FINAL REPORT:RESEARCH ON
TURBULENT
DIFFUSION

U.S. ATOMIC ENERGY COMMISSION

March 16, 1974

Contract No. AT (11-1) - 3284

with the Department of Mechanics and Materials Science
The Johns Hopkins University - Baltimore, Md. 21218

Principal Investigator: Professor Stanley Corrsin

The principal research problems pursued under this contract were

- (a) experiments on a nearly homogeneous turbulent shear flow ,
- (b) experiments on diffusion of scalar contaminant in isotropic turbulence ,
- (c) experiments on diffusion of scalar contaminant in a turbulent boundary layer ,
- (d) computer modeling of diffusion in both isotropic turbulence and homogeneous turbulent shear flow ,
- (e) theoretical analysis of fluid material line growth in homogeneous turbulence ,
- (f) preliminary experimental and theoretical studies of the propagation of a concentration interface across an isotropic turbulence.

The following Ph.D. degrees were earned with dissertations supported by this contract:

J. J. Riley (1971): "Computer Simulations of Turbulent Dispersion. "

D. J. Shlien (1971): "Dispersion Measurements of a Fluid Sheet in Two Turbulent Flows. "

V. G. Harris (1974): "Experimental Studies in a Field of Nearly Homogeneous Sheared Turbulent Flow. "

MASTER

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Others who participated appreciably in the research program were

Professor Stanley Corrsin, Program Director,

Dr. Francis H. Champagne, as a post-doctoral visitor,

Dr. J.A.H. Graham, as a post-doctoral visitor,

Professor John Foss, as a visitor.

Several students assisted at various times.

Publications and reports (other than the three dissertations listed above) on work supported in whole or in part by this contract:

Champagne, F.H., Harris, V. G. and Corrsin, S. (1970) "Experiments

on Nearly Homogeneous Turbulent Shear Flow," Jour. Fluid Mechanics,

41 (1) 81-139 (supported primarily by O.S.R., U.S. Air Force).

Riley, J. and Corrsin, S. (1971) "Simulation and Computation of Dispersion

in Turbulent Shear Flow," Proc. Conf. on Air Pollution Meteorology,

Amer. Met. Soc., 16-21.

Corrsin, S. (1972) "'Backward Diffusion' in Turbulent Flow," Physics of

Fluids, 15, (6), 986-7.

Corrsin, S. (1972) "Simple Proof of Fluid Line Growth in Stationary

Homogeneous Turbulence," Physics of Fluids, 15 (8), 1370-2.

Shlien, D.J. and Corrsin, S. (1974) "A Measurement of Lagrangian

Velocity Autocorrelation in Approximately Isotropic Turbulence,"

Jour. Fluid Mechanics, 62, (2), 255-71.

Riley, J. J. and Corrsin, S. (1974) "The Relation of Turbulent
Diffusivities to Lagrangian Velocity Statistics for the Simplest
Shear Flow," Jour. Geophysical Research, in the press.

The following manuscripts based on work supported in whole or in part
by this contract are in preparation:

Shlien, D.J. and Corrsin, S., " Dispersion Measurements in a Turbulent
Boundary Layer. "

Harris, V.G., Graham, J.A.H. and Corrsin, S., "Measurements on
the Downstream Growing State of a Nearly Homogeneous Turbulent
Shear Flow. "

Foss, J., Corrsin, S. and Shlien, D.J., " Propagation of a weak thermal
interface across isotropic turbulence. "

The research progress contributed by work under this contract can be outlined by the summaries (where they exist) of the "publications and reports" listed above.

- 1) Champagne, F.H., Harris, V. G. and Corrsin, S. (1970), Jour. Fluid Mech. 41 (1) 81-139:

With a transverse array of channels of equal widths but differing resistances, we have generated an improved approximation to spatially homogeneous turbulent shear flow. The scales continue to grow with downstream distance, even in a region where the mean velocity gradient and one-point turbulence moments (component energies and shear stress) have attained essentially constant values. This implies asymptotic non-stationarity in the basic Eulerian frame convected with the mean flow, behaviour which seems to be inherent to homogeneous turbulent shear flow.

Two-point velocity correlations with space separation and with space-time separation yield characteristic departures from isotropy, including clear 'upstream-downstream' unsymmetries which cannot be classified simply as axis tilting of ellipse-like iso-correlation contours.

