The structure of turbulent channel flow with passive scalar transport

By Y. Guezennecc, D. Stretch2 & J. Kim3

The simulations of a turbulent channel flow with various passive markers were examined to investigate the local mechanisms of passive scalar transport. We found significant differences between the local transport of heat and momentum, even when the molecular and turbulent Prandtl numbers are of order one. These discrepancies can be attributed to the role of the pressure. We also found that the heat is a poor marker of the vorticity field outside of the near wall region and that scalar transport over significant distances results from the aggregate effect of many turbulent eddies.

1. Introduction

Our objective was to make use of the direct numerical simulations of a turbulent channel flow with passive scalars (Kim & Moin, 1989) to investigate the relationship between the transport of a passive scalar and the underlying turbulent eddy structures. Specifically, our objectives were fourfold:

1. The validation of experimental techniques such as heat tagging and smoke visualization often used by experimentalists to “mark” turbulent structures.
2. The investigation of the role of the coherent structures in a turbulent channel flow for the transport of a passive scalar.
3. The modeling of the scalar transport based on the mechanistic understanding of the coherent structures.
4. The study of the interaction between large scales and the wall layer, and the relation, if any, between the two wall layers.

The data bases examined were those described by Kim & Moin (1989), with additional cases subsequently obtained by J. Kim. More specifically, all cases correspond to a turbulent channel flow at a Reynolds number $Re_c = 180$ with fully developed hydrodynamics. The simulations were performed with three scalars simultaneously with $Pr = 0.1, 0.7$ and $2.0$, respectively. For this study, we concentrated our efforts on the $Pr = 0.7$ case unless otherwise noted. The various simulations differed by their boundary conditions for the thermal field and the state of their thermal development. Case I corresponded to a fully developed thermal field with uniform heat generation throughout the channel and both walls cold. Case II corresponded

1 The Ohio State University
2 Center for Turbulence Research
3 NASA Ames Research Center
to a fully developed thermal field with one hot wall and one cold wall. It was chosen because the average heat flux remains constant at any distance from the wall. The remaining three cases were time developing thermal fields, with time history available with a time spacing $\Delta t^+ = 3$. Case III corresponds to a cold channel flow where one wall was suddenly heated at $t = 0$. Case IV was similar but with a heat source at the center line instead of a hot wall and Case V was similar to Case III with one wall heated and the other cooled. These latter three cases were intended for the study of the development of the thermal field and for using the heat as a marker to study the interaction between various regions of the flow.

The notation used in this report is as follows: $u$, $v$, $w$ denote streamwise, vertical and spanwise velocity fluctuations respectively. In the text $\theta$ is used to denote temperature fluctuations while the character $t$ is used for temperature in the diagrams.

2. Validation of the Heat as a Marker of Vorticity

The underlying motivation for this task is the extensive use by experimentalists of passive markers (heat, smoke or dye) to study the structure of turbulent wall bounded flows. We wanted to investigate what the scalar really marks and how that varies with the distance from the wall. To address this important question, we correlated the temperature field (or the gradients of the temperature field) with various components of the vorticity or enstrophy field. Not only did we examine pointwise correlation coefficients but also conditional correlation coefficients and spatial correlations. The data from case II were used for this investigation.

Case II

![Figure 1](image.png)

**Figure 1.** Conditional correlation coefficients between the temperature and the vorticity magnitude as a function of the distance from the wall. Temperature thresholds are $-\sigma_\theta$, $0$, $\sigma_\theta$, $2\sigma_\theta$, $-\sigma_\theta$, $-2\sigma_\theta$.

