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Experimental Studies of Reynolds Number Dependence of Turbulent Mixing and Transport

by

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Summary

Predicting turbulent mixing and transport remains a critical problem in industrial flows (combustion chambers, mixers, ventilation systems etc.) and in the environment (smoke plumes etc.). The mixing and transport processes are often a strong function of Reynolds number (Re) and yet there is a paucity of information on their Re dependence. Here we propose experiments of passive scalar mixing in isotropic grid turbulence whereby the Taylor Reynolds number (R_λ) will be varied from 30 to over 400 ($60 < R_\lambda < 10,000$). We will achieve the high R_λ by means of an active grid, which consists of grid bars with small wings that rotate and flap in a random way. We propose to study basic statistics (pdf, spectra etc.) of a homogeneous passive scalar (linear mean profile,) as well as of an inhomogeneous scalar (passive line source) as a function of Re . There are many problems concerning the nature of the fine scale structure of a scalar (eg. the existence of derivative skewness, the relation of the scalar spectrum to the velocity spectrum, and the rate of spreading (dispersion) of a contaminant plume), placing the similarity theory developed over the past 40 years in doubt, yet there is no information concerning its Reynolds number dependence in isotropic turbulence. The passive scalar will be temperature, although some experiments will be done using helium (which has a Schmidt number of 0.23). Particular emphasis will be placed on higher order statistics of both the signal and its derivative. Our experiments will be related to theory and modelling and to recent advances in Direct Numerical Simulations. We will also do further work on mixing in a jet (also as a function of Re) and will relate this work to the (shearless) grid turbulence. The duration of the proposed research is three years.

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1 Introduction

The Kolmogorov phenomenological model of turbulence, postulating an inertial (almost dissipationless) cascade and isotropy of the small scales, is well established and there is sufficient evidence that the resulting scaling is approximately correct, although the details of the dynamics are still not understood (see Kraichnan, 1991, and the other papers in the special issue of the Proceedings of the Royal Society, commemorating the 50th anniversary of Kolmogorov's original paper). Apart from providing essential guidance in reporting experimental results, it has played a key role in modelling and simulations. For example, Large Eddy Simulation (LES) is based on the ability to model the small scales *à la* Kolmogorov (Reynolds, 1990).

Soon after Kolmogorov stated his similarity arguments, Corrsin (1951) and Obukhov (1949) independently extended the theory to the case of a passive scalar advected and smeared by the velocity field. For a fluid of unity Prandtl or Schmidt number (the main case to be considered is this proposal), there were no surprises. For example, the similarity arguments, assuming local isotropy of the scalar field, showed that spectrum of the scalar was similar to that of velocity, both exhibiting a power law exponent of $-5/3$ in the inertial subrange. Thus there was good cause to believe that the details of the structure of the scalar field would follow automatically with better understanding of the velocity, and that investigation of the scalar would not supply of itself, anything fundamentally new about the structure of the velocity field. However in recent years, we have found that almost the opposite is true: experiments have shown that the scalar field exhibits more anomalies than the velocity field when cast in the light of Kolmogorov-Obukhov-Corrsin (KOC) similarity theory (Sreenivasan, 1991, Holzer and Siggia, 1993) and moreover, the scalar is proving to be an exquisitely sensitive detector of the structure of the turbulence itself, revealing subtle aspects of its behavior.

