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Stably Stratified Isokinetic Turbulent Mixing Layers: Comparison Of PIV-Measurements And Numerical Calculations

Stabil stratifizierte isokinetische Mischungsschichten: Vergleich zwischen PIV Messungen und CFD-Rechnungen

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Abstract

The turbulent mixing of coolant streams of different temperature and density causes severe temperature fluctuations, which may lead to thermal fatigue in the junctions where mixing occurs. The aging phenomena resulting from thermal fatigue is the reason for an increased interest in measuring and predicting the flow field and turbulent mixing flow patterns evolving downstream of a mixing point. To study the fundamental mixing phenomena, the current co-flow isokinetic water experiments were carried out in a square channel with Reynolds-Numbers covering the range of Re$= 5 \cdot 10^3$ to 10^5 at various relative densities. Particle Image Velocimetry (PIV) was used to measure the velocity field and the results are compared with 3D large-eddy simulations (LES). A very good agreement in shape and magnitude was found for the mean and RMS-velocity field, except for the transverse-velocity component where LES underpredicts the magnitude of the fluctuations. Spatial velocity correlation maps reveal a distinct effect of the density difference on the evolution and decay of orderly structures with downstream distance. It is shown that the correlation maps are in close agreement with the numerical results. The reduced size of these orderly structures in the presence of density differences indicate a corresponding inhibiting effect on the mixing process which requires further analysis and the use of measurement techniques that are capable of resolving the mixing process directly.

1 Introduction

One important issue in the management of aging in nuclear power plants is the monitoring and assessment of thermal fatigue. Thermal fatigue is a mechanism which results in significant degradation of the mechanical properties of a material exposed to cyclic thermal stresses, which superimposes on the mechanical loads. Due to thermal fatigue a component may fail before its design lifetime. Typical components, which are susceptible to thermal fatigue are junctions where two fluids with different temperatures mix. Following the Civaux Unit 1 (F) incident, (Chapuilot et al. 2005), for example, several T-junction experiments (Metzner and Wilke 2005) and (Walker et al. 2009) have been carried out, to study the mechanisms leading to pipe cracks as a result of thermal loading in flow mixing zones. However, there are still difficulties in predicting the location of failure with numerical codes in such mixing zones. The current water mixing experiments in the GEMIX-Facility (**Ge**neric **Mix**ing E**x**periment) are focused on the basic mechanisms of turbulent mixing in the presence of temperature and/or density gradients under isokinetic mixing conditions. The velocity field is studied using Particle Image Velocimetry (PIV) in the current experiments. To measure simultaneously the concentration field, which provides information about the mixing process, Wire-Mesh sensors (WMS) and Wall sensor (WLS) will be used, (Prasser et al. 1998). In a first step, we compare the veloc-

and using 50 % overlap for the analysis a spatial resolution of 1.5 mm is obtained. Vestosint No2158 irregular shaped seeding particles having a nominal diameter of 21 μm and a density of 1.02 g/cm^3 were injected with a variable speed syringe pump to maintain particle number densities independent of flow rate for all the experiments. For all runs 1024 double-frame, single exposure images were recorded and subsequentially analysed. Parameters for the experiments under consideration were the inlet bulk velocity, u_0, in the range from 0.2 to 1 m/s and the relative density difference, $\Delta\rho$, from 0 to 1 % between the two legs, Table 1.

