR FORMAT FOR GENERAL USE TURBULENCE MODELS

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Workshop for Computational Fluid Dynamic
Applications in Rocket Propulsion

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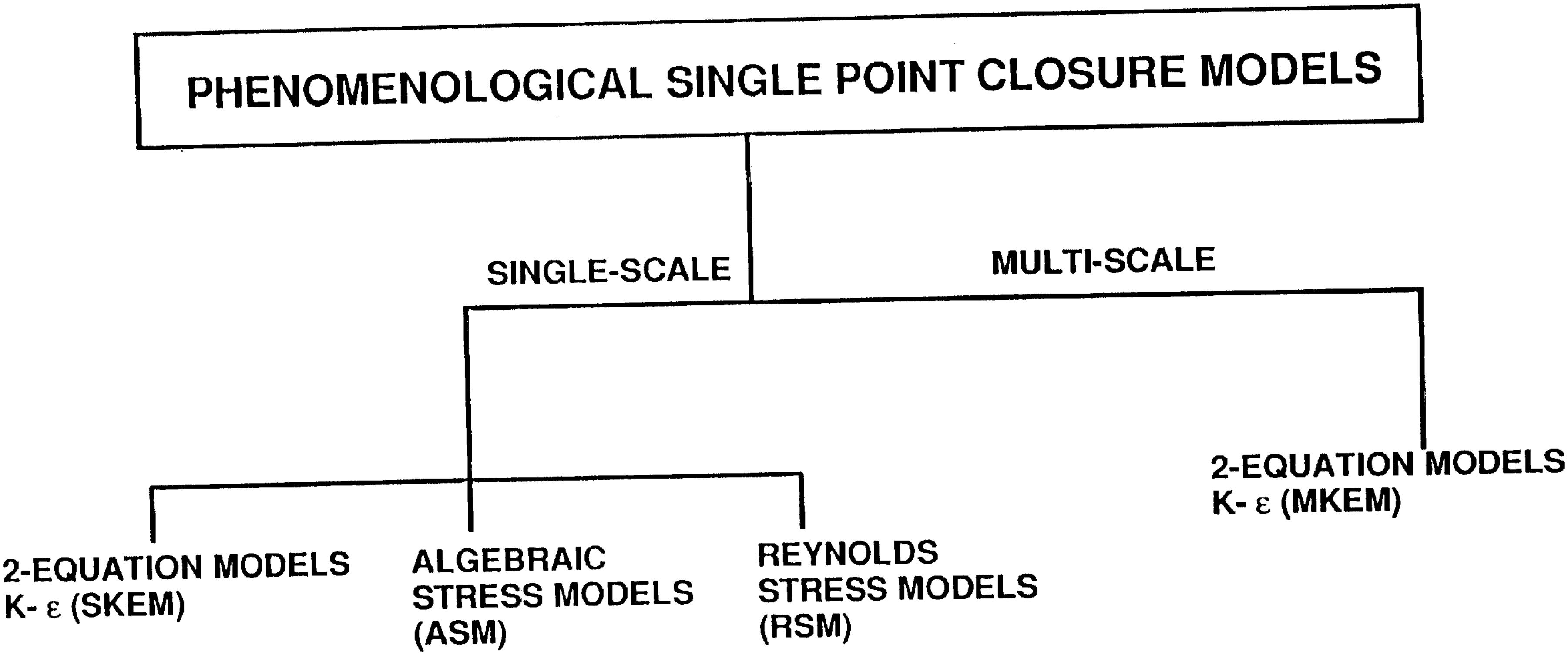
STRUCTURE OF FUTURE CODES LEADS TO DEVELOPMENT OF MODULES

- **FUTURE CODES COMPOSED AT TIME OF EXECUTION**
    - INTELLIGENT DRIVERS
    - MODULES FOR PHYSICAL MODELS

- **INTEGRAL PRE- AND POSTPROCESSING TOOLS**

- **COMMON DATA BASE**

TURBULENCE MODELS TO BE ASSESSED



PHENOMENOLOGICAL SINGLE POINT CLOSURE MODELS

SINGLE-SCALE

MULTI-SCALE

2-EQUATION MODELS
K- ε (SKEM)

ALGEBRAIC
STRESS MODELS
(ASM)

REYNOLDS
STRESS MODELS
(RSM)

2-EQUATION MODELS
K- ε (MKEM)

- THE 2-D/AXISYMMETRIC SINGLE-SCALE K-ε MODULE DECK (KEMOD-1) AND THE 2-D/AXISYMMETRIC MULTI-SCALE K-ε MODULE DECK (KEMOD-2) ARE COMPLETE

