

ADVANCED TURBULENCE MODELS FOR TURBOMACHINERY

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ABSTRACT

Development and assessment of the single-time-scale $k-\epsilon$ turbulence model with different near-wall treatments and the multi-scale $k-\epsilon$ 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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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

MULTI-SCALE

SINGLE-SCALE

2-EQUATION MODELS
K- ϵ (MKEM)

2-EQUATION MODELS
K- ϵ (SKEM)

ALGEBRAIC
STRESS MODELS
(ASM)

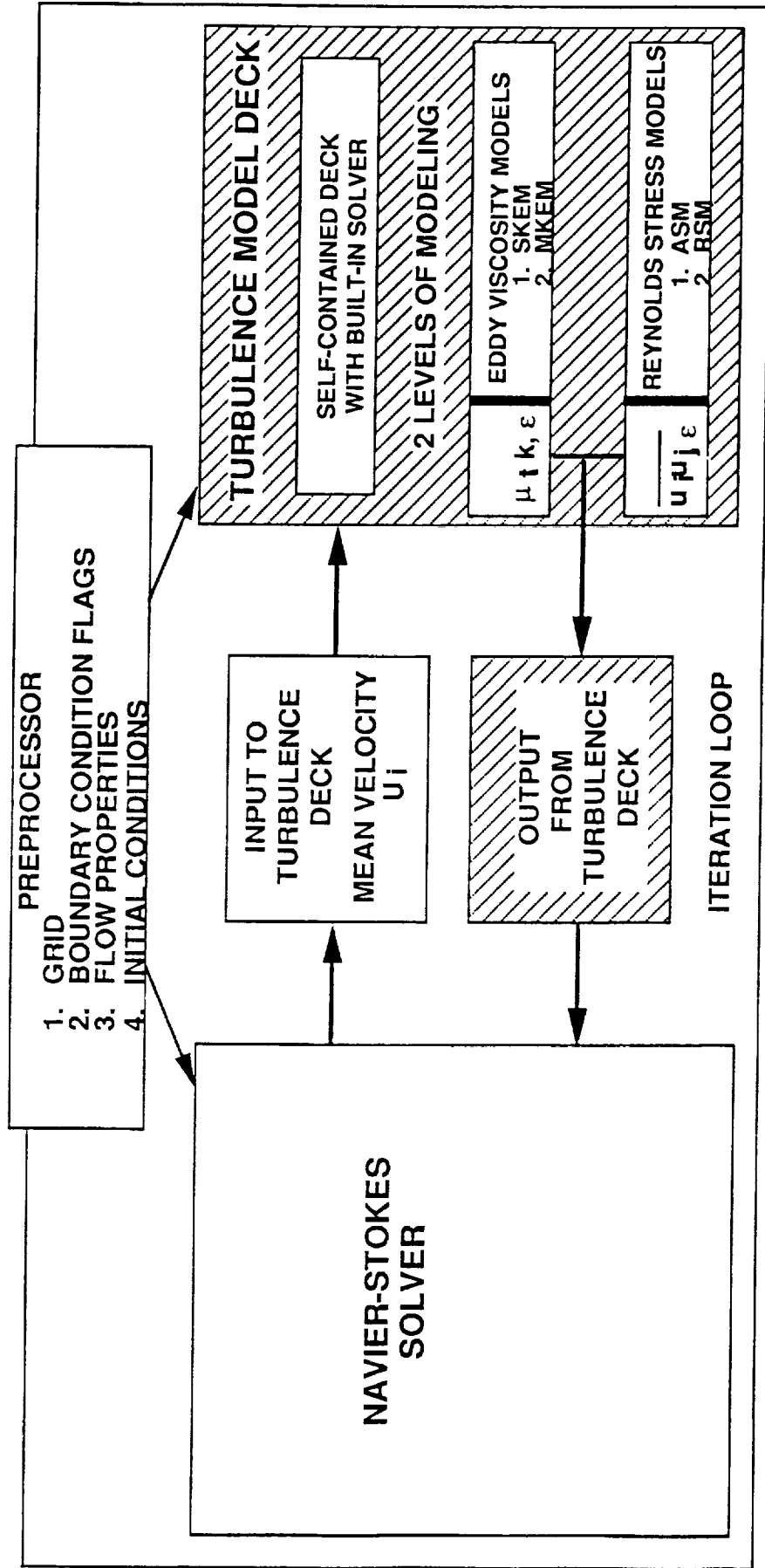
REYNOLDS
STRESS MODELS
(RSM)