3 Results

The use of optical methods for the study of mixing in the presence of strong density gradients is severely challenged by the corresponding variation of refractive index in the mixing region. The mixing zone will distort any light passing through it when there is a difference in the refractive index of the two fluids. The analysis of these blurry images with the classical cross correlation technique was not able to produce reliable velocity fields in the mixing zone, therefore the results from the case with $\Delta\rho$ =5 % will not be included here, see instead (Kapulla et al. 2009). The experimental results for run N116, i.e. for a bulk velocity of u_0=0.2 m/s, were compared with corresponding numerical calculations using 3D large-eddy-simulation (LES). In the LES approach a spatial filter operation is applied which is based on the computational mesh. All scales of the fluid motion which are resolved by the grid are captured directly in the solved equations, only the contribution of the subgrid-scale motions needs to be modeled. Thus the LES approach invokes less modeling compared to RANS models (e.g. $k-\varepsilon-$turbulence model) and is therefore more computational expensive. However, this degree of detail associated with the LES method makes it better suited to address the instantaneous mixing processes and its associated scales; therefore LES was used in this study instead of the classical $k-\varepsilon-$turbulence model. The equations describing turbulent flow are given by the conservation of mass, ρ, and momentum, ρu_i. Applying a spatially uniform filter operation, the conservation of momentum reads (Pope 2000)

$$\frac{\partial\left(\rho\overline{u_i}\right)}{\partial t}+\frac{\partial\left(\rho\overline{u_j u_i}\right)}{\partial x_j}=-\frac{\partial\overline{p}}{\partial x_i}+\mu\frac{\partial^2\rho\overline{u_i}}{\partial x_j\partial x_j}-\frac{\partial\rho\tau_{ij}^R}{\partial x_j}$$

where $\overline{p}$ is the filtered pressure field, and μ denotes the dynamic viscosity of the fluid. LES simulations are performed by using the dynamic Smagorinsky model for the subgrid scales. The unresolved traceless subscale stresses τ_{ij}^R are related to the rate of strain $\overline{S_{ij}}$ of the resolved velocity field by employing the Boussinesq eddy-viscosity concept

$$\tau_{ij}^R-\frac{1}{3}\tau_{kk}\delta_{ij}=-2\nu_T\overline{S_{ij}}$$

The eddy viscosity is defined as

$$\nu_T=\left(C_S\Delta\right)^2\left|\overline{S}\right|$$

where Δ denotes the length scale of the unresolved motion calculated from the volume of the computational cell ΔV

$$\Delta=\sqrt[3]{\Delta V}$$

and $\left|\overline{S}\right|$ is the magnitude of the strain rate defined as

$$\left|\overline{S}\right|=\sqrt{2\overline{S_{ij}S_{ij}}}$$

For the dynamic Smagorinsky model C_S is evaluated from the dynamical procedure (Germano et al. 1991)

