STRUCTURE OF EVAPORATING AND COMBUSTING SPRAYS: MEASUREMENTS AND PREDICTIONS*

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Summary

Results obtained during the first year of an investigation of the structure of sprays are briefly described. Further details may be found in Refs. 1-3.

The investigation involves both experimentation and analysis. Experimental objectives are to complete measurements of the structure of nonevaporating, evaporating and combusting sprays for sufficiently well-defined boundary conditions to allow evaluation of models of these processes (Fig. 1). Analytical objectives are to begin model evaluation using both existing and the new data (Fig. 2). The results of the investigation have application to the development of rational design methods for aircraft combustion chambers and other devices involving spray combustion (Fig. 3).

Major assumptions for the models are summarized in Fig. 4. The continuous phase is treated using a k-ε-g model of turbulence originally proposed by Lockwood and Naguib [4], which has been extensively calibrated for noncombusting and combusting single-phase flows during earlier work in this laboratory [5-7].

Three methods for treating the discrete phase are being considered: (1) a locally homogeneous flow (LHF) model, (2) a deterministic separated flow (DSF) model, and (3) a stochastic separated flow (SSF) model. The main properties of these models are summarized in Figs. 5-7. Infinitely fast interphase transport rates and local thermodynamic equilibrium are assumed for the LHF model (Fig. 5)--implying that both phases have the same temperature and velocity at each point in the flow. LHF models provide a useful limit for infinitely small particles or drops, but generally overestimate the rate of development of practical sprays [5-7]. DSF models (Fig. 6) provide for finite interphase transport rates, but assume that interphase transport can be found by ignoring effects of turbulent fluctuations. Most spray models reported to date employ this approximation. The present SSF model (Fig. 7) adapts an approach originally proposed by Gosman and Ioannides [8]. In this case, particles or drops are assumed to interact with a succession of turbulent eddies whose properties are determined by random sampling--given mean and fluctuating properties of the flow from the k-ε-g model calculations. This involves computation of a statistically significant number of particle trajectories using Monte Carlo techniques.

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Initial model evaluation employed data for dilute particle-laden jets--to avoid complications due to particle coalescence, particle collisions and polydisperse particle flows. Only a sample of the results is given here, cf. Refs. [1-3] for complete findings.

The prescription for eddy properties used in the SSF model was calibrated using theoretical results of Hinze [9]--similar to Gosman and Ioannides [8]. This analysis was for the dispersion of infinitely-small particles in a homogeneous and isotropic turbulent flow. The comparison between SSF predictions and the analytical result is illustrated in Fig. 8. Good agreement was achieved--fixing methods for estimating particle interactions with eddies. The SSF model predictions are compared with measurements of particle dispersion in a duct flow, reported by Snyder and Lumley [10], in Fig. 9. The model is seen to provide encouraging predictions of effects of particle properties on rates of particle dispersion.

The remaining comparisons between predictions and measurements consider particle-laden jets. LHF, DSF and SSF model predictions are compared with the measurements of Yuu et al. [11] in Fig. 10. The LHF and DSF models over- and under-estimate particle dispersion, while the SSF model is in good agreement with measurements. Furthermore, the DSF model indicates that the particles tend to concentrate near the centerline as axial distance increases--which is not observed. Comparison of the models with measurements of McComb and Salih [12,13], Laats and Frishman [14,15] and Levy and Lockwood [16] continues in Figs. 11-13. The SSF model yields satisfactory predictions for these flows, aside from possible effects of turbulence modulation and turbulence generation at high particle mass loadings [2,3]. This evaluation is not adequately definitive, however, due to uncertainties in initial conditions for the existing particle-laden jet data [1-3].

Evaluation of the models is continuing using data from the present investigation. A sketch of the test apparatus being used for noncombusting sprays is illustrated in Fig. 14. An air-atomizing injector sprays vertically downward along the centerline of a traversible screened enclosure. Experimental methods are summarized in Fig. 15. All techniques have been used in work to date, aside from the LDA-visibility method for drop size and velocity measurements--which requires a different optical geometry and is being deferred until other measurements are complete.

Experimental methods were established by satisfactory measurements of the properties of air jets, formed by the injector, with earlier work [5,6]. Tests were then conducted in two nonevaporating sprays having SMD of 87 and 30 μm. LHF and SSF model predictions are compared with measurements of mean gas velocity and mean liquid flux, along the spray axis, in Figs. 16 and 17. There is no fundamental limitation in the use of the LHF model in dense regions of the spray; therefore, these predictions extend from the injector exit. The separated flow models, however, are limited to dilute regions of the spray; therefore, these calculations begin at $x/d = 50$--where adequate initial conditions were available from the measurements. The prediction of the LHF model improves for the more finely atomized spray, Case 1, but is not very satisfactory. In contrast, the SSF model provides reasonably good predictions of these measurements. Predicted and measured radial profiles of liquid mass flux are plotted in Fig. 18. Similar to the results for particle-laden jets, the DSF model yields excessive concentrations of the dispersed phase near the axis, since turbulent particle diffusion is ignored. The SSF model provides fair predictions of particle spread. However, in this case, the LHF model underestimates spread rates! This effect is well-known, involving enhanced spreading of particle-laden flows by turbulent diffusion for a certain range of particle inertial properties. The fact that the SSF model correctly predicts this trend is very encouraging. Predicted and measured turbulence kinetic energy are illustrated in Fig. 19. While the LHF model underestimates the magnitude of k and the width of the flow, the SSF model provides satisfactory predictions. This, too, is encouraging, since predictions of k are an important element in estimating eddy properties for the SSF model. Good predictions of Reynolds stress were also obtained with the SSF model. Reynold stress depends on ε predictions--suggesting that this aspect of the eddy prescription is also adequate.