• 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

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



USER PROVIDED

ROCKETDYNE PROVIDED



SINGLE-SCALE k-ε MODEL

- GENERALIZED TRANSPORT EQUATION IN 2-D/AXISYMMETRIC GEOMETRY

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

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

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

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

$$S_v = -\frac{\partial P}{\partial x} - \frac{\partial}{\partial r} (\mu_e r \frac{\partial u}{\partial r}) - 2\mu_e \frac{v}{r^2} + \frac{\rho \omega^2}{r}$$

SINGLE-SCALE k-ε MODEL (CONT'D)

• W-MOMENTUM $\phi = w, \Gamma\phi_x = \mu e, \Gamma\phi_r = \mu e$

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

• TURB. KINETIC ENERGY $\phi = K, \Gamma\phi_x = \mu + \frac{\mu t}{\sigma_K} = \Gamma\phi_r$

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

• TURB. ENERGY DISSIPATION $\phi = \varepsilon, \Gamma\phi_x = \mu + \frac{\mu t}{\sigma_K} = \Gamma\phi_r$

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

SINGLE-SCALE k-ε MODEL (CONT'D)

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

$$\bullet \mu_t = C_\mu f_\mu \rho \frac{k^2}{\epsilon}$$

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

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



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

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

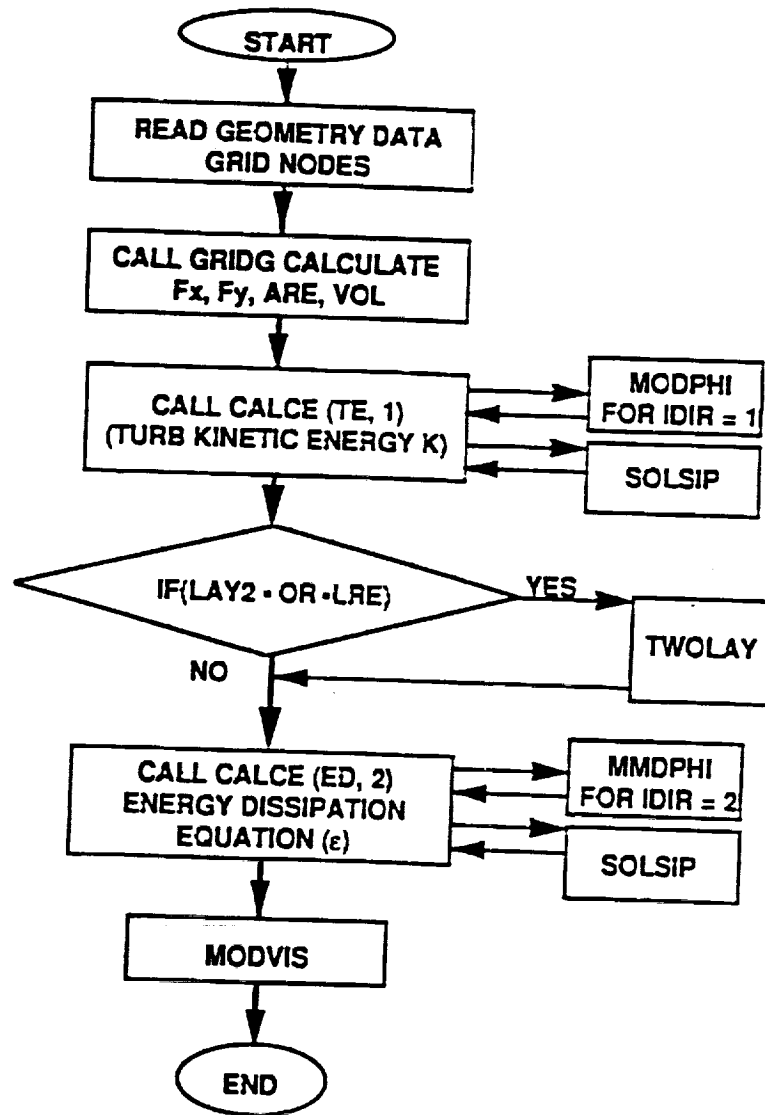
- **SUBROUTINE USERM**

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)



