Sensitivity of shallow mixing layers to upstream turbulence

An experimental study

CT5060, Master Thesis

Report

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May 2003
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Summary

Shallow mixing layers form a transition between parallel flows with different velocities. Typical for the geometry of shallow mixing layer flows is that the horizontal dimensions of the flow domain (the width and the length) are much larger than the vertical dimension (the water depth). Shallow mixing layers are frequently found in nature. For example at the confluence of two rivers, in a compound channel at the interface between the main channel and the floodplain, between the main channel and a groyne field or at a harbour entrance.

The turbulence of shallow mixing layers is characterised as highly anisotropic. The vertical shear above the bottom produces turbulence, with length scales limited by the vertical confinement whereas the transverse shear and instabilities present in the flow can result in large horizontal vortices with dimensions exceeding the water depth. These large horizontal vortices cause bottom shear stress fluctuations and contribute to the turbulent transport of matter and momentum in horizontal direction. Thus, these large horizontal vortices determine the broadening of the mixing layer region and consequently affect the development of the shallow mixing layer.

The motivation for this study was a recent study (van Prooijen & Uijttewaal, 2002a) that focused on the influence of perturbations representing the bottom turbulence imposed at the inflow boundary of a numerically modelled shallow mixing layer. In that study the hypothesis is posed, supported by linear stability analysis and a non-linear analysis (depth averaged TRANS numerical simulation model) that upstream turbulence conditions have consequences for the downstream development of a shallow mixing layer and the large horizontal vortical structures.

The hypothesis that upstream turbulence conditions have consequences for the downstream development of a shallow mixing layer and the large horizontal vortices has until now not yet been experimentally verified.

The objective of this study is to provide an experimental investigation concerning the consequences of upstream turbulence for the development of a shallow mixing layer and the large horizontal vortical structures, in size and intensity.

For this purpose two experiments are executed which only differ in intensity of the imposed upstream turbulence. An experiment is executed in which the turbulence intensity of the contiguous flows is raised using a bed of stones (rough upstream bottom) uniformly distributed over the width of the inlet section. This flow condition is compared with a second experiment without an extra source of upstream turbulence (smooth upstream bottom).

Turbulence data are obtained by means of 2D Laser Doppler Anemometry (LDA) and Particle Tracking Velocimetry (PTV). The development of the shallow mixing layer and the large horizontal vortices are evaluated using standard statistical analysis and spectral analysis.

It is concluded that different turbulence conditions have no measurable consequences for the downstream development of mean flow properties like the mixing layer width. LDA measurements show that higher energy density levels of low frequency perturbations imposed at the mixing layer inflow result in higher energy density levels of the horizontal vortices formed in the shallow mixing layer further downstream. These vortices are stronger for the experiment with a rough upstream bottom in comparison with the experiment with a smooth upstream bottom. In general, this confirms the concept of linear stability analysis that perturbing the inflow determines the turbulence characteristics downstream. However, the applicability of the linear theory cannot be established quantitatively in this study. For this purpose more detailed and more accurate experiments are needed.
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**Latin**

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<thead>
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<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tbody>
<tr>
<td>(c_r)</td>
<td>Bottom friction coefficient</td>
<td>[-]</td>
</tr>
<tr>
<td>(c_e)</td>
<td>Empirical constants (appendix B)</td>
<td>[-]</td>
</tr>
<tr>
<td>(C_k)</td>
<td>Empirical constant (paragraph 4.1.3)</td>
<td>[-]</td>
</tr>
<tr>
<td>(D_{ur}, D_{v_1})</td>
<td>Empirical constants (paragraph 4.1.3)</td>
<td>[-]</td>
</tr>
<tr>
<td>(f)</td>
<td>Frequency</td>
<td>[Hz]</td>
</tr>
<tr>
<td>(Fr)</td>
<td>Froude number</td>
<td>[-]</td>
</tr>
<tr>
<td>(g)</td>
<td>Gravitational acceleration</td>
<td>[m/s²]</td>
</tr>
<tr>
<td>(H)</td>
<td>Water depth</td>
<td>[m]</td>
</tr>
<tr>
<td>(K)</td>
<td>Depth averaged total turbulence kinetic energy per unit mass</td>
<td>[m²/s²]</td>
</tr>
<tr>
<td>(k_N)</td>
<td>Nikuradse roughness height</td>
<td>[m]</td>
</tr>
<tr>
<td>(L)</td>
<td>Length scale</td>
<td>[m]</td>
</tr>
<tr>
<td>(T)</td>
<td>Time scale</td>
<td>[s]</td>
</tr>
<tr>
<td>(u)</td>
<td>Instantaneous velocity component in the longitudinal direction</td>
<td>[m/s]</td>
</tr>
<tr>
<td>(U)</td>
<td>Time and depth averaged velocity component in the longitudinal direction</td>
<td>[m/s]</td>
</tr>
<tr>
<td>(u_\tau)</td>
<td>Shear velocity</td>
<td>[m/s]</td>
</tr>
<tr>
<td>(\Delta U)</td>
<td>Velocity difference across the mixing layer</td>
<td>[m/s]</td>
</tr>
<tr>
<td>(v)</td>
<td>Instantaneous velocity component in the transverse direction</td>
<td>[m/s]</td>
</tr>
<tr>
<td>(w)</td>
<td>Instantaneous velocity component in the vertical direction</td>
<td>[m/s]</td>
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<tr>
<td>(x)</td>
<td>Spatial coordinate in the longitudinal direction</td>
<td>[m]</td>
</tr>
<tr>
<td>(y)</td>
<td>Spatial coordinate in the transverse direction</td>
<td>[m]</td>
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<tr>
<td>(z)</td>
<td>Spatial coordinate in the vertical direction</td>
<td>[m]</td>
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<tr>
<td>(z_0)</td>
<td>Integration constant of the logarithmic velocity profile</td>
<td>[m]</td>
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**Greek**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tr>
<td>(\alpha)</td>
<td>Entrainment coefficient</td>
<td>[-]</td>
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<tr>
<td>(\delta)</td>
<td>Mixing layer width</td>
<td>[m]</td>
</tr>
<tr>
<td>(\varepsilon)</td>
<td>Dissipation of turbulence kinetic energy per unit mass</td>
<td>[(m/s)²/s]</td>
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<tr>
<td>(\lambda)</td>
<td>Relative velocity difference</td>
<td>[-]</td>
</tr>
<tr>
<td>(\nu)</td>
<td>Kinematic viscosity</td>
<td>[m²/s]</td>
</tr>
<tr>
<td>(\nu_t)</td>
<td>Turbulence viscosity</td>
<td>[m²/s]</td>
</tr>
<tr>
<td>(\rho)</td>
<td>Density of water</td>
<td>[kg/m³]</td>
</tr>
<tr>
<td>(\tau_0)</td>
<td>Bottom shear stress</td>
<td>[N/m²]</td>
</tr>
</tbody>
</table>

