# Turbulence modelling and simulations


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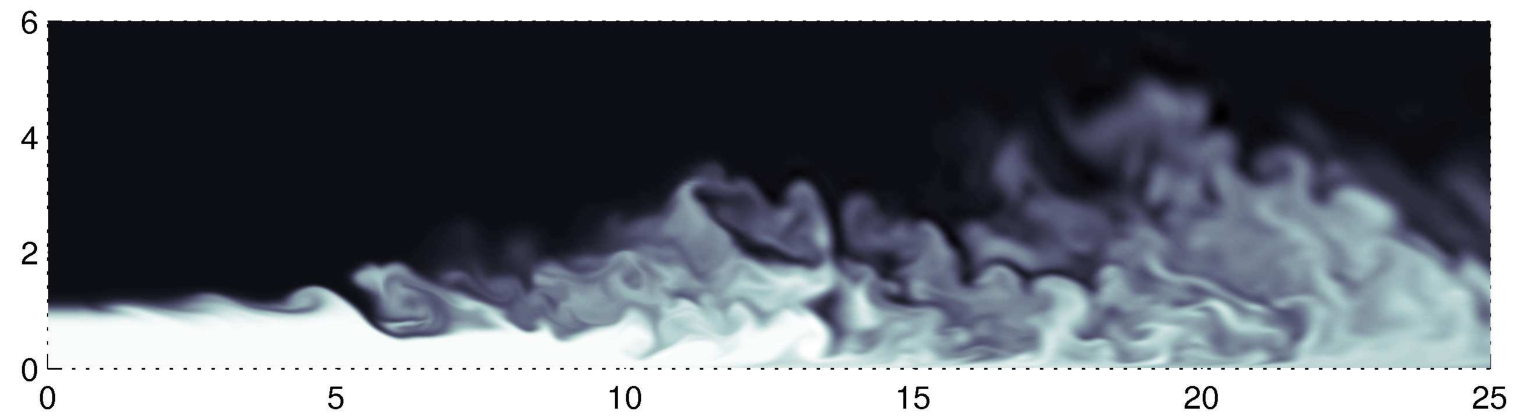
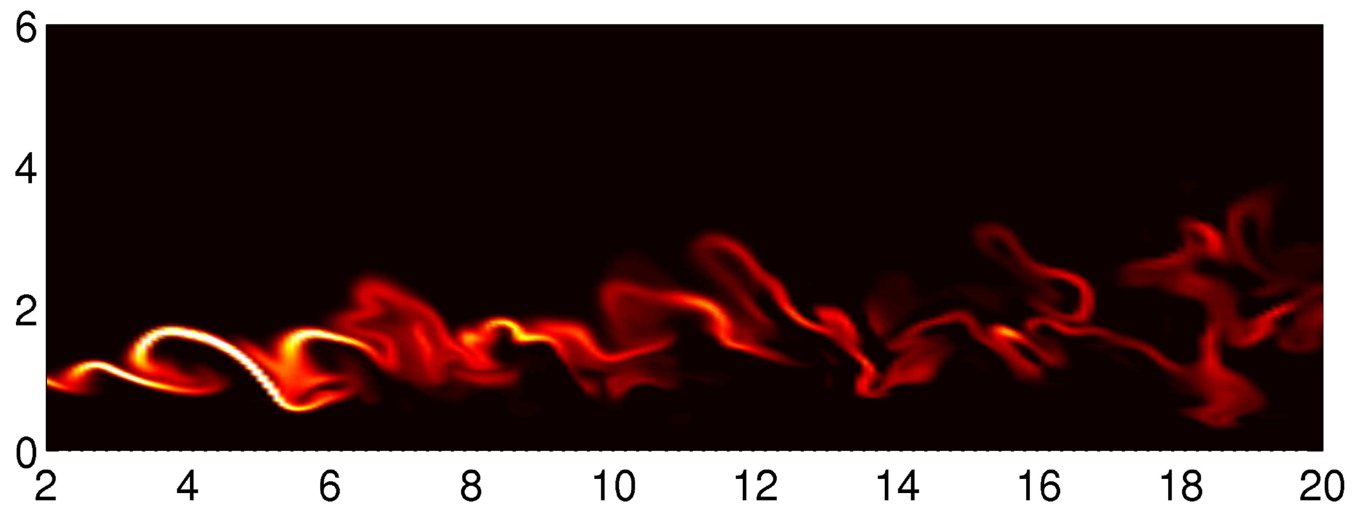
## DNS of turbulent wall-jets

