MODELING OF TURBULENT DISPERSION IN A CHANNEL FLOW

Adrien Lücker & Daniel W. Meyer
Institute of Fluid Dynamics, ETH Zurich, Switzerland

Abstract Simulations of scalar dispersion from a line source in a turbulent channel flow with a joint velocity–scalar probability density function (PDF) method were conducted. The molecular diffusion term was closed using a refined version of the mixing model of Meyer [6]. Results were compared with the detailed experimental data by Lavertu and Mydlarski [4] with wall-shear-stress Reynolds number $\mathrm{Re}_\tau = 1080$. The results reported in this work provide a more extensive validation and a significant gain in accuracy over the previous study by Bakosi and coworkers [2], where the interaction by exchange with the conditional mean (IECM) mixing model was applied. Moreover, since no conditional moments need to be calculated in our refined mixing model, computations are less expensive compared to IECM calculations.

MIXING MODEL

One of the most widely used mixing models is the interaction by exchange with the mean (IEM) model. Since it does not satisfy local isotropy of the scalar field, a velocity-conditional version of the IEM model was proposed by Pope [7]. The IECM model accounts for local isotropy and provides improved results compared to the IEM model. However, the computation of velocity-conditional scalar means in the IECM model requires a discretization in velocity probability space. In our refined mixing model, which is based on [5, 6] and used in this work, these difficulties are avoided while still accounting for local isotropy.
In the refined model, the scalar $\phi^{(i)}$ associated with particle i evolves according to

$$\frac{\mathrm{d}\phi^{(i)}}{\mathrm{d}t} = -\frac{1}{C_r t_m}(\phi^{(i)} - \phi_c^{(i)}), \tag{1}$$

where C_r is a model constant and t_m a mixing time scale. Unlike in the IECM model, the scalar concentration relaxes to $\phi_c^{(i)} \equiv (\phi_\circ^{(i)} + \phi_\bullet^{(i)})/2$, where $\phi_\circ^{(i)}$ and $\phi_\bullet^{(i)}$ are drift concentrations associated with particle i. The choice of the drift concentrations is velocity-conditioned and they are renewed based on according life time processes. The mixing time scale t_m was derived by using the laminar thermal wake model proposed by Viswanathan and Pope [9]. Near the line source, the thermal wake model accounts for molecular diffusion, which is important for sources with sizes that are small compared with the Kolmogorov scale.

RESULTS

The computational domain considered in this work corresponds to the experimental setup from Lavertu and Mydlarski [4] and is depicted in Figure 1. A heated wire or line source is placed upstream at $x = 0$ in the channel center (at $y = h$) extending in span-wise direction. The Reynolds number based on the friction velocity u_τ is $\mathrm{Re}_\tau \equiv u_\tau h/\nu = 1080$. The line source has a non-dimensional radius $\sigma_0/h = 4.23 \cdot 10^{-3}$.

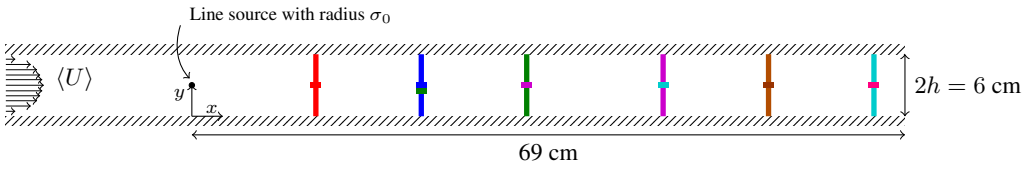

Figure 1. Sketch of the computational domain and the experimental setup used by Lavertu and Mydlarski [4]. The horizontal distance indicates the length of the computational domain. The colored lines and rectangles indicate the positions of the profiles and the probes, respectively. The same color code is used to display the results.

Since in this study we focus on the modeling of turbulent mixing, the mean velocity and Reynolds stresses were taken from the DNS [1]. A particle advection scheme based on Thomson's "well-mixed" criterion [8] was used. This ensures that the particle density remains uniform and that the mean velocities and Reynolds stresses are consistent with the prescribed flow statistics. Simulations were performed by releasing $4.4 \cdot 10^7$ particles in the computational domain. The grid used for the mixing model has 138×200 cells leading to grid-independent scalar statistics.
Cross-stream profiles of scalar moments are reported in Figure 2. There is good overall agreement between the experimental data and the simulation for all downstream positions. Similar agreement was found as well for the scalar skewness. The asymmetry in the experimental data could be interpreted as an indication of measurement errors. Moreover, for y/h

