# REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188



**1. AGENCY USE ONLY** *(Leave blank)*

**2. REPORT DATE**
8 February 1995

**3. REPORT TYPE AND DATES COVERED**
Final 1 June '91-30 Nov. '94

**4. TITLE AND SUBTITLE**
The Effect of Turbulence on Vaporization and Mixing in Fuel Sprays

**5. FUNDING NUMBERS**
DAAL03-91-G-0137

**6. AUTHOR(S)**
Domenic A. Santavicca

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
Penn State University
Mechanical Engineering Department
University Park, PA 16802

**8. PERFORMING ORGANIZATION REPORT NUMBER**

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
U. S. Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
ARO 28427.1-EG

**11. SUPPLEMENTARY NOTES**
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

**12a. DISTRIBUTION/AVAILABILITY STATEMENT**

Approved for public release; distribution unlimited.

**12b. DISTRIBUTION CODE**



**13. ABSTRACT** *(Maximum 200 words)*

An experimental study of droplet-turbulence interactions under simulated fuel spray conditions has been conducted. The behavior of individual droplets transversely injected into laminar and turbulent flows has been characterized by measuring droplet position, shape and size as a function of time. From these measurements new information has been obtained on the effects of vaporization and unsteady curvilinear motion on droplet drag and lift in laminar flows. These measurements have also provided new data which characterize the effects of turbulence on droplet drag, dispersion and secondary breakup.



**14. SUBJECT TERMS**
Droplet - Turbulence Interactions
Droplet Drag
Droplet Vaporization

**15. NUMBER OF PAGES**
9

**16. PRICE CODE**

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED | UL |

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

# THE EFFECT OF TURBULENCE ON VAPORIZATION AND MIXING IN FUEL SPRAYS

## FINAL REPORT

DOMENIC A. SANTAVICCA

FEBRUARY 8, 1995

U. S. ARMY RESEARCH OFFICE

#DAAL03-91-G-0137

PENN STATE UNIVERSITY

## STATEMENT OF PROBLEM

There have been relatively few studies of the effect of turbulence on droplet drag, droplet dispersion, droplet vaporization and secondary droplet breakup, particularly under conditions relevant to Diesel fuel sprays. The following is a brief summary of this work.

Droplet Drag: There have been numerous studies of the effects of free-stream turbulence on droplet drag [1-11]. The most pronounced effect is on the critical Reynolds number ($Re_c$) which is found to decrease with increasing turbulence intensity [1-5]. A number of studies have reported an effect of free-stream turbulence on droplet drag at Reynolds numbers both less than and greater than $Re_c$ [4-10]. Most studies have shown that droplet drag increases with increasing $I_{rel}$, which is defined as the rms fluctuation in the gas velocity divided by the relative mean droplet velocity; however, some studies show decreased drag [5,6] or negligible effects [8-10] at certain Reynolds numbers. And among those studies which show an increase, there are differences in the dependence on $I_{rel}$. Evidence of an effect of the ratio of the droplet diameter to the turbulence integral length scale [9] and of the turbulence energy spectrum have also been reported [11]. At Reynolds numbers below $Re_c$, the effect of free-stream turbulence on droplet drag is primarily attributed to changes in the structure of the droplet's wake. Although it has been clearly established that free-stream turbulence affects droplet drag, there is no consensus regarding the exact relationship between turbulence and droplet drag. In addition, most of these studies have been conducted using solid spheres and at conditions far removed from those encountered in Diesel sprays. For example, the combined effects of vaporization, which decreases droplet drag in laminar flows, and of turbulence, which is generally agreed upon to increase droplet drag, has not been studied at all.

Droplet Vaporization: Very few studies of the effect of free-stream turbulence on droplet vaporization have been reported. There have been, however, a number of studies of the effect of free-stream turbulence on heat transfer from droplets [12-15] which are indicative of the effects on vaporization. All of the heat transfer studies show that the rate of heat transfer increases with turbulence at Reynolds numbers both below and above the critical Reynolds number, where the dominant factor is the turbulence intensity. There is also some evidence that the spectral energy distribution [12,13] and the ratio of the droplet diameter to the integral length scale [14] have an effect on the rate of heat transfer. More specifically, several studies have found that the Nusselt number increases linearly with $I_{rel}$ [14,15], which is defined as the rms fluctuation in the gas velocity divided by the relative mean droplet velocity. Recently Gökalp et al. [16] reported on results from a study of the effect of free-stream turbulence on droplet vaporization. They found that the effect of mean relative velocity on the vaporization or mass transport rate increased with turbulence intensity. Their results also indicated that there was an effect of the turbulence length scale in that small scale turbulence was found to have a greater effect on the vaporization rate. And finally, they reported the somewhat surprising result that under the conditions of their tests, the vaporization rate of decane droplets increased with increasing turbulence intensity, while the vaporization rate of heptane droplets was found to be insensitive to turbulence. They argued that this was related to the ratio of the characteristic time scale for vaporization to the characteristic time scale of turbulent eddies of the same size as the droplet. These results are interesting and they are consistent with the previous studies of the effect of turbulence on heat transfer; however, they are very limited in terms of the number of conditions studied and in terms of the specific conditions studied being far removed from Diesel spray conditions.

