EFFECT OF LIQUID DROPLETS ON TURBULENCE STRUCTURE IN A ROUND GASEOUS JET

S.E. Elghobashi and A.M. Mostafa
Mechanical Engineering Department
University of California
Irvine, California 92717

Abstract

Experiments [1-5] show that the addition of solid particles or liquid droplets to free turbulent jets modifies their turbulence structure. For example the turbulence intensity and shear stress are reduced due to the presence of the dispersed phase. Although the nature of interaction between the dispersed phase and the carrier fluid is rather complex and not well understood at present [6], there have been several attempts to predict the behavior of particle-laden turbulent flows [1,7,8].

The objective of the present work is to develop and validate a second-order model which predicts the modulation of turbulence in jets laden with uniform size solid particles or liquid droplets.

The approach followed here is to start from the separate momentum and continuity equations of each phase and derive two new conservation equations. The first is for the carrier fluid's kinetic energy of turbulence and the second for the dissipation rate of that energy. Closure of the set of transport equations is achieved by modeling the turbulence correlations up to a third order.

The coefficients (or constants) appearing in the modeled equations are then evaluated by comparing the predictions with LDA-measurements obtained recently in a turbulent jet laden with 200μ solid particles. This set of constants is then used to predict the same jet flow but laden with 50μ solid particles. The agreement with the measurement in this case is very good.

References

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ASSUMPTIONS

- BOTH PHASES BEHAVE MACROSCOPICALLY AS A CONTINUUM , BUT ONLY THE CARRIER FLUID BEHAVES MICRORCOPICALLY AS A CONTINUUM
- THE DISPERSED PHASE CONSISTS OF SPHERICAL PARTICLES OF UNIFORM SIZE
- NO COLLISIONS OCCUR BETWEEN THE PARTICLES
- NO PHASE CHANGE TAKES PLACE

GOVERNING EQUATIONS

MOMENTUM OF CARRIER FLUID

$$(\rho_1\Phi_1 U_i + \rho_1\overline{\phi_1 u_i})_{,t} + (\rho_1\Phi_1 U_j U_i)_{,j} = -(1 - K\Phi_2)P_{,i} + K[\overline{\phi_2 p_{,i}} - F\Phi_2(U_i - V_i)$$

$$- \overline{F\phi_2(u_i - v_i)}] + [\mu_1\Phi_1(U_{i,j} + U_{j,i}) + \mu_1\overline{\phi_1(u_{i,j} + u_{j,i})}]_{,j}$$

$$- \frac{2}{3}(\mu_1\Phi_1 U_{\ell,\ell} + \mu_1\overline{\phi_1 u_{\ell,\ell}})_{,i} - (\rho_1\Phi_1\overline{u_i u_j} + \rho_1 U_i\overline{\phi_1 u_j} + \rho_1 U_j\overline{\phi_1 u_i} + \rho_1\overline{\phi_1 u_i u_j})_{,j} \cdot$$

MOMENTUM OF DISPERSED PHASE

$$(\rho_2\Phi_2 V_i + \rho_2\overline{\phi_2 v_i})_{,t} + (\rho_2\Phi_2 V_j V_i)_{,j} = -\Phi_2 P_{,i} - \overline{\phi_2 p_{,i}} + F[\Phi_2(U_i - V_i)$$

$$+ \overline{\phi_2(u_i - v_i)}] + [\mu_2\Phi_2(V_{i,j} + V_{j,i}) + \mu_2\overline{\phi_2(v_{i,j} + v_{j,i})}]_{,j}$$

$$- \frac{2}{3}(\mu_2\Phi_2 V_{\ell,\ell} + \mu_2\overline{\phi_2 v_{\ell,\ell}})_{,i} - (\rho_2\Phi_2\overline{v_i v_j} + \rho_2 V_i\overline{\phi_2 v_j} + \rho_2 V_j\overline{\phi_2 v_i} + \rho_2\overline{\phi_2 v_i v_j})_{,j}$$

