

Mass Loading
and
Stokes Number Effects
in
Steady and Unsteady
Particle-laden Jets

M.Eng. Science Thesis

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June 2008



References

- Albrecht, H.E., Borys, M., Damaschke, N., Tropea, C. 2003. Laser doppler and phase doppler measurement techniques, *Springer*, Germany.
- Beer, J.M. & Chigier, N.A. 1972. Combustion Aerodynamics. Applied Science Publishers, London.
- Birzer, C.H, Kalt, P.A.M, Nathan, G.J, Smith, N.L. 2005. Planer measurements of the distribution of particles in a two-phase precessing jet flow. *5th Asia Pacific Conference on Combustion*, The University of Adelaide, Adelaide, Australia 17-20 July.
- Birzer, C.H, Kalt, P.A.M, Nathan. 2007. The influence of particle mass loading on mean particle distributions in the near field of a co-annular jet. To be published.
- Borée, J. Ishima, T. Flour, I. 2001. The effect of mass loading and inter-particle collisions on the development of the polydispersed two-phase flow downstream of a confined bluff body, *J. Fluid Mech.* 443, 129-165.
- Budilarto, 2003. An experimental study on effects of fluid aerodynamics and particle size distribution in particle-laden jets. Ph.D. thesis, Purdue University.
- Chen, C.J. & Rodi, W. 1980. Vertical turbulent buoyant jets: a review of experimental data, *Pergamon Press*, Oxford.
- Crowe, C.T., Chung, J.N., Troutt, T.R. 1988. Particle mixing in free shear flows. *Prog. Energy Combust. Sci.* 14, 171-194.
- Crowe, C., Sommerfeld, M., Tsuji, Y. 1998. Multiphase flows with droplets and particles, *CRC Press*, USA
- Crowe, C.T. 2000. On models of turbulence modulation in fluid-particle flows. *Int. J. Multiphase Flow* 26, 719-727.
- Crowe, C.T. 2006. Multiphase flow handbook. *Taylor and Francis Group*, USA.
- Cui, J.L., Zhang, H.Q., Wang, B., Rong, Y., Wang, X.L. 2006. Flow visualization and laser measurement on particle modulation to gas phase turbulence. *J. Visual.-Japan* 9, 339-345.

Department of Trade and Industry (DTI). 2004. Multiphase flow technologies in coal-fired power plants, from www.berr.gov.uk/files/file20910.pdf

Dimotakis, P. E., Miake-Lye, R. C., Papantoniou, D. A. 1983. Structure and dynamics of round turbulent jets, *Phys. Fluids* 26, 3185-3192.

Eaton, J.K. & Fessler, J.R. 1994. Preferential concentration of particles by turbulence. *Int. J. Multiphase Flow* 20, suppl. 169-209.

Eaton, A.R., Frey, S.F., Cusano, D.M., Plesniak, M.W., Sojka, P.E. 1996. Development of full-field planar Mie scattering technique for evaluating swirl mixers. *Exp. Fluids* 21, 325-330.

Elghobashi, S., Abou-Arab, T., Rizk, M., Mostafa, A. 1984. Prediction of the particle-laden jet with a two-equation turbulence model. *Int. J. Multiphase Flow* 10, 697-710.

Elghobashi, S. 1994. On predicting particle-laden flows, *Appl. Sci. Res.* 52, 309-329.

England, G., Kalt, P.A.M., Nathan, G.J., Kelso, R.M. 2004. The effect of density ratio on the mean spread rate of a low pressure drop oscillating jet nozzle. *15th Australasian Fluid Mechanics Conference*, The University of Sydney, Sydney, Australia, 13-17 December.

Fan, J., Zhang, L., Zhao, H., Cen, K. 1990. Particle concentration and particle size measurements in a particle laden turbulent free jet. *Exp. Fluids* 9, 320-322.

Fan, J., Zhang, X., Chen, L., Cen, K. 1997. New stochastic particle dispersion modeling of a turbulent particle-laden round jet. *Chem. Eng. J.* 66, 207-215.

Ferrand, V., Bazile, R., Bore, J. 2001. Measurements of concentration per size class in a dense polydispersed jet using planar-induced fluorescence and phase Doppler techniques. *Exp. Fluids* 31, 597-607.

