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

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Accurate prediction of spray combustion is extremely difficult due to the complex physical and chemical phenomena encountered in this two-phase process. The interaction between droplets and the turbulent fluid, turbulence effects on chemical reaction and heat transfer (and hence on droplet vaporization) are just a few examples of the complexity. In order to understand the nature of these interactions, coordinated experimental and theoretical studies need to be performed in a stepwise manner thus isolating the phenomenon to be investigated. A turbulent non-reacting gaseous jet laden with solid particles or evaporating droplets is a flow which allows the study of the interactions between the two-phases.

The recent experiment of Modarress, et al. (1982, 1983), which was performed in parallel with the present work, provided a much needed data to help understand the behavior of two-phase turbulent jets and validate the theoretical models. Elghobashi and Abou-Arab (1983) reviewed existing turbulence models for two-phase flows and indicated that these models are based on ad hoc modifications of single-phase turbulence models. They developed a two-equation turbulence model for incompressible dilute two-phase flows which undergo no phase changes.

In order to validate the proposed model, a turbulent axisymmetric gaseous jet laden with spherical uniform-size solid particles is studied by Elghobashi, et al. (1984). The predictions of the mean flow properties of the two-phases and the turbulence kinetic energy and shear stress of the carrier phase show good agreement with the experimental data.

Mostafa and Elghobashi (1983) extended the proposed model for steady incompressible two-phase flow including phase change. This model is tested for the flow of a turbulent axisymmetric gaseous jet laden with multisize evaporating liquid droplets by Mostafa and Elghobashi (1983). To avoid the problem of density fluctuations of the carrier phase at this stage, only isothermal flow is considered and vaporization is assumed to be due to the vapor concentration gradient. The droplets are classified into finite size-groups. Each group is considered as a continuous phase interpenetrating and interacting with the carrier phase. Predicted results include distributions of the mean velocity, volume fractions of the different phases concentration of the evaporated material in the carrier phase, turbulence intensity and shear stress of the carrier phase, droplet diameter distribution and the jet spreading rate. The results are analyzed based on a qualitative comparison with the corresponding single phase jet flow.

More validation testing of the model is needed via well-defined experiments.

## REFERENCES


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2- Modarress, D., Tan, H., and Elghobashi, S., 1983, "Two-Component LDA Measurement in a Two-Phase Turbulent Jet," AIAA 21st Aerospace Sciences Meeting, Reno, Nevada.

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5- Mostafa, A., and Elghobashi, S., 1983, "A Study of the Motion of Vaporizing Droplets in a Turbulent Flow," Ninth International Colloquim on Dynamics of Explosions and Reactive Systems, Poitiers, France.

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## OBJECTIVES



- To predict the flow of a turbulent gaseous jet laden with multisize liquid droplets undergoing vaporization.

- To compare the effects, on the flow field, of vaporizing droplets with those of single phase jet.

## ASSUMPTIONS

1. Droplets in a given size-range constitute a dispersed phase - thus for k sizes there will be (k + 1) phases in the flow.

2. Each phase behaves as a continuum (macroscopically).

3. No collisions between droplets (dilute spray).

4. Droplets remain spherical as they decrease in size.

5. Velocity of vapor leaving droplet surface is equal to that of the droplet.

6. Concentration gradient is the only driving force for evaporation.

7. Drag relations of a solid sphere apply to liquid droplets (internal circulation effects on friction drag are counterbalanced by evaporation effects on pressure drag).

THE MEAN MOMENTUM EQ OF THE CARRIER PHASE

$$\rho_1 \Phi_1 U_z U_{z,z} + \rho_1 \Phi_1 U_r U_{z,r} = -\Phi_1 P_{,z}$$

*Convection*

$$+\frac{1}{r}(\Phi_1 r \mu_t U_{z,r})_{,r} - \sum_K \Phi^K (F^K + \dot{m}^K)(U_z - V_z^K)$$

*Diffusion* *Momentum Exchange*

$$\left\{ + C_{m1}\rho_1 U_{z,r}\left(\frac{\nu_t}{\sigma_\phi}\Phi_{1,r}\right) + C_{\phi s}\frac{1}{r}\left(\frac{k}{\epsilon} r \mu_t U_{z,r}\right)_{,r}\left(\frac{\nu_t}{\sigma_\phi}\Phi_{1,r}\right)_{,r} + C_{\phi s}\frac{k}{\epsilon}\mu_t U_{z,r}\left(\frac{\nu_t}{\sigma_\phi}\Phi_{1,r}\right)_{,rr} \right\}$$

