Structure of Nonevaporating Sprays, Part II: Drop and Turbulence Properties

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This is the second part of a study reporting structure measurements in the dilute portion of axisymmetric nonevaporating sprays. Measurements are compared with predictions of three typical methods for analyzing sprays: 1) locally homogeneous flow (LHF) analysis, where slip between the phases is neglected; 2) deterministic separated flow (DSF) analysis, where slip is considered but effects of drop interactions with turbulence are ignored; and 3) stochastic separated flow (SSF) analysis, where both slip and effects of drop interactions with turbulence are considered. This part of the study reports measurements of mean and fluctuating drop velocities, the variation of Sauter mean diameter, and gas-phase turbulence properties in the dilute portion of the sprays. Best agreement between predictions and measurements was obtained with the SSF analysis. For present measurements in the dilute region (void fraction greater than 99.1%), effects of drops on gas-phase turbulence properties (turbulence modulation) were small. However, as the dense spray regions near the injector were approached, the measurements indicated modification of turbulence properties by drop motion.

Nomenclature

$C_{\epsilon 3}$ = turbulence model constant
d_p = drop diameter
G = liquid mass flux
k = turbulence kinetic energy
r = radial distance
u = axial velocity
v = radial velocity
ϵ = rate of dissipation of turbulence kinetic energy
x = axial distance
ρ = density
ϕ = generic property

Subscripts

c = centerline quantity
p = drop property
0 = injector exit condition

Superscripts

$(\ )''$ = Favre-averaged fluctuating quantity
$\tilde{(\ )}$ = Favre-averaged quantity
$\overline{(\ )}$ = time-averaged quantity

Introduction

THE objective of this investigation was to complete measurements of the structure of the dilute portion of axisymmetric nonevaporating sprays, injected into a still air environment, in order to obtain a better understanding of the flow and data useful for evaluation of spray models. The new measurements were also used to begin model evaluation, considering several methods typical of recent spray analysis. The work is motivated by the need for additional experimental information sprays—expressed in several recent reviews.[1,2]

Two sprays formed with an air-atomizing injector, directed vertically downward, were considered: case 1, having a nominal Sauter mean diameter (SMD) of 30 μm and a ratio of initial liquid to airflow rate (loading ratio) of 1.78; and case 2, having an SMD of 87 μm and loading ratio of 6.48. Both sprays were turbulent, having Reynolds numbers greater than 2×10^4. Vacuum pump oil was used for the liquid; therefore, drop vaporization was negligible. Complete specifications of both sprays are presented in Ref. 3.

Three spray models were considered: 1) a locally homogeneous flow (LHF) model, where slip between the phases was neglected; 2) a deterministic separated flow (DSF) model, where slip is considered but effects of drop interactions with turbulence are ignored; and 3) a stochastic separated flow (SSF) model, where effects of both slip and turbulence/drop interactions are considered using random sampling for turbulence properties in conjunction with random-walk computations for drop motion. These models were developed earlier in this laboratory and evaluated using measurements in monodisperse particle-laden jets.[4-6] The SSF approach was based on a proposal of Gosman and Ioannides.[7] The present investigation extends the evaluation to polydisperse sprays having injector dimensions, shear rates, flow scales, and rates of flow deceleration more typical of practical sprays.

Theoretical and experimental methods, including an assessment of experimental uncertainties, are presented in the companion paper and will not be repeated here.[3] The present paper begins with a discussion of the new structure measurements and then considers effects of drop motion on turbulence properties (called turbulence modulation by Al Taweel and Landau[8]). The paper concludes by examining the sensitivity of predictions to uncertainties of initial conditions. More details concerning all aspects of the study and a complete tabulation of data are provided by Solomon.[9]

Computations

In the following, structure predictions and measurements are Favre (mass) averages, defined as follows:

$$\tilde{\phi} = \overline{\rho\phi}/\bar{\rho} \quad (1)$$

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This procedure is necessary in order to correctly represent predictions of the LHF model, which treats the sprays as variable-density single-phase flows. This distinction is of no consequence concerning measurements of separate liquid- or gas-phase properties and the predictions of the separated flow models, since the density of each phase is constant and Favre and conventional time averages are identical.

