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2) Brief Review of Major Findings

DOE Grant No DE-FG06-86ER13567

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This research project has involved intensive study of two-phase particulate dispersion in free shear flows using analytical, numerical, and experimental techniques. This work has focused on determining the importance of organized vortex structures in the particle dispersion process and recently, through two-way coupling analysis, the effect of particles or droplets on the air flow vortex structure development.

The results from these research efforts have yielded some interesting insights into the multiphase dispersion process produced by large scale organized vortex structures. These findings for one-way coupled interactions can be summarized as follows.

- a) The qualitative and quantitative character of the particle dispersion patterns in mixing layers, jet and wakes are strongly dependent on Stokes number and can be instantaneously highly anisotropic and nonhomogeneous.
- b) In mixing layers a stretching and folding operation associated with vortex structure development and pairing appears to be a dominant intermediate Stokes number particle dispersion mechanism.
- c) In wakes, where vortex pairings rarely occur, the dispersion process concentrates intermediate Stokes numbers particles into extremely thin sheet-like regions near the boundaries of the vortex structures.

For the more complex situation where the presence of particles or droplets can significantly alter the flow development through two-way mass, momentum or energy coupling several additional findings can also be listed:

- a. Stability analyses for two-way momentum coupling indicate that the presence of solid particles in plane mixing layers will decrease the amplification rate of flow disturbances. The magnitude of this effect depends on the particle mass concentration level.
- b. Stability analyses for two-way momentum coupling in plane wakes also decrease the amplification rate of flow disturbances and can transform the wake from an absolutely unstable to a convectively unstable flow.
- c. Numerical simulations involving two-way momentum coupled mixing layers show that for particle mass concentration ratio levels below 1.0 there is little change in the shear flow development. For mass concentrations ratios however close to and above 3.0 the shear flow development can be significantly inhibited.
- d. Numerical simulations involving two-way mass coupling effects from vaporizing droplets indicate that significant changes in the global character of a plane wake can be produced for droplet mass concentrations near 1.0

Recent Publications and Invited Addresses from this research are given in the following list.

MASTER

Publications

- C.T. Crowe, J.N. Chung and T.R. Troutt, "Particle Interactions with Vortices," Chp. 20, Fluid Vortices, Edit S. Green, to be published, Kluwer Academic Pub., 1994.
- T.R. Troutt, C.T. Crowe and J.N. Chung, "Multiphase Coupling Effects in Free Shear Flows," Proceedings of Eleventh Symposium on Energy Engineering Sciences, DOE Conference Publication, 1993.
- C.T. Crowe, J.N. Chung, and T.R. Troutt, "Particle Dispersion by Organized Turbulent Structures," Chpt. 18, Particulate Two-Phase Flow, Edit M. Rocco, Butterworth, Publ., 1992.
- C.T. Crowe, J.N. Chung, and T.R. Troutt, "A Review: Particle Dispersion in Organized Turbulent Structures," 1st ASME/JSME Fluids Engin. Confer., Portland, Oregon, June 23-27, 1991.
- C.T. Crowe, J.N. Chung, and T.R. Troutt, "Particle Dispersion by Large Scale Turbulent Structures," Plenary Lecture ASME/CSME Forum June 4-8, Toronto Ontario, 1990.
- N. Kamalu, N. Hanle, F. Wen, J.N. Chung, C.T. Crowe and T.R. Troutt, "Visualization of Particle Dispersion in a Plane Mixing Layer," *ASME J. FE*, **114**, 657, 1992.
- Y. Yang, J.N. Chung, T.R. Troutt and C.T. Crowe, "The Effects of Particles on the Stability of a Two-Phase Wake," *Int. J. of Multiphase Flow*, **19**, 1, 137-149, 1993.
- L. Tang, F. Wen, Y. Yang, C.T. Crowe, J.N. Chung, and T.R. Troutt, "Self-Organizing Particle Dispersion Mechanisms in Free Shear Flows", *Physics of Fluids Journal*, **A4**, (1), 1992.
- Y. Yang, J.N. Chung, T.R. Troutt and C.T. Crowe, "The Influence of Particles on the Spatial Stability of Two-Phase Mixing Layers," *Physics of Fluids Journal*, **A**, 2(10), 1990.
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- T.R. Troutt, J.N. Chung, and C.T. Crowe, "Particle Dispersion in Multiphase Mixing layers," Fluid-Particle Interactions II Conference, Davos Switzerland, May, 1990.
- Y. Yang, C.T. Crowe, J.N. Chung, and T.R. Troutt, "Quantitative Study of Particle Dispersion in a Bluff-Body Wake," *ASME FED-Vol. 166*, Gas Solid Flows, 231, 1993.
- Y. Yang, C.T. Crowe, J.N. Chung and T.R. Troutt, "Particle Dispersion in Bluff-Body Wake Flows," *Bull. Amer. Phys. Soc. Ser. II*, **38**, 2278, 1993.
- S. Wang, C.T. Crowe and T.R. Troutt, "Multiphase Coupling Effects in Free Shear Flows," accepted for Presentation 12th U.S. Nat. Congress of Applied Mechanics, Seattle, WA 1994.
- Y. Yang, C.T. Crowe, J.N. Chung and T.R. Troutt, "Experiments on Particle Dispersion in a Plane Wake Flow," in preparation, to be submitted for publication, 1994.
- S. Wang, C.T. Crowe and T.R. Troutt, "Momentum Coupling in Multiphase Free Shear Layers," in preparation, to be submitted for publication, 1994.
- C.T. Crowe, T.R. Troutt, S. Wang and Y. Yang, "Particle Dispersion in Wake-Generated Turbulence," accepted for presentation AIChE, 1st International Particle Technology Forum, Denver, 1994.
- S. Wang, C.T. Crowe and T.R. Troutt, "Mass and Energy Coupling in Two-Phase Shear Layers," in preparation, to be submitted for publication, 1994.
- J.N. Chung, "Simulation of Particle Dispersion in an Axisymmetric Jet," *J. of Fluid Mechanics*, **186**, 199-222, 1988.
- T.R. Troutt, C.T. Crowe and J.N. Chung, Proceedings of Eighth Symposium on Energy Engineering Sciences, DOE Conference Publication, 1990.