Figure 1 shows a sample of the results where the temperature fluctuations were correlated pointwise with the magnitude of the vorticity vector. The various curves
Structure of turbulent channel flow with passive scalar transport
correspond to different threshold values on the temperature fluctuations: a threshold of zero is an unconditional correlation, whereas non-zero values correspond to correlation coefficients conditional on the temperature exceeding that threshold value. It can be noted that very near the wall ($y^+ < 15$), there is a strong negative correlation between the temperature and the vorticity magnitude. This is linked to the fact that the largest contribution to the vorticity fluctuation comes from the $\nu'$ fluctuations which are strongly correlated with the temperature (see figure 2). In that region, the conditioning on strong temperature fluctuations does not significantly affect the correlations. For $y^+ > 30$, the unconditional correlation coefficient becomes mildly positive but low in magnitude, implying that the temperature (pointwise) becomes a poor marker of vortical fluid outside of the wall region. However, by conditioning the correlation on the magnitude of the temperature fluctuations, the correlation improves somewhat in particular for large positive temperature fluctuations (threshold value of $2 \sigma_\theta$).

The rapid decorrelation of the temperature and the vorticity magnitude with increasing distances from the wall partly stems from a loss of spatial phase information. This is particularly true at $y^+ = 25$ where the pointwise correlation coefficient becomes zero and changes sign. By examining the spatial correlation maps (not shown here), one notices that the strong negative correlation observed near the wall shifts in the downstream direction and that a positive correlation peak appears upstream. This continuous change of the phase relationship between the temperature and the vorticity magnitude renders the interpretation of the passive marker difficult except near the wall. In the buffer region, the vorticity magnitude is better marked by the streamwise temperature gradient, while further away from the wall the vorticity magnitude becomes weakly correlated with the strong temperature fluctuations.

Other combinations of temperature, temperature gradients and vorticity components were investigated. Away from the wall region temperature gradients correlate slightly better with the vorticity magnitude, but we did not find a particular combination that gives a high correlation. These results suggest that there is considerable uncertainty in the use of temperature as a marker for the vortical structures originating from the wall region. The reason for this will become clear later in this report.

3. The Structure of the Heat and Momentum Flux

To investigate this aspect of the problem, Case II was chosen since it had the property that the average total heat flux $q = -\overline{\nu' \theta'} + \frac{1}{Re Pr} \frac{d \overline{\theta}}{dy}$ was constant at any distance from the wall. This allowed us to examine how this same average heat flux was distributed in space and what underlying eddy structure was responsible for it as a function of the distance from the wall.

Figure 2 shows the turbulent heat and momentum fluxes as a function of the distance from the wall. As mentioned earlier the streamwise velocity is well correlated (negatively) with the temperature through a significant part of the channel. As observed before (Kim & Moin, 1989), the $\overline{\nu v}$ and $\overline{v \theta}$ have comparable magnitudes
FIGURE 2. Turbulent heat and momentum fluxes as a function of the distance from the wall. Curves are \(\frac{\bar{u}_v}{\sigma_u \sigma_v}, \frac{\bar{v}\theta}{\sigma_v \sigma_\theta}; \frac{\bar{u}\theta}{\sigma_u \sigma_\theta}.\)

(and opposite signs) in the wall and log region, which means that the turbulent Prandtl number \(P_{rt}\) is nearly unity. The molecular Prandtl number \(P_r\) is also of order one (0.7) in this case. However, the fluctuations in the products \(uv\) and \(v\theta\) as measured by their root mean square values \(\sigma_{uv}\) and \(\sigma_{v\theta}\), are quite different. The turbulent heat flux has a fluctuation level more than twice that of the momentum flux, despite their nearly equal mean values. This difference led us to believe that the turbulent transport of a passive scalar may be significantly different from the momentum transport locally and instantaneously, despite being associated with the same eddy structures, and despite the average transport \(\bar{u}v\) and \(\bar{v}\theta\) being similar.