The LHF analysis requires minimal specifications of initial conditions, similar to a single-phase flow; therefore, the LHF computations were started at the injector exit. The separated flow model calculations were started at $x/d = 50$, which is the position nearest the injector where spatial resolution was adequate and breakup of liquid sufficiently complete to conform to assumptions of these models. Complete details on specification of initial conditions and the computations appear elsewhere.[3,9] Effects of turbulence modulation in the near-injector region are implicitly included in the initial conditions, while the effect was small far downstream. Therefore, the SSF model predictions shown on the figures neglect effects of turbulence modulation since we wished to minimize the number of empirical constants in the analysis. Estimates of the effects of turbulence modulation are considered separately at the end of this paper.

Structure Measurements

Centerline Drop Properties

Predicted (DSF and SSF models) and measured mean axial drop velocities for the two sprays are illustrated in Figs. 1 and 2. Drop velocities become more uniform with increasing distance from the injector since large drops, having initially higher slip velocities, are decelerated more rapidly than small drops due to the nonlinear nature of the drag law. At $x/d = 50$ and 100, drops with $d_p < 30$ μm had velocities up to 30% less than the gas velocity, while the largest drops had velocities up to 100% greater than the gas-phase value. Far downstream, at $x/d = 600$, however, velocity differences between the two phases become small. The SSF model predicts more rapid deceleration than the DSF model for each drop size. This effect is also due to the nonlinearity of the drag law interacting with turbulent fluctuations—an appreciable effect for the drop Reynolds number range encountered in sprays.[1] In general, the SSF predictions provide the best agreement with measurements (the LHF predictions, not shown, generally underestimate drop velocities; cf. Ref. 3).

Measurements and SSF model predictions of the axial variation of fluctuating axial drop velocities for the case 1 spray are illustrated in Fig. 3. The DSF and LHF model predictions are not shown since the DSF model cannot predict this parameter (drop motion is assumed to be deterministic) and the LHF model gave poor predictions of mean drop velocities. The SSF model underestimates the measurements, particularly for large drops, which is similar to its behavior for particle-laden jets.[4-6] Experimental limitations may contribute to this, since small sample sizes limited the accuracy of fluctuation measurements for large drops.[3] The assumption of isotropic velocity fluctuations in the SSF model may also be a factor. Turbulence measurements, discussed later, exhibit nonisotropy with streamwise fluctuations greatest, similar to single-phase jets.[10,11] Therefore, the assumption of isotropy would tend to reduce streamwise particle fluctuation levels as observed in Fig. 3. A multistress turbulence model would be required to include this effect.

The comparison between predicted and measured streamwise drop velocity fluctuations for the case 2 spray are similar to the case 1 results.[3] However, data scatter is greater for case 2 when $x/d \geq 250$, due to the slow rate of ligament breakup in this spray, which limited accuracy for specifying initial velocity fluctuations.

An interesting feature of the present results is the variation of SMD along the axis illustrated in Fig. 4 for both sprays. Predictions from the SSF and DSF models are shown on the figure. The SMD increases gradually with axial distance, with this behavior being modeled correctly by the SSF model. In contrast, the DSF model yields the wrong trend. This is due to effects of size-dependent turbulent dispersion of drops, which is considered in the SSF approach but neglected using the DSF method.

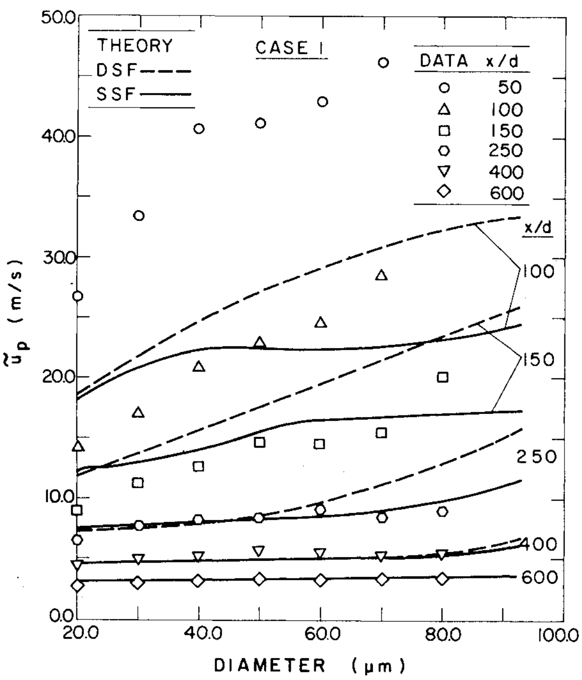

Fig. 1 Mean streamwise drop velocities along the axis of the case 1 spray.