The conclusions, to date, are summarized in Fig. 20. The main conclusion is that the SSF model provides encouraging predictions for these multiphase flows--with minimal added empiricism. It will be most interesting to examine this methodology for evaporating and combusting sprays--where effects of concentration fluctuations must be considered along with velocity fluctuations. The main limitation of the evaluation, thus far, is adequate specification of initial conditions for the present data base. Tests during the next report period are designed to eliminate this deficiency (Fig. 21).

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Objectives: Complete measurements of spray structure suitable for evaluation of models.

Configuration: Axisymmetric spray or particle-laden jet in a quiescent environment.

Specific Cases:

I. Air jet (calibration).

II. Particle-laden jet (sand particles).

III. Non-evaporating spray (low-volatility oil).

IV. Evaporating spray (Freon-11).

V. Combusting spray (n-Pentane).

Figure 1.- Experimental Objectives.

Objectives: Complete evaluation of typical models using both existing and new data.

Models:

I. Locally homogeneous flow (LHF)--Infinitely fast interphase transport rates.

II. Deterministic separated flow (DSF)--Finite interphase transport rates considering particle response to mean motion.

III. Stochastic separated flow (SSF)--Finite interphase transport rates but particles respond to individual eddies.

Evaluation: Gas jets, solid-particle-laden jets, nonevaporating sprays, evaporating sprays and combusting sprays.

Figure 2.- Analytical Objectives.

POTENTIAL CONTRIBUTIONS OF THE RESULTS ARE:

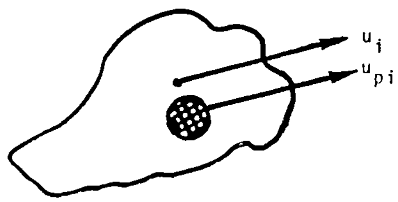
1. THE DEVELOPMENT OF RATIONAL DESIGN METHODS FOR AIRCRAFT COMBUSTION CHAMBERS, GAS-TURBINE COMBUSTORS, FURNACES, STRATIFIED-CHARGE I.C. ENGINES AND DIESEL ENGINES.
2. IMPROVED UNDERSTANDING OF THE PROPERTIES OF TURBULENT PARTICLE/DROP-LADEN FLOWS.

Figure 3.- Applications of the investigation.

1. STEADY, AXISYMMETRIC, LARGE REYNOLDS NUMBER, BOUNDARY-LAYER FLOW.
2. k-ε-g TURBULENCE MODEL WHICH IS WELL-CALIBRATED FOR NONCOMBUSTING AND COMBUSTING SINGLE-PHASE JETS.
3. NEGLIGIBLE KINETIC ENERGY AND VISCOUS DISSIPATION OF MEAN FLOW AND RADIATION.
4. EXCHANGE COEFFICIENTS OF ALL SPECIES AND HEAT IDENTICAL.
5. CONTINUOUS-PHASE IS IN LOCAL THERMODYNAMIC EQUILIBRIUM.
6. DSF AND SSF ONLY: DILUTE PARTICULATE FLOW SO EFFECTS OF TURBULENCE GENERATION AND DISSIPATION BY PARTICLES, PARTICLE COLLISIONS, AND ADJACENT-PARTICLE DISTURBANCES OF INTERPHASE TRANSPORT RATES ARE NEGLIGIBLE.

Figure 4.- Major assumptions of the models.

ASSUMPTION: INFINITELY FAST INTERPHASE TRANSPORT RATES, I.E., PARTICLE AND CONTINUOUS PHASE VELOCITIES AND TEMPERATURES ARE IDENTICAL AND LOCAL THERMODYNAMIC EQUILIBRIUM INCLUDES BOTH PHASES.



$u_{pi} = u_i,\ T_p = T,\ G_{ip} = G_i$

NOTES:

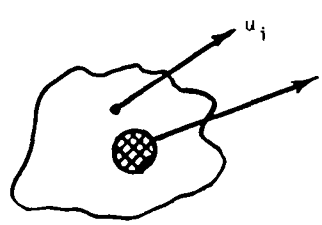
I. CORRECT LIMIT FOR INFINITELY SMALL PARTICLES.