The high wave-number structure is roughly locally isotropic although the turbulence Reynolds number based on Taylor 'microscale' and r. m. s.

turbulent velocity is only 130. Departures from isotropy in the turbulent velocity gradient moments are measurable.

The approximation to homogeneity permits direct estimation of all components of the turbulent pressure/velocity-gradient tensor, which accounts for inter-component energy transfer and helps to regulate the turbulent shear stress. It is found that its principal axes are aligned with those of the Reynolds stress tensor. Finally, the Rotta (1951, 1962) linear hypothesis for intercomponent energy transfer rate is roughly confirmed.

- 2) Riley, J. and Corrsin, S. (1971), Proc. Conf. on Air Pollution Meteorology, Amer. Met. Soc., 16-21:

The dispersion of fluid material points and of small, "alien" particles on both homogeneous, turbulent shear flows and isotropic turbulence is studied by numerical simulation of the flow field. The method is to set up a mathematical model of the isochoric Eulerian field. Fourier modes are injected at random times, and made to decay in strength and migrate to larger wave numbers by algorithms designed to represent some of the non-linear effects. Numerical values are chosen to approximate experimentally measured Eulerian velocity correlation functions.

Some unrealistic Lagrangian results appear in the isotropic case,

presumably because of the omission of the non-linear mode interaction.

In the shear flow case, however, the mean velocity gradient effect dominates asymptotically, and the model appears to give satisfactory dispersion predictions. Velocity autocorrelations for small solid spheres of density greater than that of the fluid are also computed.

- 3) Corrsin, S. (1972), Physics of Fluids, 15 (6), 986-7:

For homogeneous, unsheared, stationary turbulence, it is shown that the dispersion of starting position $\underline{x}_0$ (at $t = 0$) for an ensemble of material points which arrive at position $\underline{x}$ at time t is equal to the dispersion of material points starting at position $\underline{x}$, in the same time interval. The question is inspected in both Lagrangian and Eulerian frames.

- 4) Corrsin, S. (1972), Physics of Fluids, 15 (8), 1370-2:

With the assumption that two fluid points which are far enough apart move independently in homogeneous, stationary, turbulence, it is inferred that (1) remote points will separate on the average and (2) fluid material lines will lengthen on the average. To prove monotonic line growth an additional assumption is needed.

- 5) Shlien, D.J. and Corrsin, S. (1974), Jour. Fluid Mechanics, 62 (2) 255-71:

By measuring the heat dispersion behind a heated wire stretched across a wind tunnel (Taylor 1921, 1935), the Lagrangian velocity autocorrelation was determined in an approximately isotropic, grid-generated turbulent flow. The techniques were similar to previous ones, but the scatter is less. Assuming self-preservation of the Lagrangian velocity statistics in a form consistent with recent measurements of decay in this flow (Comte-Bellot & Corrsin, 1966, 1971), a stationary and an approximately self-preserving form for the dispersion were derived and approximately verified over the range of the experiment.

Possibly the most important aspect of this experiment is that data were available in the same flow on the simplest Eulerian velocity autocorrelation in time, the correlation at a fixed spatial point translating with the mean flow (Comte-Bellot & Corrsin, 1971). Thus, the Lagrangian velocity autocorrelation coefficient function calculated from the dispersion data could be compared with this corresponding Eulerian function. It was found that the Lagrangian Taylor microscale is very much larger than the analogous Eulerian microscale (76 ms compared with 6.2 ms), contrary to an estimate of Corrsin (1963). The Lagrangian integral time scale is roughly equal to the Eulerian one, being larger by about 25%.

Riley, J.J. and Corrsin, S. (1974), Jour. Geophysical Research. In press:

Assuming that mean turbulent transport can be modelled by a flux-gradient term, the turbulent diffusivities are related to statistical properties of the Lagrangian velocity field for the case of a homogeneous, stationary shear flow. The use of the result in dealing with problems of a more practical nature is discussed.

Shlien, D. J. and Corrsin, S., "Dispersion Measurements in a Turbulent Boundary Layer."

Dispersion in a turbulent boundary layer was measured behind a long heated wire located on the wall, at 1.66 momentum thickness from the wall, in the intermittent region and where the intermittency just equals one. Mean temperature profiles approached an asymptotic shape, independent of the source (tagging wire) distance from the wall. A turbulent Prandtl number, defined by $\left[\frac{U_\infty}{\nu_t} \frac{\partial}{\partial x} \left(\frac{1}{2} \overline{Y^2} \right) \right]^{-1}$ (U_∞ is the free stream velocity, x is downstream distance, $\overline{Y^2}$ the centroid-centered second moment of the mean temperature profile, and ν_t is an average boundary layer eddy viscosity), was approximately equal to the molecular one and thus not far from the "Reynolds analogy" value of 1. Furthermore it was approximately independent of downstream position and showed little variation with source

distance from the wall. Mean wall temperatures (concentrations) as a function of downstream distance were fitted with simple power laws.