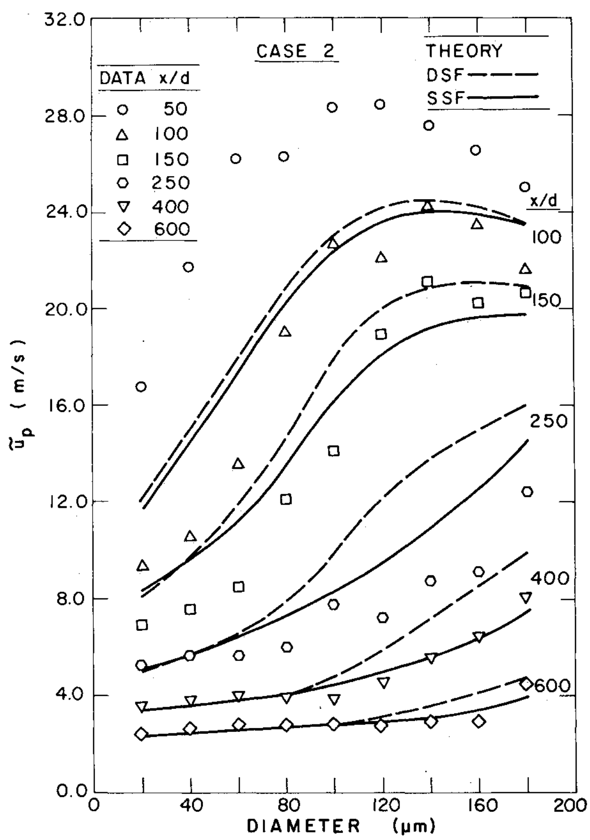

Fig. 2 Mean streamwise drop velocities along the axis of the case 2 spray.

Radial Profiles of Drop Properties

Measured and predicted (SSF model) mean axial drop velocities at $x/d = 250$ are illustrated in Figs. 5 and 6 for the two sprays. Measurements and predictions are in reasonably good agreement for the case 1 spray (Fig. 5). As expected, drop velocities decrease with increasing radial distance since drops near the edge of the flow are moving through gas having lower velocities. Drop velocities also vary systematically with size. Drops with $d_p < 30$ μm had velocities 10-50% less than the gas velocity, while the largest drops had velocities 15-30% greater than the gas phase. These observations are similar to the results for drop velocities along the axis discussed earlier. Drop velocities for the case 2 spray (Fig. 6) vary to a greater degree since the larger drops in this spray tend to maintain their velocities. The effect of the late breakup of ligaments introduces uncertainties in these results, however, as indicated by data scatter for $d_p > 120$ μm. Even so, the model predicts trends correctly and is in fair quantitative agreement with the measurements.

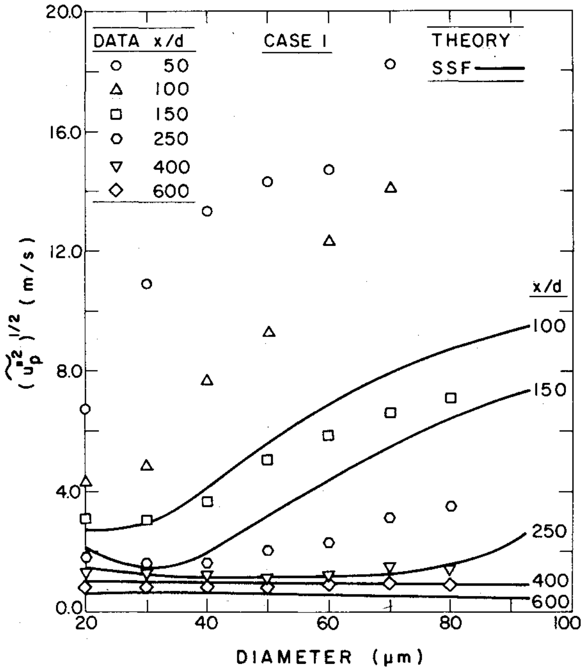

Fig. 3 Fluctuating streamwise drop velocities along the axis of the case 1 spray.