The investigation aims at studying plane turbulent wall-jets for mixing and combustion applications through DNS. An isothermal jet is simulated as well as a warm jet in a cold environment and a cold jet in a warm environment with equal temperatures in the coflow and at the wall. The density variations in the two non-isothermal turbulent wall-jets are significant. Reynolds and Mach numbers at the inlet are equal in all cases. For the DNS a fully compressible code is used with a temperature dependent viscosity and a sixth-order compact finite difference scheme for spatial discretization. The influence of the varying temperature on the jet development, turbulence statistics and mixing is studied and shown to be large. The top figure shows a snapshot of the passive scalar concentration in the warm jet.

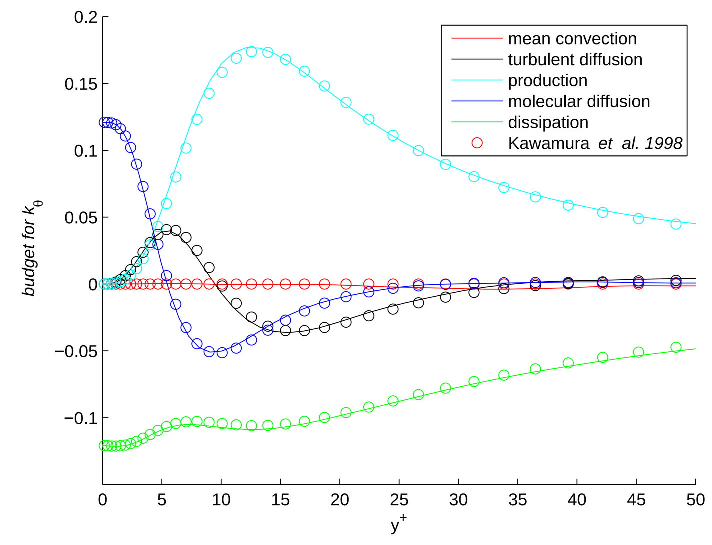
A DNS of a simple reaction in a plane turbulent wall-jet is also carried out. At the inlet a fuel is injected in the jet while an oxidizer is added in the coflow. Turbulent mixing occurs and a single, irreversible reaction between an oxidizer and a fuel forming a product $O + F \longrightarrow P$ takes place. The jet is isothermal and no heat is released during the reaction. A snapshot of the reaction rate in bottom figure shows the turbulent mixing of the fuel and the oxidizer which then react in thin, sheet-like reaction zones.