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

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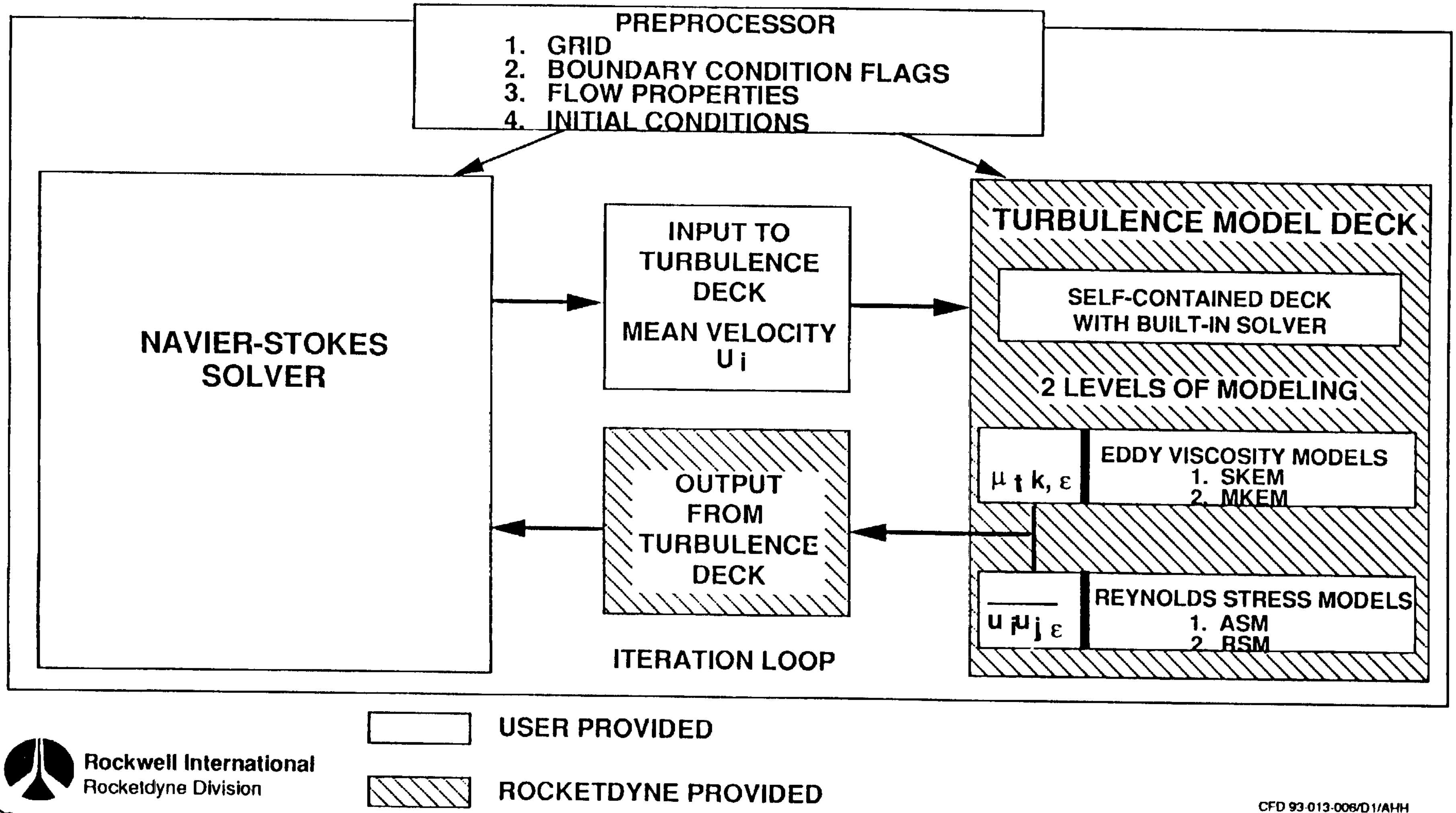
TURBULENCE MODEL DECK STRUCTURE AND INTEGRATION WITH NAVIER-STOKES SOLVER

- MODULES ARE BASED ON THE PHENOMENOLOGICAL SINGLE POINT TURBULENCE CLOSURE MODELS
- THEY ARE STRUCTURED BASICALLY TO ACCEPT AS INPUT THE MEAN FLOW VELOCITIES FROM A N-S SOLVER AND TO RETURN TURBULENCE QUANTITIES TO THE SOLVER



PREPROCESSOR

1. GRID
2. BOUNDARY CONDITION FLAGS
3. FLOW PROPERTIES
4. INITIAL CONDITIONS

NAVIER-STOKES SOLVER

INPUT TO TURBULENCE DECK

MEAN VELOCITY U_i

OUTPUT FROM TURBULENCE DECK

ITERATION LOOP

TURBULENCE MODEL DECK

SELF-CONTAINED DECK WITH BUILT-IN SOLVER

2 LEVELS OF MODELING

μ_t k, ε

EDDY VISCOSITY MODELS
1. SKEM
2. MKEM

$\overline{u_i u_j}$ ε

REYNOLDS STRESS MODELS
1. ASM
2. RSM

USER PROVIDED

ROCKETDYNE PROVIDED

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SINGLE-SCALE k-ε MODEL

- GENERALIZED TRANSPORT EQUATION IN 2-D/AXISYMMETRIC GEOMETRY

$$\frac{\partial(\rho u\phi)}{\partial x} + \frac{1}{r}\frac{\partial}{\partial r}(\rho r v\phi) = \frac{\partial}{\partial x}\left(\Gamma\phi_x \frac{\partial\phi}{\partial x}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(r\Gamma\phi_r \frac{\partial\phi}{\partial r}\right) + S\phi$$

- U-MOMENTUM $\phi = u,\ \Gamma\phi_x = 2\mu_e,\ \Gamma\phi_r = \mu_e$

$$S_u = -\frac{\partial P}{\partial x} + \frac{1}{r}\frac{\partial}{\partial r}\left(\mu_e r \frac{\partial v}{\partial x}\right)$$

- V-MOMENTUM $\phi = v,\ \Gamma\phi_x = \mu_e,\ \Gamma\phi_r = 2\mu_e$

$$Sv = -\frac{\partial P}{\partial x} - \frac{\partial}{\partial r}\left(\mu_e r \frac{\partial u}{\partial x}\right) - 2\mu_e \frac{v}{r^2} + \frac{\rho w^2}{r}$$

SINGLE-SCALE k-ε MODEL (CONT'D)

- W-MOMENTUM

$$\phi = w, \quad \Gamma_{\phi x} = \mu_e, \quad \Gamma_{\phi r} = \mu_e$$

$$S_w = -\frac{\rho v w}{r} + \frac{w}{r^2}\frac{\partial}{\partial r}(r\mu_e)$$

- TURB. KINETIC ENERGY

$$\phi = K, \quad \Gamma_{\phi x} = \mu + \frac{\mu_t}{\sigma_k} = \Gamma_{\phi r}$$

$$S_\phi = G - \rho\varepsilon$$

- TURB. ENERGY DISSIPATION

$$\phi = \varepsilon, \quad \Gamma_{\phi x} = \mu + \frac{\mu_t}{\sigma_k} = \Gamma_{\phi r}$$

$$S_\phi = \frac{\varepsilon}{k}(c_1 f_1 G - c_2 f_2 \rho\varepsilon)$$

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SINGLE-SCALE k-ε MODEL (CONT'D)

