Vaporization Behavior of Turbulent Polydisperse and "Equivalent" Monodisperse Sprays

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The concept of using an equivalent monodisperse spray to represent the vaporization behavior of polydisperse sprays is examined by numerically solving two turbulent sprays. One involves the injection of Freon-11 in a still environment at room temperature, while the other is a methanol spray in a quiescent, hot environment. The use of three mean sizes, Sauter mean diameter, volume median diameter, and surface area mean diameter, is investigated. Results indicate that the volume median diameter and Sauter mean diameter simulate the vaporization behavior of realistic polydisperse sprays reasonably well. The surface area mean diameter does not provide as good a simulation as the other two diameters.

Introduction

THE purpose of this work is to explore whether an "equivalent" monodisperse spray can adequately represent the behavior of a given polydisperse spray, and, if it can, what is the droplet size of this equivalent spray. The work is important because adequate initial conditions are currently not available for spray computations and, in addition, the numerical effort involved in solving realistic polydisperse sprays may be considerably reduced if a single size can be used to represent a polydisperse spray. In the past, researchers have often employed the Sauter mean diameter[1] to represent a polydisperse spray. There is no evidence, however, to establish that this is the most suitable diameter for simulating the behavior of polydisperse sprays. The issue has been investigated by Dickinson and Marshall,[2] Alkidas,[3] Aggarwal and Sirignano,[4] Aggarwal,[5] and Ingebo.[6] These studies, which consider a variety of spray situations, fail to reach any general conclusion as to which mean droplet size best represents the behavior of a polydisperse spray. Moreover, only idealized sprays have been analyzed in these investigations.

The present study is directed toward examining the above issue by considering a more realistic situation of a vaporizing turbulent spray where the initial size distribution is obtained experimentally. Two cases are considered. The first is an evaporating Freon-11 spray produced by an air-atomizing injector in a still environment. Experimental data for initial conditions are available for this case. The second is an evaporating methanol spray produced by an air-atomizing injector in a hot environment. Since no experimental data are available for this case, the initial conditions are assumed to be the same as in the first case. For both cases, results are obtained for the polydisperse spray and compared with those for three equivalent monodisperse sprays represented, respectively, by the Sauter mean diameter (D_{32}), the surface area mean diameter (D_{20}), and the volume median diameter ($D_{v0.5}$).

The present investigation is different from earlier work[2-5] in that experimentally obtained size distribution and initial conditions for both phases are employed and a more realistic spray configuration is considered. Moreover, all of the mean droplet diameters, as reported in the literature, are compared simultaneously in the present study.

Brief Description of the Physical Model

The following assumptions are used for the gas phase: Mean flow is axisymmetric and steady; boundary layer approximations apply; exchange coefficients of all species and heat are equal; buoyancy affects mean flow only; and mean kinetic energy is negligible. The analysis employs Favre-averaged governing equations and a k-ε-g turbulence model for the gas phase.[7]

The liquid phase is treated by solving Lagrangian equations of motion and transport for trajectories of a statistically significant sample of individual droplets. This involves dividing the droplets into n groups (defined by position, diameter, and velocity) at the initial condition, and then computing their subsequent life histories in the flow. The stochastic-separated-flow formulation of Ref. 7 is adopted for droplet calculations.

Other assumptions and the complete formulation of the separated-flow model are given in Ref. 7.

Results

For the Freon-11 and methanol sprays, the vaporization behavior of a given polydisperse spray is compared with those of monodisperse sprays, as represented by $D_{v0.5}$, D_{32}, and D_{20}, respectively. The definition of various mean diameters can be found in Ref. 1. The comparison is presented in terms of the distributions of fuel vapor mass fraction and liquid flux, as these two are the most sensitive gas-phase and liquid-phase properties in a vaporizing spray.

Results for the Freon-11 Spray

For this case, the initial conditions for the calculations were taken from the experimental data of Ref. 7 at $x/D = 50$. Here, x denotes the axial location for the circular jet, and D denotes the orifice diameter. Twelve droplet sizes were used for the polydisperse spray. For monodisperse sprays, $D_{v0.5}$, D_{32}, and D_{20} were calculated using the experimental size distribution. The initial velocity of these monodisperse sprays was obtained by assuming that the velocity for a given drop size is the same as the experimental value for that size.