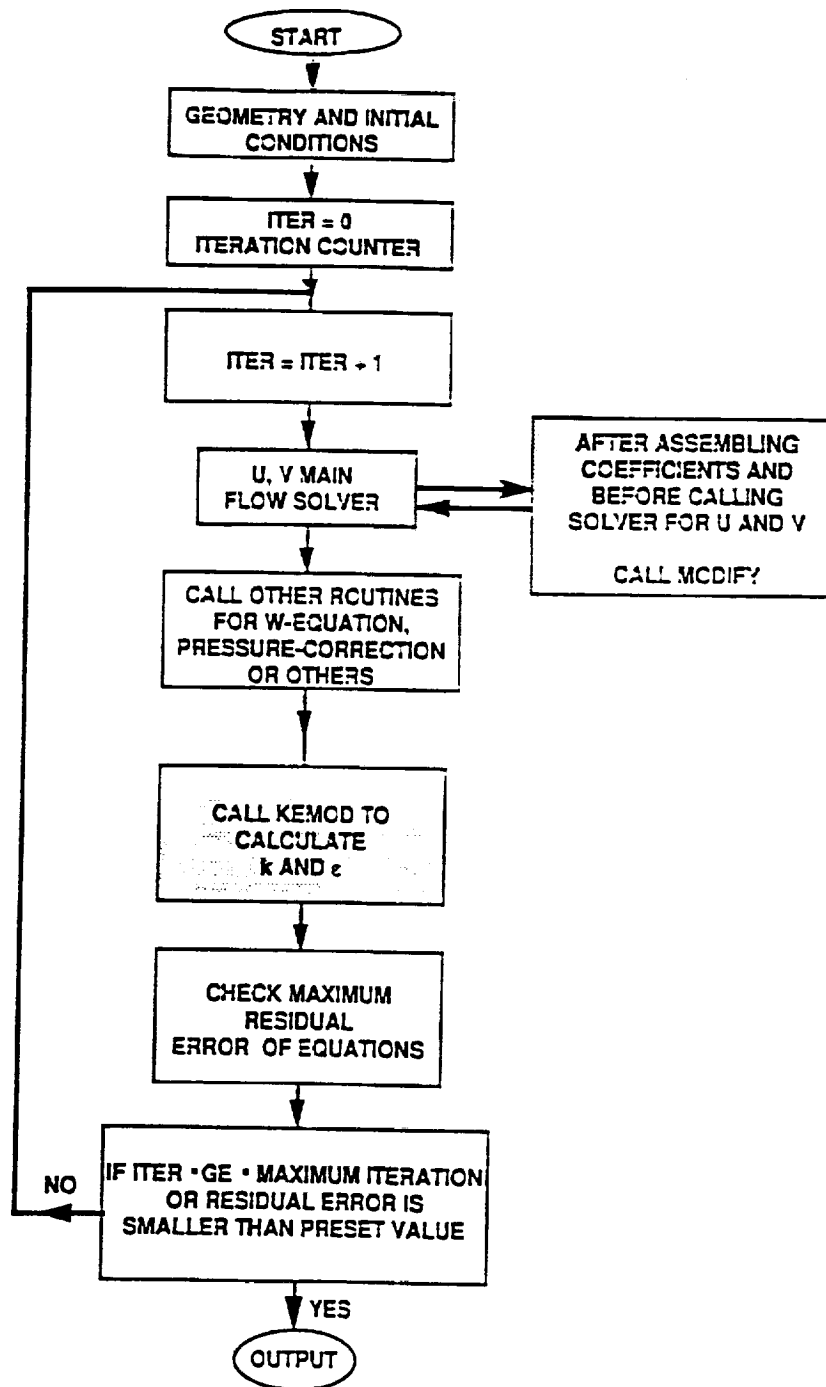
KEMOD FLOW CHART



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KEMOD-1 MODULE DECK (CONT'D)