- $G \quad = \mu_e \left\{ 2\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial r}\right)^2 + \left(\frac{v}{r}\right)^2 \right] + \left(\frac{\partial u}{\partial r} + \frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial w}{\partial x}\right)^2 + \left(\frac{\partial w}{\partial r} - \frac{w}{r}\right)^2 \right\}$

- $\mu_t \quad = C_\mu f_\mu \rho \frac{k^2}{\varepsilon}$

  $\mu_e \quad = \mu + \mu_t$

  $C_\mu \quad = 0.09, \; c_1 = 1.44, \; c_2 = 1.92, \; \sigma_k = 1.0, \; \sigma_\varepsilon = 1.0$

KEMOD-1 MODULE DECK

- KEMOD-1 IS THE SINGLE-SCALE K-ε TURBULENCE MODULE DECK. IT CONSISTS OF TWO SEPARATE ROUTINES KEMOD AND MODIFY WHICH HAVE TO BE LINKED TO THE MAIN FLOW SOLVER
- KEMOD IS CALLED WITHIN THE ITERATION LOOP OF THE MAIN FLOW SOLVER
- THE MEAN VELOCITIES AND OTHER VARIABLES ARE PASSED TO THE MODULE THROUGH ITS ARGUMENT LIST (EXPLAINED IN THE USER'S MANUAL)
- A NONSTAGGERED BODY FITTED GRID ARRANGEMENT IS USED BY THE MODULE. IT USES THE MEAN FLOW VARIABLES (VELOCITIES AND MASS FLUXES) TO CONSTRUCT THE DISCRETIZED ALGEBRAIC EQUATION
- DISCRETIZED ALGEBRAIC EQUATIONS ARE SOLVED BY STONE'S STRONGLY IMPLICIT SOLVER

KEMOD-1 MODULE DECK (CONT'D)

SUBROUTINE GRIDG

READS GRID NODE LOCATIONS PASSED FROM MAIN SOLVER AND FOR THE FIRST ITERATION CALCULATES GRID RELATED QUANTITIES (CELL AREAS AND VOLUME, NORMAL DISTANCES FROM SOLID BOUNDARIES AND INTERPOLATION FACTORS)

SUBROUTINE CALCE

ASSEMBLES THE COEFFICIENTS AND SOURCE TERMS FOR THE DISCRETIZED K AND ε TRANSPORT EQUATIONS IN THE FORM

$$A_P \phi_P = \sum_{i = E, W, N, S} A_i \phi_i + S\phi$$

THE SUBROUTINE SOLVES THE DISCRETIZED EQUATIONS AFTER MODIFYING THE SOURCES AND BOUNDARY CONDITIONS FOR THE PARTICULAR PROBLEM

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KEMOD-1 MODULE DECK (CONT'D)

- SUBROUTINE TWOLAY

CALLED IF THE TWO-LAYER OR THE LOW-REYNOLDS NUMBER MODELS ARE USED. IT CALCULATES THE COEFFICIENTS NEEDED TO DESCRIBE THE ENERGY DISSIPATION AND EDDY VISCOSITIES CLOSE TO A WALL

- SUBROUTINE SOLSIP

SOLVES THE SYSTEM OF ALGEBRAIC K AND ε EQUATIONS USING STONE'S STRONGLY IMPLICIT METHODS

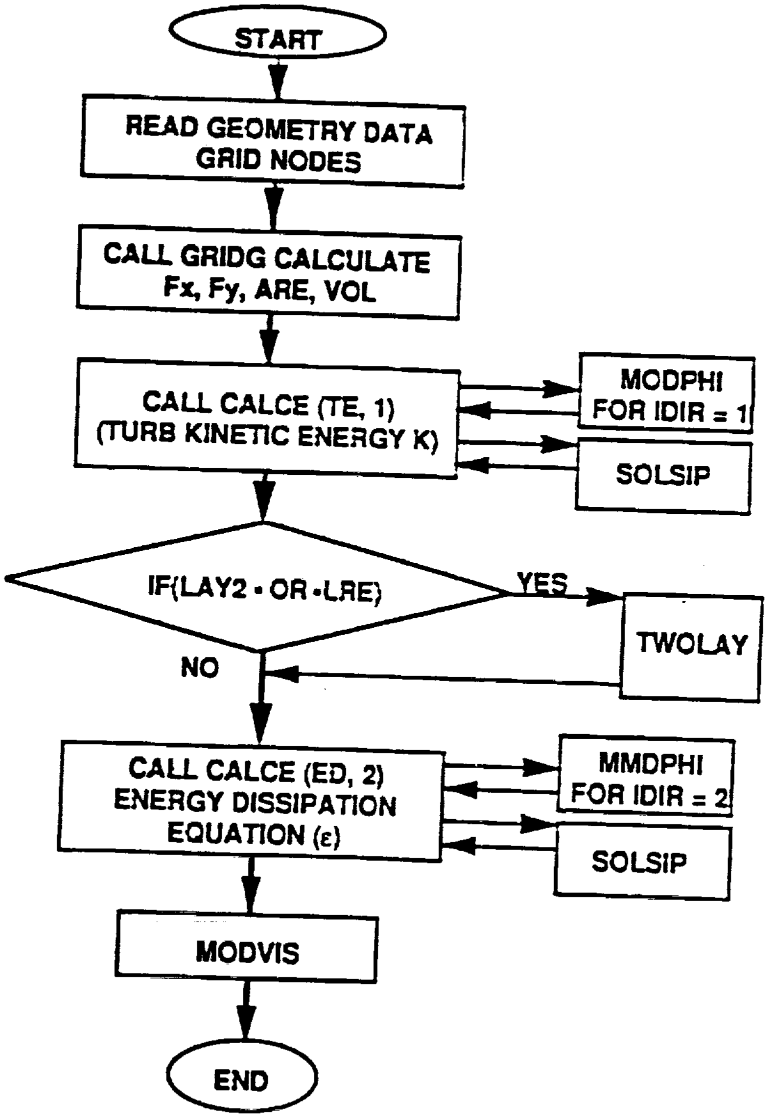
- SUBROUTINE USERM

THIS SUBROUTINE HAS DIFFERENT ENTRY SECTIONS WHERE VARIABLES ARE UPDATED AND BOUNDARY CONDITIONS ARE SET

- SUBROUTINE MODIFY

THIS IS THE ONLY SUBROUTINE THAT HAS TO BE CALLED FROM THE MOMENTUM EQUATION SOLVER OF THE MAIN ROUTINE. IT UPDATES THE FLUX SOURCE TERM OF THE DISCRETIZED MOMENTUM EQUATION DUE TO WALL SHEAR STRESSES