- R.A. Gore, C.T. Crowe, J.J. Riley, and T.R. Troutt, "Particle Dispersion by Large Scale Vortex Structures," *Particulate Science and Technology J.*, Vo. 7,3, 201, 1989.
- L. Tang, C.T. Crowe, J.N. Chung and T.R. Troutt, "Effect of Momentum Coupling on the Development of Shear Layers in Gas-Particle Mixtures," Proc. Intl. Conf. on Mechanics of Two-Phase Flows, National Taiwan University, pp. 387-391, 1989.
- N. Kamalu, L. Tang, T.R. Troutt, J.N. Chung and C.T. Crowe, "Particle Dispersion in Developing Shear Layers", Proc. Intl. Conf. on Mechanics of Two-Phase Flows, National Taiwan University, 1989, pp. 199-202.
- Y. Yang, J.N. Chung, T.R. Troutt and C.T. Crowe, "The Effects of Particles on the Stability of a Two-Phase Wake," *Int. J. of Multiphase Flow*, 19, 1, 137-149, 1993.
- L. Tang and C.T. Crowe, "A Numerical Model for Droplets Dispersing in a Developing Plane Shear Layer including Coupling Effects," *Numerical Methods for Multiphase Flows*, ASME FED Vol. 91, pp. 27-34, 1990.
- L. Tang and C.T. Crowe, "Particle Dispersion in Developing Shear Layers," Proc. Intl. Conf. on Mech. of Two-Phase Flows, National Taiwan Univ., pp. 199-202, 1989.
- C.T. Crowe, "The State-of-the-Art in the Development of Numerical Models for Dispersed Phase Flows," Proc. Intl. Conference on Multiphase Flows - '91 Tsukuba, Vol. 3, pp. 49-60, 1991.
- J.N. Chung, T.R. Troutt and C.T. Crowe, "Modeling of Droplet-Gas Interaction in a Spray Combustion Engine," Presented at the Intl. Symp. on Diagnostics and Modeling of Combustion in Internal Combustion Engines, Kyoto, Japan, 1990.
- C.T. Crowe, "Numerical Models for Particle Dispersion in Turbulent Flow," Proceedings of Workshop on Mixing and Demixing Processes in Multiphase Flows with Application to Propulsion Systems held at Marshall Space Flight Center, AL, NASA Conf. Pub. 3006, pp. 87-107, 1988.

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- T.R. Troutt, Multiphase Mixing in Free Shear Flows, Eighth Symposium on Energy Engineering Science, DOE, Argonne, IL, 1990.
- C.T. Crowe, The State-of-the-Art in the Development of Numerical Models for Dispersed Phase Flows, Keynote Lecture, Intl. Conf. on Multiphase Flows - '91 Tsukuba, Japan, Sept. 1991.
- C.T. Crowe, Particle Dispersion in Large Scale Turbulent Structures, Korea Advanced Institute of Science and Technology, Taejon, Korea, Oct. 1, 1991.
- C.T. Crowe, A Review: Particle Dispersion in Organized Turbulent Structures, Invited Presentation, ASME-JSME Joint Fluid Dynamics Conference, Portland, Sept., 1991.
- T.R. Troutt, "Coupling Effects in Multiphase Free Shear Flows," Eleventh Symposium on Energy Engineering Sciences DOE, Argonnes IL, 1993.
- C.T. Crowe, Particulate Motion and Dispersion in Large Scale Turbulent Structures, General Lecture, CSME Mechanical Engineering Forum, Toronto, Can., June, 1990.
- C.T. Crowe, "Particle Dispersion in Large-Scale Turbulent Structures," NSF-DOE Workshop on Flow of Particulates and Fluids, NIST, Gaithersburg, MD, 1990.
- C.T. Crowe, T.R. Troutt and J.N. Chung, "Numerical Modeling of Two-Phase Free Shear Layers," Invited Presentation, ASME Open Forum on Multiphase Flows, Lake Tahoe, Nev., June 1994.

3) Statement of Anticipated Unexpected Balance at End of Current Funding Period

We do not anticipate a remaining balance at the end of the current funding period.

4) Significant Modification to Program of Work Described in Proposal

We have not made any significant modifications to our proposed program of work.

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