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Spanwise domain effects on streamwise vortices in the plane turbulent mixing layer

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ABSTRACT

Large Eddy Simulation is used to assess the influence of the spanwise domain extent on the evolution of the spatially stationary streamwise structure that exists in the simulated plane turbulent mixing layer. The mixing layers originate from a physically-correlated inflow condition, which produces accurate mixing layer mean flow statistics. For all three spanwise domains considered a spatially stationary streamwise structure is present. The streamwise structure is artificially confined when its wavelength matches that of the spanwise domain extent, and a criterion for confinement is postulated. The confinement has no significant negative impact on either the computed flow statistics, or the growth of the large-scale spanwise structures. These results demonstrate that the streamwise structure rides passively on the large-scale spanwise vortex structure. A simulation lacking in a spanwise direction produces poor turbulence statistics, and is not a reliable representation of the real mixing layer flow.
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1. Introduction

Numerical simulation of the plane turbulent mixing layer has been a topic of academic research for over thirty years. The mixing layer is viewed as an important canonical test case in numerical simulation as its geometric simplicity permits its careful study on high-fidelity meshes. Simulation methods such as Direct Numerical Simulation (DNS), and Large Eddy Simulation (LES), should be able to capture the salient large-scale features of the mixing layer, as the flow is dominated by large-scale, spanwise-orientated vortex structures. These structures were first observed experimentally by Brown & Roshko [1]. Subsequent experimental flow visualisations showed that a 'streaky' streamwise structure develops in the mixing layer [2]. This streaky structure is a visual manifestation of spatially stationary streamwise vortices [3,4]. Whilst these spatially stationary streamwise vortices persist far into what is normally defined as the self-similar region of the flow, their evolution has been the subject of some controversy. In some experiments the streamwise vortices maintained a constant spacing over many generations of pairing interactions between primary structures [5,6] whilst in other studies the streamwise structure spacing increased in a stepwise manner, in conjunction with the spanwise structure interactions [3,7]. The origin of these streamwise vortices was linked to flow conditions upstream of the trailing edge of the splitter plate [4]. Small changes in the mixing layer initial conditions (note that initial conditions in experiments are termed inflow conditions in simulations, and these two terms are used interchangeably in this article) affected by changing the screens in the upstream wind tunnel section [3,7], or switching the legs in which the freestreams are generated [8], can produce quantifiable changes in the measured properties of the streaky structure.

As noted above, numerical simulation should be able to capture these salient flow features in the mixing layer. For reasons of computational cost the earliest simulations of the flow type were of the temporal form. In a temporal mixing layer the freestreams are set in opposition and the flow develops temporally within a doubly-periodic computational domain. The roll-up of the mixing layer [9], the pairing of primary vortices [10], and transition to turbulence in the mixing layer [11], were all studied in the temporal form. The influence of the initial conditions on the temporal mixing layer was observed in both Direct Numerical Simulation [12], and Large Eddy Simulation, investigations [13]. The work of Balaras et al. [13] noted that the spanwise domain extent had an influence on the vortical structures present in the flow—smaller domains enforce two-dimensionality on the flow, whilst larger domains result in a more three-dimensional flow-field.

Modern computing power now permits the simulation of the spatially-developing mixing layer. The streamwise vortex structure that forms in simulations of the spatially-evolving mixing layer is, however, a function of the imposed inflow conditions. When low-level three-dimensional random perturbations are superposed on a mean inflow velocity profile, a helical structure is observed in the mixing layer [14]. These oblique primary rollers undergo localised or helical pairings, which can lead to the vortex structure attaining a chain-link fence type appearance [15].

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The imposition of highly two-dimensional random perturbations, however, resulted in the formation of thin streamwise vortices between the primary spanwise rollers [14]. In these simulations, however, evidence for the presence of a spatially stationary streamwise vortex structure was lacking. Recent research by McMullan and Garrett [16] has shown that the imposition of low-level, physically-correlated fluctuations in an initially-laminar mixing layer, leads to the formation of spatially stationary streamwise vortices. The evolution of these streamwise vortices agreed extremely well with comparable experimental data [4], and their origin was associated with residual streamwise vorticity in the upstream laminar boundary layers.

In three-dimensional simulations of turbulent flows it is important that the spanwise domain does not artificially impose a maximum spanwise wavelength on the flow. For mixing layers with a white noise inflow fluctuation environment the local aspect ratio of the flow, defined as the ratio of spanwise domain extent to local momentum thickness, must be greater than ten throughout the computational domain in order to prevent artificial confinement by the spanwise domain [17]. Artificial confinement of the flow has an adverse effect on the computed flow statistics [18,19], and leads to an alteration of the coherent structure dynamics [17]. As described above, simulations of the mixing layer with a white noise disturbance environment leads to oblique spanwise vortices that undergo localised interactions. It is not clear if the aspect ratio criterion postulated by McMullan [17] also holds for simulations of the mixing layer where spatially stationary streamwise vortices are present.