KEMOD-1 MODULE DECK (CONT'D)



KEMOD FLOW CHART

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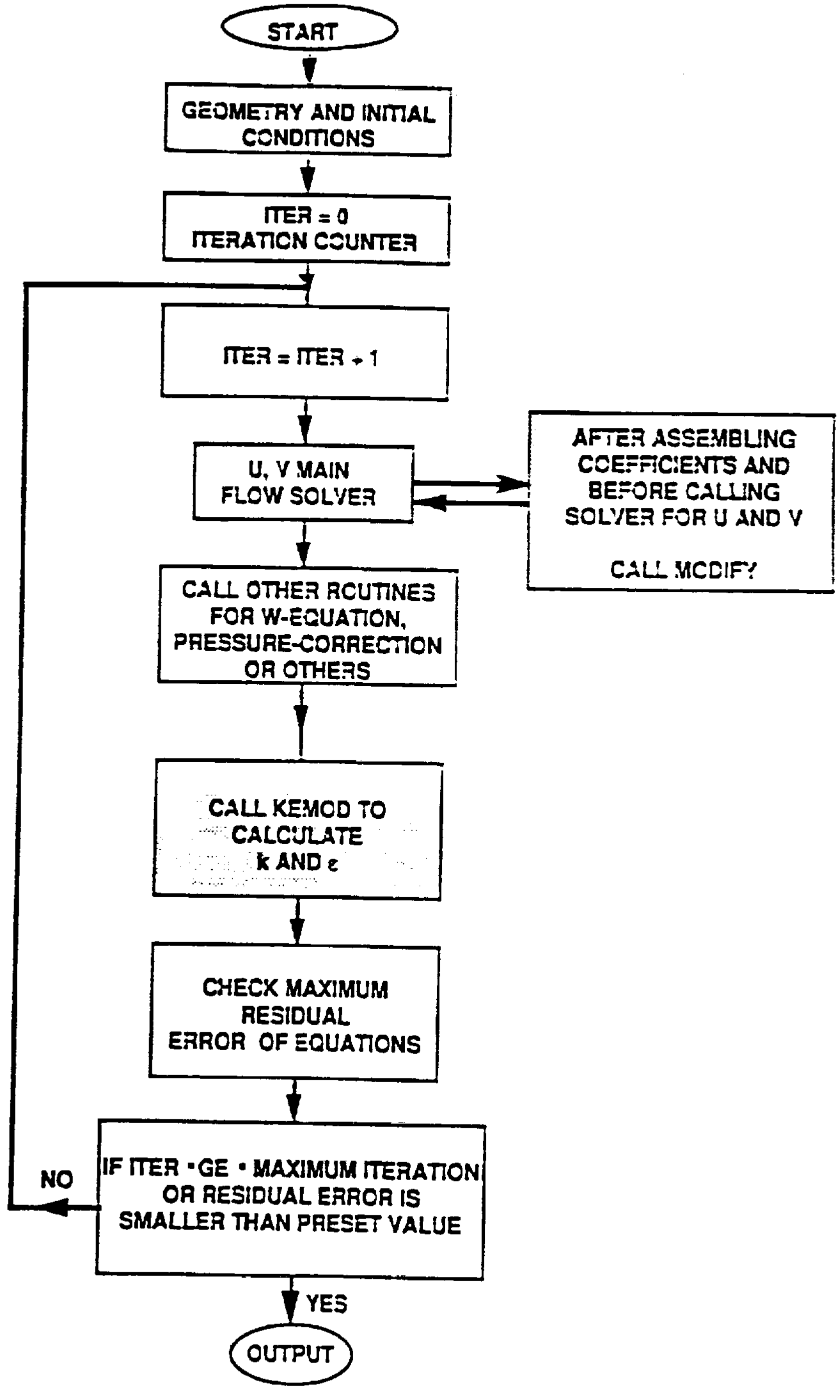
KEMOD-1 MODULE DECK (CONT'D)



START

GEOMETRY AND INITIAL CONDITIONS

ITER = 0
ITERATION COUNTER

ITER = ITER + 1

U, V MAIN FLOW SOLVER

AFTER ASSEMBLING COEFFICIENTS AND BEFORE CALLING SOLVER FOR U AND V

CALL MODIFY

CALL OTHER ROUTINES FOR W-EQUATION, PRESSURE-CORRECTION OR OTHERS

CALL KEMOD TO CALCULATE k AND ε

CHECK MAXIMUM RESIDUAL ERROR OF EQUATIONS

IF ITER •GE • MAXIMUM ITERATION OR RESIDUAL ERROR IS SMALLER THAN PRESET VALUE

OUTPUT

KEMOD-1 INTERFACE WITH A MAIN SOLVER

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MULTI-SCALE k-ε MODEL

- DERVIED BY PARTITIONING THE TURBULENT ENERGY SPECTRUM INTO TWO SETS OF WAVE NUMBER REGIONS (PRODUCTION AND DISSIPATION RANGES) GIVING TWO EVOLUTION EQUATIONS FOR EACH REGION
- PARTITION LOCATION IS DETERMINED AS PART OF THE SOLUTION
- TURBULENT KINETIC ENERGY IN THE PRODUCTION RANGE OF THE SPECTRUM

$$\phi = k_p, \Gamma_{\phi x} = \Gamma_{\phi r} = \mu + \frac{\mu_t}{\sigma_{kp}}$$

$$S_{kp} = G - \rho \varepsilon_p$$

MULTI-SCALE k-ε MODEL (CONT'D)