$$+ g_i\Phi_2(\rho_2 - \rho_1) + f_i \cdot$$

CONTINUITY

The mean continuity equation of the dispersed phase is

$$\Phi_{2,t} + (\Phi_2 V_i)_{,i} + \overline{(\phi_2 v_i)}_{,i} = 0 \quad ;$$

the mean global continuity is

$$\Phi_1 + \Phi_2 = 1.$$

TURBULENCE KINETIC ENERGY

$$\underbrace{\rho_1 \phi_1 U_1 k_{,1} + \rho_1 \phi_1 U_2 k_{,2}}_{\text{CONVECTION}} \; - \underbrace{\frac{1}{r}\left(\rho_1 \phi_1 r \frac{\nu_t}{\sigma_k} k_{,2}\right)_{,2}}_{\text{DIFFUSION}}$$

$$- \underbrace{\rho_1 \phi_1 \nu_t (U_{1,2})^2}_{\text{PRODUCTION : } P}$$

$$+ \underbrace{\left\{ \frac{4}{3} c_\phi \rho_1 \frac{k^2}{\varepsilon} \left(\frac{\nu_t}{\sigma_\phi} \phi_{1,2}\right)_{,2} U_{2,2} - c_\phi \rho_1 \nu_t \frac{k}{\varepsilon} \left(\frac{\nu_t}{\sigma_\phi} \phi_{1,2}\right)_{,2} \right\}}_{\text{EXTRA PRODUCTION : } P_e}$$

$$+ \underbrace{\rho_1 \phi_1 \varepsilon}_{\text{DISSIPATION}}$$

$$+ \underbrace{\left\{ \begin{aligned} & F \phi_2 k \left(1 - \int_0^\infty \left(\frac{\Omega_1 - \Omega_R}{\Omega_2}\right) f(\omega)\, d\omega\right) \\ & - F (U_2 - V_2) \left(\frac{\nu_t}{\sigma_\phi} \phi_{1,2}\right) \\ & + c_\phi F \frac{k^2}{\varepsilon} \left(1 - \int_0^\infty \left(\frac{\Omega_1 - \Omega_R}{\Omega_2}\right) f(\omega)\, d\omega\right) \left(\frac{\nu_t}{\sigma_\phi} \phi_{1,2}\right)_{,2} \end{aligned} \right\}}_{\text{EXTRA DISSIPATION : } \varepsilon_e} = 0$$

DISSIPATION RATE OF TURBULENCE ENERGY

$$\underbrace{\rho_1 \phi_1 U_1 \varepsilon_{,1} + \rho_1 \phi_1 U_2 \varepsilon_{,2}}_{\text{CONVECTION}} \; - \underbrace{\frac{1}{r}\left(\rho_1 \phi_1 r \frac{\nu_t}{\sigma_\varepsilon} \varepsilon_{,2}\right)_{,2}}_{\text{DIFFUSION}}$$

$$- \underbrace{c_{\varepsilon 1} \left(\frac{\varepsilon}{k}\right) (P + P_e)}_{\text{TOTAL PRODUCTION}} + \underbrace{\rho_1 \phi_1 \left(\frac{\varepsilon}{k}\right) \left(c_{\varepsilon 2}\, \varepsilon + c_{\varepsilon 3}\, \varepsilon_e\right)}_{\text{TOTAL DISSIPATION}} = 0$$

VALUES OF THE CONSTANTS

$c_{\varepsilon 1} = 1{\cdot}43$
$c_{\varepsilon 2} = 1{\cdot}92$
$\sigma_k = 1{\cdot}0$
$\sigma_\varepsilon = 1{\cdot}3$