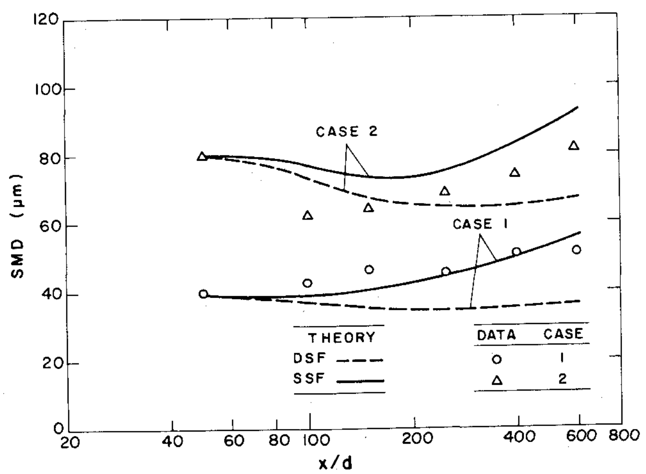

Fig. 4 SMD along the axes of the sprays.

Measured and predicted (SSF model) radial profiles of SMD at $x/d = 250$ are illustrated in Fig. 7 for the two sprays. The variation of SMD at this location is due to a combination of initial radial drop velocities and turbulent dispersion since the SMD was relatively uniform at $x/d = 50$. The SSF model provides a reasonable estimation of the measurements. In both cases, there is a slight increase in the fraction of larger drops and the SMD toward the edge of the spray.

Gas-Phase Turbulence Properties

All three components of the velocity fluctuations were measured, allowing k to be computed. These results are il-

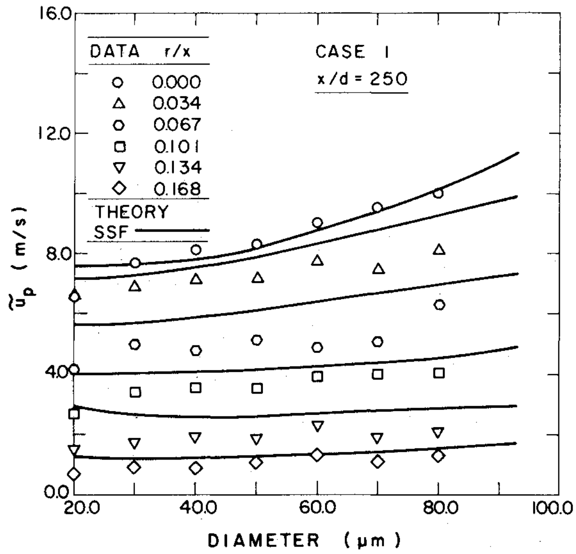

Fig. 5 Radial variation of mean streamwise drop velocities at $x/d = 250$ for the case 1 spray.

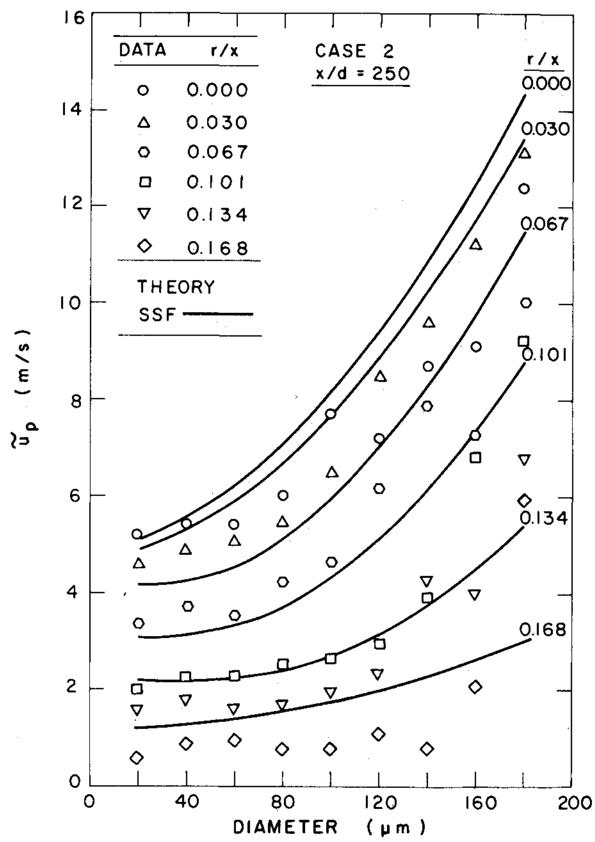

Fig. 6 Radial variation of mean streamwise drop velocities at $x/d = 250$ for the case 2 spray.

lustrated in Fig. 8. The results in Fig. 8 show the unusual width of the continuous phase in these sprays in comparison to single-phase jets, e.g., single-phase jets have widths comparable to the LHF predictions shown in the figure. The effect is strongest near the injector, where radial drop velocities induced by the injector and dense spray processes of drop formation, collisions, and breakup probably all play a role in the phenomena. The SSF model, which includes effects of turbulent drop dispersion, appears to represent this behavior in the dilute-spray region. With increasing distance from the injector, time scales of relaxation for drop motion and turbulence become comparable; therefore, the flow tends to decay toward the LHF prediction.