*New turbulent correlations*

THE MEAN MOMENTUM EQ OF THE K th PHASE

$$\rho_2 \Phi^K V_z^K V_{z,z}^K + \rho_2 \Phi^K V_r^K V_{z,r}^K = -\Phi^K P_{,z}$$

$$+\frac{1}{r}(\Phi^K r \mu_P^K V_{z,r}^K)_{,r} + F^K \Phi^K (U_z - V_z^K)$$

$$+ C_{m1}\rho_2 V_{z,r}^K\left(\frac{\nu_P^K}{\sigma_\phi}\Phi_{,r}^K\right) + C_{\phi s}\frac{1}{r}\left(\frac{k}{\epsilon} r \mu_P^K V_{z,r}^K\right)_{,r}$$

$$+ C_{\phi s}\frac{k}{\epsilon}\mu_P^K V_{z,r}^K\left(\frac{\nu_t^K}{\sigma_\phi}\Phi_{,r}^K\right)_{,rr} + (\rho_2 - \rho_1) g$$

*gravity force*

THE MEAN CONTINUITY OF THE K th PHASE

$$\rho_2(\Phi^K V_z^K)_{,z} + \rho_2(\Phi^K V_r^K)_{,r} - \rho_2\left(\frac{\nu_t^K}{\sigma_\phi}\Phi_{,z}^K\right)_{,z} - \rho_2\left(\frac{\nu_t^K}{\sigma_\phi}\Phi_{,r}^K\right)_{,r}$$

*New turbulent correlations*

$$= -\dot{m}^K \Phi^K$$

*mass loss due to evaporation*

THE MEAN GLOBAL CONTINUITY

$$\Phi_1 + \sum_K \Phi^K = 1$$

$C_{m1} = 0.4$ & $C_{\phi s} = 0.1$

## THE CONCENTRATION EQUATION:

$$\rho_1 \Phi_1 U_z C_{,z} + \rho_1 \Phi_1 U_r C_{,r} = \frac{1}{r}\left(\rho_1 r \Phi_1 \frac{\nu_t}{\sigma_c} C_{,r}\right)_{,r}$$

*Convection* *Diffusion*

$$+\rho_1 C_{,r}\left(\frac{\nu_t}{\sigma_\phi}\Phi_{1,r}\right) + \sum_K \Phi^K \dot{m}^K (1 - C)$$

*Sources*

THE TURBULENCE KINETIC ENERGY $(K)$

$$\rho_1 \Phi_1 U_z K_{,z} + \rho_1 \Phi_1 U_r K_{,r} = \rho_1 \Phi_1 \nu_t U_{z,r}^2$$

Convection — Main Production $(P)$

$$+ \frac{2}{3} \rho_1 C_{\phi s} \left(\frac{\nu_t}{C_\mu}\right)\left(\frac{\nu_t}{\sigma_\phi} \Phi_{1,r}\right)_{,r} U_{r,r} - \rho_1 C_{\phi s} \left(\frac{K}{\epsilon}\right) \nu_t \left(\frac{\nu_t}{\sigma_\phi}\right) \Phi_{1,r} U_{z,r}^2$$

Extra production $(P')$

$$+ \frac{1}{r}\left(\rho_1 r \Phi_1 \frac{\nu_t}{\sigma_k} K_{,r}\right)_{,r}$$

Diffusion

$$- \rho_1 \Phi_1 \epsilon$$

main Dissipation $(\epsilon)$

$$\left\{ \begin{array}{l} - \sum_k K \Phi^k (F^k + \dot{m}^k)\left(1 - \int^{\infty} \left(\frac{\Omega_1 - \Omega_E}{\Omega_E}\right) F(\omega)\, d\omega\right) \\ + \sum_k (F^k + \dot{m}^k)\left[ (U_r - V_r^k)\left(\frac{\nu_p^k}{\sigma_\phi} \Phi_{,r}^k\right) \right. \\ \left. \quad - C_{\phi s}\left(\frac{\nu_t}{C_\mu}\right)\left(\frac{\nu_p^k}{\sigma_\phi} \Phi_{,r}^k\right)_{,r} \left(1 - \int_0^{\infty} \frac{\Omega_1 - \Omega_E}{\Omega_E} F(\omega)\, d\omega\right)\right] \end{array} \right\}$$