Four Constants For Single-Phase Flows

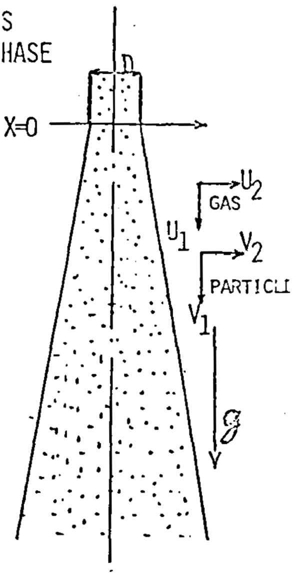
$c_\phi = 0{\cdot}1$
$c_{\varepsilon 3} = 1{\cdot}2$
$\sigma_\phi = 1.0$

Three Additional Constants For Two-Phase Flows

A SAMPLE CALCULATION

THE FLOW:
- o A TURBULENT ROUND JET ISSUES FROM A PIPE.
- o THE JET FLUID CONSISTS OF A CONTINUOUS LIGHT PHASE (AIR) AND A PARTICULATE PHASE OF UNIFORM SIZE AND SPHERICAL.
- o NO PHASE CHANGE TAKES PLACE

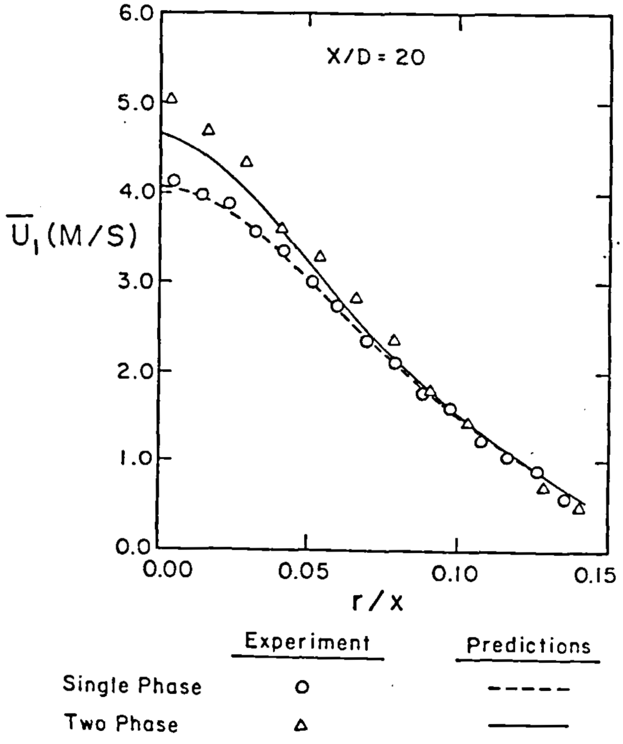
REQUIRED: CALCULATE THE VELOCITY COMPONENTS (u_1, u_2), (v_1, v_2), AND THE VOLUME FRACTIONS ϕ_1, ϕ_2, TURBULENCE PROPERTIES (ENERGY AND LENGTH SCALE) AS FUNCTIONS OF (x, r).