In the far downstream regions, levels of k are comparable to those in single-phase jets since the flow is dilute. The agreement between predictions of the SSF model and the measurements is also reasonably good far downstream. Since turbulence levels roughly correspond to values estimated ignoring effects of drop motion on turbulence properties, effects of turbulence modulation were probably small in these regions.

Near the dense-spray region, i.e., $x/d=50$ and 100, values of k are substantially lower than single-phase jets. This suggests that turbulence modulation is important in these dense regions of the sprays. Moreover, at $x/d=100$, the SSF model significantly overestimates turbulence levels near the axis. The sensitivity study (discussed later) indicates that the initial values of ϵ at $x/d=50$ have a relatively large influence on predicted k values in this region. All the required initial conditions were measured at $x/d=50$, except for ϵ, which was calculated using measured values of k, Reynolds stress, and the mean velocity gradient.[3] Near the centerline, the mean velocity gradient and Reynolds stress are very small; therefore, slight errors in the measurements can result in large uncertainties for ϵ at the initial condition, contributing to overestimation of turbulence levels near the axis.

Predicted and measured profiles of Reynolds stress are illustrated in Fig. 9. The SSF predictions are adequate for both sprays. This is consistent with the reasonably good predictions of mean velocities and k obtained with this model for the test sprays.

Effects of drops on turbulence properties are more evident when individual components of velocity fluctuations are examined. Measured radial profiles of u', v', and w' are illustrated in Figs. 10 and 11 for the finely and coarsely atomized sprays. Predictions of these quantities using the SSF model are also illustrated on the figures. The predictions were obtained assuming $(\tilde{u}''^2:\tilde{v}''^2:\tilde{w}''^2)=(1:0.5:0.5)\,k$, which is approximately observed in the fully developed region of single-phase round jets.[10,11] Predictions constructed in this manner are in fair agreement with the measurements, particularly in the region far from the injector. A notable feature of the results, however, is that levels of anisotropy are rather high for positions near the injector and generally exceed levels observed for comparable values of x/d in single-phase jets.[10,11] Since this region abuts the dense-spray portion of the flow, it is likely that drops are responsible for the higher degree of anisotropy since effects of slip are preferentially transmitted to the streamwise velocity component, i.e., streamwise drop velocities are greatest.

High levels of anisotropy are of concern since the present prescription of eddy properties in the SSF model is based on the assumption of isotropic turbulence. This could be responsible for the consistent underestimation of streamwise particle velocity fluctuation levels with the SSF model, seen in the present study and Ref. 6. The observed level of anisotropy, however, is not much greater for the more heavily loaded case 2 jet. This occurs since the large drops in this spray do not exchange momentum as readily as small drops, thus liquid-phase momentum, which contributes to anisotropy, tends to be carried into the dilute spray region, where the effect is less noticeable. High levels of anisotropy also suggest that multistress models of particle-laden flows might profitably be examined in order to gain more insight concerning particle-turbulence interactions.

Turbulence Modulation

Turbulence modulation was theoretically examined using the SSF formulation of Shuen et al.[6] The effect contributes particle source terms in the governing model equations for k and ϵ. To the extent that the particle trajectory calculations are correct (using modeled turbulent eddy properties), the source term in the k equation is exact and involves no new empirical

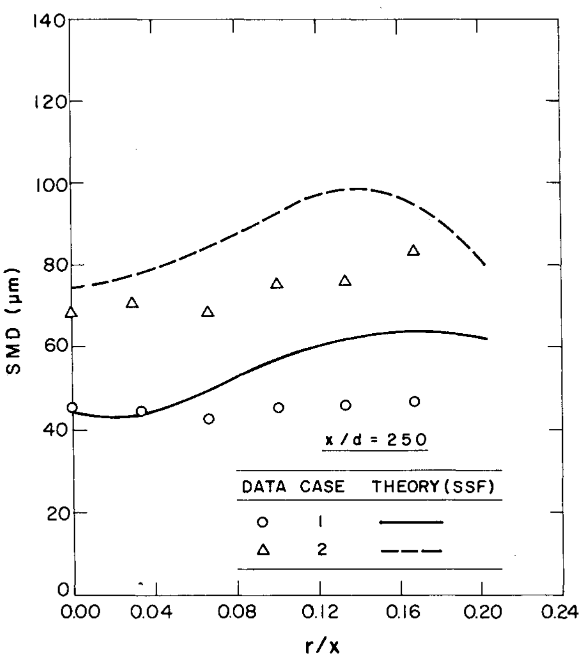

Fig. 7 Radial variation of SMD at $x/d=250$ for the sprays.