Extra Dissipation $(\epsilon')$

THE DISSIPATION RATE OF TURBULENCE ENERGY $(\mathcal{E})$

$$\rho_1 \Phi_1 U_z \mathcal{E}_{,z} + \rho_1 \Phi_1 U_r \mathcal{E}_{,r} = \frac{1}{r}\left(\rho_1 r \Phi_1 \frac{\nu_t}{\sigma_\epsilon} \mathcal{E}_{,r}\right)_{,r}$$

Convection — Diffusion

$$+ C_{\epsilon 1} \frac{\mathcal{E}}{K} (P + P')$$

Production

$$- \frac{\mathcal{E}}{K}\left(C_{\epsilon 2} \epsilon + C_{\epsilon 3} \epsilon'\right)$$

Dissipation

TURBULENT DIFFUSIVITY OF LIQUID DROPLETS

$$\nu_p^k = \frac{\nu_t}{\sigma_r^k}$$

$\sigma_r^k$ : From Peskin's formula but using other length scales.

## INTERFACE PROPERTY TRANSFER

- **MASS TRANSFER:**

$$\dot{m}^k = \frac{12 D \rho_1}{(d^k)^2} \ln(1 + B)\, Sh^k$$

$$B = \frac{C_L - C_\infty}{1 - C_L},$$

$$Sh^k = 2 + 0.55\, R_e^{k^{1/2}}\, Sc^{1/3},$$

$Sc = \nu_1 / D$

$C_\infty$ : From it's Conservation eqn.

$C_L$ : From Clausius-Clapeyron expression.

- **MOMENTUM TRANSFER:**

$$F^k = \left(\frac{3}{4 d^k}\right) \rho_1 C_D^k |\vec{U} - \vec{V}^k|$$

$$C_D^k = \frac{24}{R_e^k}\left[1 + 0.1935 (R_e^k)^{0.635\omega}\right] \quad 20 \leq R_e^k \leq 200$$

$$\text{or} \quad C_D^k = \frac{24}{R_e^k}\left[1 + 0.135 (R_e^k)^{0.82 - 0.05\omega}\right] \quad 0 < R_e^k < 20$$

$$\omega = \log_{10} R_e^k$$

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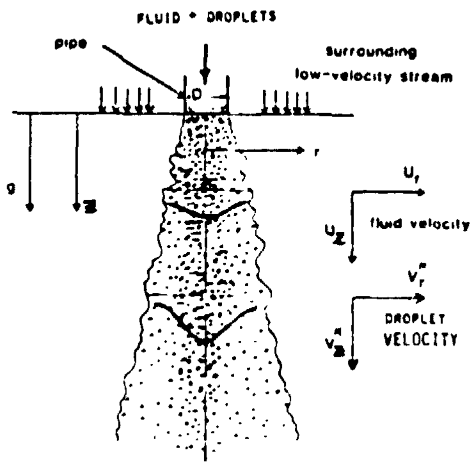
THE FLOW CONSIDERD




- FLUID : Air
  REYNOLDS NUMBER : 30,000
- DROPLETS : Methanol Alcohol $CH_3OH$
  DROPLET DIAMETER : 100, 80, 60, 40 & 20 μm with equal mass ratios
  LOADING MASS RATIO : 0.0, 0.1, 0.25 & 0.5
  LIQUID DENSITY : 810 kg/m³
  VAPOR DENSITY : ≈ 1 kg/m³
- FLUID AND DROPLETS EXIST AT UNIFORM AND CONSTANT TEMPERATURE.