KEMOD-1 INTERFACE WITH A MAIN SOLVER



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MULTI-SCALE k-ε MODEL

- DERIVED 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

$$\phi = k_p, \Gamma\phi_x = \Gamma\phi_r = \mu + \frac{\mu t}{\sigma k_p}$$

$$S_{k_p} = G - \rho\epsilon_p$$

MULTI-SCALE k-ε MODEL (CONT'D)

- ENERGY TRANSFER RATE IN THE PRODUCTION RANGE OF THE SPECTRUM

$$\phi = \varepsilon_p, \quad \Gamma_{\phi_x} = \Gamma_{\phi_r} = \frac{\mu_t}{\sigma_k k_p}$$

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

- TURBULENT KINETIC ENERGY IN THE DISSIPATION RANGE OF THE SPECTRUM

$$\phi = k_t, \quad \Gamma_{\phi_x} = \Gamma_{\phi_r} = \frac{\mu_t}{\sigma_k k_t}$$

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

MULTI-SCALE k-ε MODEL (CONT'D)

- ENERGY DISSIPATION RATE IN THE DISSIPATION RANGE

$$\phi = \epsilon_t, \Gamma_{\phi x} = \Gamma_{\phi r} = \mu + \frac{\mu_t}{\sigma \epsilon_t}$$

and

$$S_{\epsilon_t} = \rho C_{t1} \frac{\epsilon_p^2}{k_t} + \rho C_{t2} \frac{\epsilon_t \epsilon_p}{k_t} - \rho C_{t3} \overline{k_t^2}$$

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

$$\sigma_{k_p} = 0.75, \sigma_{\epsilon_p} = 1.15, \sigma_{k_t} = 0.75, \sigma_{\epsilon_t} = 1.15$$

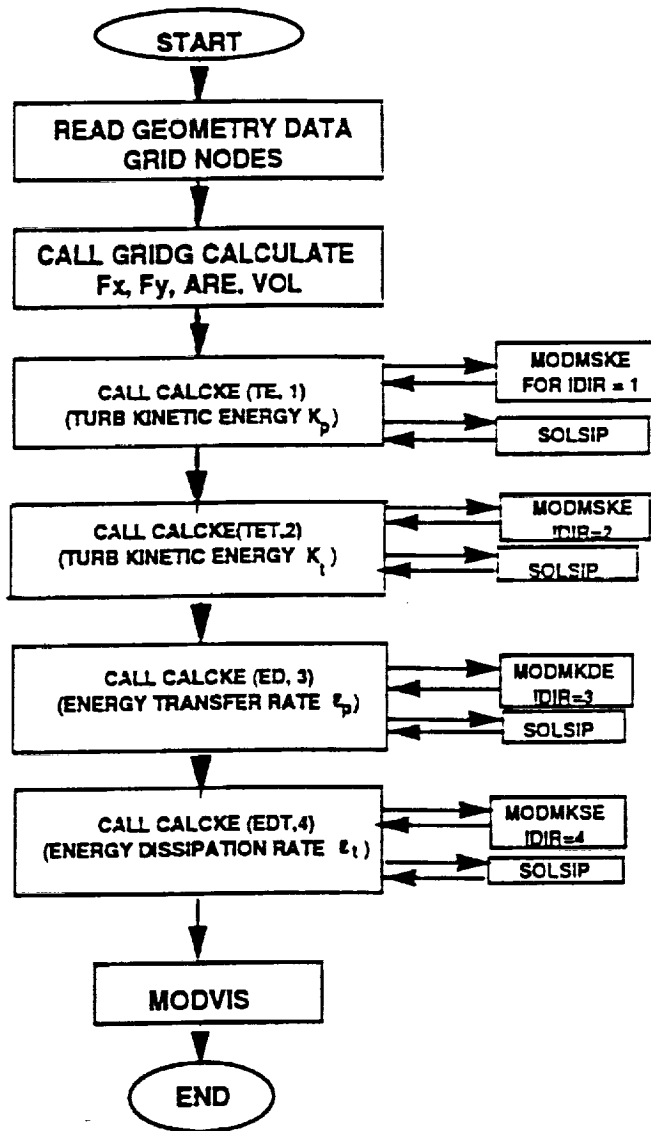
$$C_{p1} = 0.21, C_{p2} = 1.24, C_{p3} = 1.84, C_{t1} = 0.29$$