There appear to be two basic ways in which the passive scalar field departs from KOC predictions. First, there is persistent skewness of the temperature derivative in the direction of the mean gradient, even at high Reynolds numbers, violating the postulate of isotropy of the small scales. This characteristic has been studied in most detail in shear flows with nonlinear mean temperature profiles (see Sreenivasan, 1991, for a summary of the various experiments done in jets, wakes and boundary layers), but has also been observed in isotropic grid turbulence with a linear mean profile (Budwig et al. 1985; Thoroddsen and Van Atta, 1992), although there is no information on Reynolds number dependence for this case. Secondly, for isotropic turbulence the scalar spectrum shows a power law behavior well before its appearance in the velocity spectrum. In particular, for a linear mean profile in isotropic low Reynolds number grid turbulence (Jayesh, Tong and Warhaft, 1994), the power law exponent of the spectrum and its dilation with Reynolds number is quite consistent with KOC predictions, although there is a lack of local isotropy of the scalar field and the requirement of high Reynolds number is violated (there is considerable overlap between the integral and dissipation scale spectra). No similar such scaling is observed in the velocity field suggesting that a simple explanation of the observed scalar spectrum using KOC arguments is unlikely. On the other hand, for shearflows the opposite holds. Here inertial subrange scaling occurs first for the velocity field (Sreenivasan, 1991). Added to these departures from expected KOC behavior are two further anomalies; the existence (under certain conditions) of broad, exponential tails in the scalar probability density function in a velocity field that is (one point) Gaussian (Jayesh and Warhaft, 1991, 1992; Gollub et al. 1991), and stronger kurtosis in the scalar derivative than the velocity derivative (Mestayer, 1982), suggesting the scalar is more intermittent at the small scale than velocity. These aspects, while not in any obvious violation of KOC theory, also suggest that the scalar field cannot be explained in an analogous way to the velocity field. As Holzer and Siggia (1993) have recently pointed out, while the above experimental results show significant deriations from theoretical predictions, they

do not yet point to a new or refined theory.

The KOC theory is based on the assumption of very large Reynolds numbers while the Re obtainable in controlled laboratory experiments is moderate. Understanding these laboratory flows is, of course, our main concern since they pertain to the real problems of mixing (etc.) that need solving. Moreover, as Kraichnan (1991) has recently stated, moderate Reynolds number flows have their own rich and interesting structures. Yet to understand these flows it is vital to determine how their structure and statistics vary with Reynolds number. From this we may be able to determine how the flow approaches the high Reynolds number limit. On the other hand knowing the detailed structure of a flow at one Re tells us little.

In terms of basic flows, we have scanty evidence for how passive scalar statistics vary with Re . For instance, one of the most studied statistics is the scalar derivative skewness, S_θ (which should be zero on the basis of local isotropy and symmetry). However a compilation of existing shear flow data shows persistent skewness (of around 0.8) even to very high R_λ for various shear flows (Sreenivasan, 1991). While S_θ is definitely not zero, the data is too scattered to properly determine a trend. As Sreenivasan points out "Clearly a result of this importance deserves to be based on more satisfactory data obtained in better-controlled circumstances". At the more basic level of isotropic, shearless turbulence, there is no data at all concerning Reynolds number dependence of scalar mixing (apart from our preliminary work to be described below).

The major objective of the experiments to be described in this proposal is to study scalar transport and mixing as a function of Reynolds number. The velocity field will be isotropic and homogeneous while the scalar field will be either homogeneous (fluctuations with or without a mean scalar gradient) or inhomogeneous (heated line source). By means of a specially constructed active grid (see below), and also by modifications of existing wind tunnels, we intend to vary $R_\lambda (\equiv u\lambda/\nu$ where u is the velocity rms, λ is the Taylor micro-scale and ν is the viscosity) from approximately 30 to over 400. This corresponds to a

variation of the turbulence Reynolds number, $Re(\equiv u\ell/\nu$ where ℓ is the integral scale) from approximately 50 to 10,000. We believe (see below) this Reynolds number range will provide strong evidence for asymptotic values of Re while at the same time cover the main range of Re relevant to practical mixing problems. Our results will have direct bearing on modelling and simulations (see below) and will provide a point of reference for direct simulations that are now beginning to examine Re dependence in basic flows. I emphasize that at present there appears to be no other work on Re dependence of scalar mixing in such basic flows.