**Subscripts**

- \(c\) Of the centre of the mixing layer
- \(d\) Dominant mode
- \(r\) Of the bottom friction
- \(i, j\) Indices
- \(0\) Initial value
- \(x\) In the longitudinal direction
- \(y\) In the transverse direction
- \(1\) Of the fast stream
- \(2\) Of the slow stream

**Symbols**

- \(\cdot\) Deviation of the mean value
**Abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>DNS</td>
<td>Direct Numerical Simulation</td>
</tr>
<tr>
<td>DFT</td>
<td>Discrete Fourier Transform</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>HPV</td>
<td>High-resolution Particle Velocimetry</td>
</tr>
<tr>
<td>LDA</td>
<td>Laser Doppler Anemometry</td>
</tr>
<tr>
<td>LES</td>
<td>Large Eddy Simulation</td>
</tr>
<tr>
<td>PIV</td>
<td>Particle Imaging Velocimetry</td>
</tr>
<tr>
<td>PTV</td>
<td>Particle Tracking Velocimetry</td>
</tr>
<tr>
<td>RANS</td>
<td>Reynolds Averaged Navier Stokes</td>
</tr>
<tr>
<td>TRANS</td>
<td>Transient Reynolds Averaged Navier Stokes</td>
</tr>
<tr>
<td>1D</td>
<td>One-dimensional</td>
</tr>
<tr>
<td>2D</td>
<td>Two-dimensional</td>
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<tr>
<td>3D</td>
<td>Three-dimensional</td>
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1 Introduction

1.1 Problem description

This section is subdivided in five subparagraphs. First, the practical relevance of the dynamics of shallow mixing layers is explained. Second, results obtained from recent studies on the subject of sensitivity of shallow mixing layers to upstream bottom turbulence are presented. Subsequently, the reader is introduced to some characteristic features regarding the mean flow and the turbulence of shallow flows (paragraph 1.1.3) and shallow mixing layer flows (paragraph 1.1.4). In paragraph 1.1.5 turbulence models incorporated in current numerical simulation models used in hydraulic and environmental engineering practice are discussed with regard to possible consequences of upstream bottom turbulence for the dynamics of shallow mixing layers.

1.1.1 Practical relevance

Shallow mixing layers are a particular case of shear flows and are frequently found in nature. In this study large horizontal coherent vortices are considered to be an intrinsic feature of this type of shear flow. These large horizontal energetic vortices with dimensions exceeding the water depth cause bottom shear stress fluctuations and are predominantly responsible for the turbulent transport of matter and momentum. Examples of large horizontal vortices caused by transverse shear are found at the confluence of two rivers (Chu en Babarutsi, 1998) see figure 1-1, in a compound channel at the interface between the main channel and the floodplain (Kinoshita, 1984), between the main channel and a groyne field (Uijtewaal et al., 2001) or in a harbour entrance between the river and the harbour (Booij, 1986).

Figure 1-1 Confluence of the Meghna and Padma rivers, Bangladesh (Ashworth et al., 1996)

Nowadays, there is a demand for reliable predictions (predictions with relatively small margins) regarding the response of natural water systems to future climatological scenarios (expected rise in sea level, higher flood levels, etc.) and the impacts of alternative scenarios of measures for the sustainability and optimisation of functions as safety, navigation, ecology, agriculture and recreation in the future. These predictions are essential for strategical decisions, which have to be made related to the layout of natural watersystems. In practice, these predictions are a result of exploratory investigations using numerical models.

A proper knowledge of the dynamics of large horizontal coherent vortices, formed in shallow mixing layers, is of key importance regarding the proper and efficient implementation of the relevant physical processes in these numerical simulation models.
As a result, the quality of predictions made in exploratory investigations using numerical models can be improved.

1.1.2 Background of the study

For a proper understanding of the dynamics of the large horizontal vortices, it is important to know when large horizontal vortices are formed and how these large horizontal vortices develop in the flow. There are different ways to investigate the development of large horizontal vortices in shallow mixing layers: laboratory experiments, analytical methods and numerical simulations. As a result of considerable advances in computer power and experimental observation techniques, substantial research has been performed over the past decades to obtain insight in the dynamics of this type of shear flow. Despite this research, shallow shear flows are not fully understood, especially the interaction between the large-scale motion and the small-scale motion. Several questions remain unanswered, as: ‘How does the energy transfer take place from the large-scale motion to the small-scale motion?’ and ‘Does bottom turbulence trigger instabilities that lead to the development of large horizontal vortices?’

A recent study (Van Prooijen & Uijttewaal, 2002a), which focuses on the last question, uses a linear stability analysis (analytical method) and a non-linear analysis using a depth averaged Transient Reynolds Averaged Navier Stokes (TRANS) simulation model. This study shows that perturbations at the inflow boundary, representing the bottom turbulence, have consequences for the downstream development of the shallow mixing layer and the large horizontal vortices. Linear behaviour as found in the linear analysis is also found by this non-linear analysis. The non-linear analysis shows that for a case without perturbations imposed at the inflow boundary no large horizontal vortices are found in the shallow mixing layer while cases with a perturbed inflow boundary do show the presence of large horizontal coherent vortices. A consequence of linear behaviour is that the intensity of these evolved vortices appears to be proportional to the intensity of the perturbations imposed at the inflow boundary. This study also shows that if large horizontal coherent vortices are present, the mixing layer width grows faster. So, the growth of the mixing layer width is related to the development of the large coherent vortices. Since the influence of the small-scale bottom turbulence within the TRANS simulation model is exclusively modelled as a dissipative term, large horizontal vortices cannot originate out of this modelled bottom turbulence. The inflow boundary conditions appear to be the only way to initiate the development of large horizontal vortices. However, turbulence produced in the bottom boundary layer serves as a disturbance that is always present in shallow mixing layers. In practice, this bottom turbulence can attain a wide range of intensities depending on the bottom roughness and obstacles in the flow. Moreover, depth averaging may suppress details that are important for the generation of vortices. For example, the production term of 3D-bottom turbulence is omitted due to integration over the vertical.

The hypothesis that upstream turbulence conditions have consequences for the downstream development of a shallow mixing layer and the large horizontal vortices is not yet confirmed experimentally. Therefore this study is initiated.

1.1.3 Characteristics of shallow flows

Most natural flows in hydraulic and environmental engineering practice, like low land rivers, estuaries and coastal waters, are characterised as shallow. In these flows, the horizontal dimensions of the flow domain (the width and the length) are much larger than the vertical dimension (the water depth). There are many rivers for example, which have a width-depth ratio larger than one hundred. Therefore these flows are called shallow-water flows.