Secondary Droplet Breakup: Although there have been numerous studies of secondary breakup in laminar flows, very little is known about secondary breakup in turbulent flows. In 1955, Hinze proposed two concepts related to this phenomenon [17]. One is that breakup occurs when the total local shear stress is greater than the sum of the surface tension forces and viscous stresses inside the droplet. The second is that only the energy associated with eddies smaller than the droplet diameter is available to cause the droplet to breakup. He also argued that this would cause a "bulgy" mode of breakup, whereby the droplet develops protuberances and breaks up into a small number of relatively large droplets. Although there have been a few experimental studies [18-21] supporting these concepts, including photographic evidence of the breakup mechanism [21], much research remains to be done before secondary droplet breakup in turbulent flow is understood and can be predicted.

Droplet Dispersion: Classical particle dispersion theory, which is based on a statistical description, was developed by Taylor [22] and predicts that dispersion increases with time squared for times much shorter than the integral time scale and with time linearly for times much greater than the integral time scale. In 1971, Snyder and Lumley [23] experimentally confirmed Taylor's theory. More recently, various dispersion models [24-27] have been developed based on the interaction between the droplet and individual eddies in the turbulent flow. In these models, dispersion is dependent on the droplet relaxation time, the turbulence integral time scale and the characteristic interaction time between the droplet and the flow. A limitation of Taylor's dispersion theory and an unresolved difficulty in the more recent trajectory-type dispersion models is accounting for situations which are typical of real sprays where the droplets have non-negligible inertia and large relative mean velocity, and as a result, the interaction time between the droplet and the turbulent eddies is changing with time. Dispersion measurements under such conditions are necessary for successful development and validation of current trajectory-type dispersion models.

## RESULTS FROM ARO-FUNDED STUDY

The results from the recently completed study can be separated into two parts. The first part pertains to a study of the effects of vaporization and unsteady curvilinear motion on droplet drag and lift in a laminar flow. The results from this part of the current study are as follows:

1) Under the experimental conditions of this study, the drag coefficient was not modified by unsteady curvilinear droplet motion. Lift was observed, but only at relatively high droplet Reynolds number (20<Re<38) and under vaporizing conditions. The effect of lift on the droplet trajectory was significant even though the magnitude of the lift coefficient was relatively small ($C_L/C_D$ » 0.1-0.15).

2) Several existing engineering drag correlations were examined, based on directly measured droplet acceleration. Drag coefficients calculated using numerically proposed drag correlations (the Chiang and Sirignano [28] correlation and the Renksitzbulut and Yuen correlation) showed better agreement with measured drag coefficients than those calculated by the experimentally developed correlation of Chen and Yuen [29]. However, the calculated trajectories in the present experiments were relatively insensitive to these drag correlations, even though the drag coefficients predicted by these correlations differ by 20-30%.

The second part of the current study pertains to a study of the effects of free-stream turbulence on droplet drag, droplet dispersion and secondary droplet breakup. The results from this part of the current study are as follows:

1) The time-averaged drag force on a droplet in a turbulent flow increased as relative turbulence intensity increased under the present experimental conditions. The time-averaged drag force in a turbulent flow was large compared with that in a laminar flow at the same $Re_d$, for example, as much as 85% at $I_{rel} = 40\%$.

2) An empirical correlation between the time-averaged drag and the relative turbulence intensity was developed. The drag force estimated using this correlation agrees well with the measured drag force, i.e., within 20%. This correlation implies that changes in the time-averaged drag coefficients under the present experimental condition might not be significant, but the effect of velocity fluctuations on the time-averaged dynamic pressure force $(1/2\rho_g \overline{U}_{rel}^2)$ is significant.

3) Photographs of droplet breakup in turbulent flows have been taken which show that the nature of the breakup process is phenomenologically different in a turbulent flow. The so-called "bulgy" breakup mechanism [17] was observed, as well as the fact that fewer and larger droplets are produced compared to the laminar case.

4) Using the drag correlation developed in this study, the onset condition of droplet breakup in a turbulent flow was predicted. The onset condition of breakup predicted using the drag correlation agreed well with experimental observations. This agreement supports the validity of the proposed drag correlation. On the other hand, the critical droplet Weber number suggested by Hinze [17], which was developed based on the assumption that the droplet interacts only with microscale turbulence, was also examined in the present breakup experiment. The result indicated that the droplet cannot be broken up at the condition predicted by Hinze. This implies that the turbulence scale associated with droplet momentum transfer is not the microscale, but the macroscale.