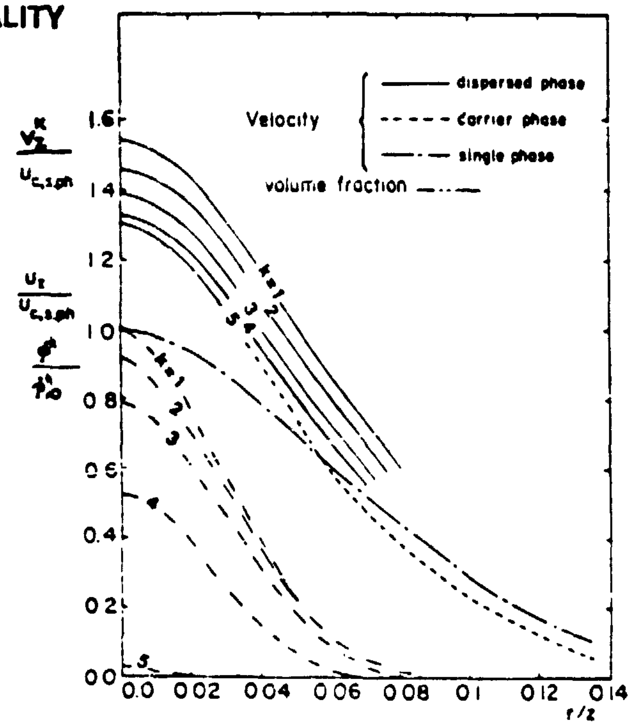



Fig 1 Normalized mean velocities and volume fractions profiles at z/D = 20 and at $X_o$ = 0.5

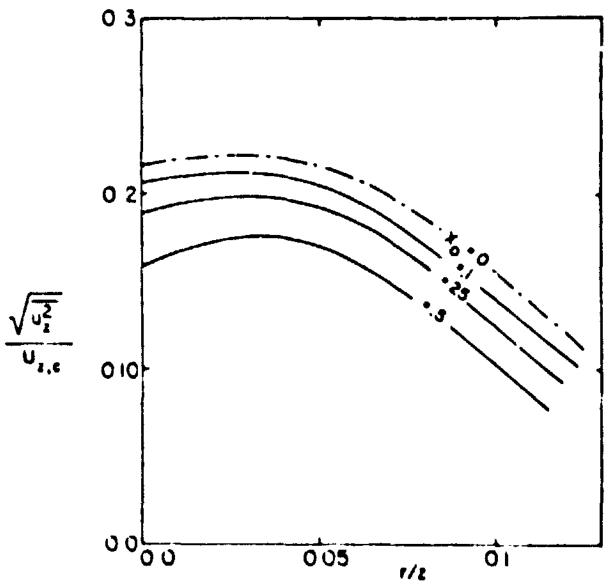



Fig 2 The turbulence intensity distribution under different mass loading ratios at z/D = 20

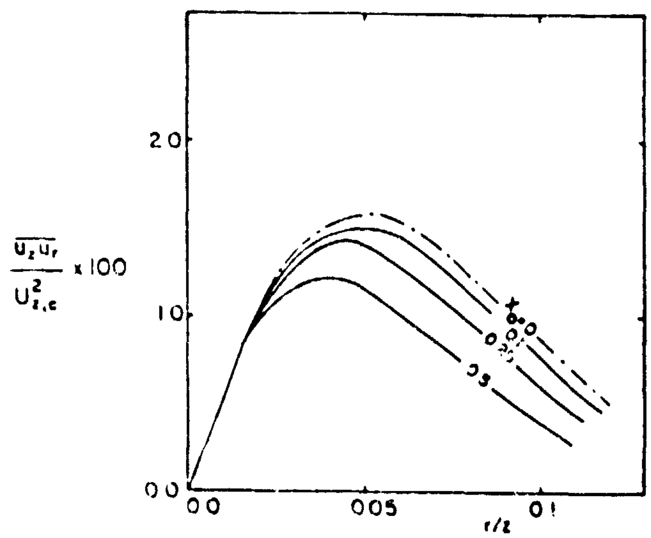



Fig 3 The shear stress distribution under different mass loading ratios at z/D = 20