II. MAXIMUM PARTICLE RESPONSE TO TURBULENT FLUCTUATIONS.

III. COMPUTATION EQUIVALENT TO SINGLE-PHASE FLOW.

Figure 5.- Properties of the LHF model.

ASSUMPTION: FINITE INTERPHASE TRANSPORT RATES WITH PARTICLES RESPONDING TO MEAN MOTION.



$u_{pi} = \bar{u}_{pi} \neq u_i$

$T_p \neq T$

$G_{ip} \neq G_i$

NOTES:

I. PARTICLE DISPERSION IGNORED--ONLY VALID FOR "LARGE" PARTICLES.

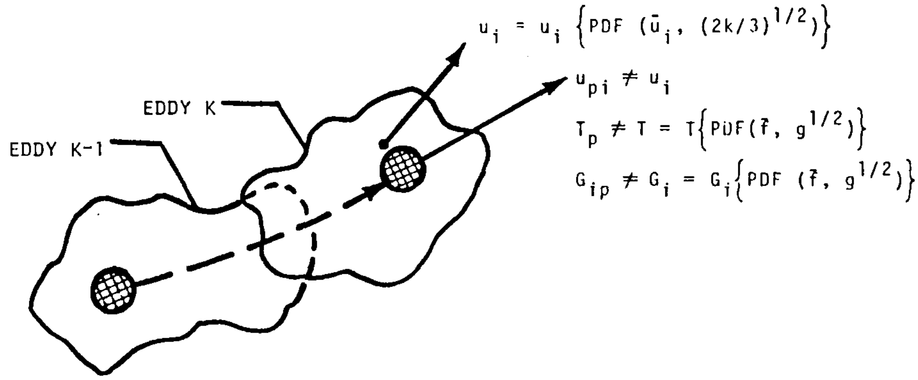
II. TYPICAL APPROACH IN CURRENT SPRAY MODELS.

III. EULERIAN CALCULATION FOR CONTINUOUS PHASE WITH DISTRIBUTED SOURCE TERMS FROM PARTICLE INTERACTIONS.

IV. LAGRANGIAN CALCULATION OF PARTICLE TRAJECTORIES.

Figure 6.- Properties of the DSF model.

ASSUMPTION: FINITE INTERPHASE TRANSPORT RATES WITH PARTICLES INTERACTING WITH A SUCCESSION OF INDIVIDUAL EDDIES WHOSE PROPERTIES ARE FOUND BY RANDOM SAMPLING OF LOCAL TURBULENCE PROPERTIES.



NOTES:

I. MAXIMUM PARTICLE DISPLACEMENT AND TIME OF EDDY INTERACTION ARE: $L_e = C_\mu^{3/4} k^{3/2}/\epsilon$, $t_e = L_e/(2k/3)^{1/2}$

II. PROVIDES PREDICTIONS OF FLUCTUATING PARTICLE PROPERTIES AND TURBULENT PARTICLE DISPERSION.

III. COMPUTATION SIMILAR TO DSF MODEL--MONTE CARLO TECHNIQUE TO FIND PARTICLE TRAJECTORIES.

Figure 7.- Properties of the SSF model.

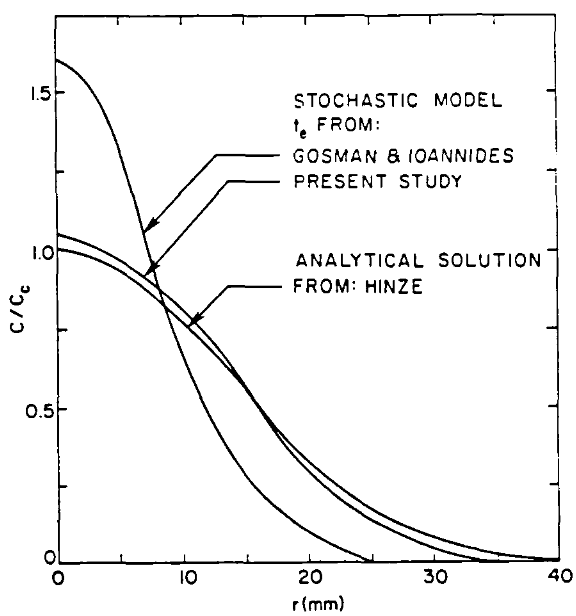


Figure 8.- SSF predictions for the dispersion of infinitely small particles in a homogeneous isotropic flow (analytical results from Hinze [9]).