The vaporization behavior of polydisperse and monodisperse sprays is portrayed in Figs. 1 and 2. The axial and radial variation of freon vapor mass fraction is almost identical for the four sprays, indicating an excellent correlation between the

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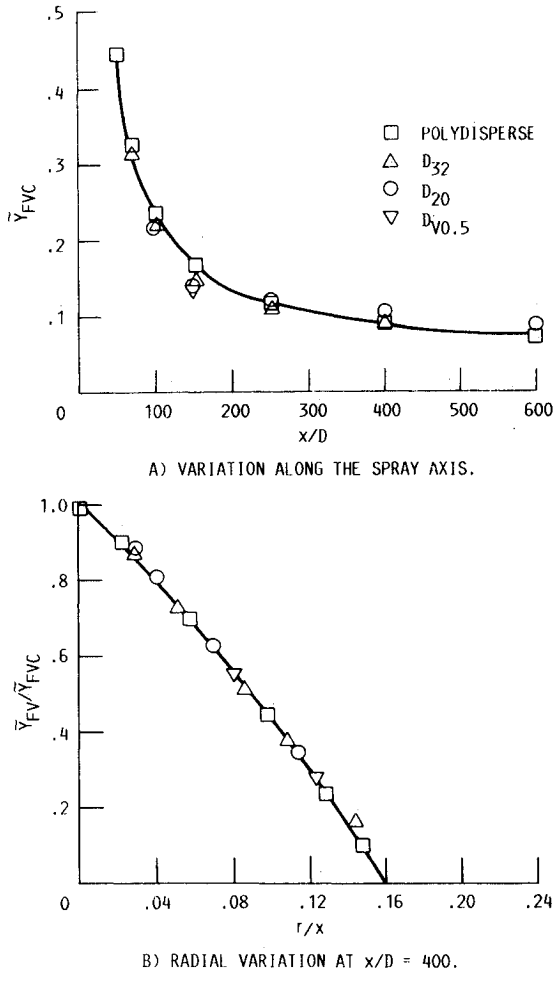

Fig. 1 Freon vapor mass fraction distribution in the turbulent evaporating spray.

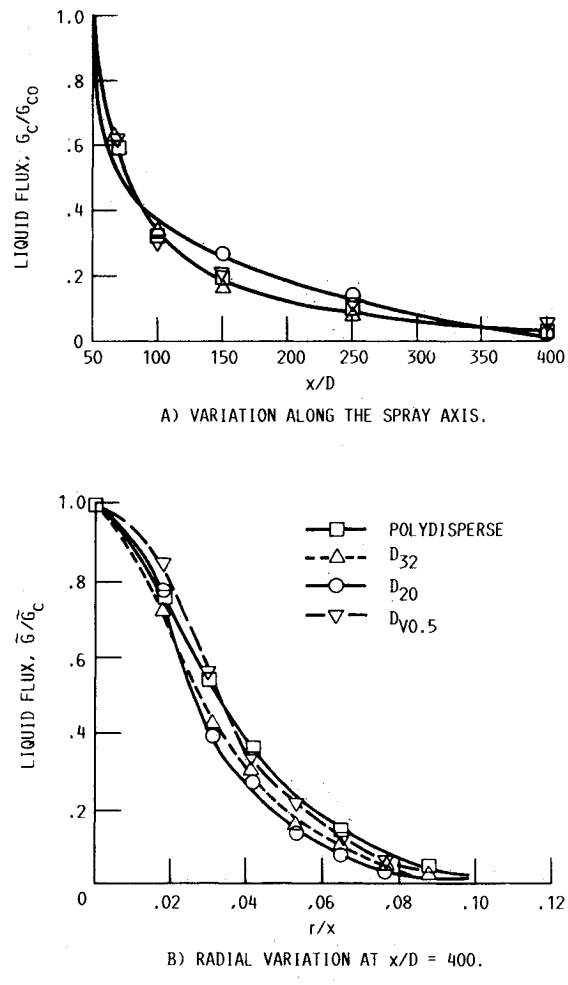

Fig. 2 Axial and radial variation of liquid freon flux.

polydisperse and monodisperse sprays. This is because the freon vapor mass fraction has the maximum value at the initial x station ($x/D = 50$), and its subsequent variation is largely controlled by the mixing processes rather than by the liquid-phase processes. The liquid-flux profiles, shown in Fig. 2, are perhaps more representative of the degree of correlation between the polydisperse and monodisperse sprays. Note that the liquid flux in Fig. 2a is normalized by its value at $x/D = 50$, whereas that in Fig. 2b is normalized by the corresponding centerline value. The results indicate that both $D_{v0.5}$ and D_{32} sprays simulate the vaporization behavior of the polydisperse spray quite well. The D_{20} spray also provides an acceptable simulation, but not as good as that of $D_{v0.5}$ and D_{32}.

