

Final Report for Period: 06/2003 - 05/2006

Submitted on: 06/07/2006

Principal Investigator: Webster, Donald R.

Award ID: 0303406

Organization: GA Tech Res Corp - GIT

Title:

The small-scale structure of the fluctuating passive scalar field in a turbulent boundary layer

Project Participants

Senior Personnel

Name: Webster, Donald

Worked for more than 160 Hours: Yes

Contribution to Project:

Post-doc

Graduate Student

Name: Dasi, L. Prasad

Worked for more than 160 Hours: Yes

Contribution to Project:

Prasad was a graduate research assistant and completed a Ph.D. thesis as part of this project. He designed and constructed the measurement system, collected the data, and performed data analysis. Currently, he is a post-doc in Biomedical Engineering at Georgia Tech.

Name: Schuerg, Frank

Worked for more than 160 Hours: Yes

Contribution to Project:

Frank was a graduate research assistant and completed a M.S. thesis as part of this project. He developed the code to do the fractal dimension analysis of iso-surface contours and performed preliminary calculations. He is currently a Ph.D. student at the Universität Stuttgart in Germany.

Name: Miller, Ronald

Worked for more than 160 Hours: Yes

Contribution to Project:

Ron was a graduate research assistant and completed a M.S. thesis as part of this project. He performed the multipoint correlation function analysis. He is currently employed by Parsons Brinckerhoff, Inc. in Atlanta, GA.

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

Other Collaborators or Contacts

Activities and Findings

Research and Education Activities:

The focus of this study is the scaling behavior of structure functions and the usefulness of multi-point correlation functions for a turbulent passive scalar field. The structure functions, scalar variance spectrum, and multi-point correlation functions are calculated from spatial variations directly. This is a departure from previous studies, which often employed the frozen turbulence approximation to utilize time records of the scalar concentration. In addition, we studied the fractal geometry of concentration iso-surfaces. A box counting algorithm was applied to determine the coverage count for the iso-surface in each image.

Three flows were measured in the flume corresponding to $Re = 5000, 10,000, \text{ and } 20,000$. The turbulent characteristics were fully quantified via high-resolution Particle Tracking Velocimetry (PTV) measurements. The image analysis code was written from scratch and tested extensively. The code follows the basic hybrid PIV-PTV technique described by Cowen & Moinsmith (1997) with improvements added for second order accurate differencing and continuous shifting to minimize peak locking. The mean velocity and Reynolds stress profiles agree very well with previous measurements (via LDV and hotwire anemometry) for similar Re and water depth.

The scalar field was a plume generated by a high Schmidt number dye released iso-kinetically in the inertial layer of a fully developed turbulent boundary layer. Three nozzle diameters (2.2 mm, 4.7 mm, and 9.4 mm) were used to study the effects of the injection length scale on the local structure of the scalar field generated downstream. A high-resolution planar laser induced fluorescence (PLIF) technique recorded long-time series of the concentration along the nozzle centerline in a vertical plane parallel to the flow at six downstream distances. The laser sheet thickness and camera pixel spacing were of the order of the Batchelor length scale, thereby fully resolving the spatial structure.

Findings:

The local structure was found to be far from isotropic and was influenced even at the smallest scales by large-scale anisotropy and the presence of the mean scalar gradient. The local structure was also influenced by the initial injection length scale and the Reynolds number of the flow. The PDF of the scalar fluctuations was found to be non-Gaussian and dependent on large-scale anisotropy. The PDF of scalar gradients showed that the large-scale anisotropy of the scalar field influences the structure at the smallest scales. The spectrum of the scalar field was observed to deviate from the $k^{-5/3}$ prediction in the inertial convection regime due to large-scale anisotropy, external intermittency, and low Reynolds number. For the smallest injection length scale, a cascade bypass was observed with the inertial-convective regime scaling close to k^{-1} . In the viscous-convective regime, there was no evidence of Batchelor's k^{-1} scaling law. The downstream evolution of the scaling exponents of the even-ordered structure functions appeared to be inversely correlated with the skewness and kurtosis of the scalar fluctuations. The saturation of the scaling exponents was stronger with presence of mean-gradients.

The fractal geometry of the two-dimensional transects of passive scalar iso-surfaces was dependent on Reynolds number, injection length scale, and concentration threshold of the iso-surfaces. The iso-surfaces were found to possess scale-dependent geometric properties. The fractal dimension was 1.0 at the smallest length scale and increased in a universal manner to reach a local maximum at a scale around the Kolmogorov length scale. At larger scale the fractal dimension was eventually less than 1.0 due to large scale intermittency. A new parameter, the coverage length underestimate, was found to have universal behavior in the viscous-convective regime and hence was a useful tool for many mixing applications. The lacunarity of the iso-surface structure was introduced to show that the instantaneous scalar field was most in-homogenous around the Kolmogorov scale.