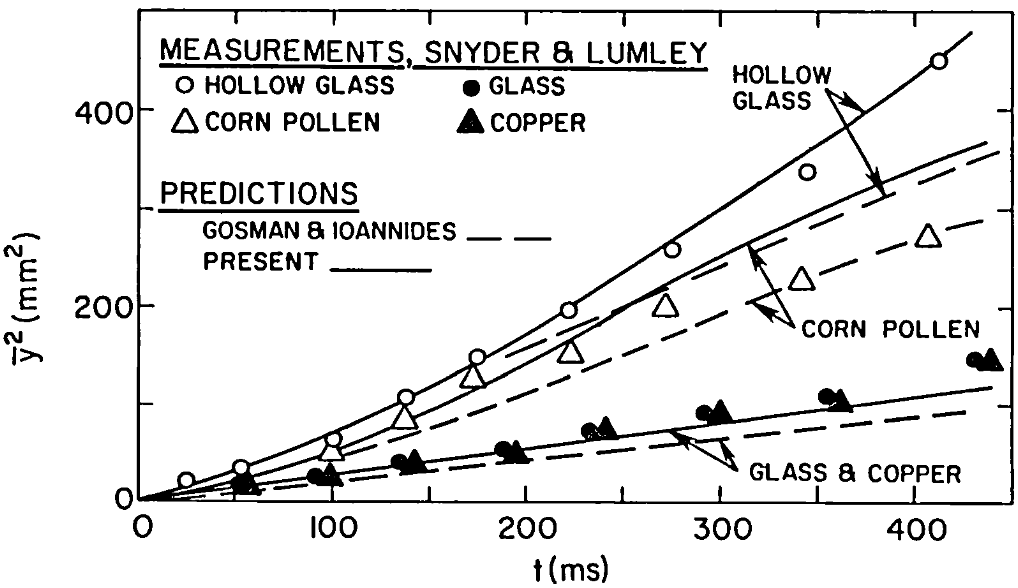


Figure 9.- Predicted and measured particle dispersion in a uniform grid-generated turbulent flow (measurements from Snyder and Lumley [10]).

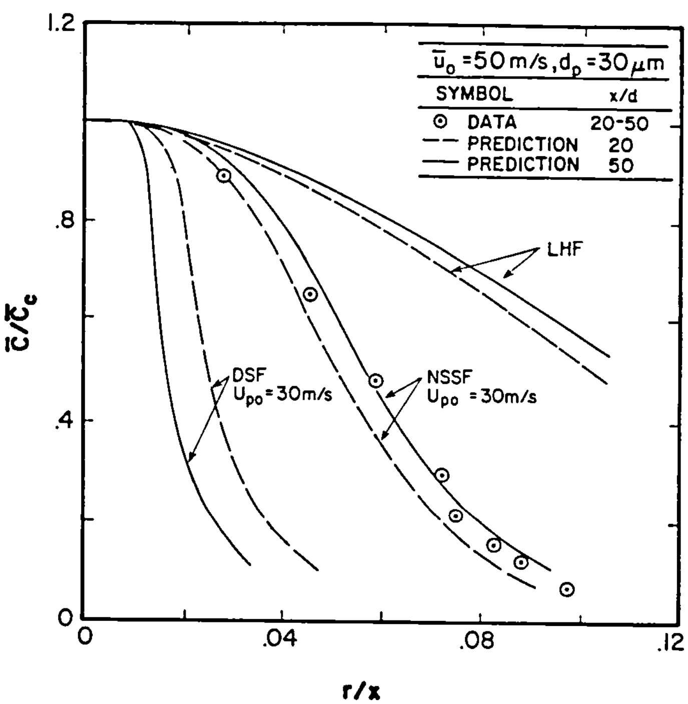


Figure 10.- Comparison of LHF, DSF, and SSF predictions of particle dispersion with the measurements of Yuu, et al. [11].