Figures 3 and 4 show the contributions of the individual velocity and temperature fluctuations to the turbulent momentum and heat flux, respectively. For the case of the momentum, it can be observed that both \(u\) and \(v\) fluctuations are equally correlated (but with opposite sign) with contributions to the momentum flux. The change of sign around \(y^+ = 20\) corresponds to the point where the momentum flux changes from being dominated by fourth quadrant motions (sweeps) near the wall to second quadrant motions (ejections) away from the wall. For the scalar field near the wall \((y^+ < 25)\), the heat flux contributions are predominantly from cold fluid moving towards the wall, corresponding to fourth quadrant motions in the velocity field. Both \(v\) and \(\theta\) are equally correlated with \(v\theta\) in this region. It should be noted that this is also the region where \(\sigma_{uv}\) is approximately equal to \(\sigma_{v\theta}\). In the region away from the wall \((y^+ > 25)\) the individual correlations between \(v\) and \(\theta\) and the turbulent heat flux are quite different. The temperature fluctuations have near zero correlation with the turbulent heat flux. This seems to indicate significant local countergradient transport. It should also be noted that this is the region where the fluctuations in the instantaneous turbulent heat flux are considerably higher.
than those of the turbulent momentum flux. There is therefore a lot of "churning" of the scalar field by the eddies, but little actual mixing. This point is further illustrated by examining the instantaneous velocity and temperature field. Figure 5 represents a cut of the channel perpendicular to the flow (yz plane). The spanwise and normal velocity components are shown as a vector plot and the color contours
represent iso-levels of streamwise velocity fluctuations $u$ on the top or temperature fluctuations $\theta$ on the bottom. The same number of contours was used for both fields. It can be seen that for the same eddy structures, the temperature field seems to be "wrapped" around the eddies more than the streamwise momentum. In other words, a fluid particle being displaced in the normal direction by an eddy keeps its temperature marking longer than it does its momentum marking. Figure 5 is for a case where the molecular Prandtl number is of order one (0.7), but examination of scalar fields corresponding to $Pr = 0.1$ and 2.0 indicated that the observed effects are not sensitive to Prandtl number. The high Prandtl number case exhibits sharper temperature interfaces but no significant changes in terms of the "wrapping" around. Hence, the more rapid loss of momentum marking by a fluid particle cannot be attributed to diffusive effects.

If one examines the instantaneous transport equations for momentum and temperature, one significant difference is the absence of the pressure gradient term on the right hand side of the temperature equation. Since the diffusive terms are similar for both equations, the pressure must be responsible for the difference in behavior between the two fields. To further quantify this point, the correlation coefficients between the acceleration terms in the Navier-Stokes equations and the pressure and viscous terms was calculated for each of the components. These are shown as a function of the distance from the wall in figure 6. Similarly, the root mean square values for those terms were also calculated and are shown in figure 7.

Figure 7. Root mean square fluctuations of the various terms contributing to the total accelerations as a function of the distance from the wall.

It can be observed that for the streamwise acceleration, the viscous terms are slightly dominant in terms of magnitude and correlation near the wall ($y^+ < 30$), but that away from the wall, the pressure gradient term is almost the sole contributor to the streamwise acceleration. More surprisingly, the normal and spanwise
FIGURE 5. Comparison between the instantaneous streamwise velocity fluctuation field (top) and temperature fluctuation field (bottom), highlighted with the vector plot of the spanwise and normal velocity components.
acceleration terms are completely dominated by the pressure gradient term, even in the so-called viscous region at $y^+ = 10$. In other words, the cross-stream dynamics are essentially inviscid! The viscous terms only play an indirect role through the streamwise convection which ties in the normal and spanwise velocity component through the incompressibility constraint. The dominant role played by the pressure in the momentum transport explains the differences observed between the momentum and scalar field. The absence of any significant effect of the molecular Prandtl number mentioned earlier is consistent with the small contribution to the acceleration terms by the viscous forces. In other words, once a fluid element has been displaced in the normal direction by a turbulent eddy, it retains most of its heat marking due to the lack of a strong diffusive effect (on the time scale of the eddy dynamics) until it is “churned” again by the next eddy. On the other hand, the same fluid element loses its streamwise momentum marking very fast, as strong pressure gradient forces are generated locally to exchange the momentum of that fluid element with its surroundings. The turbulence is thus more efficient at “mixing” the momentum than the heat, while the temperature retains a higher degree of unmixedness and appears to “wrap” around the eddies as described earlier. These observations are consistent with the fact that for the same net average heat flux as momentum flux ($Pr_T = 1$), there is a higher level of fluctuations ($\sigma_{u\theta} > \sigma_{uv}$). There is significantly more local heat transfer in both directions (i.e. down-gradient and counter-gradient transport) for a small net gradient transfer. This was further verified by comparing the p.d.f. of the instantaneous heat and momentum fluxes (not shown here).
4. Pattern Recognition of the Dominant Eddy Structure

In order to further quantify the above observations regarding the structure of the scalar flux, we applied an automated pattern eduction method to analyze the flow. Details of the method are reported elsewhere (Stretch, 1989; Stretch, Kim and Britter, 1990). It is based on an iterative convolution between a reference pattern and the data.