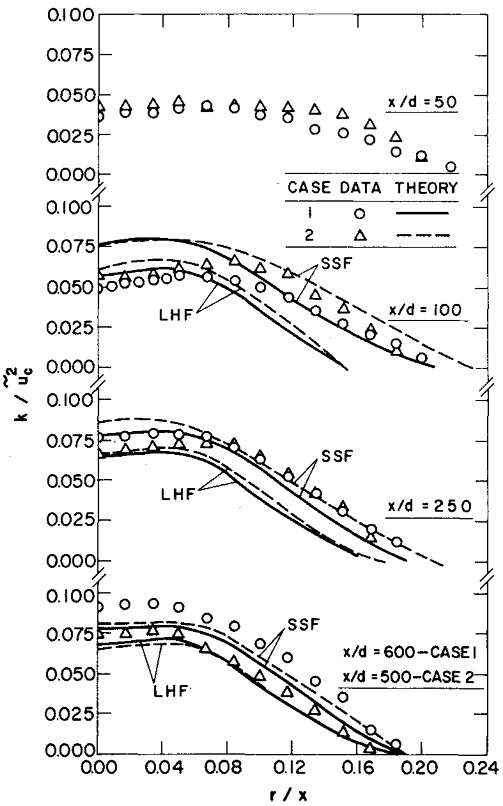

Fig. 8 Gas-phase turbulence kinetic energy in the sprays.

Table 1 Summary of turbulence modulation study[a]

Output variables, $x/d = 250$	$C_{\epsilon 3}$ 0.1	1.0	3.0
Case 1 spray			
$\bar{u}_c$	5.1	4.3	2.7
$k_c/\bar{u}_c^2$	−13.7	−10.8	−4.8
$(\overline{u''v''})_{max}/\bar{u}_c^2$	−8.3	−6.6	−3.2
$\bar{G}_c$	5.9	6.2	1.7
SMD_c	−3.7	− 1.8	2.9
$\bar{u}_{pc}$: d_p (μm) = 20	4.4	5.9	1.7
90	6.4	10.6	6.5
Case 2 spray			
$\bar{u}_c$	4.9	2.7	−2.8
$k_c/\bar{u}_c^2$	−13.8	−5.8	14.0
$(\overline{u''v''})_{max}/\bar{u}_c^2$	−10.1	−5.7	5.3
$\bar{G}_c$	2.7	−0.2	−6.2
SMD_c	0.6	−0.5	1.2
$\bar{u}_{pc}$: d_p (μm) = 20	7.7	3.5	−4.7
180	0.2	6.0	−0.3

[a]Entries show percentage change in predicted output variable upon inclusion of turbulence modulation terms for $C_{\epsilon 3}$ shown.

Table 2 Summary of sensitivity study[a]

Output variables, $x/d = 100$	Input variables $\bar{u}_p$	$(\bar{u}_p''^2)^{1/2}$	$\bar{v}_p$	$(\bar{v}_p''^2)^{1/2}$	ϵ
Case 1 spray					
$\bar{u}_p$	1	~0	~0	~0	9
$k_c/\bar{u}_c^2$	1	~0	~0	~0	−25
$\bar{G}_c$	3	17	−8	−15	−2
SMD_c	−9	15	−14	−4	−12
$\bar{u}_{pc}$: d_p (μm) = 20	−4	−5	−4	−2	3
50	22	9	3	2	4
90	31	−7	11	−13	−4
Case 2 spray					
$\bar{u}_c$	1	~0	~0	~0	9
$k_c/\bar{u}_c^2$	−1	~0	~0	~0	−25
$\bar{G}_c$	5	−9	−26	−20	−12
SMD_c	−6	−6	−5	−4	−4
$\bar{u}_{pc}$: d_p (μm) = 20	3	2	~0	−5	4
100	13	~0	−6	−6	−6
180	22	~0	~0	−2	~0

[a]Entries show percentage change in predictions by raising input variable by 25%.

constants. This is not true for the particle source term in the ϵ equation, however, where an empirical coefficient, $C_{\epsilon 3}$, must be introduced. The value of $C_{\epsilon 3}$ has not been established due to uncertainties in existing measurements and the fact that past measurements have largely been confined to dilute flows where effects of turbulence modulation are not large enough to provide an accurate fit. Therefore, following Shuen et al.,[6] values of $C_{\epsilon 3}$ were varied in the range 0.1-3 in order at least to gain some insight concerning potential effects of turbulence modulation in the present sprays.