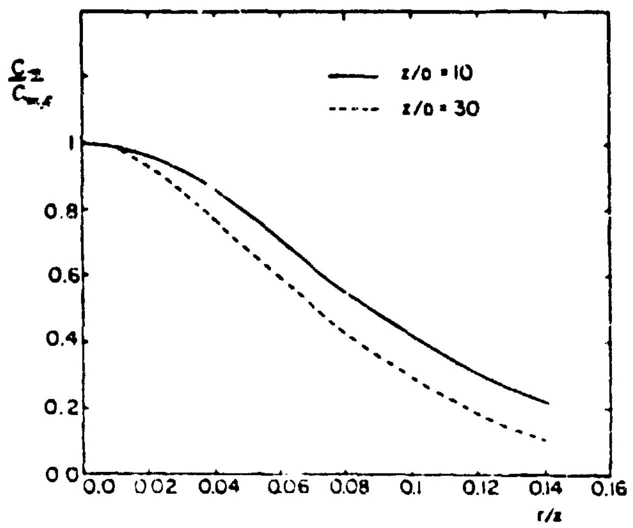



Fig 4 Normalized vapor concentration at different stations and at $X_o$ = 0.5

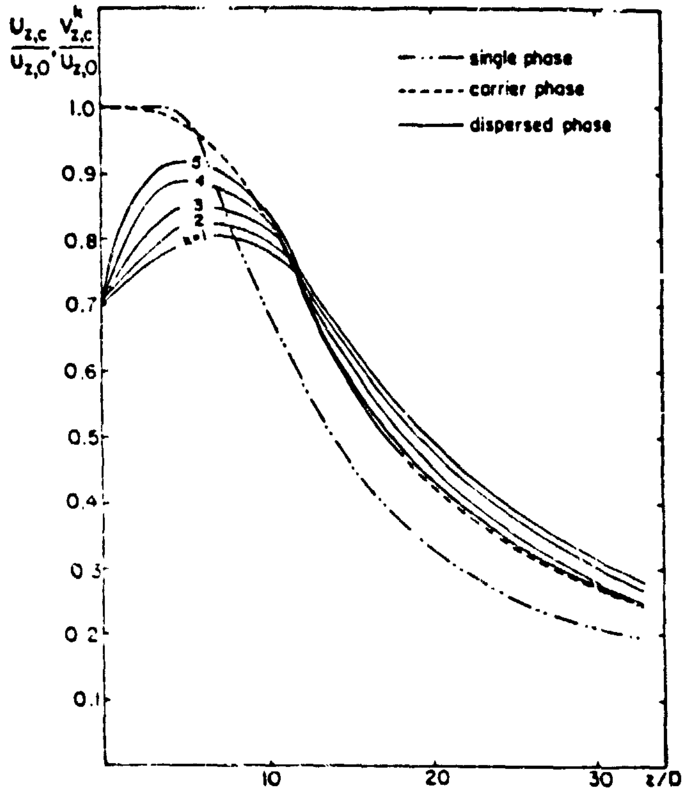



Fig 5 The axial distribution of the mean velocities at $X_o$ = 0.5

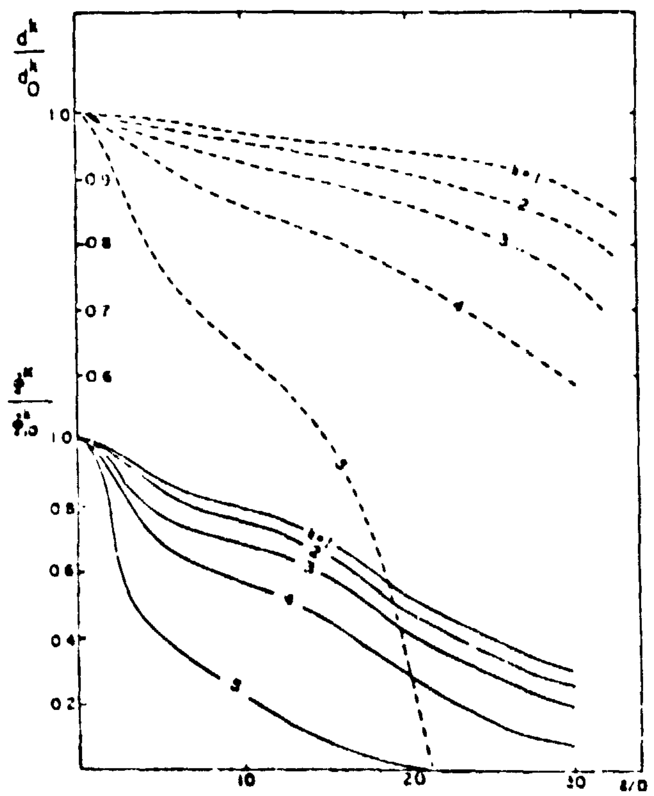



Fig 6 The axial distribution of the volume fractions and the average diameters at $X_o$ = 0.5