The two-point correlations of the fluctuating scalar field indicated that as the scalar field evolves downstream, the anisotropic influence of the tracer injection method diminished, and the scalar field became dominated by the mean velocity shear. As the scalar filaments aligned with the mean velocity gradient, the elliptical shape associated with the contours of the correlation function tilted in the direction of the mean velocity gradient.

Three-point correlations of the fluctuating scalar field were calculated based on configuration geometries defined by previous researchers. The first configuration follows Mydlarski & Warhaft (1998), who employed two cold-wire measurements and Taylor's frozen turbulence hypothesis. The three-point correlation contours of the concentration fluctuations associated with the cold-wire measurements exhibited a symmetric characteristic V-shape. Similar symmetric properties were observed in the current study. The symmetry associated with well-correlated points was represented by concentric, circular contours, which indicates universal behavior of the fluctuating scalar field for these points. The contours with smaller values retained symmetric properties but developed a concave-sided hexagonal shape that resembles the characteristic V-shape reported in previous research. The second set of configurations followed on recent theoretical predictions, which indicated that the three-point correlation of the fluctuating scalar field was dependent on the size, shape, and orientation of the triangle created by the three points. The current study analyzed two geometric configurations (isosceles and collinear). The geometric configurations were defined to ensure that the influence of the shape remains constant as the configuration was rotated, translated, and dilated. As the isosceles

configuration was rotated, the value of the three-point correlation function remained unchanged. However, as the collinear configuration was rotated, the three-point correlation function varied. Therefore, the influence of the orientation angle between the three-point configuration and the mean concentration gradient varied depending on the specified geometry. Additionally, the scaling exponent in the inertial-convective regime for the dependence of the correlation function on the size of the triangle pattern was calculated. Observations of the three-point correlation function were presented in terms of the scaling exponent associated with triangular sizes in the inertial-convective regime. The scaling exponent remained independent of the orientation angle between the three-point configuration and the mean concentration gradient. At intermediate downstream distances, the scaling exponent appeared dependent on the injection length scale and independent of the Reynolds number.

Training and Development:

The 3 graduate students have received extensive training on state-of-the-art concentration and velocity measurements. The skills developed include laser operation, optics design, digital camera operation, and image processing. All three students also have received training on small-scale turbulence theory. All three students completed a thesis (2 M.S. and 1 Ph.D.) as part of this project.

Outreach Activities:

Dr. Webster has been active in bringing K-12 students to visit the fluid mechanics laboratory each year. We have had Cub Scout dens, Girl Scout troops, and other youth groups visit the laboratory. In addition, the Office of Minority and Special Programs at Georgia Tech organizes visits by Pre-college Engineering Program (PREP) students to the laboratory. The environmental fluid mechanics laboratory is an impressive visual experience for these visitors, which builds interest in engineering in general and fluid mechanics in particular. Dr. Webster has also volunteered to speak to Pre-Engineering Technology (PET) Bridge Program for minority high school students in the Atlanta area.

Journal Publications

L.P. Dasi, F. Schuerg, and D.R. Webster, "The Geometric Properties of High Schmidt Number Passive Scalar Iso-surfaces in Turbulent Boundary Layers", *Journal of Fluid Mechanics*, p. , vol. , (). in modest revision based on reviews

R.J. Miller and D.R. Webster, "Multipoint Correlations of the Concentration Fluctuations Associated with a Turbulent Passive Scalar Field", *Phys. Fluids*, p. , vol. , (). in final edits for submission

L.P. Dasi and D.R. Webster, "One-dimensional Spectral Characteristics of High Schmidt Number Passive Scalar Fields in Turbulent Boundary Layers", *Phys. Fluids*, p. , vol. , (). in preparation

Books or Other One-time Publications

Frank Schuerg, "Fractal Geometry of Iso-surfaces of a Passive Scalar in a Turbulent Boundary Layer", (2003). Thesis, Published Bibliography: M.S. Thesis, Georgia Institute of Technology

L.P. Dasi and D.R. Webster, "Small-scale Characteristics of the Fluctuating Passive Scalar Field in a Turbulent Boundary Layer", (2003). Conference Proceedings, Published Bibliography: 3rd International Symposium on Turbulence and Shear Flow Phenomena, Sendai, Japan

L.P. Dasi and D.R. Webster, "Structure Functions and Multi-point Correlation Functions of a Passive Scalar Field in a Turbulent Boundary Layer", (2003). Conference Proceedings, Published Bibliography: DFD03 Meeting of The American Physical Society, East Rutherford, NJ. Also Bulletin of American Physical Society, Vol. 48, No. 10, p. 186