Findings of the turbulence modulation study are summarized in Table 1. Entries in the table give the percentage change in predicted properties at $x/d = 250$ when the turbulence modulation terms are included. This was the position where the influence of turbulence modulation could be reasonably assessed. At $x/d = 500$ or 600, the flow is too dilute. On the other hand, while the sprays are denser and turbulence modulation effects are greater near the injector, effects of turbulence modulation are already absorbed in the initial condition specifications, and some axial distance is required for differences to build up. Results are shown for $C_{\epsilon 3} = 0.1$, 1.0, and 3, which covers the range considered during computations.

Varying $C_{\epsilon 3}$ in the range 0.1-3 has a systematic effect on computed gas-phase properties. In this range of $C_{\epsilon 3}$, the maximum effect is about 15%, which is only slightly greater than experimental uncertainties. Furthermore, as discussed earlier, the SSF model without inclusion of turbulence modulation performed reasonably well in the dilute regions of the test sprays. Therefore, in the dilute regions of the sprays, where comparison between measurements and predictions could be made with reduced effects of initial conditions, the results indicate that effects of turbulence modulation are too small to evaluate accurately the proposal of Shuen et al.[6] to treat the effect.

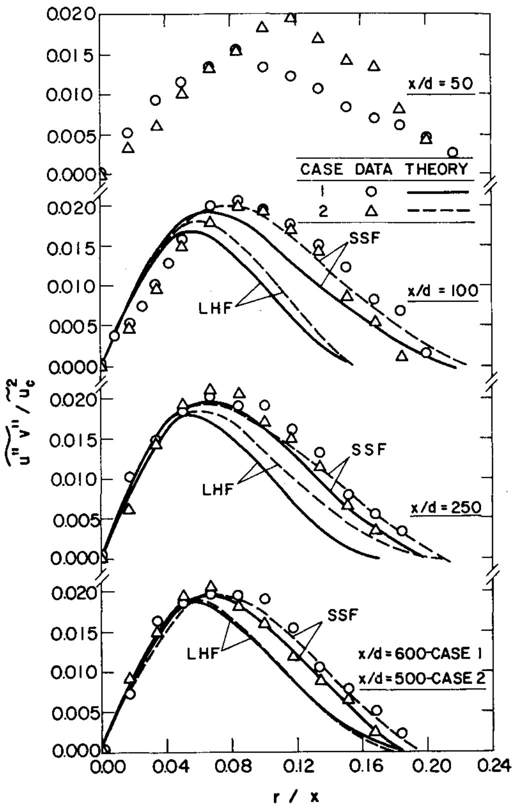

Fig. 9 Gas-phase Reynolds stress in the sprays.

Sensitivity Study

Specification of initial conditions is of vital importance to predictions using the separated flow models of sprays. While measurements of initial gas-phase mean and turbulent properties were reasonably accurate, calculated initial conditions for ϵ involved greater uncertainties due to small errors in mean velocity and Reynolds stress measurements near the centerline.

Uncertainties also exist in measurements of initial axial fluctuating drop velocities for the larger drops since sample sizes were insufficient to obtain a statistically accurate measurement. Furthermore, initial conditions of mean and fluctuating radial drop velocities were not measured but were estimated based on measured spray angles and limited photographic observations.[3] Due to these uncertainties, the sensitivity of SSF model predictions to the variation of these parameters was examined.

Sensitivity results are summarized in Table 2. The entries show the percentage change in predictions at $x/d = 100$ brought about by raising the indicated input parameter by 25%, with all other input parameters unchanged. This was the location where effects of initial conditions were greatest. It is seen that initial values of ϵ have a relatively large influence on the predicted values of k at this location. This could explain the discrepancy between measurements of k and predictions of the SSF model near the flow centerline at $x/d = 100$ (cf. Fig. 8).