Another noteworthy observation is that the $D_{v0.5}$ and D_{32} sprays slightly overpredict the liquid flux near the center, but underpredict near the jet boundary as compared to the polydisperse spray. Since the center part of the jet is relatively cold, only the smaller droplets in the polydisperse spray undergo vaporization. In the outer region, the vaporization rate is higher for the monodisperse sprays since the gas temperature is higher. The D_{20} spray exhibits a similar behavior for most of the jet (for $x/D > 100$). However, the differences between the D_{20} and polydisperse sprays are now more severe as compared to the $D_{v0.5}$ and D_{32} sprays.

The major conclusion from the above results is that the vaporization behavior of polydisperse sprays can be represented by the equivalent monodisperse sprays. The use of $D_{v0.5}$ or D_{32} best represents the polydisperse spray behavior, although D_{20} also provides an acceptable correlation. It should be noted, however, that the freon spray, due to its fast vaporization and a high initial fuel vapor concentration, may not be a good test case for examining the degree of correlation between the polydisperse and equivalent monodisperse sprays. This issue is pursued further by using a methanol spray.

Methanol Spray Results

The physical model for this case is essentially the same as that for the freon case, except that a methanol spray in hot, still surroundings (a temperature of 800 K) is considered. The methanol vapor distribution in the axial direction is given in Fig. 3a. The agreement among the polydisperse, D_{32}, and $D_{v0.5}$ sprays is quite reasonable. In contrast, the D_{20} spray indicates significant departure from the polydisperse spray. The radial distribution of liquid flux at $x/D = 150$ is given in Fig. 3b. The D_{32} spray provides the best correlation to the polydisperse results. In addition, except near the jet boundary, the liquid-flux values are higher for the D_{32} and $D_{v0.5}$ sprays because the small droplets in the polydisperse spray are vaporizing faster. Unlike the freon case, the jet interior is hot, and the vaporization there is significant in the present case. Also, the convective effect on vaporization is the largest at the jet axis, which makes the liquid flux at the axis lower as compared to that in the interior. The liquid flux is underpredicted for the D_{20} spray, indicating faster vaporization for this case as compared to the polydisperse spray.

The differences between the polydisperse and monodisperse sprays are more significant for methanol than freon, as shown in a comparison of Figs. 1a and 3a and of Figs. 2b and 3b. This is because of the large amount of initial fuel vapor for the freon spray; the methanol vapor mass fraction is zero, initially. Consequently, the differences in the vaporization behavior of polydisperse and monodisperse sprays are better highlighted for the methanol case. A more interesting observation is that even for