D.R. Webster and F. Schuerg, "Fractal Geometry of Iso-surfaces of a Passive Scalar in a Turbulent Boundary Layer", (2003). Conference Proceedings, Published Bibliography: DFD03 Meeting of The American Physical Society, East Rutherford, NJ. Also Bulletin of American Physical Society, Vol. 48, No. 10, p. 149

L.P. Dasi and D.R. Webster, "Effect of Intermittency, Initial Conditions, and Large-scale Anisotropy on the Small-scale Structure of a Passive

Scalar Field", (2004). Conference Proceedings, Published

Bibliography: DFD04 Meeting of The American Physical Society, Seattle, WA, November, 2004. Also Bulletin of American Physical Society, Vol. 49, No. 9, p. 146

D.R. Webster, L.P. Dasi, and F. Schuerg, "Scale-dependant Fractal Measures of Iso-surfaces of a Passive Scalar in Turbulent Boundary Layers", (2004). Conference Proceedings, Published

Bibliography: DFD04 Meeting of The American Physical Society, Seattle, WA, November, 2004. Also Bulletin of American Physical Society, Vol. 49, No. 9, p. 146

D.R. Webster and R.J. Miller, "Multi-point Correlation Functions of a Passive Scalar Field in a Turbulent Boundary Layer", (2005). Conference Proceedings, Published

Bibliography: DFD05 Meeting of The American Physical Society, Chicago, IL, November 2005. Also Bulletin of American Physical Society, Vol. 50, No. 9, p. 153

L.P. Dasi and D.R. Webster, "Geometric Characteristics of Passive Scalar Interfaces for Plumes in Turbulent Boundary Layers", (2005). Conference Proceedings, Published

Bibliography: 4th International Symposium on Turbulence and Shear Flow Phenomena, Williamsburg, VA, June 2005.

L.P. Dasi, "The Small-Scale Structure of Passive Scalar Mixing in Turbulent Boundary Layers", (2004). Thesis, Published

Bibliography: Ph.D. Thesis, Georgia Institute of Technology

R.J. Miller, "A Study of Passive Scalar Mixing in Turbulent Boundary Layers using Multipoint Correlators", (2005). Thesis, Published

Bibliography: M.S. Thesis, Georgia Institute of Technology

Web/Internet Site

Other Specific Products

Contributions

Contributions within Discipline:

We have employed a unique approach of using the spatial variation of the concentration field to directly calculate structure functions, scalar variance spectrum, and multipoint correlation functions. Further, we extended previous studies of isotropic turbulence by releasing the scalar in a well-defined velocity gradient, i.e. the inertial layer of a fully developed turbulent boundary layer. The results provide unique insight to concentration fluctuations in turbulent shear flows. The following is a brief list of specific contributions:

Demonstrated the dependence of the tails of the PDFs of scalar fluctuations and scalar gradient on the initial conditions of the plume (i.e. injection size).

Established the dependence of the inertial-convective scaling of the scalar power spectrum on large-scale anisotropy.

Independently confirmed the cascade-bypass phenomena.

Established the absence of Batchelor scaling in the viscous-convective regime for the current flow conditions.

Established the correlation between the structure function scaling exponents and kurtosis of scalar fluctuations.

Established the universality of the coverage dimension and the new parameter, coverage length underestimate, in the viscous-convective regime.

Introduced lacunarity to quantify the in-homogeneity of the concentration isosurfaces.

Verified that the two-point correlation contours of the concentration fluctuations indicate that anisotropic conditions (i.e. the tilted, asymmetric, elliptical shape) develop as a consequence of the mean velocity shear.

Calculated 3-point correlation functions of the fluctuation concentration field without employing the Taylor frozen turbulence hypothesis.

Found that the influence of the orientation angle between the three-point configuration and the mean concentration gradient varies depending on the specified geometry.

Demonstrated that the scaling exponent remains independent of the orientation angle between the three-point configuration and the mean concentration gradient.

Found that at intermediate downstream distances the scaling exponent for three-point correlation functions appears dependent on the injection length scale and independent of the Reynolds number.

Contributions to Other Disciplines:

Contributions to Human Resource Development:

Training for 3 graduate students. Prasad Dasi is currently a post-doc in Biomedical Engineering at Georgia Tech. Frank Schuerg is currently a Ph.D. student at the Universität Stuttgart in Germany. Ron Miller is currently employed by Parsons Brinckerhoff, Inc. in Atlanta, GA.

Contributions to Resources for Research and Education:

Contributions Beyond Science and Engineering:

Categories for which nothing is reported:

Organizational Partners

Any Web/Internet Site

Any Product

Contributions: To Any Other Disciplines

Contributions: To Any Resources for Research and Education

Contributions: To Any Beyond Science and Engineering