In shallow-water the flow is restricted by the presence of two boundaries: a bottom and a free surface. Both boundaries dampen the vertical motions and force the mean
flow to a nearly horizontal 2D motion. As a consequence, shallow flows can be considered as quasi-2D flows.

A characteristic of shallow flows is that the turbulent boundary layer extends over the entire water depth. In shallow flows the bottom shear stress slows down the mean flow, resulting in a vertical gradient of the horizontal velocities. This vertical gradient of the horizontal velocities is responsible for the production of bottom turbulence. A quasi-cyclic process of ejection and sweep events near the bottom produces the structure of this 3D turbulence. This corresponds with the notion that large 3D coherent structures appear to be present in this type of shear flow. The water depth limits the length scale of these 3D coherent structures.

1.1.4 Characteristics of shallow mixing layer flows

A mixing layer develops for instance, at the confluence of two shallow flows with different velocities. The mixing layer forms a transition between the two shallow flows and is considered to be a typical case of shear flows. The development of the shallow mixing layer is predominately determined by the velocity difference across the mixing layer and the growth of the large horizontal vortices, which appear to be present in this type of flow. These large horizontal vortices dominate the turbulent transports in the transverse direction. The width of the shallow mixing layer increases in downstream direction. However, the spreading rate is suppressed in downstream direction due to the bottom friction. The influence of the bottom friction on the growth of the shallow mixing layer is two-fold:

- First, the bottom friction is responsible for the decrease of the velocity difference across the shallow mixing layer in the downstream direction.
- Second, the bottom friction has a damping influence on the large horizontal vortices in the mixing layer.

Due to the velocity difference between the contiguous shallow-water flows, a velocity gradient in the transverse direction originates. The velocity gradient in the transverse direction and the presence of instabilities are responsible for the generation of large horizontal coherent vortices in this type of shear flow. The axes of these large horizontal vortices can be slightly tilted with respect to the vertical (Uijttewaal & Booij, 2000). The horizontal dimensions of these large horizontal coherent vortices are approximately of the order of magnitude of the mixing layer width. This means that the large horizontal vortices can attain dimensions much larger than the water depth.

The geometrical confinement of shallow shear flows exerts influence on the properties of the turbulence:

- First, the limited water depth is responsible for the quasi-2D structure of the large horizontal vortices. The limited water depth prohibits these vortices to be stretched in the vertical direction. As a result, the transfer of turbulence kinetic energy from the large scales to the small scales is suppressed. These large coherent vortices in a shallow mixing layer are characterised as quasi-2D and not as fully 2D, because in reality there are disturbances in the vertical direction on a scale much smaller than the diameter of a vortex. Moreover, the flow in a vortex is not exactly the same at every elevation in the water column.
- Second, the bottom in shallow-water flows gives rise to bottom turbulence, which in the presence of a vertical gradient transfers turbulence kinetic energy from the large quasi-2D vortices to heat resulting in a loss of large-scale turbulence kinetic energy, see for example Chu en Babarutsi (1988). It is noted that the transfer of turbulence kinetic energy to heat occurs in the smallest scales of the bottom turbulence where viscous friction is large enough.
- Third, the bottom friction has a stabilising influence on the production of large horizontal vortices, which is related to the decrease of the transverse velocity difference across the mixing layer in downstream direction. This stabilising influence
of the bottom friction gives rise to a reduced growth rate of large horizontal vortices (Uijttewaal en Booij, 2000).

The simultaneous occurrence of large horizontal vortices and the bottom-generated turbulence in shallow mixing layers leads to highly anisotropic turbulence properties.

1.1.5 Numerical simulation models

Improving the modelling of physical processes in lowland rivers, estuaries and coastal waters is a challenge to hydraulic and environmental engineers. Numerical simulation models are a promising tool to evaluate the impacts of future climatological scenarios and long-term strategies, which eventually will have consequences for the layout of natural water systems. In order to describe the turbulence in shallow mixing layers, current turbulence models incorporated in these numerical simulation models, are not optimal. Modelling of the interaction between the large quasi-2D vortices and the bottom-generated turbulence, and of the simultaneous occurrence of different turbulence length scales in shallow mixing layers, is very difficult, especially when classical Reynolds-averaged turbulence models are used. Different turbulence models can be used, varying from 1-equation models with a scalar turbulence viscosity to two equation models. This implies that isotropic turbulence is assumed.

Since the large Reynolds number requires a huge computational effort for the direct numerical simulation (DNS) of this type of shear flow, a quasi-2D (depth-averaged) LES may be a more promising and suitable numerical technique. A depth-averaged LES only resolves the dynamics of the large vortices. This technique represents the large-scale vortices well on the computational grid whereas the small-scale vortices have to be modelled with a subgrid-scale model. While a depth-integrated model saves computational time, it may suppress details which are important for the generation of vortices. For example, the production term of 3D-bottom turbulence disappears due to integration over the vertical. In a quasi-2D LES the subgrid-scale model corresponds with vortices with length scales smaller than the water depth, while in a 3D LES the subgrid-scale model represents the small-scale dissipative vortices. This small-scale turbulence shows more isotropy and homogeneity than the large horizontal vortices. This means that the subgrid-scale model of the depth-averaged LES has to be adapted for the mutual interaction between the bottom turbulence and the quasi-2D turbulence. The possibility that the bottom turbulence affects the development of a shallow mixing layer and the large horizontal vortices in size and intensity is for the time being not taken into account in these numerical simulation models.

1.2 Problem definition

Linear stability analysis and non-linear analysis (Van Prooijen & Uijttewaal, 2002a) suggest that upstream turbulence conditions have consequences for the development of a shallow mixing layer and the large horizontal vortices in size and intensity. This is not yet confirmed experimentally. If the influence exerted by the bottom turbulence on the development of a shallow mixing layer and the large horizontal vortices appears to be substantial, which the theory suggests (linear analysis and non-linear analysis), then this will have consequences for the modelling of the turbulence of such complex and highly anisotropic flow. Eventually, the influence of the bottom-induced turbulence on the development of a shallow mixing layer and the large horizontal vortices has to be incorporated in some way.
1.3 Objective

Because little is known about the influence of bottom-induced turbulence on the development (formation) of large horizontal vortices, a study is initiated with the following objective:

Providing an experimental investigation concerning the consequences of upstream turbulence for the development of a shallow mixing layer and the large horizontal vortical structures, in size and intensity.

1.4 Approach

The sensitivity of a shallow mixing layer and the large coherent vortices in it to upstream turbulence is investigated experimentally. The experiments are executed in a shallow-water facility at the Laboratory for Fluid Mechanics of the Faculty of Civil Engineering of the Delft University of Technology. This facility was specially built for investigations of shallow flows.