- **ENERGY TRANSFER RATE IN THE PRODUCTION RANGE OF THE SPECTRUM**

$$\phi = \varepsilon_p, \ \Gamma_{\phi x} = \Gamma_{\phi r} = \frac{\mu_t}{\sigma_{kp}}$$

$$S_{\varepsilon p} = \frac{1}{\rho} C_{p1} \frac{G^2}{K_p} + C_{p2} \frac{G \varepsilon_p}{k_p} - \rho \, C_{p3} \frac{\varepsilon_p^2}{k_p}$$

- **TURBULENT KINETIC ENERGY IN THE DISSIPATION RANGE OF THE SPECTRUM**

$$\phi = k_t, \ \Gamma_{\phi x} = \Gamma_{\phi r} = \frac{\mu_t}{\sigma_{kt}}$$

$$S_{kt} = \rho \varepsilon_p - \rho \varepsilon_t$$

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MULTI-SCALE k-ε MODEL (CONT'D)

- **ENERGY DISSIPATION RATE IN THE DISSIPATION RANGE**

$$\phi = \varepsilon_t, \Gamma_{\phi x} = \Gamma_{\phi r} = \mu + \frac{\mu_t}{\sigma_{\varepsilon t}}$$

and

$$S_{\varepsilon t} = \rho C_{t1} \frac{\varepsilon_p^2}{k_t} + \rho C_{t2} \frac{\varepsilon_t \varepsilon_p}{k_t} - \rho C_{t3} \frac{\varepsilon_t^2}{k_t}$$

- **MODEL IS SIMILAR TO THAT USED BY KIM AND CHEN WITH CONSTANTS**

$$\sigma_{kp} = 0.75, \sigma_{\varepsilon p} = 1.15, \sigma_{kt} = 0.75, \sigma_{\varepsilon t} = 1.15$$

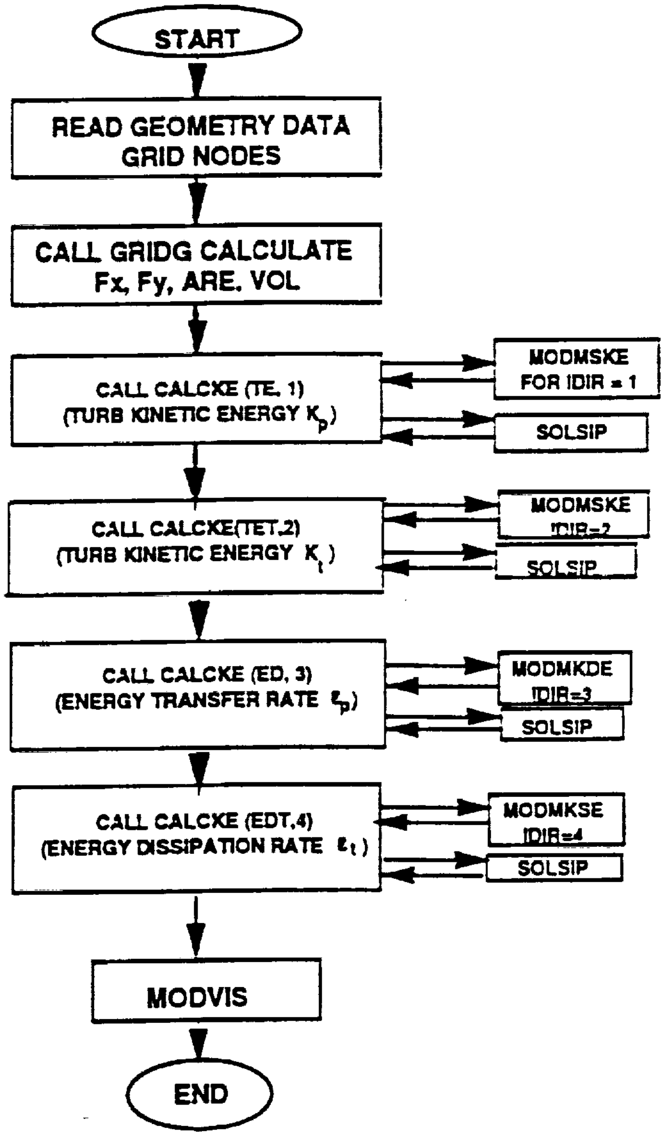
$$C_{p1} = 0.21, C_{p2} = 1.24, C_{p3} = 1.84, C_{t1} = 0.29$$

$$C_{t2} = 1.28, C_{t3} = 1.66 \text{ and } C_\mu = 0.09$$

KEMOD-2 MODULE DECK

- KEMOD-2 IS A MULTI-TIME SCALE K-ε TURBULENCE MODULE DECK. IT CONSISTS OF TWO MAIN ROUTINES KEMOD AND MODIFY
- KEMOD IS CALLED WITHIN THE ITERATION LOOP OF THE MAIN FLOW SOLVER
- MEAN VELOCITIES AND OTHER VARIABLES ARE PASSED TO THE MODULE THROUGH ITS ARGUMENT LIST (EXPLAINED IN THE USER'S MANUAL
- THE MODULE IS STRUCTURED IN A SIMILAR WAY TO KEMOD-1 AND SUBROUTINE CALCE ASSEMBLES THE COEFFICIENTS AND SOURCE TERMS FOR THE DISCRETIZED K_p, ε_p, K_t, ε_t TRANSPORT EQUATIONS

KEMOD-2 MODULE DECK (CONT'D)



START

READ GEOMETRY DATA
GRID NODES

CALL GRIDG CALCULATE
Fx, Fy, ARE. VOL

CALL CALCKE (TE. 1)
(TURB KINETIC ENERGY K_p)