5) The droplet dispersion experiment conducted in the present study showed that the dispersion increased as a function of $t^3$, while the relative droplet velocity decreased. This increasing rate of dispersion was compared with that predicted by the classical dispersion theory which assumes that the droplet relative velocity is constant and predicts that dispersion increases as a function of $t^2$. Using the concept of droplet interaction time with turbulence eddies, the rapidly increasing dispersion under the present experimental conditions was explained.

## PUBLICATIONS AND TECHNICAL REPORTS

Song, Y.-H., D. A. Santavicca. An Experimental Study of Drag and Lift Acting on Evaporating Droplets Following Curvilinear Trajectories in a Laminar Flow, submitted to Combust. Sci. and Tech. (1994).

Song, Y.-H., D. A. Santavicca. An Experimental Study of Droplet Motion in a Highly Turbulent Flow, submitted to Combust. Sci. and Tech. (1995).

## PARTICIPATING SCIENTIFIC PERSONNEL

Domenic A. Santavicca (Principal Investigator)
Young-Hoon Song (Ph.D. 1994)
Timothy Spegar
Thomas Prevish

## REFERENCES

1. Torobin, L. B. and Gauvin, W. H., Can. J. Chem. Eng., Vol. 38, p. 189 (1960).

2. Torobin, L. B. and Gauvin, W. H., AIChE. J., Vol. 7, p. 615 (1961).

3. Dryden, H. L., Schubauer, G. B., Mock, W. G. and Skramstad, H. K., NACA Rep. No. 581 (1937).

4. Clift, R. and Gauvin, W. H., Proc. Chemeca '70, Butterworths, Melbourne, Vol. 1, pp. 14-28 (1970).

5. Uhlherr, P. H. T. and Sinclair, C. G., Proc. Chemeca '70, Butterworths, Melbourne, Vol. 1, pp. 1-13 (1970).

6. Petrak, D., Chem. Tech. (Leipzig), Vol. 28, pp. 591-595 (1976).

7. Clamen, A. and Guavin, W. H., AIChE. J., Vol. 15, pp. 184-189 (1969).

8. Sivier, K. R. and Nicholls, J. a., NASA Contract. Rep. CR-1392 (1969).

9. Zarin, N. A., NASA Contract. Rep. CR-1585 (1970).

10. Zarin, N. A. and Nicholls, J. R., Combust. Sci. Technol., Vol. 3, pp. 273-285 (1971).

11. Kestin, J., Adv. Heat Transfer, Vol. 3, pp. 1-32 (1966).

12. Mujumdar, A. S., Ph.D. Thesis, McGill Univ., Montreal (1971).

13. Seeley, L. E., Ph.D. Thesis, Univ. of Toronto (1972).

14. Raithby, G. D. and Eckert, E. R. G., Int. J. Heat Mass Transfer, Vol. 11, pp. 1233-1252 (1968).

15. Eastop, T. D., Ph.D. Thesis, C.N.A.A. London (1971).

16. Gökalp, I., Chauveau, C., Simm, O. and Chesneau, X., Comb. and Flame, Vol. 89, pp. 286-298 (1992).

17. Hinze, J. O., AIChE. J., Vol. 1, pp. 289-295 (1955).

18. Hughmark, G. A., AIChE. J., Vol. 17, p. 1000 (1971).

19. Paul, H. I and Sleicher, C. A., Chem. Eng. Sci., Vol. 20, pp. 57-59 (1965).

20. Sleicher, C. A., AIChE. J., Vol. 8, pp. 471-477 (1962).

21. Collins, S. G. and Knudsen, J. G., AIChE. J., Vol. 16, pp. 1072-1080 (1976).

22. Taylor, G. I., Proc. Lond. Math. Soc., Ser. 2, Vol. 20, pp. 196-212 (1921).

23. Snyder, W. H. and Lumley, J. L., J. Fluid Mech., Vol. 48, pp. 41-71 (1971).

24. Gosman, A. D. and Ioannides, E., AIAA Paper No. 81-0323 (1981).

25. Boysan, F., Ayers, W. H. and Switherbank, J., Trans. I. Chem. E., Vol. 60, pp. 222-230 (1982).

26. Shuen, J. S., Chen, L. D. and Faeth, G. M., AIChE. J., Vol. 29, pp. 167-170 (1993).

27. MacInnes, J. M. and Bracco, F. V., Phys. of Fluids (in press).

28. Chiang, C. H., Raju, M. S. and Sirignano, W. A., Int. J. Heat Mass Transfer, Vol. 35, pp. 1307-1324 (1992).

29. Chen, L. W. and Yuen, M. C., Combust. Sci. and Tech., Vol. 14, pp. 147-154 (1976).