$$C_S=-\frac{1}{2}\frac{L_{ij}M_{ij}}{M_{ij}M_{ij}}$$

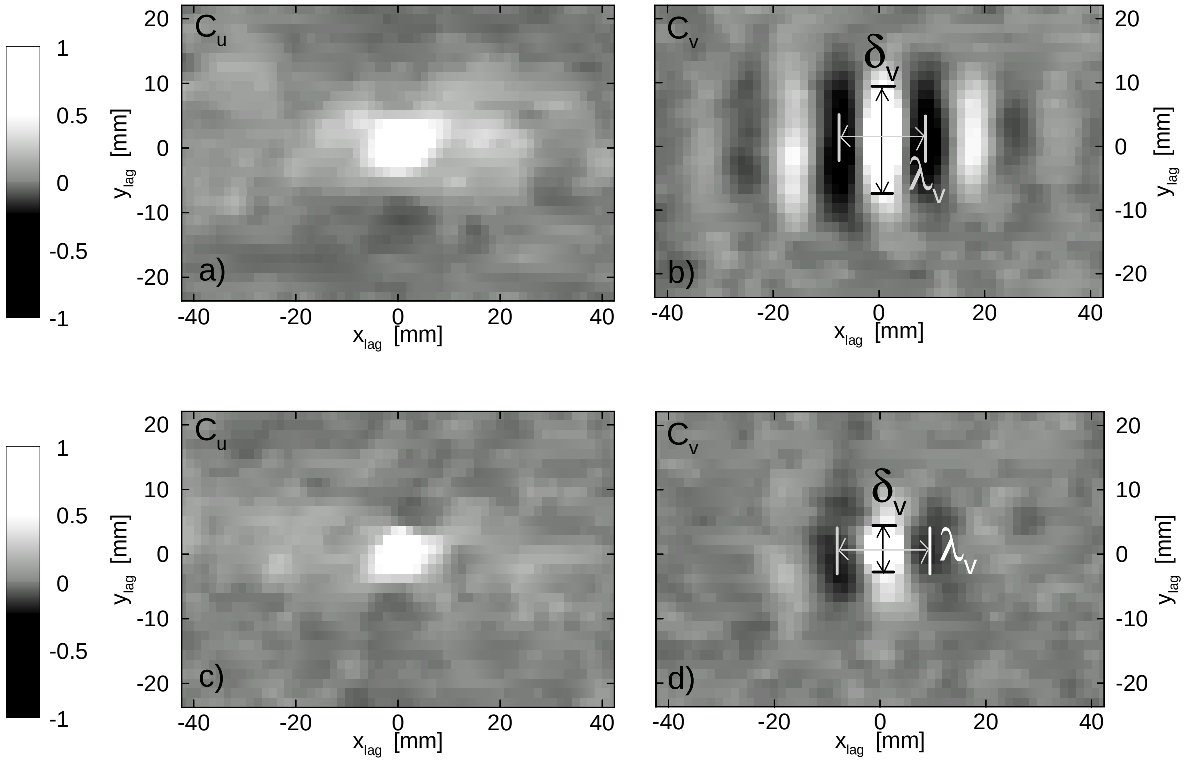

Figure 3: *Correlation map in the mixing zone for a bulk velocity of 0.2 m/s (upper two images, N116) and 1.0 m/s (lower two images, N122) for u' (left two images) and v' (right two images). Images a) and b) run N116 and images c) and d) run N122.*

in the streamwise direction, u, predicted by LES is very similar to the mean velocity profile in the corresponding experiment, except in the region close to the splitter plate (0 $<$x$<$100 mm) where the code calculates smaller velocities and the boundary layers which were better resolved by the fine mesh used in the code. To highlight these findings for both the experimental and numerical results, vertical profiles of the mean velocity u, the standard deviation σ_u as well as σ_v were extracted at x=150 mm and 350 mm, respectively. It is found that the experimental mean velocity exhibits an asymmetry in the lower flow profile, Figure 2 c-I) caused by inferior construction of the flow conditioning grids. Future experiments will be performed with a new improved inlet section and a new water loop with more accurate flowmeters. When the standard deviation in σ_u from experiment and LES is compared, the result is also in good agrement for the most part, except near the walls where LES predicts a drop in σ_u as dictated by non-slip boundary conditions but experiments show that σ_u only continues to grow, figure 2 c-II und d-II. This discrepancy is of little significance to the study which is concerned with the mixing process in the center of the channel. When the standard deviation in σ_v from experiment and LES is compared, there is a difference, Figure 2 c-III und d-III. Although the profile shapes are similar, the experiment shows almost twice the σ_v as the LES predicts. This might be caused a) by a redistribution of fluctuations from the v to the w velocity components in the LES calculation or b) by increased measurement errors in the experiment resulting from relatively small particle shifts. This topic requires further investigation.

The correlation concept can be used in fluid mechanics to determine, how strongly flow properties – velocities for the present case – at different spatial locations vary together. The correlation strength can be interpreted as a measure of the information exchange between these locations. The correlation coefficient C at a given point (x_{lag},y_{lag}) in the correlation map is obtained by correlating the velocities at the reference location (x_0, y_0) with the velocities at a nearby location (x_0+x_{lag},y_0+y_{lag}). Using the decomposition $U=u+u'$ where u denotes mean und

one finds a weak developing zone and for x>150 mm, δ_v remains almost constant. Similar to figure 4 a), the correlation coefficient C_v can be extracted from figure 3 along a horizontal line $y_{lag}=0$ (y=0 mm), the results show a periodic repetition with a single dominant wavelength λ_v in figure 5 a). It should be noted that this wavelength was extracted by eye and plotted as a function of downstream distance in figure 5 b). The wavelength increases with downstream distance showing a faster growth for higher Re-numbers. For higher downstream distances it becomes difficult to determin the wavelength accurately since the periodicity becomes less pronounced especially for lower Re-numbers. The experimental and numerical results were

