FINAL REPORT
FUNDAMENTAL STUDIES OF SPRAY COMBUSTION

S.C. Li, Paul A. Libby and Forman A. Williams

Center for Energy and Combustion Research
Department of Mechanical and Aerospace Engineering
University of California, San Diego
La Jolla, CA 92093-0411

This represents the final report for contract DE-F003-87ER13685. Our research on spray combustion, involving both experimental and theoretical components, has addressed droplet and spray characteristics in laminar counterflowing streams, laminar counterflow spray diffusion flames, and impingement of sprays on hot surfaces, both with and without a flame present, and flame structure and flame chemistry. This project has generated twenty six publications and received two *Best Technical Paper Awards* (1996, 1998) from ASME International Gas Turbine Institute.

References

[1] Li, S.C., Libby, P.A., and Williams, F.A., 1991, "On The Structure of Spray Diffusion Flames," The Western States Sections/The Combustion Institute, Los Angeles, CA, October 13-15, 1991.

[2] Li, S.C., Libby, P.A., and Williams, F.A. 1992, "Experimental and Theoretical Studies of Counterflow Spray Diffusion Flames," *Twenty-Fourth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, pp.1503-1512 (1992).

[3] Li, S.C., Libby, P.A., and Williams, F.A., 1992, "Measurements in Two-phase Counterflowing Streams Using a Phase Doppler Particle Analyzer," The Western States Sections/The Combustion Institute, Berkeley, CA, October 12-13, 1992.

DISCLAIMER

[4] Li, S.C., Libby, P.A., and Williams, F.A. 1993, "Spray Structure in Counterflowing Streams with and without a Flame," *Combustion and Flame*, 94: 161-177 (1993).

[5] Li, S.C., Libby, P.A., and Williams, F.A., "An Experimental and Theoretical Study on Spray Structure in Two-Phase Counterflowing Streams with and without a Flame," AIAA Paper No. 93-1769 (1993).

[6] Li, S.C., Libby, P.A., and Williams, F.A., "Droplet Relative Motion and spray Structure in Counterflowing Streams," *Fluid Mechanics and Heat Transfer in Sprays*, J.W. Hoyt et al. (ED.), The American Society of Mechanical Engineers, pp. 20-25 (1993).

[7] Li, S.C., Libby, P.A., and Williams, F.A., "A Laminar Counterflow in a Narrow Channel," The 46th Meeting of the American Physical Society, Albuquerque, NM, November 21-23, 1993.

[8] Li, S.C., Libby, P.A., and Williams, F.A., "Oscillations of a Sphere in Counterflowing Streams," Western States Meeting, The Combustion Institute, Salt Lake City, Utah, March 22-23, 1993.

[9] Li, S.C., Libby, P.A., and Williams, F.A., " An Experimental and Theoretical Study of Spray Impingement on a Hot Surface in Reacting Stagnation Flows," AIAA Paper No. 94-3281 (1994).

[10] Li, S.C., Libby, P.A., and Williams, F.A., "Spray Impingement on a Hot Surface in Reacting Stagnation Flows," *AIAA Journal*, 33: 1046-1055, June (1995).

[11] Li, S.C., Ilincic, "Influence of Sprays on Strained Partially Premixed Flames," AIAA Paper No. 95-2555 (1995).

[12] Li, S.C., Libby, P.A., and Williams, F.A., "Turbulent Spray in Stagnation Flows," *Atomization and Sprays*, 5: 287-304 (1995).

[13] Li, S.C. and Williams, F.A., "Experimental and Numerical Studies of Two-Stage Methanol Flames," *Twenty-Sixth Symposium (International) on Combustion*, The Combustion Institute, pp.1017-1024 (1996)

[14] Li, S.C., Ilincic, N. and Williams, F.A., " Reduction of NO_x Formation by Water Sprays in Strained Two-Stage Flames," , ASME Paper NO. 96-GT-545, (presented at ASME TURBO-EXPO'96, Birmingham, England UK, June 10-13, 1996).

[15] Li, S.C., Libby, P.A., and Williams, F.A., "Droplet Trajectories in Spray Counterflowing Flames," work in process, 1996.

[16] Li, S.C., Ilincic, N. and Williams, F.A., "Reduction of NO_x Formation by Water Sprays in Strained Two-Stage Flames," *Journal of Engineering-for Gas Turbines and Power* Vol.119, No.4, pp. 836-843 (1997).

[17] Li, S.C., "Spray Stagnation Flames," *Progress in Energy and Combustion Science*, Vol.23, pp.303-347, 1997.

[18] Li, S.C. and Williams, F.A., "NO_x Reduction in Diesel-Fuel Flames by Additions of Water and CO_2," *1997 Diesel Engine Emissions Reduction Workshop*, Sponsored by DOE Office of Transportation Technologies, San Diego, July 28-31, 1997.

[19] Li, S.C., Ilincic, N. and Williams, F.A., " Reduction of NO_x Formation by Water Sprays in Strained Two-Stage Flames," *ASME Journal of Engineering for Gas Turbines and Power*, 119:836-843 (1997).

[20] Li, S.C. and Williams, F.A., "Experimental and Numerical Studies of NO_x Formation in Two-Stage Methane-Air Flames," ASME Paper No. 98-GT-73.

[21] Li, S.C. and Williams, F.A., "Formation of NO_x, CH_4 and C_2 Species in Laminar Methanol Flames," *Twenty-Seventh Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, pp.485-493 (1998).

[22] Li, S.C. and Gebert, K., "Spray Characterization of High Pressure Gasoline Fuel Injectors with Swirl and NOn-Swirl Nozzles," SAE Paper No. 981935, (to be published in the 1998 SAE Transactions).

[23] Li, S.C. and Williams, F.A., "NO_x Formation in Two-Stage Methane-Air Flames," *Combustion and Flame*, 118:399-414 (1999).

[24] Li, S.C., Williams, F.A. and Gebert, K., "A Simplified Fundamentally Based Method for Calculating NOx Emission in Lean Premixed Combustors," *Combustion and Flame*, 119:367-373 (1999).

[25] Waly, M.M.Y., Li, S.C. and Williams, "Experimental and Numerical Studies of Two-Stage Ethane-Air Flames," ASME Paper No. 99-GT-108, (to be published in *Journal of Engineering for Gas Turbines and Power*).

[26] Li, S.C. and Williams, F.A., "Experimental and Numerical Studies of Two-Stage Heptane Spray Flames," AIAA Paper No. 99-0211 (1999).