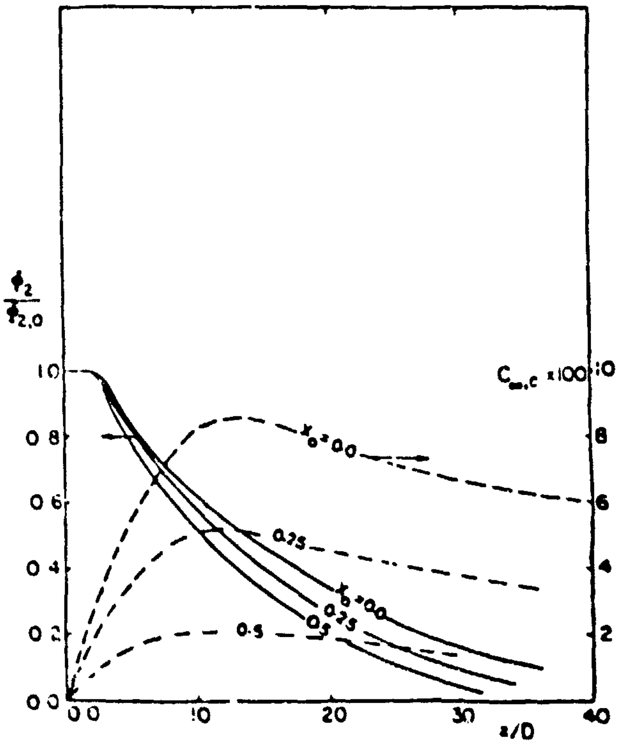



Fig 7 The axial distribution of the droplets volume fraction and vapor concentration

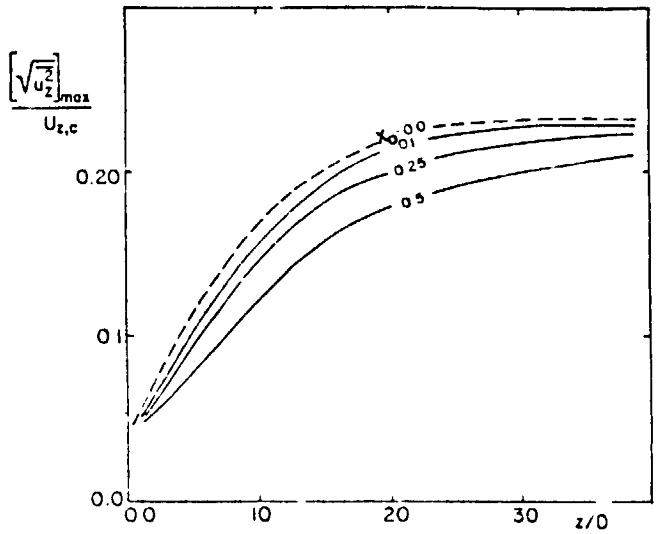



Fig 8 The axial distribution of the maximum turbulence intensity under different mass loading ratios

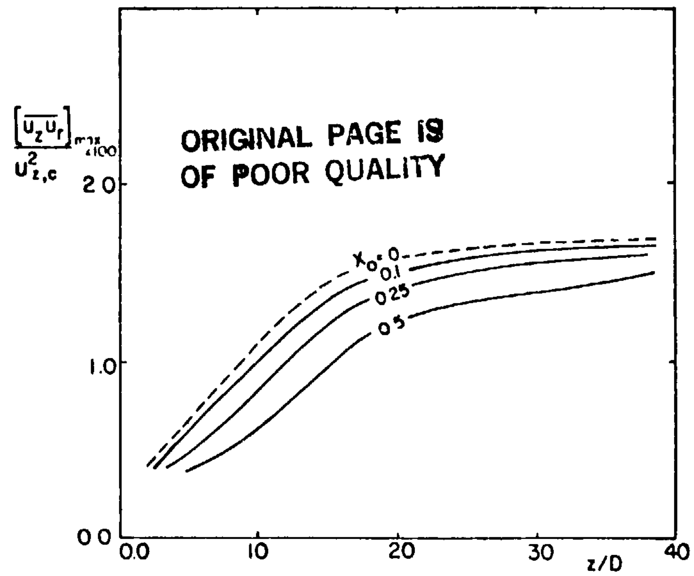





Fig 9 The axial distribution of the maximum shear stress under different mass loading ratios