Two experiments are executed which differ in intensity of the imposed turbulence upstream. An experiment (labelled experiment 1) is executed in which the turbulence intensity of the contiguous flows is raised using a bed of stones (rough upstream bottom) uniformly distributed over the width of the inlet section. This flow condition is compared with a second experiment (labelled experiment 2) without an extra source of upstream turbulence (smooth upstream bottom).

Turbulence data are obtained by means of experimental techniques for measurements in water flows like Particle Tracking Velocimetry (PTV) and 2D Laser Doppler Anemometry (LDA).

1.5 Outline of this thesis

The research described in this report concerns an experimental investigation of the influence of upstream turbulence on the development of shallow mixing layers and the large horizontal coherent vortices in it. The following chapters of this report are organised as follows. Chapter 2 provides a quantitative description of the development of a two-stream shallow mixing layer over a horizontal bottom and the large coherent vortices in it as presented by Van Proojen & Uijttewaal (2002b) including a discussion of the implications which result from the sequence and type of modelling with regard to the analysis of data obtained from the experiments. In appendix I the reader is introduced to some basic flow stability theory in order to elucidate the modelling described in chapter 2. In chapter 3 some characteristic features of coherent vortices are presented and a selection of available literature covering experiments on the subject of sensitivity of turbulent mixing layers to upstream turbulence is presented. Chapter 4 deals with the laboratory experiments. The experimental set-up, measurement techniques, measurement programmes and data analysis are described. In chapter 5 results are presented and analysed. Furthermore, the applicability of the models presented in chapter 2 is discussed. Finally, conclusions and recommendations are presented in chapter 6.
2 Development of a shallow mixing layer

This chapter describes the modelling of the development of two-stream shallow mixing layer over a horizontal bottom and the large coherent vortices in it as presented by Van Prooijen & Uijttewaal (2002b). The modelling is split in two stages. In the first stage, described in section 2.1, the evolution of the mean base flow is modelled using a quasi-1D model based on self-similarity. This model is able to simulate some characteristic properties of the development of shallow mixing layers. These properties are a downstream decrease of the velocity difference across the mixing layer, a downstream reduction of the growth of the mixing layer width and a transverse displacement of the mixing layer centre towards the slow stream in downstream direction. The second stage is presented in section 2.2; a linear stability analysis is described, which uses the modelled base flow to predict the development of the large coherent vortices. In section 2.3 implications that result from the sequence and type of modelling are discussed with regard to the analysis of data obtained from the experiments conducted in this study. In appendix I an introduction is given on some basic flow stability theory in order to elucidate the modelling described in this chapter.

2.1 Mean flow evolution

Experiments show that in shallow-water mixing layers the transverse velocity component is much smaller than the streamwise velocity component. This implies that the transverse free surface slope is much smaller than the longitudinal free surface slope. If it is assumed that the transverse mean velocities in both contiguous flows, the transverse variation of the water depth and the transverse variations of the bed friction coefficient can be neglected, a set of two coupled 1D models can be used to describe the interaction of the contiguous flows over a horizontal bottom. Assuming a horizontal bottom, for both flows the following steady flow models are used:

\[ M_1 : U_1 \frac{\partial U_1}{\partial x} + g \frac{\partial H}{\partial x} + c_f \frac{U_1^2}{H} = 0 \]
\[ M_2 : U_2 \frac{\partial U_2}{\partial x} + g \frac{\partial H}{\partial x} + c_f \frac{U_2^2}{H} = 0 \]

(2.1)

with \( M_i \) the 1D equation of motion, \( U_i \) the streamwise velocity component in the fast or slow stream, \( H \) the water depth, \( g \) the gravitational acceleration and \( c_f \) the bed friction coefficient. An expression for the bed friction coefficient is determined using the depth integrated Prandtl-Von Karman logarithmic profile, a relation for the equivalent roughness height for a hydraulically smooth bottom (viscous length scale) and an expression in which the product of the bed friction coefficient and the squared depth averaged velocity balances the squared friction velocity. The following relation is used to obtain the bed friction coefficient for a hydraulically smooth bottom:

\[ \frac{1}{\sqrt{c_f}} = \frac{1}{\kappa} \left( \ln \left( \text{Re} \sqrt{c_f} \right) + 1 \right) \]

(2.2)

where \( \kappa \) is the Von Karman constant (0.41) and \( \text{Re} = U_c H / \nu \) the local Reynolds number and \( \nu \) the kinematic viscosity and \( U_c = \sqrt{2} \times (U_1 + U_2) \).

Because the transverse slope of the free surface can be neglected, the driving force (the longitudinal free surface slope) is assumed to be equal for both contiguous flows. However, the streamwise velocity component varies in transverse direction so the bottom shear stress also varies in transverse direction. As a consequence the fast stream is decelerated and the slow stream is accelerated, which means that the velocity difference decreases in downstream direction. A simple expression for the downstream
evolution of the velocity difference is obtained by subtracting the equations of motion of both contiguous flows and subsequently integrating over $x$:

$$
\frac{(U, \Delta U)}{(U, \Delta U)_0} = \exp \left( \frac{-2c_f x}{H} \right)
$$  \hspace{1cm} (2.3)

in which $\Delta U$ is defined as $(U_1 - U_2)$. This simple evolution function can only be applied to shallow flows with a width much larger than the width of the mixing layer. This model does not take into account the decrease in width of the contiguous flows as a result of the mixing layer development.

Using the equation of continuity it can be demonstrated that the velocity in the centre of the mixing layer can be approximated by a constant, consequently $U_c$ drops out of equation 2.3. The discharge at the inlet section should be equal to the discharge far downstream. This leads to the following expression:

$$
U_c = \frac{1}{2} \left( U_1(x_0) + U_2(x_0) \right) = U(x_0)
$$  \hspace{1cm} (2.4)

where $U_1(x_0)$ and $U_2(x_0)$ are defined as initial streamwise velocities outside the mixing layer at the upstream boundary and $U(x_0)$ the uniform streamwise velocity far downstream. However, experiments show that $U_c$ increases slightly in downstream direction. In a stationary subcritical transverse uniform flow above a horizontal bottom the water depth decreases downstream to overcome the bottom friction. A convex longitudinal free surface slope is established. By means of the 1D equation of motion and the continuity equation it can be shown that the streamwise velocity component increases in downstream direction:

$$
\frac{\partial H}{\partial x} = -c_f \cdot \left( \frac{Fr^2}{1 - Fr^2} \right)
$$  \hspace{1cm} (2.5)

in which Fr is defined as the Froude number.