Ferrand, V., Bazile, R., Bore, J. Charnay, G. 2003. Gas-droplet turbulent velocity correlations and two-phase interaction in an axisymmetric jet laden with partly responsive droplets. *Int. J. Multiphase Flow* 29, 195-217.

Field, M.A., 1963. Entrainment into an air jet laden with particles. The British coal utilisation research association, Members' information circular, 273.

Fleckhaus, D., Hishida, K., Maeda, M. 1987. Effect of laden solid particles on the turbulent flow structure of a free round jet. *Exp. Fluids* 5, 323-333.

Frishman, F., Hussainov, M., Kartushinsky, A., Mulgi, A. 1997. Numerical simulation of a two-phase turbulent pipe-jet flow loaded with polydispersed solid admixture. *Int. J. Multiphase Flow* 23, 765-796.

Frishman, F., Hussainov, M., Kartushinsky, A., Rudi, U. 1999. Distribution characteristics of the mass concentration of coarse solid particles in a two-phase turbulent jet. *J. Aerosol Sci.* 30, 51-69.

George, W. K. 1989. The self-similarity of turbulent flows and its relation to initial conditions and coherent structures, *Hemisphere*, In Recent Advances in Turbulence, (ed. R. E. A. Arndt & W. K. George), 39-73.

George, W. K. 1990 Governing equations, experiments and experimentalist. *Expt. Therm. Fluid Sci.* 3, 557-566.

Gillandt, I., Fritsching, U., Bauckhage, K. 2001. Measurements of the phase interaction in dispersed gas/particle two-phase flow. *Int. J. Multiphase Flow* 27, 1313-1332.

Gore, R.A. & Crowe, C.T. 1989. Effect of particle size on modulating turbulent intensity. *Int. J. Multiphase Flow* 15, 279-285.

Hardalupas, Y., Taylor, A.M.K.P., Whitelaw, J.H. 1989. Velocity and particle-flux characteristics of turbulent particle-laden jets. *Proc. R. Soc. London, Ser. A* 426, 31-78.

Hetsroni, G. 1989. Particles-turbulence interaction. *Int. J. Multiphase flow* 15, 735-746.

Hishida, K., Kaneko, K., Maeda, M. 1985. Turbulence structure of gas-solids two-phase circular jet. *Nippon Kikai Gakkai Ronbunshu, B Hen* 51, 2330-2337.

Hussainov, M., Kartushinsky, A., Mulgi, A., Rudi, U. 1996. Gas-solid flow with the slip velocity of particles in a horizontal channel. *J. Aerosol Sci.* 27, 41-59.

Hussein, H.J., Capp, S.P., George, W.K. 1994. Velocity measurements in a high-Reynolds-number, momentum-conserving, axisymmetric, turbulent jet. *J. Fluid Mech.* 258, 31-75.

Ivanov, Y.V., Laats, M.K., Frishman, F.A. 1970. Translated from *Inzhenerno-*

Intergovernmental Panel on Climate Change (IPCC). 2007. Fourth assessment report - summary for policy makers.

Kelso, R.M. 2001. A mechanism for jet precession in axisymmetric sudden expansions, *14th Australasian Fluid Mechanics Conference*, Adelaide University, Adelaide, Australia, 10-14 December 2001.

Kundu, P.K. & Cohen, I.M. 2002. Fluid Mechanics, *Academic Press*, USA.

Laats, M.K. 1966. Experimental study of the dynamics of an air-dust jet. Translated from *Inzhenerno-Fizicheskii Zhurnal*, 10, 11-15.

Laats, M.K. & Frishman, F.A. 1970. Assumptions used in calculating the two-phase jet. *Translated from Izv. SSR. Mekhanika Zhidkosti Gaza* 5, 186-191.

Lazaro, B.J. & Lasheras, J.C. 1989. Particle dispersion in a turbulent, plane, shear layer. *Phys. Fluids A*. 1, 1035-1044.

Lee, S.K., Lanspeary, P.V., Nathan, G.J., Kelso, R.M., Mi, J. 2003. Low kinetic-energy loss oscillating-triangular-jet nozzles. *Exp. Therm. Fluid Sci.* 27, 553-561.

Lee, S.K., Lanspeary, P.V., Nathan, G.J., Kelso, R.M. 2004. Surface-flow patterns in oscillating-triangular-jet nozzles. *15th Australasian Fluid Mechanics Conference*, The University of Sydney, Sydney, Australia, 13-17 December.