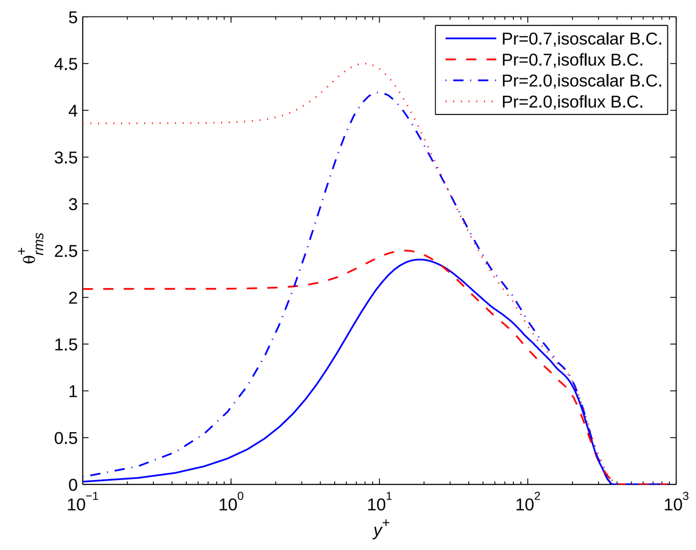


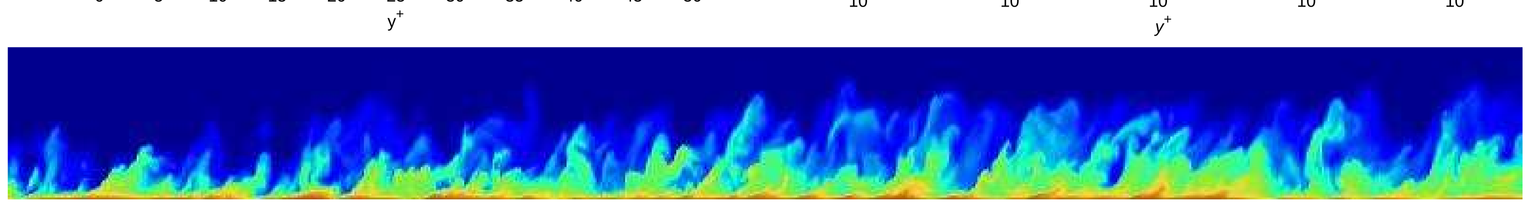


## DNS of boundary layer flows

Wall-bounded turbulent shear flows can be found in many engineering applications and are of fundamental interest. In order to better understand these flows, a spatially developing turbulent boundary layer with passive scalar transport has been investigated via DNS. The highest Reynolds number based on the free-stream velocity and momentum thickness is $Re_\theta = 830$. Many low and high order statistics are collected during the simulation. Due to the large computational effort of DNS, only five passive scalars are included with Prandtl numbers $Pr$ ranging from 0.2 to 2 and both isoscalar and isoflux boundary conditions are imposed. The left figure plots the budget of the fluctuating scalar variance $k_\theta$ in the near wall region and shows the excellent agreement with channel flow data (Kawamura *et al.*, 1998). The right figure highlights the impact of different wall boundary conditions; the differences are only noticeable in the near wall region. Finally, a snapshot of the scalar distribution in wall-normal plane is shown in the bottom figure.