$$
\frac{\partial U}{\partial x} = \frac{U}{H} \cdot \frac{\partial H}{\partial x}
$$  \hspace{1cm} (2.6)

In shallow mixing layers the streamwise velocity component varies in the transverse direction. Experimental results show that for shallow mixing layers self-similarity of the transverse profile is found. Self-similarity implies that the transverse profiles of the streamwise velocity can be described with a self-similarity model. A profile function, of the form of a hyperbolic tangent, can be used to model the mean streamwise velocity field:

$$
U(x, y) = U_c + \frac{\Delta U(x)}{2} \tanh \left( \frac{y - y_c(x)}{\frac{1}{2} \delta(x)} \right)
$$  \hspace{1cm} (2.7)

where $\delta$ is defined as the mixing layer width and $y_c$ is defined as the transverse position of the centre of the mixing layer. The 2D formulation of the streamwise velocity field is now reduced to a formulation that depends only on the downstream position $(x)$. The mean flow field can be calculated by defining the evolution of $\delta$ en $y_c$ in downstream direction.
The downstream evolution of the shallow-water mixing layer can be described in terms of the evolution of the width of the shallow-water mixing layer. The most practical and simple expression for the mixing layer width is the ratio of the velocity difference $\Delta U$ across the mixing layer to the maximum transverse gradient of the mean streamwise velocity:

$$\delta \equiv \frac{\Delta U}{\left(\frac{\partial U}{\partial y}\right)_{\text{max}}} \quad (2.8)$$

The presence of a single length scale is a characteristic of self-preserving mixing layers. The presence of two length scales, the water depth and the mixing layer width, suggests that shallow mixing layers cannot have the property of self-preservation. Despite the presence of two length scales, measurements show (Uijttawaal en Booij, 2000), that transverse distributions of the mean flow and turbulence characteristics can be scaled with a single length scale (the mixing layer width). This result can be ascribed to the presence and dominant role of the large coherent vortices in shallow mixing layers, which justifies the description of the evolution of the shallow mixing layer by a single length scale. These large coherent vortices generated by the transverse shear and with dimensions of the order of the mixing layer width (exceeding the water depth) play a role in the entrainment of mass and momentum and thus in the growth of the mixing layer in down stream direction. Thus, the development of the mixing layer is affected by the presence of the large coherent vortices.

![Figure 2-1 Mixing layer development](image)

*Figure 2-1 Mixing layer development*

In an unbounded self-preserving mixing layer, the growth of the mixing layer is proportional to the relative velocity difference and a proportionality factor, which is called the entrainment coefficient ($\alpha$):

$$\frac{d\delta}{dx} = \alpha \frac{\Delta U(x)}{U_c} \quad (2.9)$$

The entrainment coefficient has a value of $\alpha = 0.085$ as empirically determined from free or unbounded mixing layers (Lesieur, 1997). The influence of the shallowness on the growth of the shallow mixing layer is incorporated in the development of the velocity difference. The growth of the shallow mixing layer diminishes to zero as the mixing layer width approaches a maximum value at $x \to \infty$. The following expression is obtained substituting the development of the velocity difference in equation 2.9 and integrating with respect to the longitudinal coordinate:
\[ \delta(x) = \alpha \cdot \lambda_0 \cdot \frac{H}{c_f} \left( 1 - \exp\left( -\frac{2 \cdot c_f \cdot x}{H} \right) \right) + \delta_0 \]  
(2.10)

where \( \lambda_0 = (U_1 - U_2)_0/(U_1 + U_2)_0 \) and \( \delta_0 \) is a correction for the presence of an initial width of the mixing layer. The origin of this initial width is related to the finite thickness of the splitter plate and the development of boundary layers at both sides of the splitter plate as a result of the no slip condition. \( \delta_0 \) is approximately order water depth.

The centre of the mixing layer shifts towards the slow stream as a result of the deceleration of the fast stream, acceleration of the slow stream and continuity. The displacement of the mixing layer centre towards the slow stream can be determined using an integral mass balance with the integrand limits at the sidewall of the slow stream and the position of the mixing layer centre, which balances the discharge through the inlet section of the slow stream:

\[ Q_{2,0} = H \int_{-0.5H}^{y_i} U(x,y)dy \]  
(2.11)

### 2.2 Evolution of coherent vortices

Van Prooijen & Uijttewaal (2002b) have demonstrated that linear stability analysis can be used to predict the development of large horizontal coherent vortices in a shallow mixing layer for a given mean velocity field. The linear stability analysis used by Van Prooijen & Uijttewaal (2002b) is divided in two stages.

In the first stage, the mean velocity field is modelled using a quasi-1D model based on self-similarity (described in section 2.1). In the second stage, perturbations are superimposed on the modelled base flow and are substituted in the depth and short time averaged shallow-water equations. As a result of averaging over the water depth and averaging over a short time the vertical shear is replaced by the bottom shear stress. The bottom shear stress is calculated as the product of the bed friction coefficient and the squared depth averaged velocity. Short time averaging implies that only the large-scale vortices can be resolved; as a consequence, the small-scale 3D-bottom turbulence has to be modelled. The small-scale 3D bottom turbulence is modelled using a constant turbulence viscosity, which can be derived by averaging the parabolic turbulence viscosity distribution over the water depth. Linearizing the equations for the perturbations and using the rigid lid approximation (\( Fr < 0.5 \)) an Orr-Sommerfeld type equation with bottom shear stress terms is derived.

Comparing the linear stability analysis used by Van Prooijen & Uijttewaal (2002b) with inviscid linear stability analysis, it is concluded that the turbulence viscosity and bottom shear stress terms stabilise the flow. The Orr-Sommerfeld type equation and a given base flow can be used to predict if an imposed perturbation (wave number) is stable or unstable (decaying or growing). Because the viscous and bottom friction terms are retained, the dissipative terms can become larger than the production terms, resulting in negative growth rates (decay). This effect is especially significant for longer distances (several times the water depth) downstream from the apex of the splitter plate. From the Orr-Sommerfeld type of equation it can be derived that the dissipative influence of the bottom friction is the same for each perturbation (wave number) and the dissipative influence of the turbulence viscosity is proportional to the squared wave number. Thus the turbulence viscosity affects the smaller large scales more than the larger large scales.

In experiments the development of the quasi-2D coherent vortices in shallow mixing layers can be measured using significant peaks in 1D energy density spectra of the transverse velocity fluctuations calculated at the centre of the mixing layer. These peaks identify the presence of large coherent vortices in the flow. In shallow mixing layers the peak shifts towards the low wave number range moving in downstream di-
rection. This corresponds with the growth of the large coherent vortices in down-stream direction.