Although a basic hypothesis of the theory was contradicted by the data, the constant b in Batchelor's (1959, 1964) theory for the mean particle

displacement perpendicular to the wall was calculated for $y_{tag} = 0$.

It agreed closely with estimates of Ellison (1959) and Pasquill (1966). The restrictions of the theory were not satisfied for the other source positions.

Comparison with Poreh and Cermak's (1964) measurements (of similar Reynolds number) showed some areas of agreement.

Harris, V.G., Graham, J.A.H. and Corrsin, S., "Measurements on the Downstream Growing State of a Nearly Homogeneous Turbulent Shear Flow."

A technique introduced by Champagne, Harris and Corrsin (1970), is used to generate an almost homogeneous, linear mean velocity gradient, turbulent shear flow. The turbulence in this wind tunnel approximation to homogeneous turbulent shear flow is explored, and the resulting measurements are reported.

With the mean strain rate ($d\bar{U}_1/dx_2 \approx 44 \text{ sec}^{-1}$) higher than that reported by Champagne, Harris and Corrsin (1970), as well as other investigators, [Mulhearn and Luxton (1970), and Rose (1966)], it was hoped that questions

concerning the possible existence of an asymptotic state and its nature could be resolved. Indeed the conjecture [Corrsin (1963)], anticipating the continuing growth of scales as well as turbulent energy has been confirmed. In many respects, however, the flow can be considered approximately homogeneous.

Two-point velocity correlation functions and scales were measured, and the correlations of narrow-band-filtered velocity signals. These narrow-band correlations can be interpreted as "sections" at constant wave number when the filter center frequency is adjusted to correct for the accompanying mean velocity difference between horizontal strata with separation in the shear direction.

The two-point isocorrelation contours in the planes parallel to the mean velocity and mean velocity gradient direction appear much more like tilted ellipses than was the case for the low-shear flow reported in Champagne et al. (1970).

Foss, J., Corrsin, S. and Shlien, D.J., "Propagation of a weak thermal interface across isotropic turbulence."

It was discovered by Johnson (1957, 1959) and independently by Nicholl (1958, 1970) that when a fully turbulent boundary layer flows over a step function in mean wall temperature, the downstream temperature

field propagates outward with an instantaneously sharp front, which is contained within, and is well wrinkled by, the random turbulent motion. Presumably this thermal front is partially analogous to the turbulence front at a free stream boundary discovered by Corrsin (1943) and first measured quantitatively by Townsend (1948). A theoretical model of the turbulence (hence vorticity) front as a "laminar superlayer" was proposed by Corrsin and Kistler (1955).

In an attempt to devise the simplest possible front problem, we decided to create & to study a thermal front in isotropic turbulence. The (nearly) isotropic turbulence was generated by a traditional square-mesh, biplane grid placed in a uniform air stream. The thermal front was created by heating the horizontal rods on the upper half of the grid.

The temperature field downstream of the grid was documented in terms of the mean, r. m. s. and intermittency measurements at selected locations. Experimental difficulties disallowed the intermittency measurements except at the nearest location, $x/M = 56$; consequently, a comprehensive examination of the thermal front was frustrated.* However, the available results have been interpreted in such a manner that the effects of molecular diffusivity in this turbulent mixing problem are clarified. These effects are quite significant as regards the detailed structure of the temperature field although their effects on the mean temperature are quite small, as could be

* x is downstream distance from grid; M is grid mesh size.

anticipated.

The behavior of the mean temperature distribution in this half-heated grid flow may be described by the postulate of a dominant turbulent transport mechanism ($k_T/k \gtrsim 40$ ^{*}). The r.m.s. temperature distribution and the behavior of the thermal superlayer (the surface separating ambient and heated fluid) demonstrate the pronounced importance of the molecular diffusivity. An analytical formulation for the temperature probability density function has proved useful in the assessment of the molecular diffusivity effects and the interpretation of the experimental observations.

*

k_T is "turbulent diffusivity"; k is molecular diffusivity.