MODMSKE
FOR IDIR = 1

SOLSIP

CALL CALCKE(TET.2)
(TURB KINETIC ENERGY K_t)

MODMSKE
IDIR=2

SOLSIP

CALL CALCKE (ED, 3)
(ENERGY TRANSFER RATE ε_p)

MODMKDE
IDIR=3

SOLSIP

CALL CALCKE (EDT,4)
(ENERGY DISSIPATION RATE ε_t)

MODMKSE
IDIR=4

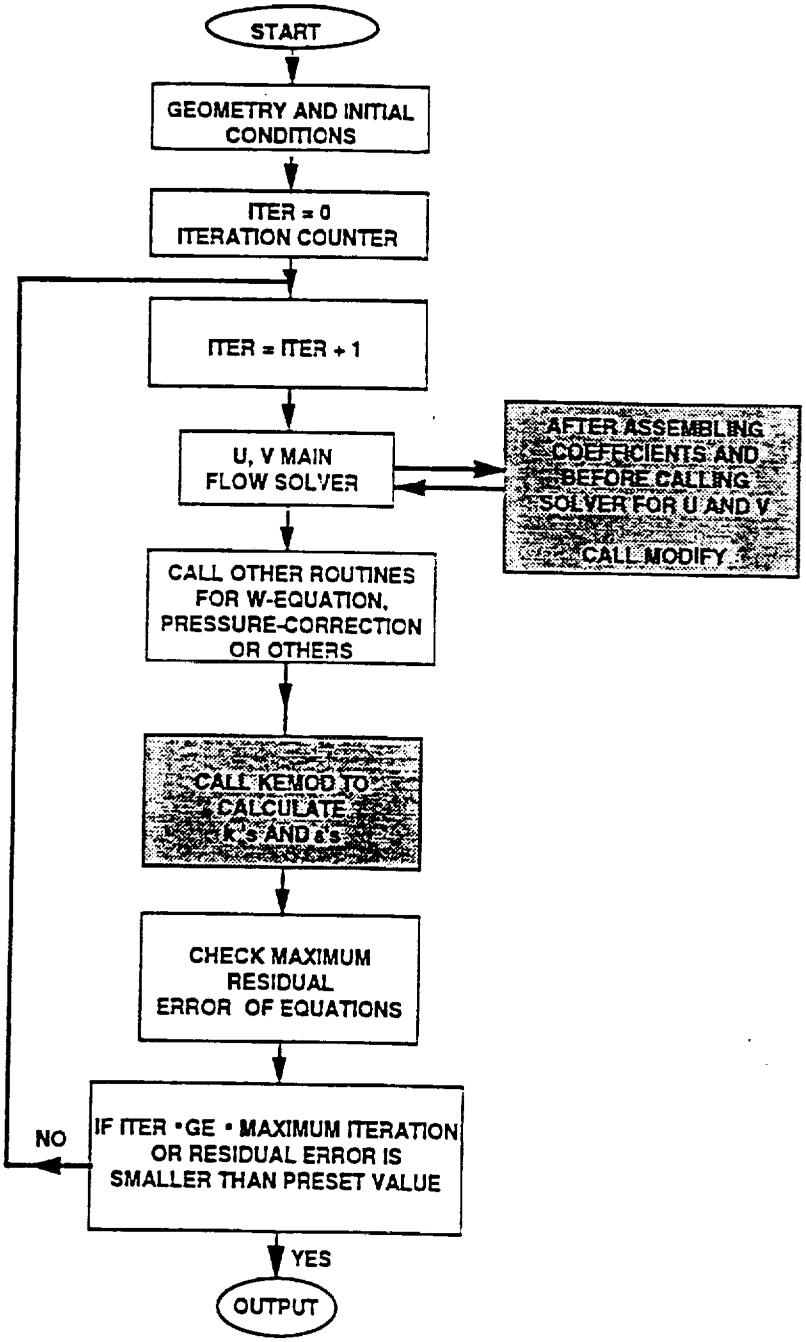
SOLSIP

MODVIS

END

KEMOD-2 FLOW CHART

KEMOD-2 MODULE DECK (CONT'D)



START

GEOMETRY AND INITIAL CONDITIONS

ITER = 0
ITERATION COUNTER

ITER = ITER + 1

U, V MAIN FLOW SOLVER

AFTER ASSEMBLING COEFFICIENTS AND BEFORE CALLING SOLVER FOR U AND V
CALL MODIFY

CALL OTHER ROUTINES FOR W-EQUATION, PRESSURE-CORRECTION OR OTHERS

CALL KEMOD TO CALCULATE k's AND ε's

CHECK MAXIMUM RESIDUAL ERROR OF EQUATIONS

IF ITER •GE • MAXIMUM ITERATION OR RESIDUAL ERROR IS SMALLER THAN PRESET VALUE

NO

YES

OUTPUT

KEMOD-2 INTERFACE WITH MAIN SOLVER

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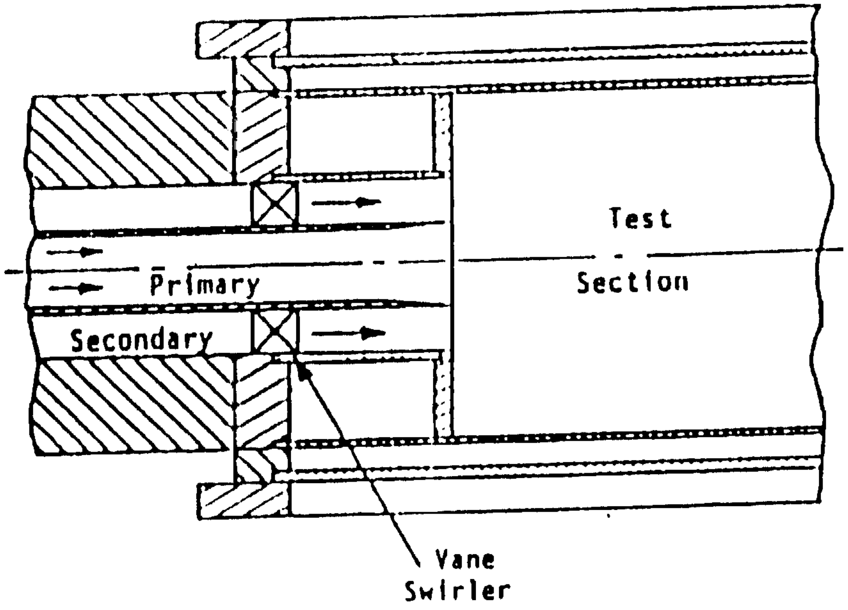
ROBACK AND JOHNSON – SWIRLING COAXIAL JETS DISCHARGING INTO AN EXPANDED DUCT