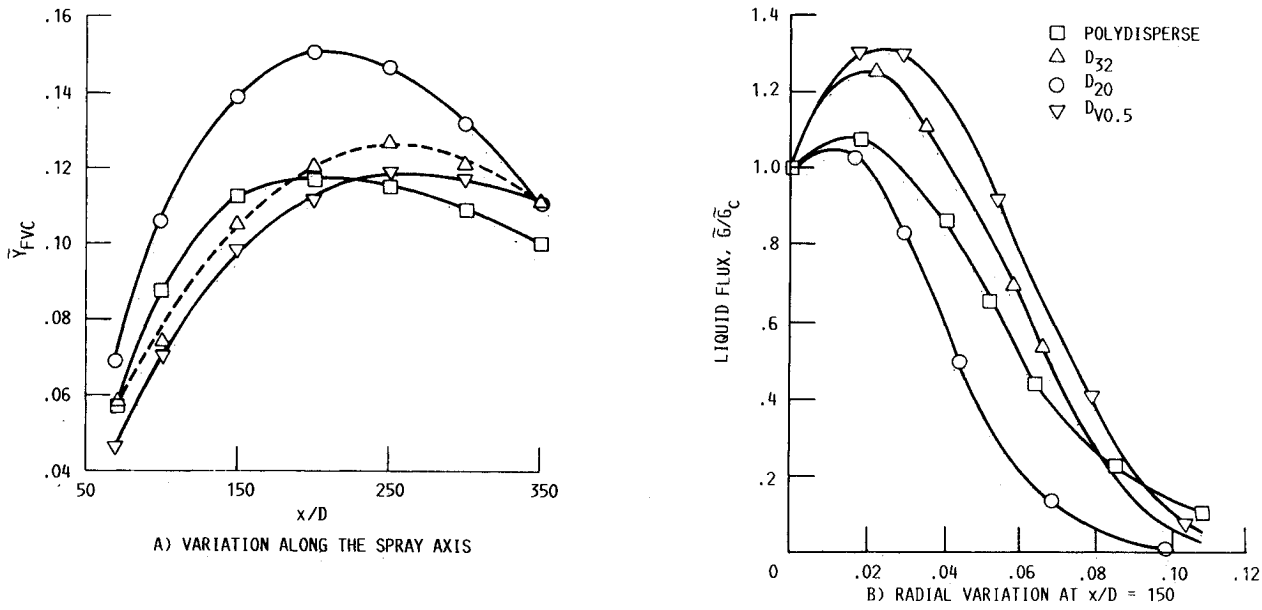

Fig. 3 Variation of methanol vapor mass fraction and liquid flux.

Table 1 Comparison of total liquid mass flow rate and total vapor mass flow rate for the four methanol sprays

	Total liquid mass flow rate, kg/s			
x/D	Polydisperse	D_{32}, m	$D_{v0.5}$, m	D_{20}, m
50	2.39×10^{-4}	2.39×10^{-4}	239×10^{-4}	2.39
$\times 10^{-4}$				
70	2.09	2.04	2.12	1.89
100	1.77	1.74	1.83	1.50
150	1.34	1.27	1.38	0.98
200	0.98	0.86	1.00	0.58
250	0.70	0.52	0.66	0.27
300	0.47	0.26	0.38	0.07
350	0.30	0.09	0.17	0.004
	Total vapor mass flow rate, kg/s			
50	0	0	0	0
70	0.25×10^{-4}	0.22×10^{-4}	0.21×10^{-4}	0.31
$\times 10^{-4}$				
100	0.56	0.51	0.49	0.69
150	0.99	0.99	0.94	1.21
200	1.34	1.39	1.33	1.61
250	1.62	1.73	1.67	1.92
300	1.85	1.99	1.95	2.1
350	2.01	2.15	2.15	2.15

methanol, the results for the D_{32} and $D_{v0.5}$ sprays are quite encouraging.

Table 1, which gives the axial variation of total liquid and vapor mass flow rate, provides a global comparison of the vaporization behavior of polydisperse spray with its equivalent monodisperse sprays. Again, the degree of correlation between the polydisperse and $D_{v0.5}$ sprays and between the polydisperse and D_{32} sprays is quite acceptable up to $x/D = 250$. It deteriorates further downstream, but is unimportant as much of the liquid has already vaporized.

Conclusions

The structure of evaporating turbulent sprays was numerically computed and the use of equivalent monodisperse sprays for simulating the vaporization behavior of realistic polydisperse sprays was investigated. Three mean diameters that were examined are the Sauter mean diameter, volume median diameter, and surface area mean diameters. The most important major conclusions are:

1) For the Freon case, the degree of correlation between the polydisperse and equivalent monodisperse sprays is generally excellent. Among the three mean diameters, $D_{v0.5}$ and D_{20} provide the best and the worst representation of polydisperse spray behavior, respectively. The D_{32} results are quite close to those for $D_{v0.5}$.

2) For the methanol case, the correlation between the equivalent monodisperse and polydisperse sprays is not quite as good as for freon, but is still acceptable. Again, $D_{v0.5}$ best simulates the vaporization behavior of the polydisperse spray. The methanol results are perhaps more typical of a turbulent vaporizing spray than the freon results because of the high initial vapor concentration in the latter.

3) The use of a suitable mean diameter is also desirable due to the reduction in computational efforts by a factor of six. This will become more of an issue as advanced vaporization models[8] are employed, or if combustion is considered.

The general conclusion is that the use of a suitable defined monodisperse spray for representing a realistic polydisperse spray is quite encouraging. Either $D_{v0.5}$ or D_{32} could be employed for modeling the vaporization behavior of polydisperse sprays.

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