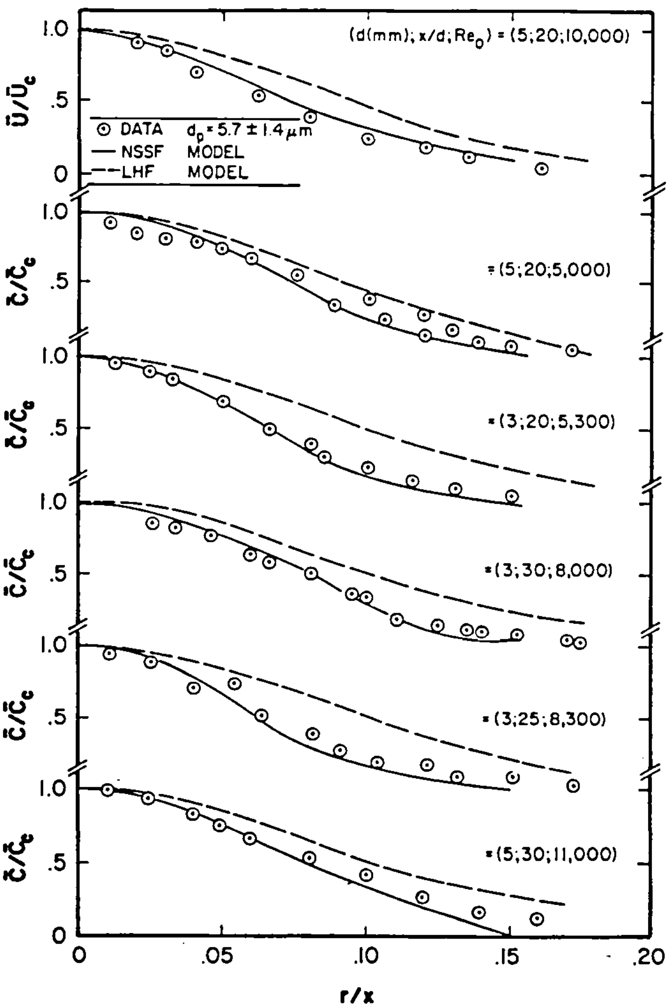


Figure 11.- Comparison of LHF and SSF predictions with the measurements of McComb and Salih [12,13].

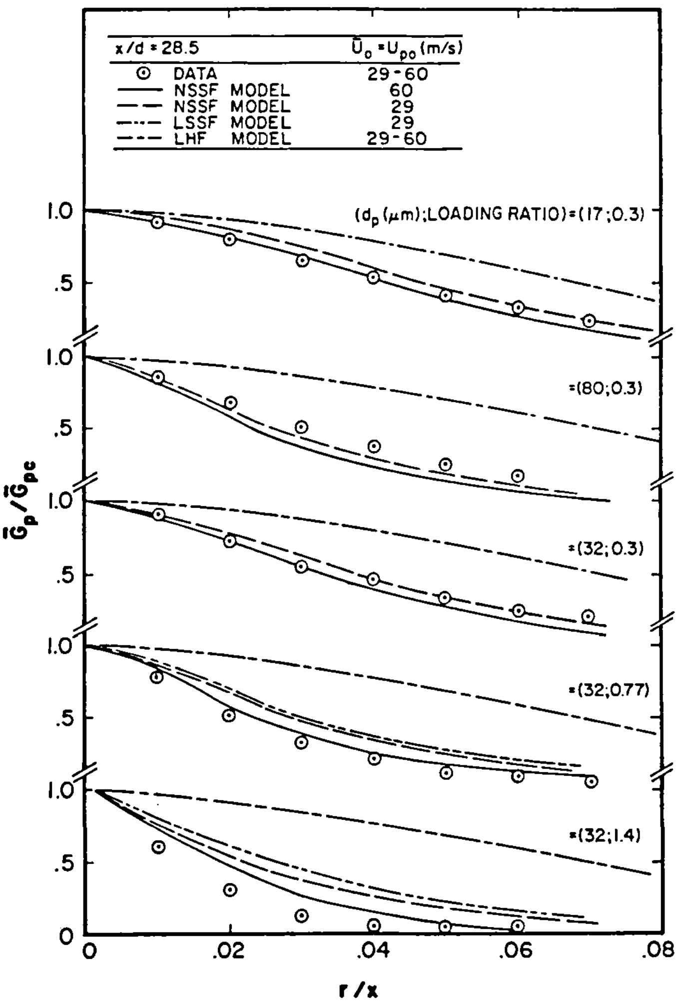


Figure 12.- Comparison of LHF and SSF predictions with particle mass velocity measurements of Laats and Frishman [14,15].

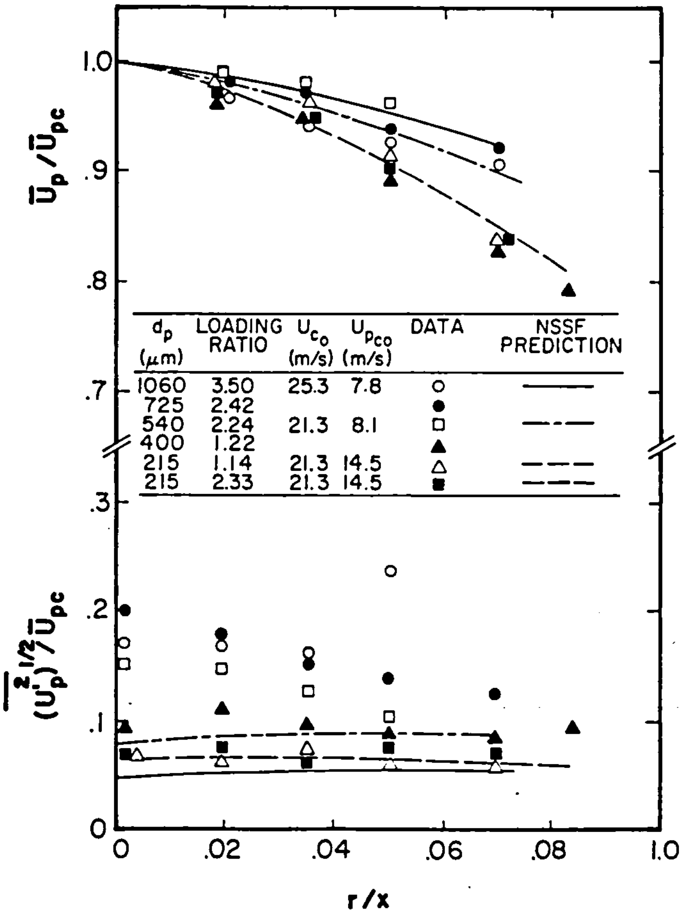


Figure 13.- Predicted and measured mean and fluctuating particle velocities (data from Levy and Lockwood [16]).