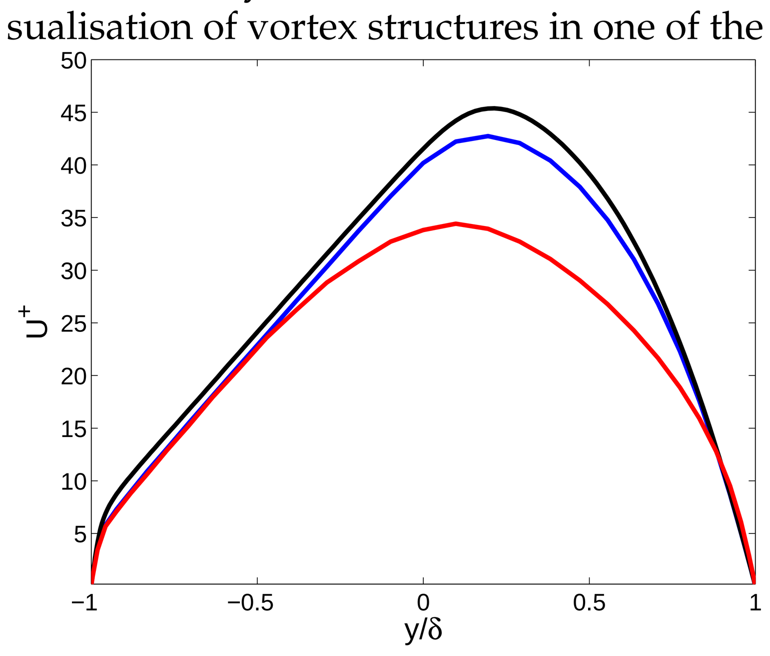



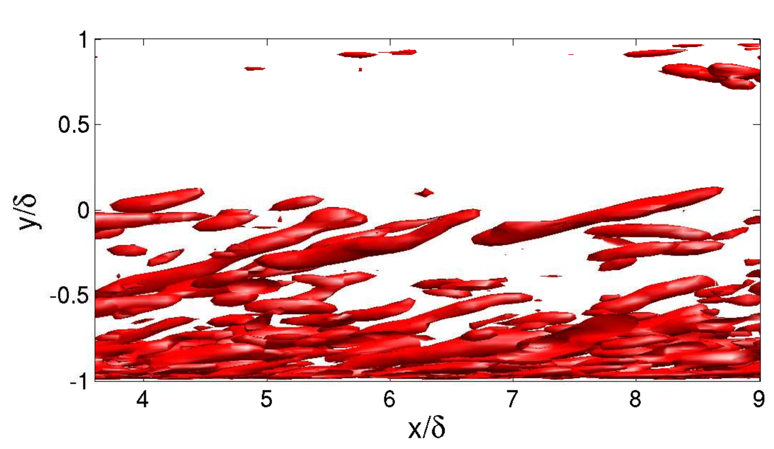



Recently, a more efficient parallelization for the numerical code has been implemented. This allows us to run simulations at higher Reynolds numbers within a longer and wider computational boxes. Based on the DNS data, subgrid-scale models for LES shall be developed. Additionally, more scalars, both active and passive, will be included which allows us to examine the scalar statistics for different Prandtl and Richardson numbers, and boundary conditions. Examining how the "Reynolds analogy" factor increases with the free-stream turbulence intensity will help us to understand heat transfer during bypass transition.

## New explicit algebraic subgrid stress models for LES

New explicit subgrid stress models are proposed involving the strain rate and rotation rate tensor, that can account for rotation in a natural way. The new models are based on the same methodology that leads to the EARSM formulation for RANS and are validated through LES of rotating channel flow. One dynamic and one non-dynamic model is proposed. The non-dynamic model is a computationally efficient subgrid-scale model which outperforms the standard wall-damped Smagorinsky model. For example, in the left figure we can see that for the mean streamwise velocity the LES of rotating channel flow with the non-dynamic model (blue line) agrees much better with DNS data (black line) than the LES with the standard Smagorinsky model (red line). The new explicit dynamic model is the most accurate and represents an alternative to the dynamic Smagorinsky model. The model is less computationally expensive than the dynamic Smagorinsky model because it involves fewer test filter operations. The proposed explicit dependence on the system rotation included in both new models improves the description of the mean velocity profile and the turbulent kinetic energy at high rotation rates. Comparison with the dynamic Smagorinsky model shows that the avoidance of the eddy viscosity assumption improves the description of both the Reynolds stress anisotropy and the subgrid-scale stress anisotropy. LES of rotating channel flow at $Re_\tau = 950$ have also been carried out and reveal Reynolds number effects on turbulence statistics. The right figure shows a visualisation of vortex structures in one of the simulation.





## Modelling of turbulent gas-particle flow

If particles are transported by the gas-phase, but do not affect the flow there is only one-way coupling. This is the case when the volume fraction of the particles is very low. When the particle volume fraction is higher particles affect the flow due to drag, leading to complex interactions between the particle- and the gas-phase called two-way coupling. An Eulerian model was developed for turbulent gas-particle flow that takes into account two-way coupling. A $\mathrm{K}$-$\omega$ model was used as turbulence model. The difference between one- and two-way coupling simulations was investigated for different particle volume fractions and particle diameters.

Computed mean particle volume fractions $\phi$ normalised with the initial particle volume fraction $\phi_0$ for one-way (1W) and two-way coupling (2W) for four different $\phi_0$ are shown in the left figure. The high particle concentration close to the wall is the result of turbophoresis; particles drift from regions of high turbulence intensity to regions with low turbulence intensity near the wall. As $\phi_0$ increases the effects of two-way coupling are stronger and the normalised particle volume fraction decreases. The relative mean streamwise velocity between particle- and gas-phase, $\mathrm{U_p} - \mathrm{U_g}$, for different particle diameters is shown in the right figure. Particles with larger diameters have a higher mean relative velocity. In the near wall region the larger particles are leading the flow due to inertia gained in the core of the flow. The particles lag the flow in the core of the channel for all particle diameters because of gravity. The study shows that the influence of two-way coupling and turbophoresis are significant even at relatively low particle volume fractions and must be included in models of turbulent gas-particle flows.