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

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

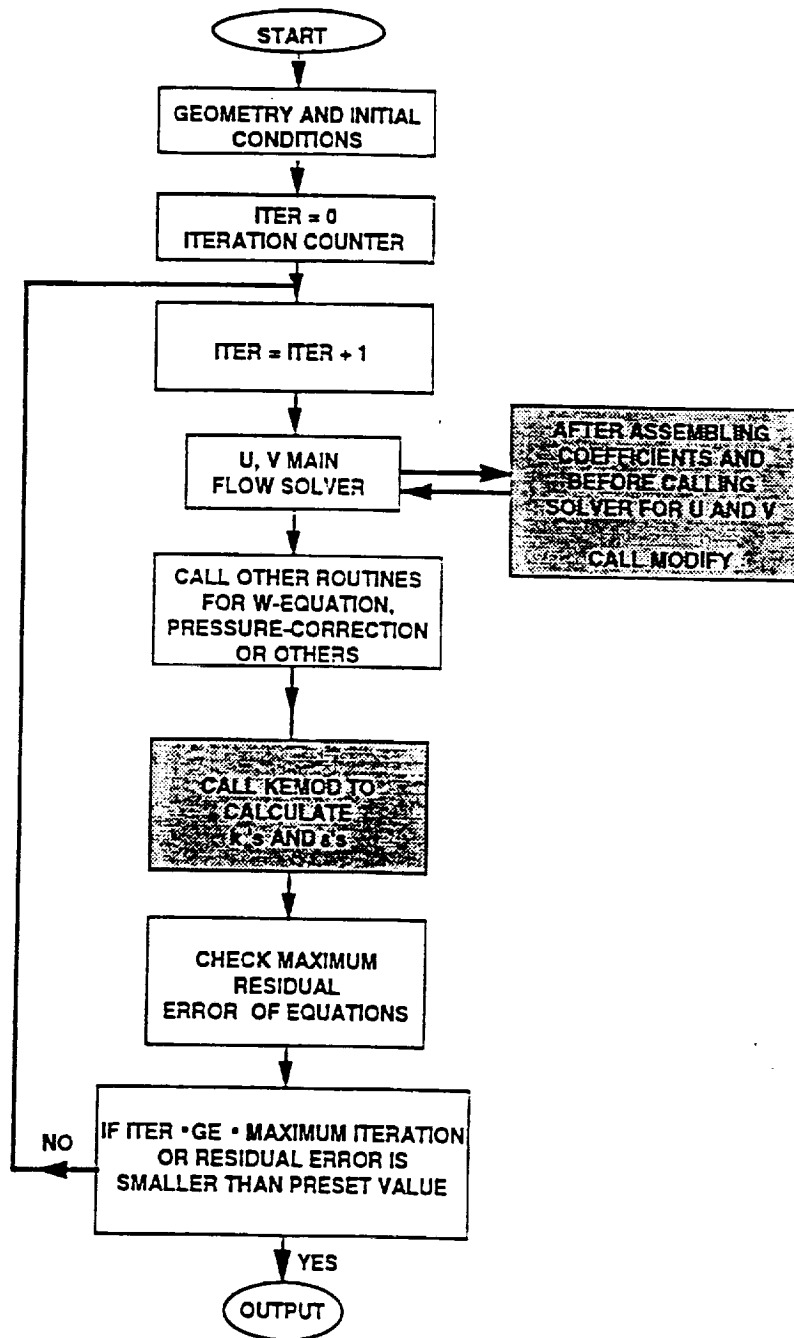
KEMOD-2 MODULE DECK (CONT'D)