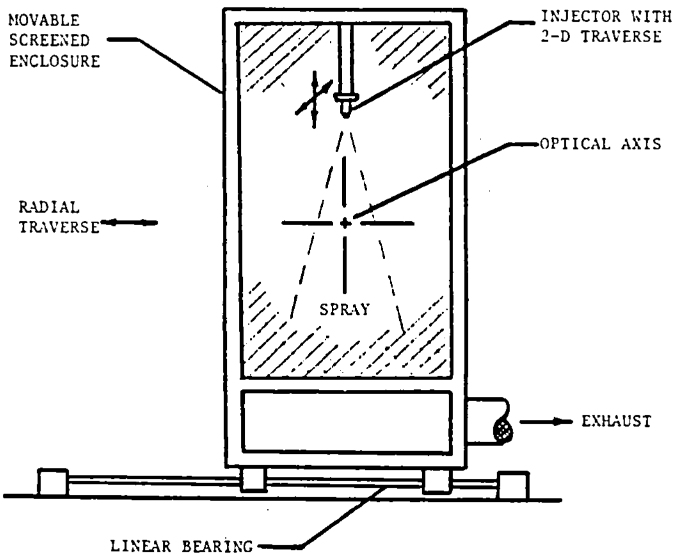


Figure 14.- Sketch of the experimental apparatus.

MEASUREMENT	TECHNIQUE
MEAN AND FLUCTUATING GAS AND PARTICLE VELOCITIES	LASER-DOPPLER ANEMOMETER (LDA)
DROP (PARTICLE)--SIZE DISTRIBUTIONS	FRAUNHOFER DIFFRACTION (MONITORING NONEVAPORATING FLOWS ONLY)
DROP-SIZE DISTRIBUTIONS	SLIDE IMPACTION
DROP SIZE AND VELOCITY	LDA-VISIBILITY METHOD
MEAN LIQUID (PARTICLE) FLUX	ISOKINETIC SAMPLING AND FILTERING (NONEVAPORATING FLOWS ONLY)
MEAN TEMPERATURE	SHIELDED, FINE-WIRE THERMOCOUPLE
MEAN COMPOSITION	ISOKINETIC SAMPLING AND ANALYSIS WITH GAS CHROMATOGRAPH

Figure 15.- Summary of experimental methods.

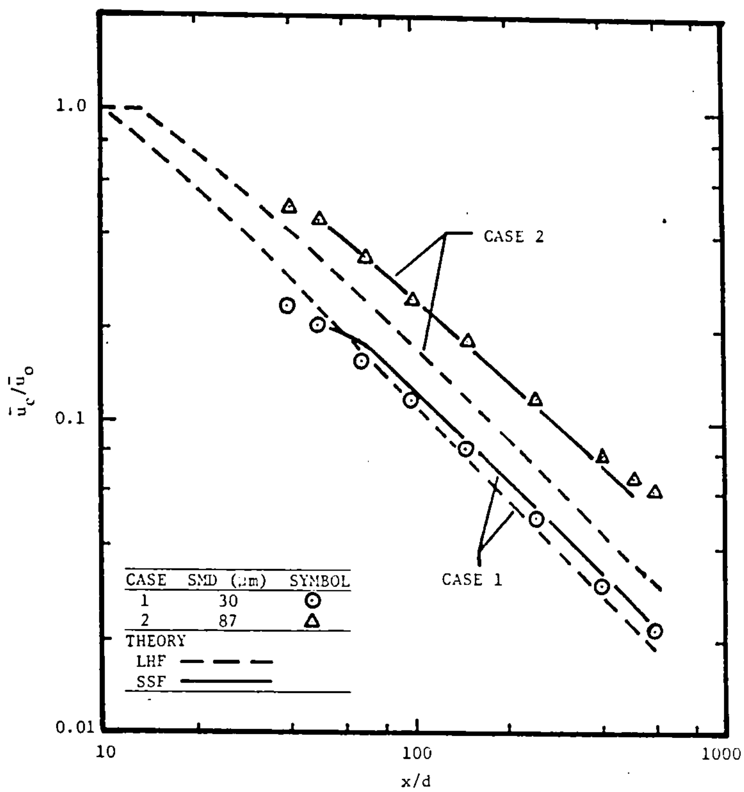


Figure 16.- Predicted and measured mean gas velocities along the axis of nonevaporating sprays.