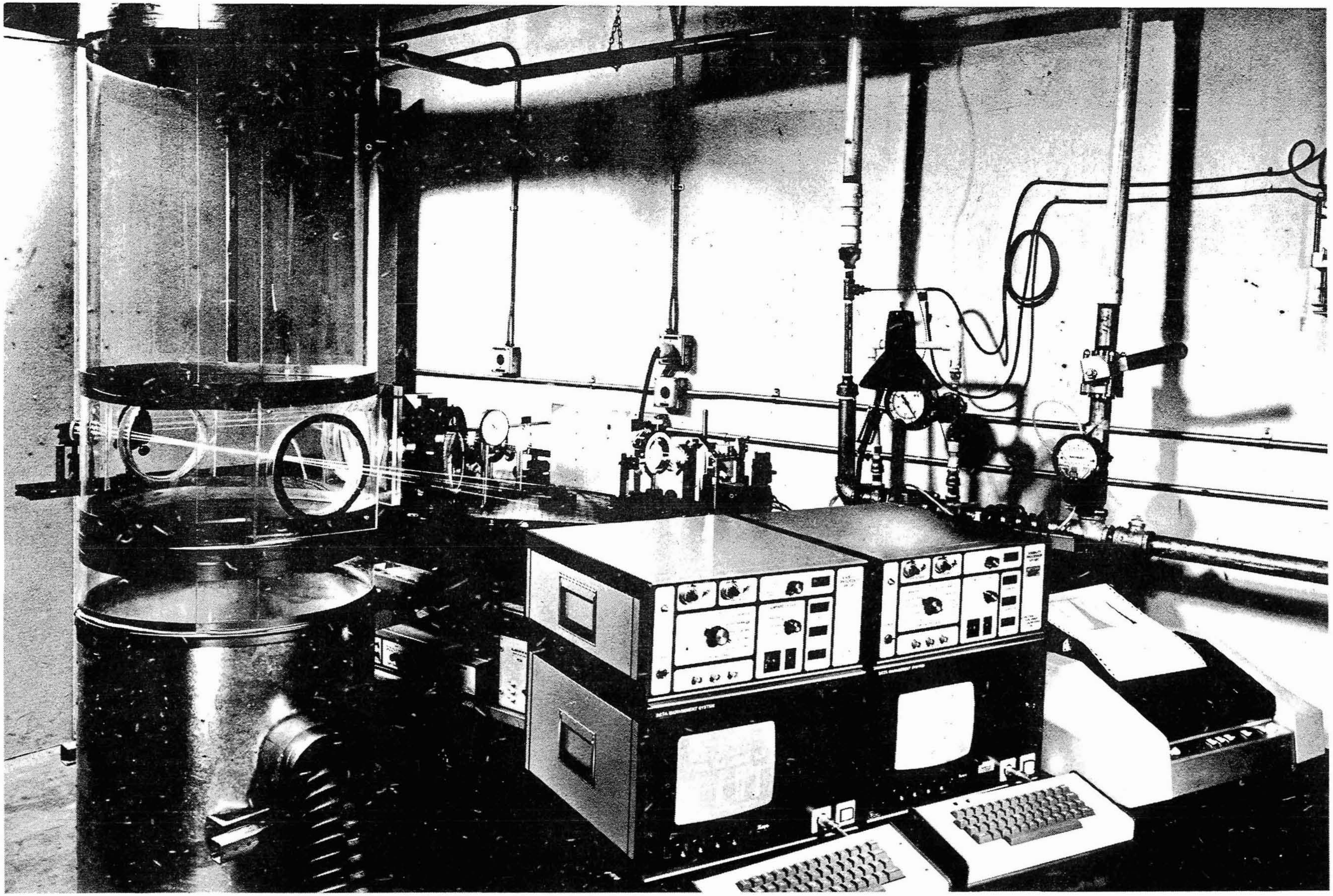


NOZZLE CONDITIONS:

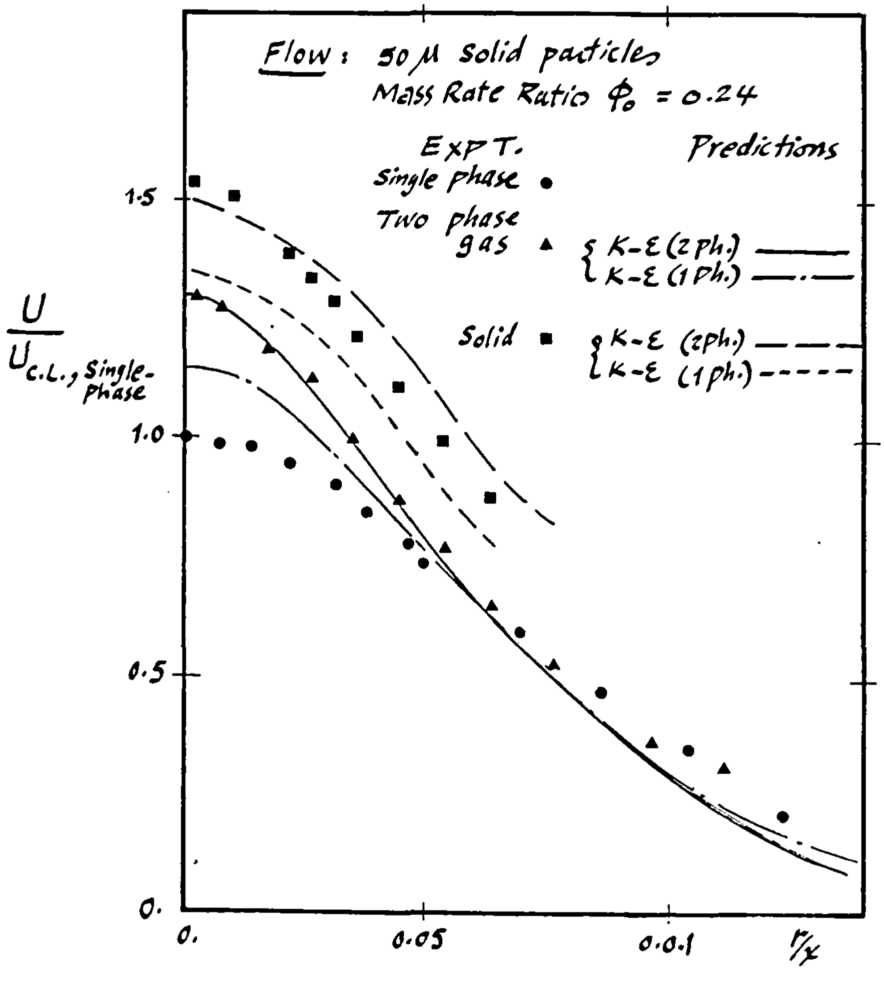
• MEAN GAS VELOCITY AT CENTERLINE	12.6 M/S
• REYNOLDS NUMBER	16500.
• PARTICLE SIZE	200. μ
• PARTICLE DENSITY	2990. KG/M^3
• MASS RATIO	0.64
• VOLUMETRIC RATIO	2.6×10^{-4}