Liljegren, L.M. & Vlachos, N.S. 1990. Laser velocimetry measurements in a horizontal gas-solid pipe flow. *Exp. Fluids*. 9, 205-212.

Long, M.B., Chu, B.T., Chang, R.K. 1981. Instantaneous two-dimensional gas concentration measurements by light scattering. *AIAA J.* 19, 1151-1163.

Longmire, E.K. & Eaton, J.K. 1992. Structure of a particle-laden round jet. *J. Fluid Mech.* 236, 217-257.

Luo, K., Klein, M., Fan, J, Cen, K. 2006. Effects on particle dispersion by turbulent transition in a jet. *Phys. Lett. A* 357, 345-350.

Manias, C.G. & Nathan, G.J. 1994. Lox NO_x clinker production. *World cement*, 25, 54-56.

Melville, W. K. & Bray, K.N.C. 1979, Two-phase turbulent jet. *Int. J.*

Heat Mass Transfer 22, 279-287.

Merrow, E.W., Phillips, K.E., Myers, C.W. 1981. Understanding cost growth and performance shortfalls in pioneer process plants. *The Rand Corporation*, Santa Monica, USA.

Mi, J., Nobes, D.S., Nathan, G.J. 2001. Influence of jet exit conditions on the passive scalar field of an axisymmetric free jet. *J. Fluid Mech.* 432, 91-125.

Mi, J., Nathan, G.J., and Luxton, R.E. 1999. Oscillating Jets. Australian Patent Application No. PP 12194/99, (PCT/AU98/00959), Publication Date: 5 Aug 1999, Awarded in Australia: 18 April, 2002. The US Patent No. 6685102 (2004.2), European Pat. No. 1032789 (2004.9), Australian Pat. No. 746248 (2004.2), New Zealand Pat. No. 504470 (2003.7).

Modarress, D., Tan, H., Elghobashi, S. 1984a. 2-component LDA measurement in a 2-phase turbulent jet. *AIAA J.* 22, 624-630.

Modarress, D., Wuerer, J., Elghobashi, S. 1984b. An experimental study of turbulent round two-phase jet. *Chem. Eng. Commun.* 28, 341-354.

Morris, G.J., Jurewicz, J.T., Palmer, G.M. 1992. Gas-solid flow in a fluidically oscillating jet. *J. Fluids Eng.* 114, 362-366.

Mostafa, A.A., Mongia, H.C., McDonell, V.G., Samuelson, G.S. 1989. Evolution of particle-laden jet flows: A theoretical and experimental study. *AIAA J.* 27, 167-183.

Munson, B.R., Young, D.F., Okiishi, T.H. 2002. Fundamentals of fluid mechanics, *John Wiley & Sons*, USA.

Nathan, G.J. 1988. The enhanced mixing burner. PhD. Thesis, Adelaide University

Nathan, G.J., Hill, S.J., Luxton, R.E. 1998. An axisymmetric 'fluidic' nozzle to generate jet precession. *J. Fluid Mech.* 370, 347-380.

Nathan, G.J. & Hill, S.J. 2002. Full Scale Assessment of the Influence of a Precessing Jet of Air on the Performance of Pulverised Coal Flame in a Cement Kiln, *6th European Conference on Industrial Furnaces and Boilers (INFUB)*, Lisbon, Portugal, April 2-5.

Nathan, G.J., Mi, J., Alwahabi, Z.T., Newbold, G.J.R., Nobes, D.S. 2006. Impacts of a jet's exit flow pattern on mixing and combustion performance.

Prog. Energy Comb. Sci. 32, 496-538.

Newbold, G.J.R., Nathan, G.J., Luxton, R.E. 1997. Large scale dynamics of an unconfined precessing jet flame. *Combust. Sci. Tech.* 126, 71-95.

Owen, P.R. 1969. Pneumatic transport. *J. Fluid Mech.* 39, part 2, 407-432.

Parham, J. 2000. Control and optimisation of mixing and combustion from a precessing jet nozzle. Ph.D. thesis, Adelaide University.

Pope, S.B. 2000. Turbulent flows, Cambridge University Press, New York, USA.

Rajaratnam, N. 1976. Turbulent Jets, Elsevier scientific publishing company, Amsterdam.

Richards, C.D. & Pitts, W.M. 1993. Global density effects on the self-preservation behaviour of turbulent free jets. *J. Fluid Mech.*, 254, 417-435.