R. ROBACK AND B. JOHNSON, "MASS AND MOMENTUM TURBULENT TRANSPORT EXPERIMENT WITH CONFINED SWIRLING COAXIAL JETS," NASA CR-168252, 1983

GEOMETRY



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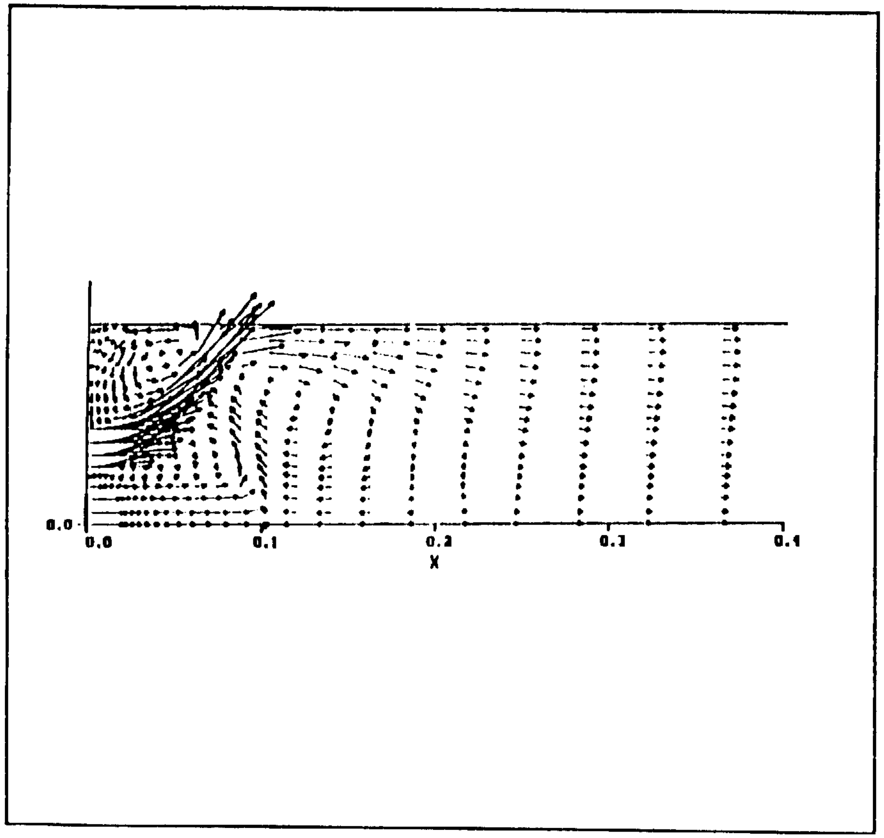
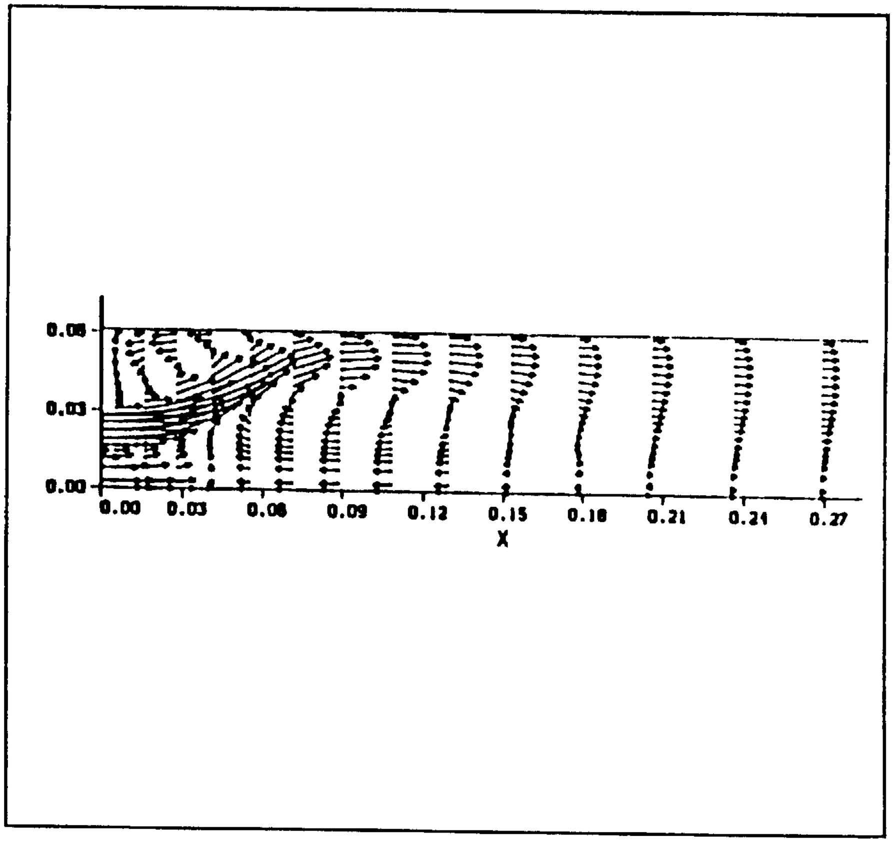
ROBACK AND JOHNSON RESULTS
VELOCITY VECTORS