I am well aware of the strides that are being made in direct numerical simulations and wish neither to compete or suggest that they are less important than experiment. However experiment is necessary, providing a different perspective. The two approaches are complimentary and different results are sometimes achieved when the same problem is explored. We will return to this below. At present, DNS can achieve an R_λ of around 150-200 in simple homogeneous flows, (eg. She *et. al.* 1993) about the same value as experiment using conventional techniques. The lattice size goes up approximately linearly with R_λ and thus the next generation of machines (1024 nodes) may be in the range $300 < R_\lambda < 400$. These may, if priority is given to scalar mixing, provide corroborative results for the proposed homogeneous experiments but the inhomogeneous experiments will still be out of reach.

While the main thrust of the proposal is to study scalar mixing in grid turbulence, we will be doing parallel experiments of scalar mixing (again, varying the Re) in a jet, thereby extending our earlier work in this subject (see below). The jet experiments will provide a contrast to the isotropic flow measurements and from these we may determine which characteristics are solely confined to shear flows, and which are common both to sheared and unsheared flows. Some measurements will also be done using helium as the passive scalar, providing a way of investigating Schmidt number effects over a limited range.

The work we propose is of a fundamental nature. However we believe it will have direct bearing on the modelling of mixing and combustion processes. Both are dependent on the

details of the fine scale structure, where interaction at the molecular level begins to take place. Lack of isotropy of the scalar at the small scales implies that, for example, LES modelling will have to be modified if it is to work correctly. Scalar mixing involves dispersion and as has been shown (e.g. Pope, 1994), such processes are extremely Reynolds number dependent. At present there is virtually no experimental data to base these models on. The relation of our proposal to modelling will be further discussed in Section 4.

2 Experimental Technique

The main set of experiments will be done in existing wind tunnels and jet facilities. However we wish to design and construct an active turbulence grid, as well as increase the speed (and mesh size) of our largest tunnel in order to achieve the R_λ mentioned in the introduction.

The problem with conventional (bi-planar, *passive* grids) is that the turbulence intensity is low ($< 5\%$). Thus although the flow is homogeneous and close to isotropic, the relatively low value of u (the rms velocity) precludes high turbulence Reynolds numbers. Many years ago, Corrsin suggested placing propellers on the grid to increase u but it is unclear whether this was implemented (Lumley, private communication). Gad El Hak and Corrsin (1974) did publish work on a grid with jets, but this only modestly increased the R_λ . There have been attempts to construct active grids (Ling and Wan, 1972) again with limited success. However a significant advance has been made recently at the Department of Energy in Japan by Makita (1991). He designed, constructed and tested an active bi-plane grid with randomly vibrated agitator wings. The results are particularly encouraging: in a tunnel of only $0.7 \times 0.7 \text{ m}^2$, Makita achieved an R_λ of nearly 400, with the isotropy of the fluctuations comparable to that observed in conventional grid turbulence ($u/v \sim 1.2$ compared to 1.1 with passive grids. Here u is the longitudinal rms and v is the lateral). The pdf's of the velocity and its derivatives were well behaved and the spectrum showed two decades of inertial subrange,

with a slope close to $-5/3$. Our objective is to follow the broad design of Makita, adapting it to our larger wind tunnel, and to the study of scalar mixing.

Briefly, Makita places agitator wings on each grid mesh. The wings are triangular in shape. A regular pulse generator rotates the grid bars (and hence the wings) and at the same time the motor is fed by a random pulse which reverses the rotation of the grid bar. Thus the wing always in rotational motion, reverses its direction randomly, providing a flapping motion. Each bar is separately controlled, providing random flapping between bars. The rotation speed of the bars was fixed but this must depend on the mean velocity. Makita had a rotation speed of 2 Hz and a mean speed, U , of 5 m/s. The turbulence downstream ($x/M = 50$), had a length scale ℓ , of 19.7 cm although the mesh size, M , was only 4.7 cm (in conventional grid turbulence $\ell \sim M$). (Makita thinks that the spectral slope of slightly less than $-5/3$ that he observed, was due to the large eddies being approximately the same size as the wind tunnel; such a problem will not occur in our design (see below).) The Kolmogorov scale, η , was decreased from 0.65 mm to 0.21 mm using the active grid.