KEMOD-2 FLOW CHART



KEMOD-2 MODULE DECK (CONT'D)



KEMOD-2 INTERFACE WITH MAIN SOLVER



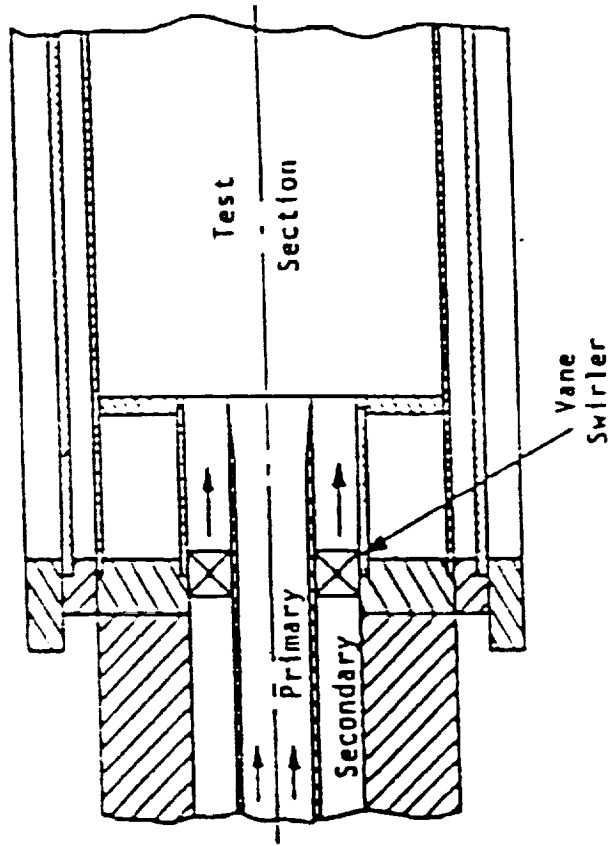
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