Abstract
This paper presents a method of turbulence initialisation in Large-Eddy Simulations of homogeneous turbulence. The method is proposed for CFD codes solving the Navier-Stokes equations in Cartesian coordinates where spectral forcing is not possible. The forcing technique and the resulting turbulence characteristics are discussed. The method is used to initiate ambient turbulence in diesel-fuel injection simulations. The possible influence of the ambient turbulence on the spray structure is reproduced.

1 Introduction
Increasing power of computers allows still more realistic simulations of the turbulence in computational fluid dynamics. Large-Eddy Simulations (LES) are becoming feasible for research of the effects of turbulence on different fluid dynamics related processes. Spectral forcing methods have been earlier developed (e.g. [1]) and successfully applied for research (e.g. [2]). However, in codes solving the Navier-Stokes equations in Cartesian coordinates different treatment is necessary. This paper presents a method developed for initialisation of the ambient turbulence in LES of high-momentum liquid fuel injections, where the 1-D convection required for the presented forcing technique does not affect the solution significantly.

2 Numerical Method

2.1 KIVA-LES code
The code used is a version of the well-known KIVA-3V code (for governing equations see ref. [3]) into which LES modifications proposed in [4] were implemented. The governing equations are filtered using the box filter. The subgrid turbulence is modelled by the k-\Delta model proposed by Menon et al. (see in [4]).

2.2 Forcing technique
The simulations are performed on a hexahedral domain with size of L\times L\times 2L in i, j, k-directions and with periodic boundary conditions in each direction. The schematic representation of the technique is shown in Fig. 1. 1-D laminar flow (convection) is initiated first in the k-direction. The turbulence is forced by adding random velocity components in the lateral directions at isolated locations corresponding to large length scales. Independent Ornstein-Uhlenbeck processes govern the random velocity components that are imposed at \Delta t time increments and calculated from Eq. (1).

\[
U'(t + \Delta t) = U'(t) - U'(t) \frac{\Delta t}{T_{OU}} + \left(2\frac{\sigma_{OU}^2 \Delta t}{T_{OU}}\right)^{\frac{1}{2}} \zeta(t)
\]

(1)

The two input parameters \(T_{OU}\) and \(\sigma_{OU}\) represent the integral time scale and the standard
deviation of the process, respectively. The value \( \zeta(t) \) is a standardized Gaussian random variable.

The computational grid is composed of hexahedral cells with a uniform spacing of \( N \times N \times 2N \). The testing grid is shown in Fig. 2.

![Fig. 1. Schematic representation of the turbulence-forcing technique.](image)

After an initial period, the subgrid turbulent kinetic energy stabilizes and a homogeneous velocity field is developed in the domain, see Figs. 3 and 4.

![Fig. 3. Development of the subgrid turbulent kinetic energy.](image)

![Fig. 4. Velocity iso-surface corresponding to the initial convective velocity indicating homogeneous turbulence structure.](image)

A detailed analysis of the turbulence characteristics (in [5]) revealed that the turbulence is homogeneous and near isotropic in the domain. The mean velocity is zero in the lateral directions and it is equal to the initial convective velocity in the third direction (see Fig. 5). Accordingly, the applied forcing technique generates homogeneous isotropic turbulence with 1-D latent convection. This latent convection causes modulation toward the smaller scales of turbulence what is indicated by the longitudinal correlations shown in Fig. 6. The longitudinal energy spectra, shown in Fig. 7, indicate clear inertial range behaviour.

2.3 Turbulence characteristics

After an initial period, the subgrid turbulent kinetic energy stabilizes and a homogeneous
obeying $-5/3$ power law (according to the Kolmogorov’s hypotheses). To achieve this result a parametric study was carried out and an optimised scheme performance found in [5].

3 Spray Studies

Recent injection experiments conducted in a fan-stirred vessel revealed a clear influence of the ambient turbulence on the structure of diesel-fuel sprays (see in [6]). The forcing method presented in this paper was used to initiate various turbulent fields for subsequent injection simulations. The schematic of the injection simulations is shown in Fig. 8. The injections are performed in the direction of the latent convection, i.e. negative k-direction. The results of the simulations showed qualitative differences in the spray distribution, especially in the spray front region in Figs. 9 and 10, in the same range of turbulence scales as confirmed by the experiments. These results indicate encouraging potential of the presented method.

Fig. 5. Variation of the velocity components at the centre location in the domain.

Fig. 6. Longitudinal correlation of the velocity components.

Fig. 7. Longitudinal energy spectra of the velocity components.

Fig. 8. Schematic view of the injection simulations.

Fig. 9. Comparison of spray-parcel distribution in a laminar (top) and turbulent (bottom) ambient flow.

Fig. 10. Comparison of spray-parcel distribution in a laminar (top) and turbulent (bottom) ambient flow.
Fig. 10. Comparison of fuel-vapour distribution in a laminar (top) and turbulent (bottom) ambient flow.

4 Conclusions

A method of turbulence forcing has been presented for LES of homogeneous turbulence. The technique is intended for implementation into CFD codes working in physical space coordinates where adaptation of spectral methods is difficult. The 1-D latent convection in the resulting velocity field is unavoidable and this should be considered for a particular application. In the presented case of high-momentum spray simulations the technique is well suitable for initiating the desired ambient turbulence conditions. The results of the injection simulations could reproduce the experimentally confirmed influence of the turbulence on the spray structure. Based on these results the technique can be recommended for further numerical research of the turbulence effects on high-momentum sprays.

References