Linear stability analysis can be used to model the development of 1D energy density spectra of the transverse velocity fluctuations in downstream direction using the initial 1D energy density spectrum of the transverse velocity fluctuations just downstream from the splitter plate and calculated amplification factors for the initial spectral energy density levels for certain wave numbers, equation 2.12. The amplification factors are determined integrating the growth rates for various wave numbers at given positions from the apex of the splitter plate over the streamwise coordinate.

\( E_{\nu v}(k, x_i) = E_{\nu v}(k, x_0) \exp \left( \frac{2k}{\alpha_r} \int_{x_0}^{x_i} \omega_0(k, x) dx \right) \)  \hspace{1cm} (2.12)

in which \( E_{\nu v}(k, x_i) \) is defined as the 1D energy density level of the transverse velocity fluctuations of an imposed perturbation with wave number \( k \) at a certain streamwise position \( x_i \) in the mixing layer centre, \( E_{\nu v}(k, x_0) \) is the initial 1D energy density level of the transverse velocity fluctuations of an imposed perturbation with wave number \( k \) at the origin of the mixing layer, \( k \) is the wave number of an imposed perturbation defined as \( k = \omega / U_c \), \( \omega \) is the angular frequency of an imposed perturbation and \( \alpha_r(k, x_i) \) is the growth rate of a perturbation with wave number \( k \) at a certain streamwise position \( x_i \).

Equation 2.12 takes the history of the development of large coherent structures into account. This means that the accumulation of energy at a certain wave number is considered. Thus, using linear stability analysis the development of large coherent vortices can be tracked by following a dominant mode in downstream direction. The dominant mode is defined as the wave number where the energy density spectrum attains a maximum value.

Van Prooijen & Uijttewaal (2002b) have shown the validity of this type of modelling by comparing results obtained from linear stability analysis with experimental data (two different mean flow conditions) obtained with Particle Tracking Velocimetry. It is concluded the analysis gives a good prediction of the energy density and the wave number of the large coherent vortices (dominant mode). However, this analysis does not apply to the whole wave number range of the energy density spectrum. The largest wave numbers (the smallest length scales) are not accounted for. The modelling appears to be valid for length scales, which are much larger than the water depth (> 10H).

### 2.3 Discussion

Consequences of the successful prediction of the onset of growth of large-scale fluctuations in shallow mixing layers using linear stability analysis as proposed by Van Prooijen & Uijttewaal (2002b) are:

- The sequence of modelling implies that the influence of the shallowness is only taken into account by a decreasing velocity difference across the shallow mixing layer and the influence of the large coherent vortices on the mean base flow is already taken into account in the quasi-1D model. However, non-linear analysis using a depth-averaged TRANS numerical simulation model (Van Prooijen & Uijttewaal, 2002a) shows a different development of the mixing layer width for different intensity levels of the imposed perturbations, which suggests that large horizontal coherent vortices can influence the development of the mean base flow.

- As a result of the linear behaviour of the shallow mixing layer the energy density distribution of the perturbations imposed at the inflow boundary determines the intensity of the large horizontal coherent vortices formed in the shallow mixing layer further downstream. This was confirmed by a non-linear
analysis using a depth-averaged TRANS numerical simulation model (Van Prooijen & Uijttewaal, 2002a). Linear behaviour as found in the linear stability analysis is also found by this non-linear analysis. With the TRANS numerical simulation model the development of the mixing layer is investigated too. If the energy density levels of the imposed perturbations are higher, the initial mixing layer growth rate appears to be higher. It is concluded that the enhanced rate of growth of the mixing layer is related to the growth of the large horizontal coherent vortices, which are influenced by the perturbations representing the bottom turbulence imposed at the inflow boundary of the mixing layer. Thus, perturbing the inflow determines the turbulence characteristics downstream.

In this study two experiments are executed which only differ in intensity of the imposed turbulence upstream. The sequence of modelling used in the linear stability analysis proposed by Van Prooijen & Uijttewaal (2000b) implies that the mean base flow can be considered the same for both experiments. Thus, possible differences in downstream development of the large horizontal vortices between both experiments do not result in differences in downstream development of the mean base flow. Consequently, the exponential term of equation 2.12 will be the same for a certain wave number (frequency) at the low wave number range (low frequency) at a certain streamwise coordinate for both experiments. Thus, similar amplification for the initial energy density levels of the perturbations at the low frequency range for both experiments at arbitrarily chosen streamwise positions:

$$\frac{E_{vv}(f, x)}{E_{vv}(f, x_0)}_{\text{experiment 1}} = \frac{E_{vv}(f, x)}{E_{vv}(f, x_0)}_{\text{experiment 2}}$$

(2.13)

Or ratios can be determined between the initial energy density levels of the perturbations at the low frequency range for both experiments that can also be found at arbitrarily chosen streamwise positions:

$$\frac{E_{vv}(f, x_0)_{\text{experiment 1}}}{E_{vv}(f, x_0)_{\text{experiment 2}}} = \frac{E_{vv}(f, x)_{\text{experiment 1}}}{E_{vv}(f, x)_{\text{experiment 2}}}$$

(2.14)

Because 1D energy density spectra of open channel flows have a constant energy density level at the low frequency range the peak will emerge at the same wave number (frequency) if the initial energy density spectra of both experiments have the same shape at the low frequency range.

These implications which result from the sequence and type of modelling proposed by Van Prooijen & Uijttewaal (2002b) are experimentally verified in this study.

An experiment in which the inflow boundary of a mixing layer is perturbed is not a novelty. There are several wind tunnel experiments (chapter 3) which show that perturbing the inflow boundary of a free mixing layer affects the growth rate of the mixing layer and the large coherent vortices in it.

It is noted that the sensitivity of shallow mixing layers to upstream turbulence may have already been demonstrated (unintentionally) experimentally. Experimental research conducted by Chu & Babarutsi (1988) suggests that the initial growth of the shallow mixing layer can be twice as large as the initial growth of the free mixing layer. They concluded that this is a consequence of the geometrical confinement of the flow. However, Uijttewaal & Booij (2000) suggested that a not fully developed bottom boundary layer may have been the cause for the different shallow mixing layer development compared to the initial development of free mixing layers in experiments conducted by Chu & Babarutsi. A not fully developed bottom boundary layer may have a different spectral distribution of the turbulence kinetic energy compared to a fully developed boundary layer. Different mixing layer dynamics are expected using the theory presented in this chapter. Nonetheless, the spectral distribution of the turbulence
kinetic energy at the inflow boundary of the mixing layers is not investigated by Chu & Babarutsi (1988), so this experimental evidence is inconclusive.
3 Sensitivity to upstream turbulence

In section 3.1 some characteristic features of large coherent vortices are introduced. Sections 3.2 and 3.3 describe some experiments concerning sensitivity of mixing layers to upstream turbulence conditions. As a consequence of different upstream turbulence conditions, researchers observed different mixing layer growth rates for almost identical mean flow conditions. These different mixing layer growth rates are ascribed to a different development of the large coherent vortices, which dominate the dynamics of this type of shear flow. Section 3.4 discusses the research presented in the sections 3.2 and 3.3.