Our design calls for an active grid for our large, $0.91 \times 0.91 \text{ m}^2$ and 9.0 m long wind tunnel. The mesh length will be 5.1 cm, giving a grid of 18 M square. We intend initially to work with velocities of around 4–7 m/s but plan also for higher speeds (see below). We suspect we will be able to achieve an R_λ well over 400 and possibly in the 500 to 600 range. Our large tunnel cross section will, we hope, alleviate the difficulty encountered by Makita of the largest eddies being truncated by the tunnel cross section. We will also design into our plan the ability to reduce the mesh size if necessary. The design entails 36 separate motor drivers and controllers but these are standard items and should not present any problems. We note that the high turbulence intensity (of around 16%) that the active grid will produce, will allow us to have extremely good turbulence levels very far downstream. Our tunnel will be at least 180 M long and at this downstream distance conventional grid turbulence intensity levels are very low. The high signal to noise ratio at large x/M will be of particular

importance when studying the asymptotic behavior of line sources.

We also wish to upgrade our large wind tunnel. The tunnel was built primarily to study stratified flows and we did not provide it with a high powered motor. In order to extend our Reynolds numbers range for static grids, we wish to increase the maximum speed of the tunnel from 8 m/s to 20 m/s. This should yield an R_ℓ of around 3000 using a large (13 cm) grid. This will be nearly one-third the value obtainable from the active grid and will provide validation of some of the results. We also have room to increase the length of the tunnel by 3.0 m. This will provide a maximum x/M of 230 with the active grid, but over 400 if we reduce the mesh size of the grid by 2.

3 The Experiments

3.1 Homogeneous thermal field

We will mainly be interested in experiments with a mean scalar gradient but work will also be done with scalar fluctuations without a mean gradient. The scalar will be temperature and techniques for generating the thermal fields are standard (Warhaft and Lumley, 1978; Sirivat and Warhaft, 1983).

The two main statistical descriptors of turbulent fields are the spectrum and the pdf. Both have been incorporated into the physical way we describe and characterize turbulence. Thus the Kolmogorov theory is enunciated in terms of structure functions (related to the spectrum by the Fourier transform) and the Navier-Stokes equations are written in both spectral form (Batchelor, 1953) and in pdf form (e.g. Pope, 1985) as a prelude to turbulence modelling. Yet, as discussed in the introduction, it is remarkable how tenuous our knowledge of the pdf and spectrum is for a scalar.

Although traditionally somewhat neglected in comparison with the spectrum, the scalar pdf has received much attention recently; theoretically (Chen, Chen and Kraichnan, 1989,

Punir et al., 1991; O'Brien and Jiang, 1991; Kerstein, 1991; Pope and Ching, 1993), experimentally (Castaing et al, 1989; Jayesh and Warhaft, 1991, 1992; Gollub et al., 1991) and computationally (Erswaran and Pope, 1988; Holzer and Siggia, 1993; Kerstein, 1991; Metais and Lesieur, 1992). The form of the scalar pdf determines the conditional dissipation in the pdf scalar equation (Pope, 1985) and "closure" cannot be obtained unless this is known. Our recent experiments have shown (Jayesh and Warhaft, 1992) that for $R_\ell > 70$ the pdf has broad, exponential tails; below this the pdf is purely Gaussian. The scalar dissipation rate, conditioned on the fluctuations, shows there is a high expectation of dissipation in the presence of the large, rare fluctuations that produce the exponential tails. We also showed that the velocity pdf is Gaussian at all R_ℓ . These were the first experiments to study the nature of the pdf of a scalar and its conditional dissipation as a function of R_ℓ for passive flows.