SINGLE-SCALE K-ε MODEL



MULTI-SCALE K-ε MODEL

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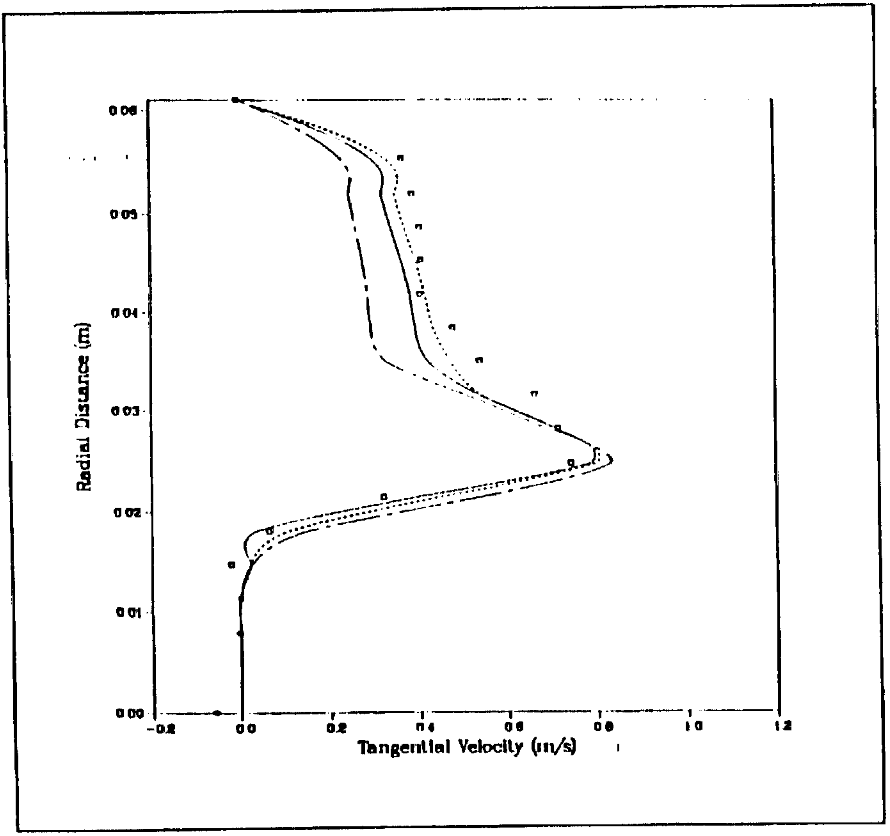
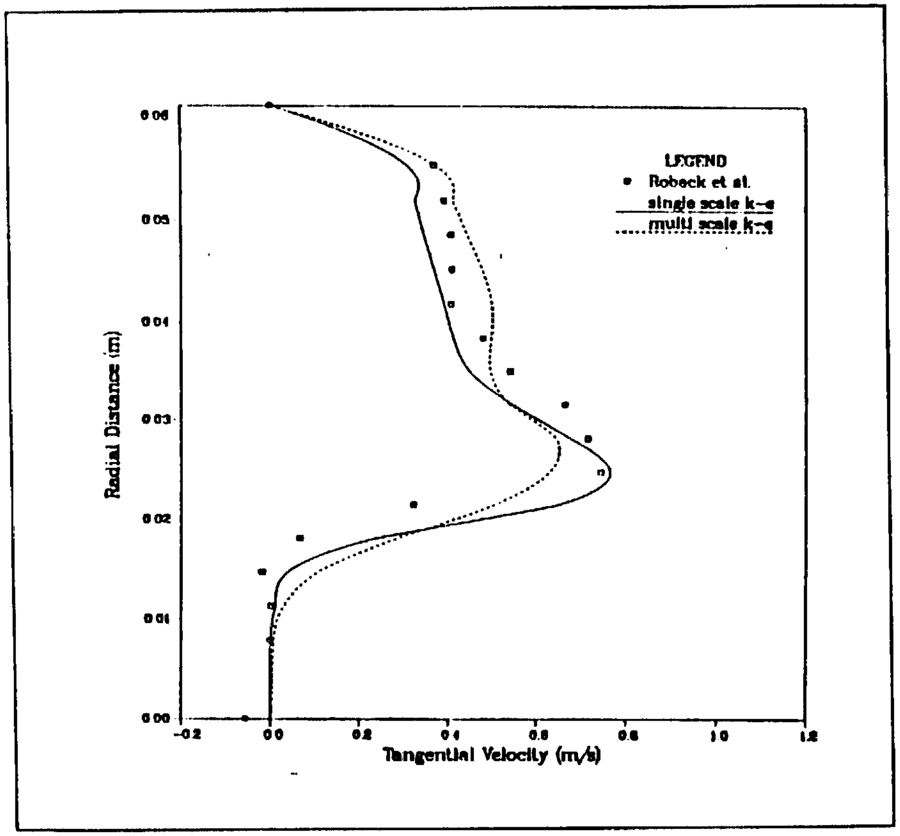
ROBACK AND JOHNSON RESULTS
TANGENTIAL VELOCITY PREDICTIONS AT X = 0.025 M

☐	DATA
———	WALL FUNCTION
— — —	LOW-REYNOLDS NO. MODEL
–·– ·–	2-LAYER MODEL



SINGLE-SCALE K-ε

☐	DATA
———	SINGLE-SCALE K-ε MODEL
— — —	MULTI-TIME SCALE K-ε MODEL



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SUMMARY

- **KEMOD-1 (2-D)**
  - SINGLE SCALE k-ε TURBULENCE MODULE COMPLETE
  - TESTED USING REACT AND USA CODES

- **KEMOD-2 (2-D)**
  - MULTISCALE k-ε TURBULENCE MODULE COMPLETE
  - TESTED USING REACT CODE

- **DEVELOPMENT OF MODULES FOR FULL AND ALGEBRAIC REYNOLDS STRESS MODELS IN PROGRESS**

- **WORK ON 3-D MODULES TO BEGIN AS SCHEDULED (FY '94)**