MEAN VELOCITY OF CARRIER FLUID

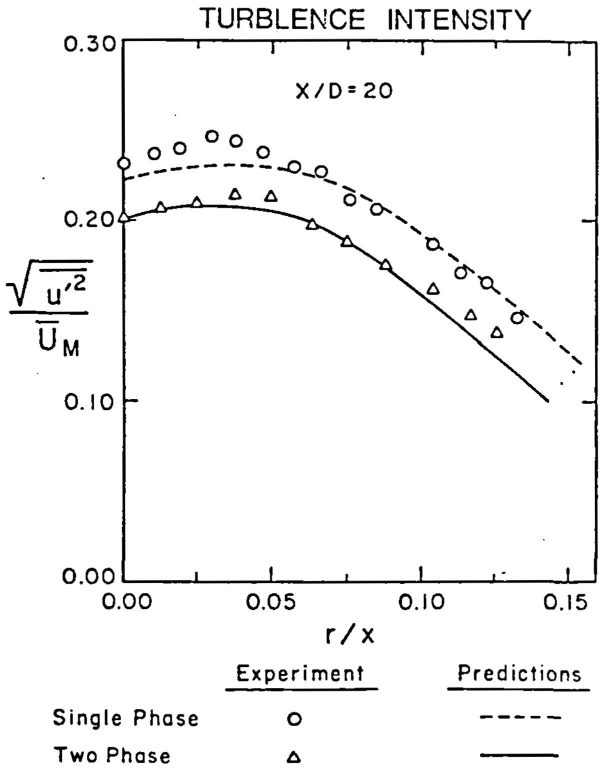




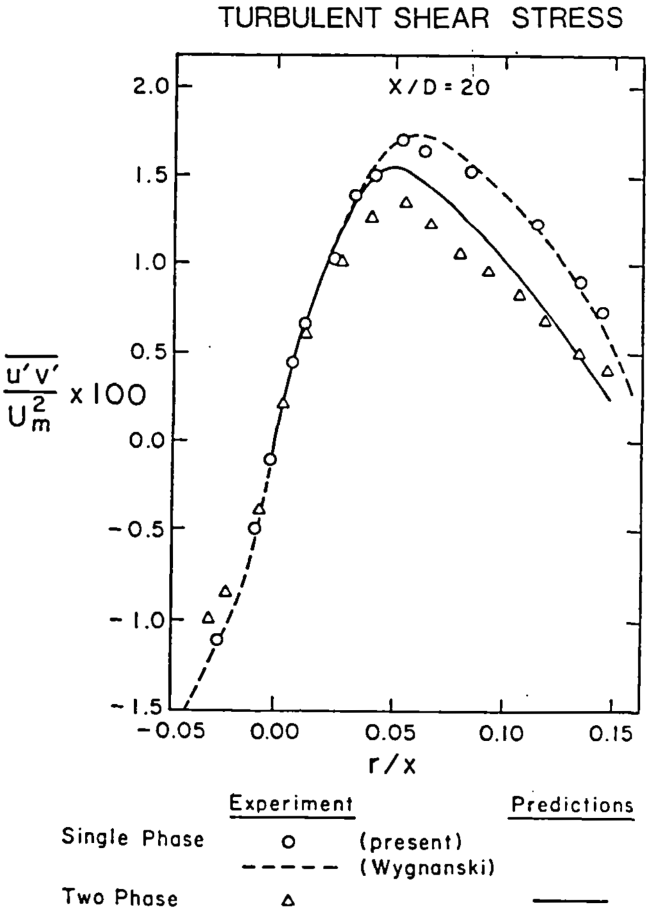
TWO PHASE FLOW EXPERIMENT



Mean Velocity Profiles at x/D = 20

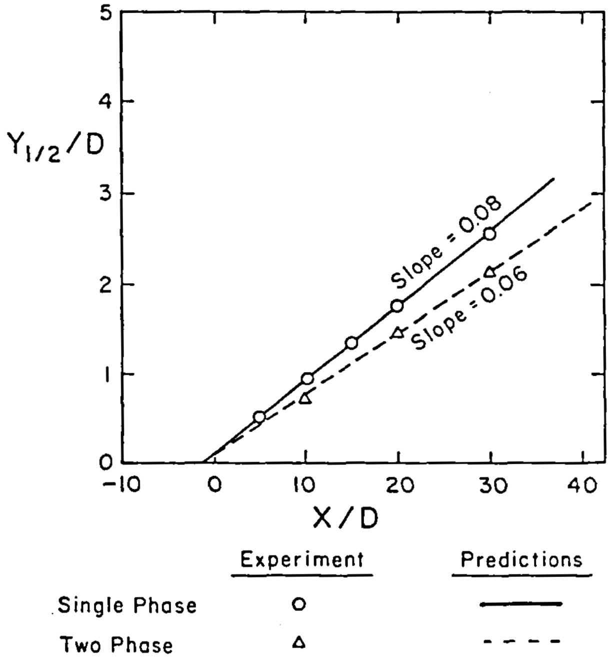


TURBLENCE INTENSITY



TURBULENT SHEAR STRESS

SPREADING RATE



CONCLUDING REMARKS

- IT HAS BEEN SHOWN THAT THE NEWLY- DEVELOPED K-ε TURBULENCE MODEL PREDICTS THE BEHAVIOR OF THE TWO- PHASE JET
- A NUMBER OF UNCERTAINTIES REMAIN AND ONE SHOULD,FOR THE PRESENT , EXERCISE DUE CAUTION IN APPLYING THE MODEL TO FLOWS THAT ARE SUBSTANTIALLY DIFFERENT FROM THE ONE COSIDERED HERE.
- EXPERIMENT IS URGENTLY NEEDED TO MEASURE MEAN AND TURBULENT QUANTITIES IN A GASEOUS JET IN WHICH UNIFORM SIZE DROPLETS ARE INJECTED.