More recently we have begun to systematically study the pdf of the scalar derivative, particularly in the presence of a mean temperature gradient, in grid turbulence. Our preliminary results show the existence of a strong skewness of the temperature derivative in the direction of the gradient (Tong and Warhaft, 1994). Its value is 1.6 (approximately twice as high as in shear flows. We have found that its value is insensitive to Reynolds number over the range, $50 < R_\ell < 1,000$. We are unsure how robust this finding is and we wish to extend the measurements to higher R_ℓ using the active grid. It is remarkable that grid turbulence shows high derivative skewness and a proper explanation is wanting. Budwig et al., (1985) and Thorodsen and Van Atta (1991) provide simple (Reynolds number independent) models. More recently Holzer and Siggia (1993) have used 2D numerical simulations to show that the velocity field in grid turbulence exhibits a similar topology to that observed in shear flows. Thus, they show there are rare events of converging and diverging separatrix and when they occur in the presence of the mean temperature gradient, a "cliff" occurs, providing the skewness. It may have been conjectured that these structures were generic

only to shear flows (occurring, as they do there, in the direction of the principal strain rate). What Holzer and Siggia are showing is that they are a very basic property of turbulence in general. However there are many basic aspects as well as details to be worked out. These include their frequency of occurrence and their relation to the dynamics of the rest of the flow field. Here the study of the scalar trace will play a key role. Thus we believe our investigation could have ramifications, not only to an understanding of the scalar field, but for the velocity field too. In this work we are collaborating closely with Siggia (Physics, Cornell). Apart from measuring derivative skewness we will also determine other relevant statistics (transverse and longitudinal structure functions and spectra as well as higher order statistics).

We now turn to the temperature spectrum, a traditionally more studied statistic, although here too there are basic problems to be addressed concerning its Reynolds number dependence. Recently we have found (Jayesh, Tong and Warhaft, 1994), over a limited Re range ($50 < Re < 1000$), that the scalar spectrum shows odd behavior when compared with the velocity spectrum. With a linear profile, it is "too well" behaved, showing a quasi-inertial subrange which has the correct dilation with Reynolds number, while violating isotropy and large separation of scales required by KOC theory. The velocity field shows no such behavior. Moreover when the scalar is inserted into the flow in the absence of a gradient, its scaling region is dependent on whether the scalar is inserted at the grid or downstream, showing a scaling region of close to $-5/3$ for the former but more like $-4/3$ for the latter. The velocity field initially shows no scaling, and when it does (at higher Re than for the scalar) it exhibits a scaling region of $-4/3$. (Our experiments are quite clean enough to discern the difference in the slopes.) Clearly, the velocity field must, at some Re (probably around $Re \sim 300-400$, Makita, (1991), Kistler and Vrebalovich, (1966)) exhibit a $-5/3$ scaling region. Thus our experiments, while resolving the low Re behavior ($30 < Re < 150$) fall short of what is an important limit (of $Re \sim 400$) in grid turbulence. Here we expect the Peclet will be

high enough to show reasonable separation of scales of the scalar field too. By going to this R_λ we feel we will be able to determine more about the pathology of the spectrum at the lower Reynolds numbers and resolve the issues discussed above (see also Jayesh, Tong and Warhaft, 1994).

We note that in direct numerical simulations the behavior of the temperature spectrum is still far from being consistent with the experimental findings. Thus, although the “anomalous” $-5/3$ region has been observed, Metais and Lesieur (1992) also show an extended -1 range that is not evident in our experiments. As mentioned in the introduction, we believe that both experiment and theory are necessary in basic studies of turbulence.

In summary, we propose to do the first comprehensive set of scalar measurements of spectra and pdf's in as a function of Reynolds number in homogeneous turbulence, over the range, $30 < R_\lambda < 400$. We will be covering new ground and anticipate new and interesting results that will elucidate basic physical processes. We will also be providing a broad data base for analysis of statistics other than the pdf and spectrum.