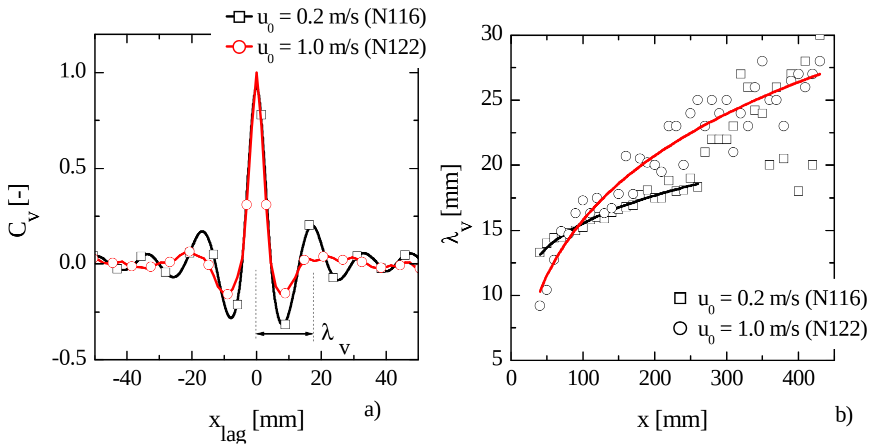

Figure 5: *One dimensional horizontal spatial correlations C_v at distance x=160 (left, N116) and characteristic wavelength λ_v as a function of downstream distance with Re-number as parameter, (right, N116 and N 122).*

also compared using correlation maps. For the numerical result only 1 instantaneous velocity field was available; therefore, in order to obtain enough samples to compute a reasonable correlation map, the correlation had to be computed over a larger area, which was chosen as x=120 mm to x=200 mm. To be consistent with the numerical results a single, randomly chosen instantaneous velocity field was extracted from the experimental results, and the correlation map was computed for the same area (x=120 mm to x=200 mm). A comparison of figure 3 with figure 6 reveals that the basic structure of the correlation map is the same regardless of the size of the area, or the number of frames that the correlation is calculated from. It should be noted, however, that less data result in a noiser correlation map, figure 6 a). Comparison of the experimental and numerical correlation maps shows that LES predicts similar orderly structures in the mixing zone. However, the structures present in the simulation are larger (in both x and y direction) than the experiment. This difference may be an important outcome,

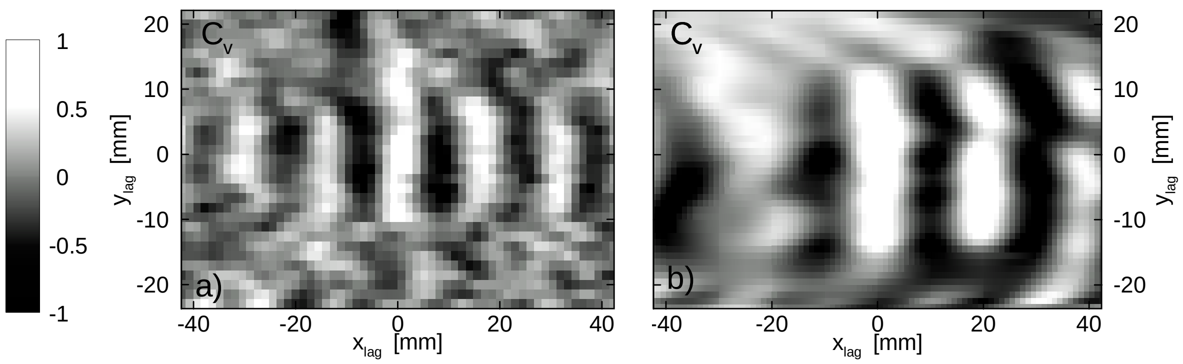

Figure 6: *Experimental (left, N116) and numerical correlation map C_v.*