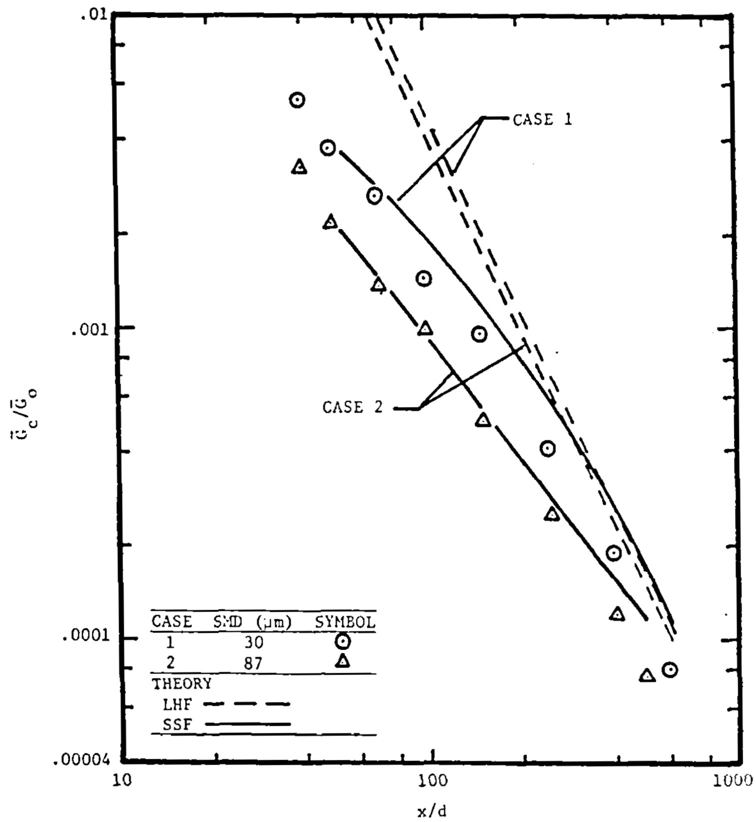


Figure 17.- Predicted and measured mean liquid mass flux along the axis of nonevaporating sprays.

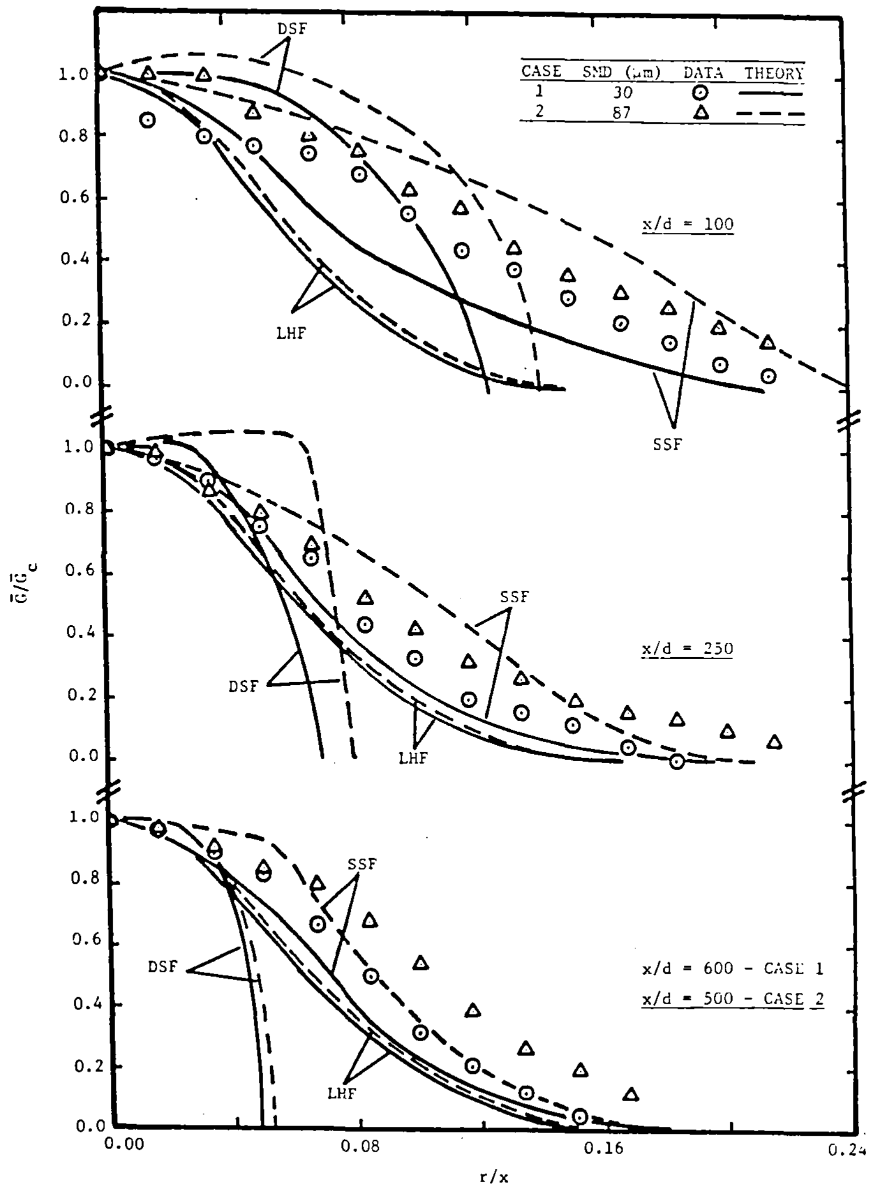


Figure 18.- Radial profiles of mean liquid mass flux in nonevaporating sprays.