3.2 Inhomogeneous scalar fields: the thermal line source

One of the simplest (and oldest) passive scalar experiments is the evolution of a scalar emanating from a fine line (or point source) in isotropic turbulence. The heated line source has received the most attention (Taylor, 1921; Townsend, 1954; Uberoi and Corrsin, 1953; Warhaft, 1984; Stapountzis et. al., 1986). The thermal field goes through three stages of evolution: molecular diffusive (close to the source), turbulent convective and finally turbulent diffusive (e.g. Warhaft, 1984). Although the scalar here is apparently a very simple inhomogeneous field, modelling is difficult. For example, there are no predictions for the evolution of the scalar variance although pdf methods (Anand and Pope, 1985) have been successful with the mean field. There are also some basic questions that have not been answered from either the theoretical or experimental viewpoint. For example, the far field state is uncer-

tain: does the ratio of the rms to mean temperature asymptote to zero or to some constant positive value? The answer to this question has practical as well as basic ramifications since a heated line source, although very much more simple, has much in common with a smoke stack, especially in the far field, when both are neutrally buoyant. We believe we will be in an excellent position to address this issue with our active grid.

The Reynolds number dependence of the evolution of a line source has not been addressed at all. (All the above experiments are for one flow condition only, and they are all approximately the same Reynolds number ($R_\lambda \sim 50$)). Predictions using pdf methods (Pope, 1994) and Lagrangian stochastic models (Sawford, 1991) suggest there is a strong dependence on Reynolds number. For example, it has been found (Yeung and Pope, 1989) that Lagrangian statistics are much more dependent on Reynolds number than are Eulerian and that the "constants" relating acceleration fluctuations to the variance, and the structure function to time increment, are strong functions of Reynolds number in the Lagrangian framework (Sawford, 1991, Pope, 1994). Parameterizing a line source is a Lagrangian problem and cannot be done unless the above "constants" are known as a function of Reynolds number. They can be obtained by observing the spreading rate of the mean and variance of a passive line source as a function of Reynolds number.

Our experiment will be an extension of Warhaft, 1984, using the active grid to vary the Reynolds number. As mentioned above, the high turbulence intensity will provide high signal to noise far downstream, where previous work with passive grids has suffered. As for the homogeneous experiments, we feel that apart from providing data for modelling we will provide new insights into the physics of this problem. It will be particularly interesting to see whether the predictions of Sawford and Pope discussed above are consistent with experiment.

3.3 Other related experiments

While 3.1 and 3.2 outline the main thrust of our proposal, we have in mind a number of related experiments that may assume a greater or lesser role as the work unfolds. These will be briefly outlined:

- a) **Use a helium as a passive scalar with a lower Schmidt number (0.23):** Over the years we have used and further developed the "Way-Libby" interference probe to measure helium fluctuations in air (Way and Libby, 1970, 1971). We are in the process of beginning further experiments using this probe, to study a buoyant smoke stack (proposal submitted to EPA, 1993). In Sirivat and Warhaft (1992) we did observe a small Schmidt number effect on the decay of helium fluctuations and it would be interesting to see if we observe such effects in the above experiments, particularly in the form of the derivative skewness and spectrum.
- b) **Use of a passive thermal mixing layer to study S_θ .** As mentioned in 3.1, we have observed values of 1.6 for the value of the temperature derivative skewness in the direction of the mean (linear) temperature gradient. This is double the value observed in shear flows (Figure 1). By studying a passive temperature step in grid turbulence (LaRue and Libby, 1981, Ma and Warhaft, 1986) we will have a non-linear (error function) mean profile for the scalar. Off center, the cross correlation between vertical velocity and temperature, $\rho_{v\theta}$, will be reduced (from -0.7 in the center, which is higher than observed in complex shear flows). We suspect that S_θ may be a function of $\rho_{v\theta}$ and this flow will provide the test. It will provide the bridge from experiment 3.1 (isotropic turbulence, homogeneous scalar) to shear flows (inhomogeneous velocity and scalar). Here the velocity field will be homogeneous but the scalar will not. Other forms of the mean temperature profile will also be studied.