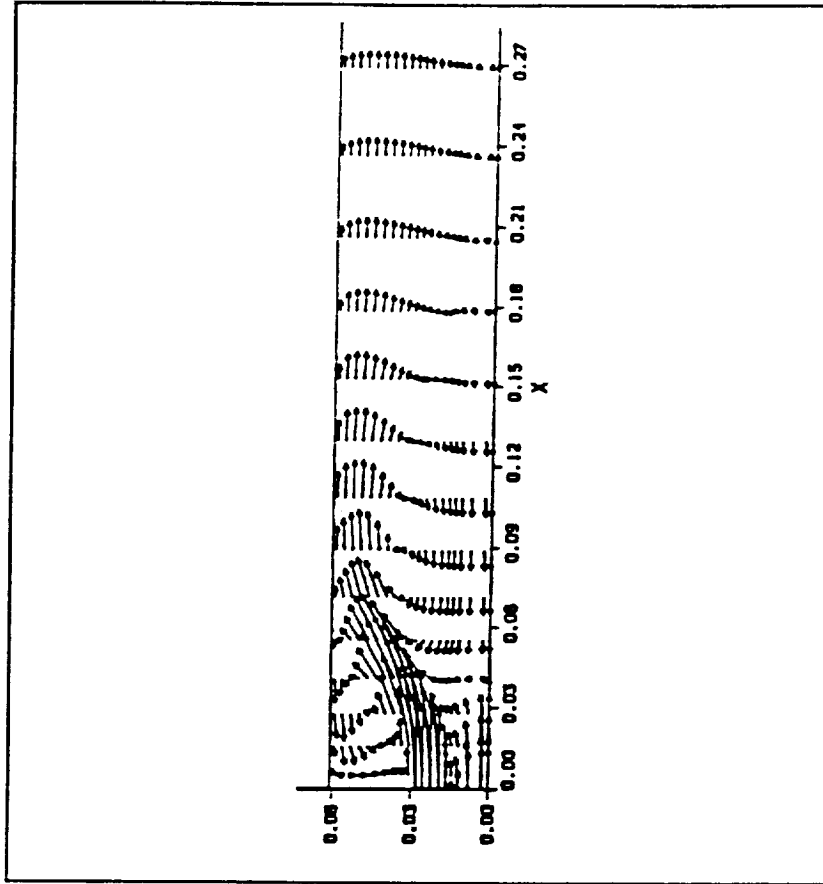
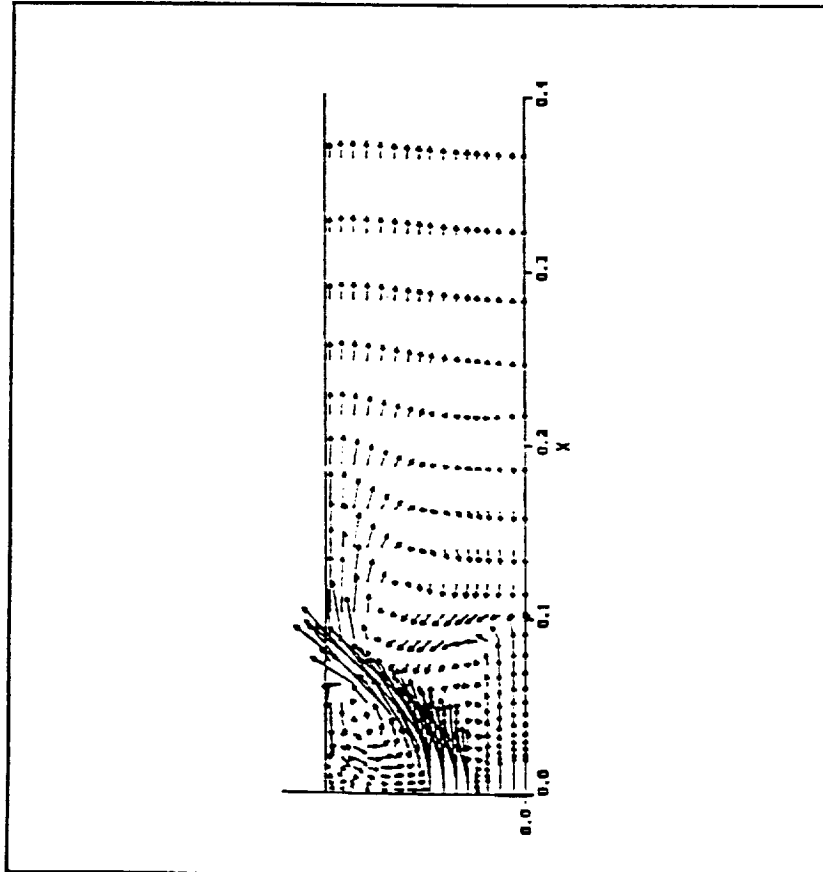
ROBACK AND JOHNSON - SWIRLING COAXIAL JETS DISCHARGING INTO AN EXPANDED DUCT