3.1 Coherent vortices

Turbulence consists of vortical structures with a variety of scales and is generally characterised by randomness and 3D vorticity fluctuations, which can be characterised in a statistical sense. Small-scale vortices, which characterise the fine structure of the turbulence, are nearly isotropic and behave to a certain extent as random motions. In contrast to small-scale vortices, large-scale vortices show coherent behaviour because they retain their character while being advected over a substantial distance. These large-scale vortices extract energy from the mean flow by means of instability processes and appear to have a life cycle including birth, development, interactions and breakdown. Thus, coherent structures show dynamic motions with a life cycle. These motions appear to be quasi-periodic and give rise to quasi-periodic oscillations of an instantaneous velocity signal. A velocity signal can then be interpreted as a superposition of fluctuations caused by small-scale turbulence with time scales $t$ and fluctuations caused by large coherent vortices with time scales $T$ (figure 3-1).

![Figure 3-1 Time signal $v$-component with time scales associated with large and small-scale motions](image)

However, large coherent vortices are not perfectly deterministic. First of all, their size, intensity and orientation vary from vortex to vortex. Second, coherent vortices move more or less randomly in space and time in turbulent shear flows. These properties are the reason that conventional long-term averaging cannot satisfactorily reveal the existence of coherent vortices and may not adequately reveal the contributions of the coherent vortices to the velocity fluctuations. Traditional stochastic methods, experimental techniques or theoretical analysis are not capable of completely revealing the
characteristics of the quasi-ordered coherent vortices. Characterising these quasi-
ordered coherent vortices requires the development of conditional sampling tech-
niques. This implies that a statistical analysis has to be used which includes a detect-
ing condition.

3.2 Sensitivity to upstream boundary layer conditions

Experimental, analytical and numerical studies on the subject of mixing layers have
been conducted for a period of about six decades. The first comprehensive study of
the mixing layer has been conducted by Liepmann & Laufer (1947). They proved that
the flow is self-similar. Self-similarity is characterised by turbulence statistics that are
independent of the downstream distance when normalised by appropriate length and
velocity scales (Tennekes & Lumley, 1972). Since then, numerous studies have shown
that for sufficiently high Reynolds numbers, the equations governing the development
of mixing layers can yield self-similar solutions.

For a wide range of Reynolds numbers, Brown & Roshko (1971) first reported the
existence of large horizontal coherent structures in free turbulent mixing layers using
a flow visualisation technique. Brown & Roshko (1974) have observed a reduction in
passage frequency of vortices with increasing downstream distance as a result of
merging interactions among adjacent vortices. Winant and Browand (1974) have ob-
served, from motion pictures, that adjacent vortices tend to roll around each other be-
fore merging and generating a larger vortex. They claimed that this process of vortex
pairing is associated with the growth of the mixing layer. However, Hernan & Jimenez
(1979) analysed digitally the Brown & Roshko’s (1974) film and concluded that most
of the growth of the mixing layer can be attributed to the growth of the large coherent
vortices rather than to the process of vortex amalgamation.

Since then, several studies dedicated to determine the origin and dynamical signifi-
cance of coherent structures in mixing layers have been conducted. In these studies it
is thought that the coherent structures play a central role in the evolution of mixing
layers. These studies cover a wide range of experimental conditions. This continuous
effort is motivated apart from technological importance also by the rather large dis-
parity in the results among the different experimental studies, even for equal flow
conditions.

As a consequence the sensitivity of the turbulent mixing layer to a variety of ex-
perimental conditions has become a subject of discussion. From wind tunnel experi-
ments it is concluded that mixing layer flows appear to be most susceptible to pertur-
bations introduced at the upstream boundary. For instance, Batt (1975) proved by
tripping the upstream boundary layer, that an approximately 30 % larger growth of a
single stream mixing layer could be reproduced for otherwise equal flow conditions in
the same facility. This result is confirmed by Hussain & Zedan (1978b). It was con-
cluded that the growth of a single stream mixing layer is dependent on whether the
initial state of the boundary layer at the splitter plate is laminar or turbulent (tripped).
In two-stream mixing layers upstream boundary layer conditions also have a signifi-
cant effect on the mixing layer growth rate. It is reported by Browand & Latigo (1979)
that the mixing layer growth rate is initially much smaller for a turbulent boundary
layer than for a laminar boundary layer. Hussain & Zedan (1978a) reported that the
single stream mixing layer growth rates depend noticeably on the upstream peak fluc-
tuation levels in both laminar and turbulent boundary layers at the splitter plate for
otherwise identical flow conditions. The mixing layer growth increases with increasing
upstream peak fluctuation level. Moreover, they have reported that streamwise peak
fluctuation levels downstream from the splitter plate depend on upstream streamwise
peak fluctuation conditions. They hypothesised that sensitivity of free mixing layers to
upstream experimental conditions can be understood more easily if the presence of
cohherent vortices is accepted in this type of shear flow. Higher mixing layer growth
rates imply a higher rate of entrainment, which appears to be controlled by the dy-
namics of large coherent vortices (Hussain & Zedan, 1978a). Hussain & Zedan
(1978a) indicate that it is not the laminar or turbulent state (expressed by the initial momentum thickness) of the inflow boundary layers that is responsible for these effects, but the fluctuation level associated with the inflow conditions. They hypothesized that the upstream boundary layer conditions affect the dynamics of large coherent vortices in mixing layers.

Slessor, Bond and Dimotakis (1998) have studied the effect of upstream conditions on mixing in a high Reynolds number two-stream mixing layer by tripping one or both boundary layers on the splitter plate. It was observed that tripping the slow stream boundary layer at the splitter plate has no significant effect on the mixing layer dynamics. However, by tripping the fast stream boundary layer it was observed that the mixing layer growth rate was smaller when compared to a case with untripped boundary layers. Moreover, from colour schlieren visualisations (figure 3-2) a decrease in 2D organisation of large-scale vortices present in the flow was observed compared to a case with untripped boundary layers, even far downstream.