c) **Continuation of our scalar mixing studies in a turbulent jet.** We are completing our experiments on turbulent dispersion (from a fine, heated circular source) in a jet. (See summary, Section 8.) In the course of this work we have become aware of shortcomings in our understanding of the conditional dissipation of the scalar. This is a vital statistic in modelling the terms in the pdf equation (Pope, 1985). We intend to do further measurements of this and related quantities using both a heated jet and the fine heated ring. We will also attempt to determine the existing sources of scatter in S_θ for the jet. This experiment is in place, no development is necessary.

4 Relation to Theory and Modelling

Our primary objective in carrying out the above experiments is not to relate a particular experiment to a particular model or theory. It is two-fold. First, it is to provide motivation for theory, modelling and computation and secondly, it is to provide tests for the broader basis of particular models and theory. Above, we have mentioned pdf modelling, Lagrangian Stochastic Modelling, Large Eddy Simulation. To this we may add Linear Eddy Modelling (Kerstein, 1991) and Mapping Closures (Kraichnan, 1991). There are many others. In all these models there are either free parameters that must be determined from experiment or implied mechanisms that can be verified experimentally. (Many of the parameters and mechanisms are common to more than one model.) Thus in LES the inertial cascade and local isotropy is a central mechanism while in Lagrangian dispersion there are model constants. In designing our experiments we have been cognisant of the issues and problems raised by the above models, and in many cases we have discussed these with the principal workers in each area.

From the viewpoint of computing there appear to be two main issues. First, DNS, although expensive, is becoming a powerful tool. Ultimately it will be more useful than

experiment for some problems. We believe for the homogeneous measurements described above, there is still need for both DNS and experiment. Initial and boundary conditions have subtle (and sometimes not so subtle) differences in each case, and at the moment there are inconsistencies that need resolution. For example, DNS of the scalar pdf show exponential tails without a mean gradient, while experiment shows the scalar pdf is close to Gaussian for this case (Métais and Lesieur, 1992, Jayesh and Warhaft, 1992). There are also differences in the scalar spectrum. For the inhomogeneous scalar (the line source experiment) there is (and will be for the foreseeable future) a Reynolds number limitation since the scalar is injected at a scale smaller than the Kolmogorov scale and spreads to scales greater than that of the integral scale of the turbulence.

Secondly, there is another class of turbulence simulation whereby the turbulence is generated by means of a synthetic forced field that does not mimic all of the turbulence characteristics. A recent example is the method of Holzer and Siggia (1993) who generate a two-dimensional turbulence field by means of an Orstein-Uhlenbeck process. This turbulence has pathological properties (for example it is not Galilean invariant) yet it appears to be a useful tool for studying scalars. Such investigations can provide greater details of the flow field than experiment but clearly, they must be checked and verified experimentally.

5 Facilities and Equipment

The experiments will be carried out in our two existing wind tunnels and in our jet facility. Our main capital expenditure will be for the construction of the new active grid and for modification of our large (0.91 x 0.91 x 9.1m) tunnel.

The construction of the active grid will require a substantial design and testing effort, involving 36 translator drivers and stepping motors. These will be driven by power supplies (2) and random noise generators. The cost of the grid will be approximately \$15,000. The

cost of a new blower will be \$4,600, and the cost of extending the wind tunnel will be \$2,000.

We also wish to provide feedback control for the heating elements in our large wind tunnel. At the moment "tunning" the flow can take 10 hours to achieve the required flow conditions. We wish to construct a heater feedback control unit to regulate the mean temperature profiles automatically. The cost will be \$3,600. A new power supply for our smoke visualization as well as for driving the thermal source is also requested (\$3,850.00).