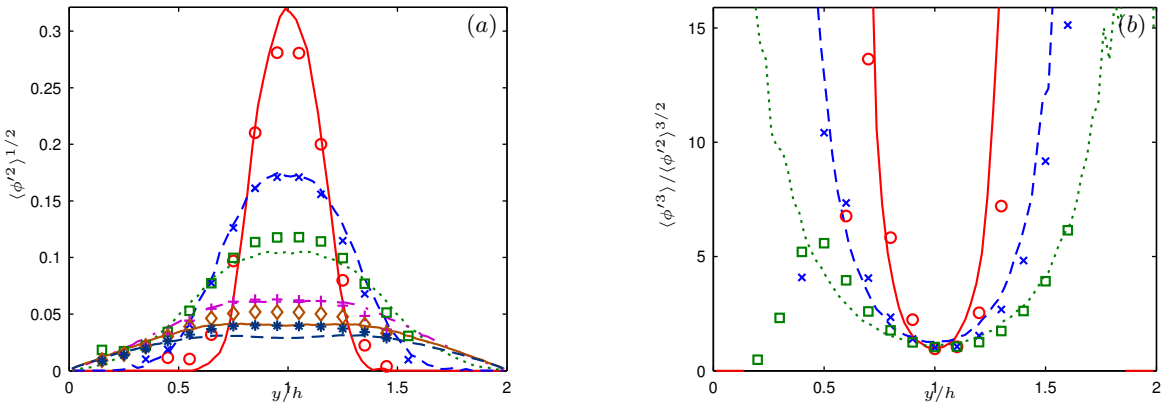

Figure 2. (a) Profiles of root-mean-square scalar values. (b) Profiles of scalar skewness. Lines – PDF calculation, symbols – experimental data [4].

away from 1, the variance becomes small and the skewness error prone since it results from a normalization with the variance.

Figure 3 shows PDFs of normalized scalar fluctuations. There is good overall agreement, but the peaks in the simulated PDFs are too high, which leads in connection with the normalization to a shift compared to the experimental data. In summary, the reported results provide a more extensive model validation and the model predictions are more accurate compared to previous studies [2, 3].

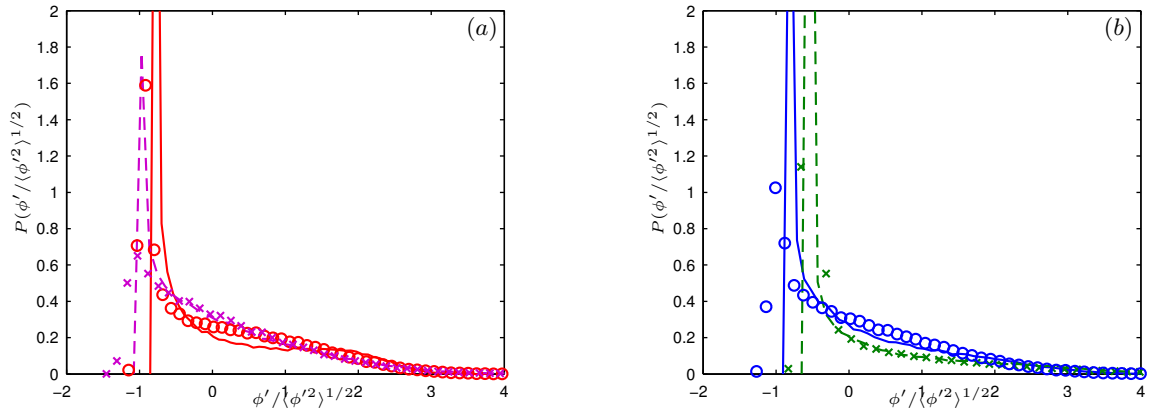

Figure 3. PDFs of the normalized scalar fluctuations. Lines – PDF calculation, symbols – experimental data [4]. (a) $y/h = 1.0$, solid line (red) – $x/h = 4.0$, dashed line (purple) – $x/h = 10.8$. (b) $x/h = 7.4$, solid line (blue) – $y/h = 1.0$, dashed line (green) – $y/h = 0.8$.

References

[1] H. Abe, H. Kawamura, and Y. Matsuo. Surface heat-flux fluctuations in a turbulent channel flow up to $\mathrm{Re}_\tau = 1020$ with $\mathrm{Pr} = 0.025$ and 0.71. *International journal of heat and fluid flow*, **25**(3):404–419, 2004.

[2] J. Bakosi, P. Franzese, and Z. Boybeyi. Probability density function modeling of scalar mixing from concentrated sources in turbulent channel flow. *Physics of Fluids*, **19**:115106, 2007.

[3] J. Bakosi, P. Franzese, and Z. Boybeyi. A non-hybrid method for the PDF equations of turbulent flows on unstructured grids. *Journal of Computational Physics*, **227**(11):5896–5935, 2008.

[4] R. A. Lavertu and L. Mydlarski. Scalar mixing from a concentrated source in turbulent channel flow. *Journal of Fluid Mechanics*, **528**:135–172, 2005.

[5] D. W. Meyer and R. Deb. Modeling molecular mixing in a spatially inhomogeneous turbulent flow. *Physics of fluids*, **24**:025103, 2012.

[6] Daniel W. Meyer. A new particle interaction mixing model for turbulent dispersion and turbulent reactive flows. *Physics of Fluids*, **22**(3):035103–17, 2010.

[7] S. B. Pope. On the relationship between stochastic lagrangian models of turbulence and second-moment closures. *Physics of Fluids*, **6**(2):973–985, 1994.

[8] D. J. Thomson. Criteria for the selection of stochastic models of particle trajectories in turbulent flows. *Journal of Fluid Mechanics*, **180**(529–556):109, 1987.

[9] S. Viswanathan and S. B. Pope. Turbulent dispersion from line sources in grid turbulence. *Physics of fluids*, **20**:101514, 2008.