Ricou, F.P. & Spalding, D.B. 1961. Measurements of entrainment by axisymmetrical turbulent jets. *J. Fluid Mech.*, 11, Part 1, 21-32.

Roquemore, W.M., Tankin, R.S., Chiu, H.H., Lottes, S.A. 1986. A study of a bluff-body combustor using laser sheet lighting. *Exp. Fluids* 4, 205-213.

Schlichting, H. 1960. Boundary-layer theory, McGraw-Hill, USA.

Sheen, H.J., Jou, B.H., Lee, Y.T. 1994. Effect of particle size on a two-phase turbulent jet. *Exp. Therm. Fluid Sci.* 8, 315-327.

Shuen, J.S., Solomon, A.S.P., Zhang, Q.F., Faeth, G.M. 1983. A theoretical and experimental study of turbulent particle-laden jets. NASA CR-168293.

Shuen, J.S., Solomon, A.S.P., Zhang, Q.F., Faeth, G.M. 1985. Structure of particle-laden jets - measurements and predictions. *AIAA J.* 23, 396-404.

Smith, N.L., Megalos, N.P., Nathan, G.J., Zhang, D.K., Smart, J.P. 1998a. The role of fuel-rich clusters in flame stabilization and NO_x emission reduction with precessing jet pulverized fuel flames. *Twenty-Seventh Symposium (International) on Combustion/The Combustion Institute*, 3173-3179.

Smith, N.L., Megalos, N.P., Nathan, G.J., Zhang, D.K., Smart, J.P. 1998b. Precessing jet burners for stable and low NO, pulverised fuel flames - preliminary results from small-scale trials. *Fuel* 77, 1013-1016.

Smith, N.L. 2000. The influence of the spectrum of jet turbulence on the stability, NO_x emissions and heat release profile of pulverised coal flames, *PhD thesis*, The University of Adelaide.

Smith, N.L., Nathan, G.J., Zhang, D.K., Nobes, D.S. 2002. The Significance of Particle Clustering in Pulverised Coal Flames. *Proceedings of the Combustion Institute* 29, 797-804.

Sorensen, H. 2005. Eksperimentel fluid mechanics, lecture notes from www.iet.aau.dk.

Soteriou, M.C. & Yang, X. 1999. Particle dispersion in variable density and viscosity shear flows. *Physics Fluids* 11, 1373-1386.

Subramanian, V. & Raman, N. 1984. Measurements of velocity and concentration for a 2-phase turbulent jet. *Can. J. Chem. Eng.* 62, 314-318.

Syred, N. 2006. A review of oscillation mechanisms and the role of the precessing vortex core (PVC) in swirl combustion systems. *Prog. Energy Comb. Sci.* 32, 93-161.

Tsuji, Y., Morikawa, Y., Tanaka, T., Karimine, K., Nishida, S. 1988. Measurement of an axisymmetric jet laden with coarse particles. *Int. J. Multiphase Flow* 14, 565-574.

Van de Hulst, H.C. Light scattering by small particles. *Dover Publ. Inc.*, USA

Vernon, C. 2006. Dr James Hansen: can we still avoid dangerous human-made climate change, from energybulletin.net/22996.html

Wall, T.F., Subramanian, V., Howley, P. 1982. An experimental-study of the geometry, mixing and entrainment of particle-laden jets up to 10 diameters from the nozzle. *Trans. Instit. Chem. Eng.* 60, 231-239.

Wark, C., Eickmann, K., Richards, C. 2000. The structure of an acoustically forced, reacting two-phase jet. *Combust. Flame* 120, 539-548.

Wicker, R.B. & Eaton, J.K. 2001. Structure of a swirling, recirculating coaxial free jet and its effect on particle motion. *Int. J. Multiphase Flow* 27, 949-970.

Wong, C.Y., Lanspeary, P.V., Nathan, G.J., Kelso, R.M., O'Doherty, T. 2003. Phase-averaged velocity in a fluidic precessing jet nozzle and in its near external field. *Exp. Thermal Fluid Sci.* 27, 515-524.

Wong, C.Y. 2005. The flow within and in the near external field of a fluidic precessing jet nozzle. PhD. Thesis, Adelaide University

Xu, G., & Antonia, R.A. 2002. Effect of different initial conditions on a turbulent round free jet. *Exp. Fluids* 33, 677-683.