We have also requested a small amount of new test gear and probe holders (\$3,225).

6 Personnel

One graduate student will do the experiments under the direction of the P.I. Three months support for Mr. Edward Jordan our research support specialist is also requested. We also wish to involve some undergraduate students in the design and testing stages of the project.

7 Timetable

We anticipate that it will take about a year to build the active grid and test it. During this first year we wish to finish our work on jet mixing, with particular emphasis on conditional dissipation and pdf measurements. The second and third years will be mainly devoted to the active grid measurements (and the related experiments (3.3, above)).

8 Current and Pending Research Support

- 1 DOE, Basic Energy Sciences "Experiments in Turbulent Mixing and Transport" (DEFC02 - 88ER13929) 3 years, expires 6/30/94. \$318,000. The present proposal is for a continuation of this research.

2 Environmental Protection Agency. Exploratory Research Fund. "Wind Tunnel Experiments of Smokestack Plume Evolution in Stable Thermal Stratifications. \$380,367. 3 years. Pending. (Submitted June 1993)

9 Research over the previous grant period (July 1991 - present)

We completed a study of the pdf of passive temperature fluctuations in grid turbulence and found that in the presence of a mean gradient the scalar pdf has exponential tails while the velocity field is Gaussian. The conditional dissipation was also determined. These are the first such experiments in grid turbulence. We have also investigated the nature of the scalar spectrum for the same conditions as the pdf. Our experiment on mixing across a shearless stably stratified density interface has also been completed. Here the density interface was located at the interface of strong and weak turbulence generated by a composite grid (Veeravalli and Warhaft JFM, **207** (1989)). We have found strong counter-gradient heat and energy flux regions within the layer and that in contrast with the passive case, large scale intermittent penetration (and transport) plays no role.

The turbulent jet experiment is near completion. The first part, concerning the action of the fine wire ring on the jet itself, is in press. We found that the fine ring drastically suppresses the turbulence (reducing the intensity by 30%). The main part of the experiment, scalar dispersion and mixing in the jet, is in final preparation. This is a jet analogue of a line source in grid turbulence, but here the source is a fine ring. It is the first such study of scalar dispersion in a jet. Finally, we have carried our experiments concerning the scalar derivative skewness along a mean temperature gradient. The results over a limited Re range are provocative and have motivated part of the present proposal.

During the grant period Jayesh finished his Ph.D (Sept. 1993). We also purchased and

brought on-line the Macintosh Quadra data acquisition system, replacing our Micro-Vax II.

Publications and presentations over the grant period are as follows:

a Publications

Jayesh, K. Yoon and Z. Warhaft, 1991, "Turbulent Mixing and Transport in a Thermally Stratified Layer Formed in Decaying Grid Turbulence," *Physics of Fluids A* **3** (5), pp 1143-1155.

Jayesh and Z. Warhaft, 1991, "Probability distribution of a passive scalar in grid-generated turbulence," *Physical Review Letters*, **67**, No. 25, pp 3503-3506.

Warhaft, Z., 1992, "Some preliminary experiments concerning thermal dispersion in a jet," in *Studies in turbulence: In recognition of Contributions by John Lumley*, ed. T.B. Gatski, S. Sarkar and C.G. Speziale, Springer-Verlag, Berlin.

Jayesh and Z. Warhaft, 1992, "Probability distribution, conditional dissipation and transport of passive temperature fluctuations in grid-generated turbulence," *Physics of Fluids A*, **4** (10) pp 2292-2307.

Jayesh, C. Tong and Z. Warhaft, 1994, "On temperature spectra in grid turbulence," *Physics of Fluids A*. (In press.) (to be published January, 1994).

Tong, C. and Z. Warhaft, 1994, "Turbulence Suppression in a Jet by Means of a Fine Ring," *Physics of Fluids A*. (In press.) (to be published January, 1994).

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11. Biographical Information

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