A sample of the results obtained is shown in figure 8(a). The diagnostics used in this example were the vertical and spanwise velocity fluctuations. The basic ensemble averaged flow structure educed by the analyses consists of attached eddies spanning the flow from the wall to near the centerline of the channel (see Stretch, 1989 and Stretch, Kim and Britter, 1990 for further details). Ensemble averages of the streamwise velocity fluctuations and the temperature fluctuations were computed at the pattern locations and are included in figures 8(b) and (c). As expected the large streamwise velocity fluctuations are associated with the upwelling and downwelling motions which are in turn associated with the attached eddy structures. It is further apparent from the ensemble averages that the scalar perturbations have a greater vertical extent than the streamwise momentum fluctuations. The scalar field also shows a slightly greater tendency to be wrapped around the vortical structures. These results are consistent with the instantaneous fields shown in figure 5 and further support the conclusions we have drawn above.

5. Time Evolution of the Temperature Field in a Developing Flow.

To quantify the effective net transport of heat by the turbulent eddies, the data from Case III was examined. Since the fluid was initially cold, the effectiveness of the net turbulent transport was judged by tracking in time the deepest penetration of the temperature disturbance. This was repeated for various levels of temperature disturbances.

The results are summarized in figure 9 for 10 different magnitudes of the temperature disturbance. Naturally, the smallest temperature disturbance penetrates the farthest and the fastest. For reference, the average penetration speed, \( V_p \), was calculated from the initial slope of these curves. For \( \theta = 0.05 \), this speed is \( 1.23u_r \), while it is \( 0.4u_r \) for \( \theta = 0.5 \). As a reference, the r.m.s. of the normal velocity fluctuations \( \sigma_v \) is of the order of \( 0.8u_r \) for the bulk of that region. Those penetration speeds computed represent an upper bound since they are calculated for the fastest penetrating disturbances. The speeds are typical of the velocity magnitudes which are induced around the vortical structures in the flow. This is consistent with our previous observation that the scalar transport is associated with these structures. However these vortices or eddies have diameters typically much smaller than the channel half width \( (d^+ \approx 20 \text{ and } \delta^+ = 180) \), a distinction which is expected to increase with Reynolds number. It therefore seems that the turbulent transport across significant distances in the normal direction results from the aggregate effect of many eddies, each transporting a material element over a distance of order their diameter at a speed of order \( u_r \), but not necessarily always in the right direction.
FIGURE 8. Samples of the pattern analysis results: zy plane views of ensemble averaged (a) velocity vectors; (b) streamwise momentum fluctuations; (c) temperature fluctuations.
as was discussed in section 3. Hence, it may take many interactions between a material element and the turbulent eddies before it is "transported" over a significant distance (say of the order of a few hundred of wall units). However, this process is still far more efficient than a strictly diffusive effect. This aggregate transport process also explains the poor marking of the vorticity field by the passive scalar.

6. Conclusions

In summary, the following conclusions were reached:

1. Outside the near wall region $y^+ < 20$, one must be very careful in interpreting the passive scalar concentration in terms of the underlying vortical eddy structure.

2. There are significant differences between the transport of momentum and heat, even when the molecular and turbulent Prandtl numbers are of order one. These differences are linked to the role of the pressure.

3. The transport of passive scalar over significant distances appears to result from the aggregate interaction of many eddies.

REFERENCES


STRETCH, D. D., KIM, J. & BRITTER, R. E. 1990 Patterns in simulated turbulent channel flow. Unpublished manuscript to be submitted