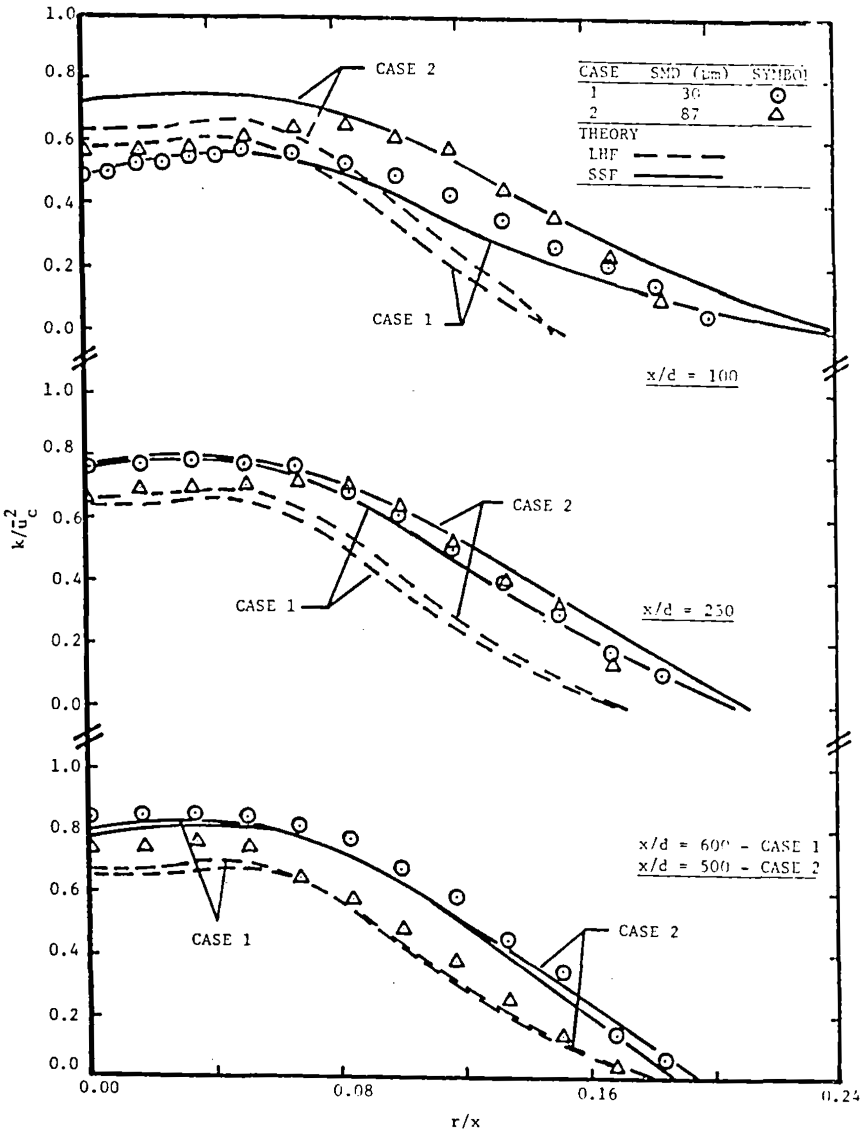


Figure 19.- Radial profiles of mean gas phase turbulent kinetic energy in nonevaporating sprays.

1. Model Performance:
   i. LHF and DSF models are valid at limits of small and large particles, but data base (and probably sprays in general) included few results at these conditions.
   ii. SSF model (particularly the NSSF version) yielded encouraging results--with minimal empiricism.
2. Decisive model evaluation was not achieved due to inadequate specification of initial conditions for most of the data base.
3. Effects attributable to turbulence generation and modulation were observed, however, the effects were small since data base was limited to dilute sprays (void fraction > 99%).

Figure 20.- Conclusions of the investigation.

Task	Status
Model Development	Completed for noncombusting flows. Combusting flows next.
Measurements	
Single-Phase Jets	Completed.
Particle-Laden Jets	Completed, aside from mean and fluctuating particle velocities.
Nonevaporating Sprays	Completed, aside from drop size and velocity measurements.
Evaporating Sprays	Completed, aside from mean and fluctuating gas velocities (in progress) and drop size and velocity measurements.
Combusting Sprays	Next.

Figure 21.- Status of the investigation.