As the mixing layer is considered a statistically two-dimensional flow, it is often common practice to simulate the mixing layer in a two-dimensional box. Two-dimensional mixing layer simulations originating from a white noise disturbance environment can produce reasonable mean flow statistics when compared to experiment [20,21], but the predicted turbulence statistics agree poorly with reference data [20,22,23]. No data have been reported for two-dimensional, initially-laminar mixing layer simulations originating from a physically-correlated inflow condition.

This paper assesses the effect of the spanwise domain extent on the spatially stationary streamwise vortices that form in simulations of the plane turbulent mixing layer. A series of Large Eddy Simulations of the plane turbulent mixing layer with varying spanwise domain lengths are performed. Mixing layers originating from initially laminar conditions are simulated, with the flow conditions based on the experimental conditions of Browand & Latigo [24]. The physically-correlated inflow condition is specified through the use of a recycling and rescaling method [25]. A further simulation is performed with the flow confined to a pseudo-two-dimensional box, which investigates the accuracy of a simulated mixing layer where the formation of a spatially stationary streamwise vortex structure is inhibited.

A brief overview of the research code is given in Section 2. The reference experiment details are described in Section 3. The simulations performed in fully-three-dimensional computational domains are presented in Section 4. The two-dimensional simulation results are described in Section 5, and conclusions are drawn in Section 6.

2. Code overview

The research code used here was described in detail in McMullan [17], and a brief overview is provided below.

The code is based on the low-Mach number approximation of the spatially-filtered governing equations. permitting the simulation of variable density flows in an incompressible computational framework. This code has been used extensively for mixing layer simulation research [16,17,22,26], and has produced accurate results over a range of Reynolds numbers. The primitive variables are discretised on a staggered-cell, finite-volume mesh. Second-order central-differencing schemes are used for the convection and diffusion terms in the solution of the momentum equation, and a flux-limited, second-order accurate upwinding scheme is used for scalar fluxes [27]. This choice of scheme for the scalar terms minimises out of bounds errors in the calculations of the passive scalar. Time advancement is achieved through the second-order accurate Adams–Bashforth method. The pressure equation is solved using a multi-grid method. The outflow boundary condition is a convective condition similar to that used in many previous studies [28], and has been shown to be passive. The transport equation for a passive scalar, $\tilde{\xi}$, is solved, and is closed through the commonly-used gradient-diffusion model. The Schmidt number of the resolved flow is $Sc = 0.7$, and the turbulent Schmidt number is set to $Sc_t = 0.3$.

The unresolved scales of motion are modelled through a subgrid-scale model, and in this study the WALE model is employed [29]. The WALE model is attractive for the simulation of mixing layers as it predicts zero eddy viscosity in the presence of pure shear. Previous studies have shown that the WALE model can produce improved predictions of the mixing layer bulk evolution when compared to the standard Smagorinsky model [26].

The inflow condition is generated by a recycling and rescaling method [25]. This method is similar to that of other rescaling methods [30], where flow is recycled within a domain upstream of the main computational domain of interest. In this virtual domain, the flow is periodically rescaled to a target set of flow statistics.

Table 1
Flow parameters.

U_1 ($\mathrm{ms^{-1}}$)	θ_1 (mm)	U_2 ($\mathrm{ms^{-1}}$)	θ_2 (mm)	R
25.6	0.457	5.2	0.86	0.66

3. Reference experiment details

The simulations presented here are based on the initially laminar flow conditions reported by Browand & Latigo [24]. The flow conditions outlined in Table 1 produced a low-speed, high Reynolds number turbulent mixing layer. The guidewalls of the test section were fixed horizontal, resulting in an adverse pressure gradient being present in the flow. This pressure gradient reduced the low-speed freestream velocity with increasing streamwise distance. Reference values of the freestream velocities are estimated at the trailing edge of the splitter plate and produce a velocity ratio parameter, defined as

$$R = \frac{U_1 - U_2}{U_1 + U_2} \tag{1}$$

of $R = 0.66$ at this location.

The flow conditions reported by Browand & Latigo [24] are a good candidate for numerical simulation as a large amount of statistical information is available for comparison. Unusually for initially-laminar mixing layer experiments, both the mean streamwise velocity and its fluctuating component were recorded in both streams. The velocity fluctuation measurement, however, was subject to a 1% error, and no information was recorded on the vertical or spanwise velocity fluctuations.

4. Three-dimensional simulations

4.1. Simulation setup

Three distinct computational domains are used in this study. These mixing layer domains and grids match those found in a previous study of spanwise domain confinement [17]. Validation

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