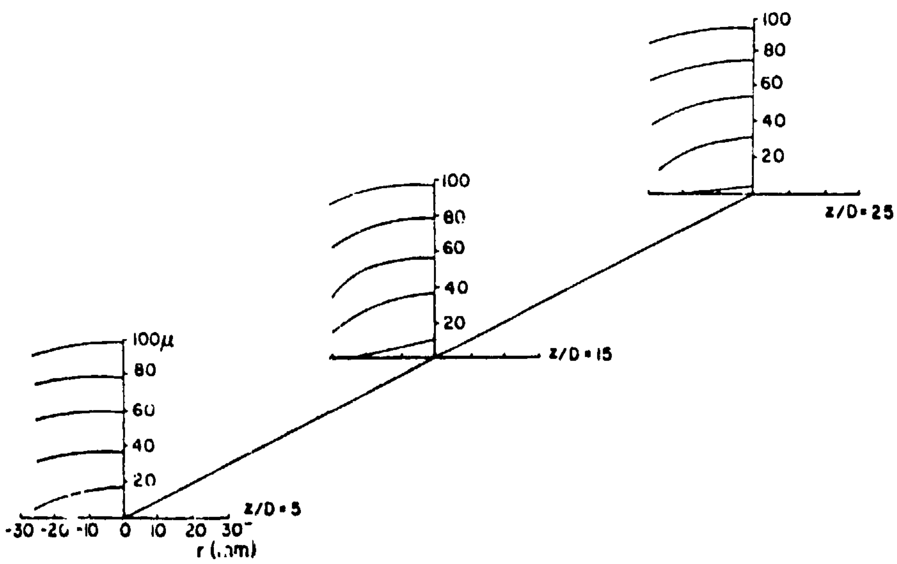



Fig 10 Radial distributions of the local droplets diameters at different axial locations and at $X_o$ = 0.5

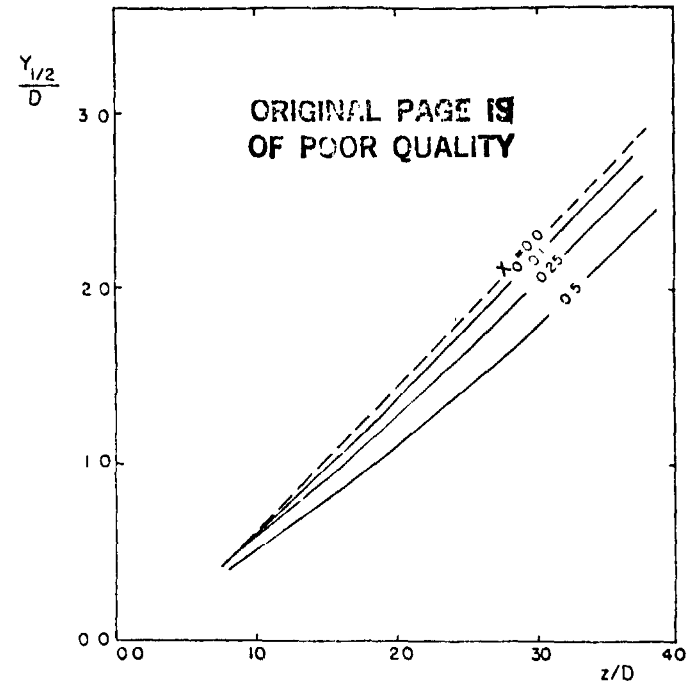



Fig 11 The spreading rate under different mass loading ratios

## SUMMARY

- The proposed turbulence model (validated experimentally for solid particles) is applied to predict the turbulent round jet laden with multisize vaporizing droplets.
- Predicted changes in the flow field (mean and turbulent quantities) are significant and should be considered in liquid spray combustion calculations.
- Experiment to validate the proposed model will be performed when funds become available.