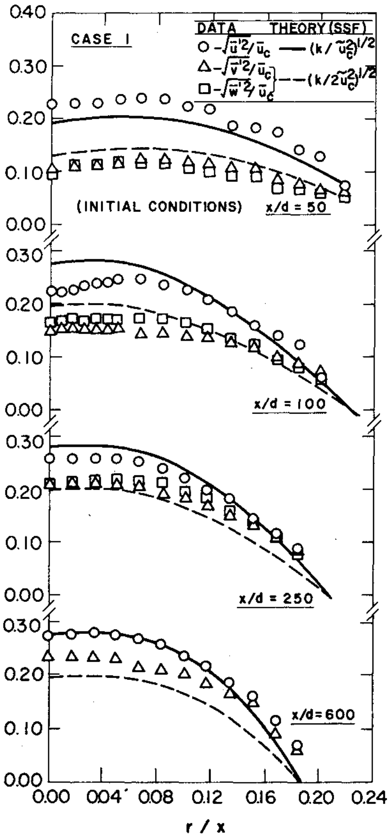

Fig. 10 Gas-phase velocity fluctuations in the case 1 spray.

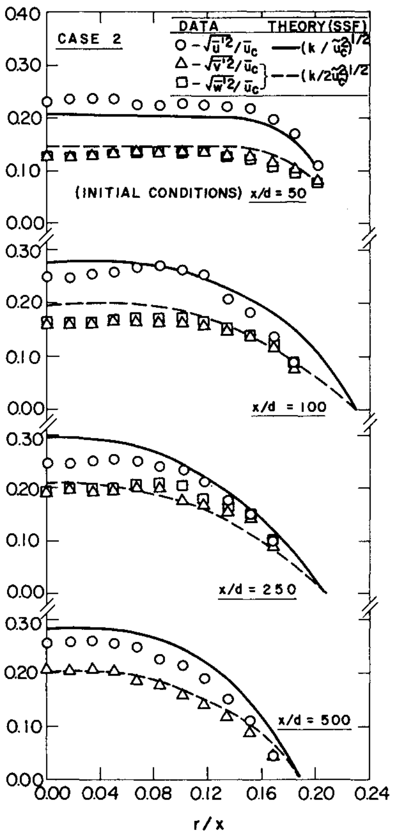

Fig. 11 Gas-phase velocity fluctuations in the case 2 spray.

In general, predicted gas-phase flow properties are not sensitive to the variation of initial drop properties, while liquid-phase predictions do show a large sensitivity. The large influence of axial drop velocity is due to effects of residence time in the flow on rates of turbulent dispersion and drop deceleration, especially for larger drops. Initial radial drop velocities, on the other hand, affect the spreading rate of the dispersed phase directly. These effects are reflected in fairly large changes in liquid mass flux.

Conclusions

Measurements of the structure of nonevaporating sprays, presented here and in Ref. 3, should be useful for evaluation of spray models. The test sprays involve flows where boundary-layer approximations apply, with well-defined boundary conditions, drop properties, and initial conditions. Test conditions were chosen to provide significant effects of interphase velocity slip and drop dispersion by turbulent fluctuations, at the limit of dilute sprays. All structure measurements and properties of the initial conditions are tabulated in Ref. 9.

Major conclusions of the study are as follows:

1) The DSF and LHF models did not provide very satisfactory predictions for the test sprays. The DSF model performed poorly due to neglect of effects of nonlinear drag interacting with turbulent fluctuations and turbulent drop dispersion. The LHF model performed poorly due to neglect of effects of slip. Both appear to have limited utility for modeling practical sprays.

2) In contrast, the SSF model gave encouraging structure predictions for the test flows. This included adequate treatment of enhanced drop dispersion, with no modification of the model from its original calibration for particle-laden jets (where effects of enhanced dispersion were not observed).[4-6]

3) In the dilute regions of the sprays, gas-phase turbulence properties were comparable to single-phase jets, suggesting negligible influence of drops on turbulence properties. As the dense-spray region near the injector was approached, however, gas-phase turbulence levels were significantly suppressed, and velocity fluctuations exhibited increased anisotropy, suggesting significant modification of turbulence properties by drops.

4) Specification of initial liquid-phase properties is the most critical factor in estimating the structure of the dilute region of sprays. This presents formidable theoretical and experimental problems associated with the dense-spray region near injectors and is probably the major limiting factor in applying spray models to practical sprays.

Acknowledgments

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