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

GEOMETRY



ROBACK AND JOHNSON RESULTS VELOCITY VECTORS



SINGLE-SCALE K-ε MODEL

MULTI-SCALE K-ε MODEL

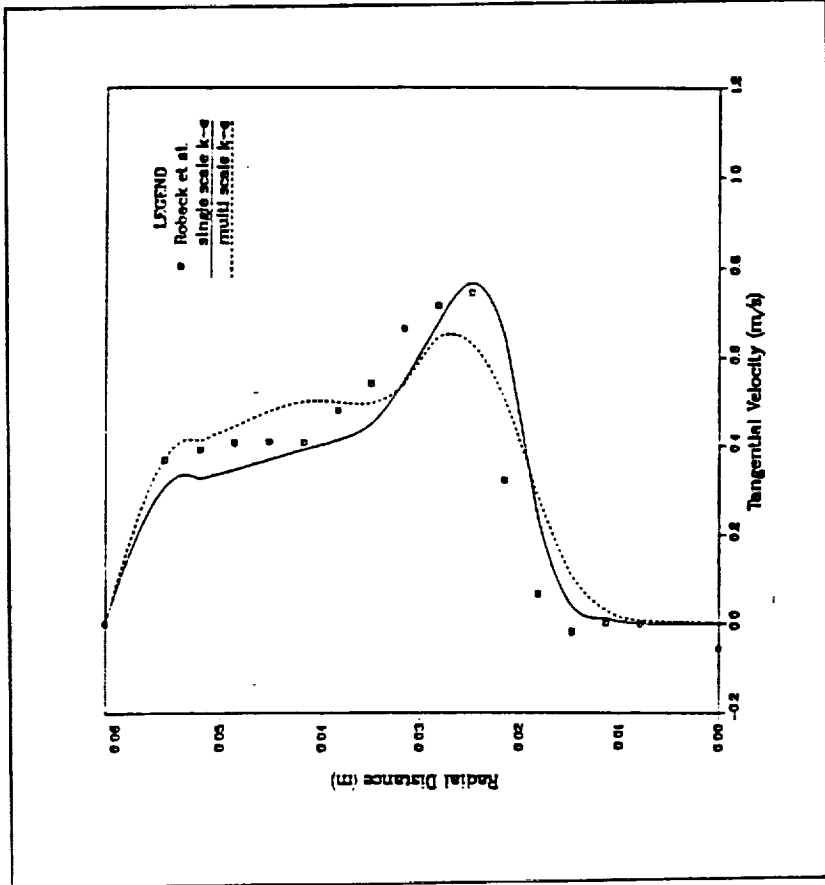
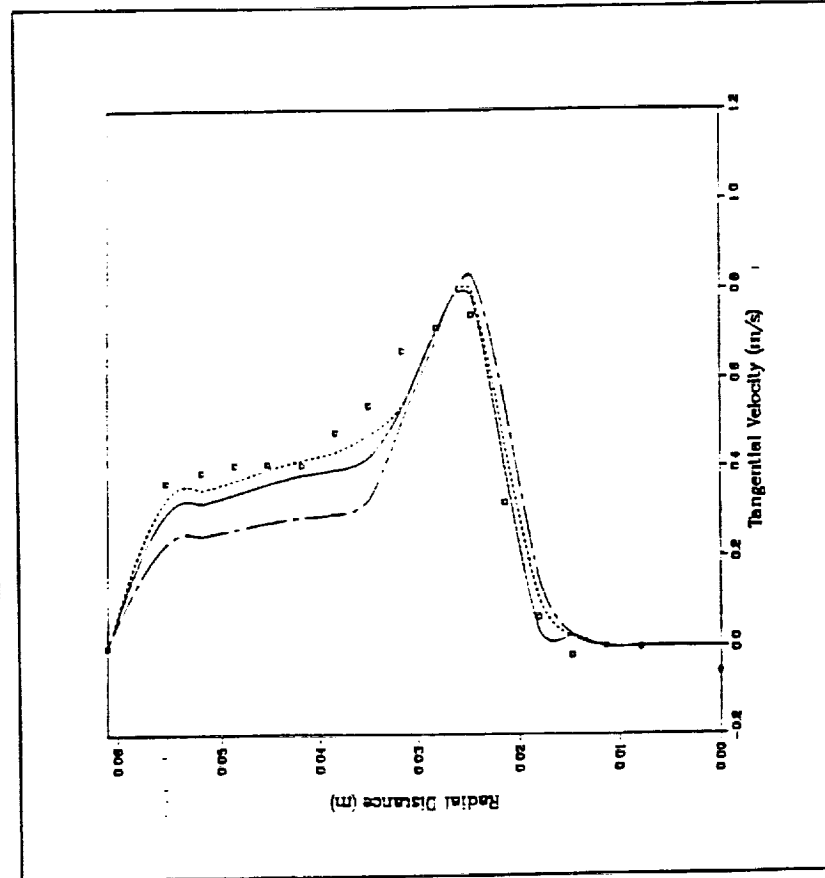


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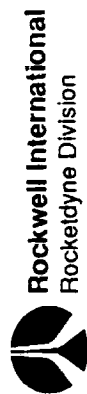
ROBACK AND JOHNSON RESULTS TANGENTIAL VELOCITY PREDICTIONS AT X = 0.025 M

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

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



SINGLE-SCALE K-ε



SUMMARY

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