Two stream mixing layer with untripped upstream boundary layers

Two stream mixing layer with a tripped fast stream boundary layer

*Figure 3-2 Colour schlieren visualisations from Slessor et. al (1998)*
3.3 Artificially forced mixing layers

The hypothesis that free turbulent mixing layers are sensitive to upstream experimental conditions has led to experiments in which the free turbulent mixing layer was artificially forced. Oster and Wygnanski (1982) studied experimentally the sensitivity of a free turbulent mixing layer to a small-amplitude 2D single frequency oscillation introduced at the origin of the flow (air streams) in a wind tunnel. The frequency and amplitude of the oscillation were varied in this study. The controlled oscillation was imposed by means of a thin flap at the trailing edge of the splitter plate, which oscillates in the transverse direction and so directly affects the lateral component of the velocity fluctuations. It was concluded that the oscillations have no significant influence on the initial velocity distribution and on the total initial turbulent energy present in the flow. The frequency of forcing was at least an order of magnitude lower than the initial instability frequency of the flow.

They determined that the growth of the mixing layer is sensitive to a periodic perturbation even if the latter is so small that it hardly contributes to the initial energy of the fluctuations. Mixing layer growth rates, the transverse distribution of the components of the Reynolds stress tensor and dynamics of the vortices are all affected by the frequency and amplitude of forcing for otherwise equal flow conditions. If the mixing layer was forced at a high frequency, it responded by an initially enhanced rate of growth compared to a lower frequency forcing. However, the growth of the mixing layer forced at a higher frequency decreases at a shorter distance from the apex of the splitter plate compared to a forcing at a lower frequency. The mixing layer attained a larger width at the end of the facility for a lower frequency forcing when compared with a higher frequency forcing. When a mixing layer was forced at higher amplitudes it responded by an enhanced rate of growth compared to a lower amplitude forcing, however the final width of the mixing layer at the end of the measurement domain was more or less the same. It was observed that oscillations at very small amplitudes tend to increase the spreading rate of the flow by enhancing the amalgamation of neighbouring vortices, but at higher amplitudes the flow resonates with the imposed oscillation. This resulted in a suppression of the mixing layer growth due to a suppression of vortex interactions.

It was also concluded in this study that the linear inviscid stability theory is capable of predicting some important features of this flow. Apparently, amalgamations of vortices do not affect the amplification resulting from linear inviscid instability. Vortex amalgamations are considered to be a result of a non-linear process. It was suggested that large vortices in the turbulent mixing layer at fairly large Reynolds numbers are governed by an inviscid instability.

Although turbulent mixing layers are known to evolve self-similarly, Oster & Wygnanski (1982) concluded that a unique self-similar state was never attained in their experiments. The sensitivity of mixing layers to small-amplitude perturbations might explain the scatter in the spreading-rate parameters of mixing layers measured by various investigators, for otherwise identical experimental configurations. This implies that mixing layers achieve self-preserving states that are dependent on the upstream conditions. Although self-similarity is found for most quantities in experiments, the detailed flow structure could be different. The exact mechanisms producing such differences and the role of large coherent vortices in this process are not well understood.

Zhou & and Wygnanski (2001) studied experimentally the response of turbulent mixing layers to a simultaneous 2D excitation at two frequencies, a fundamental and a subharmonic, introduced to the flow at the origin using a small oscillating flap. The amplitudes of the oscillations were varied. Mixing layer growths, the transverse distribution of the components of the Reynolds stress tensor components and the dynamics of the large coherent vortices are all affected by the forcing mechanism for otherwise equal flow conditions.

Their results show that the growth rate of the mixing layer excited at two frequencies is larger downstream of the apex of the splitter plate compared to a single fre-
frequency excitation. The results also show that a mixing layer excited at two frequencies with high amplitudes maintains its rate of growth further downstream compared to a mixing layer excited at two frequencies with low amplitudes. A mixing layer continuously forced by a high amplitude dual frequency excitation doubled its final width compared to a single frequency excitation and a small amplitude dual frequency excitation. For the latter cases the mixing layer widths reached at the end of the measurement domain compared.

They concluded that a mixing layer can become twice as wide by forcing the flow at two frequencies simultaneously when a dimensionless saturation value is assumed based on the predominant frequency. At a small distance from the apex of the splitter plate the fundamental frequency is amplified more rapidly than its subharmonic. The mixing layer responds by spreading faster initially. If the subharmonic has substantial energy at the saturation location of the fundamental, it may extract energy from it through resonance and thus dominate the growth of the mixing layer as long as it does not reach its new dimensionless saturation value.

They have observed from vorticity contours that for a single frequency forcing a single row of vortices can be recognised aligned with the centre of the mixing layer. For a low amplitude dual frequency forcing, vortices are displaced slightly around the mixing layer centre, which is attributed to the imposed subharmonic frequency. This transverse displacement is stronger for a dual frequency high amplitude forcing and occurs at a relatively small distance from the apex of the splitter plate when compared to a dual frequency low amplitude forcing. Vortex amalgamations also occur at a relatively small distance from the apex of the splitter plate for a dual frequency high amplitude forcing when compared to a dual frequency small amplitude forcing. Thus, the vortex dynamics are influenced by the forcing mechanism.

### 3.4 Discussion

From the research presented in the previous sections the following conclusions can be drawn:

- It shows that the downstream development of the mixing layer width and the transverse profiles of Reynolds stresses are affected by perturbations imposed at the inflow boundary. These time averaged flow properties are considered to be identifiers of a different development of large coherent vortices formed in turbulent mixing layers for otherwise equal flow conditions.
- It is suggested that upstream turbulence conditions can affect the detailed turbulence structure. For instance, tripping the boundary layers on a splitter plate can affect the large-scale structures present in the flow by a decrease in 2D organisation, which is noticeable even far downstream.
- It is concluded from wind tunnel experiments that perturbations generated in the boundary layers at both sides of the splitter plate appear to be responsible for the initiation of large coherent vortices, which determine the mixing layer dynamics. The character of these perturbations and subsequently the dynamics of these large coherent vortices are determined by the state (laminar or turbulent) of the upstream boundary layers or the peak fluctuation levels in the upstream boundary layers. In two-stream shallow mixing layer research, in addition to the boundary layers that develop at both sides of the splitter plate, the bottom boundary layer also may serve as an extra source of perturbations. It is noted that these boundary layers also need a certain distance to fully develop. The presence of a bottom boundary layer is a direct effect of the shallowness of the flow. In shallow mixing layer research both boundary layers may influence (initiate) the development of large coherent vortices and subsequently the dynamics of shallow mixing layers.
- One has to be careful drawing conclusions with regard to linking cause and consequence (for instance state of the inflow boundary layers versus peak fluctuation levels and vortex pairing processes versus growth of the vortices) of observed phenomena in this type of shear flow, which is not fully understood. It should be
noted that researchers have never directly observed vortex amalgamations in turbulent shallow mixing layer flows. The bottom turbulence produced in the bottom boundary layer may work as an effective viscosity, which may damp events such as vortex pairings.

- The research presented indicates that it is known and generally accepted among researchers that turbulent mixing layers are sensitive to turbulence conditions at the inflow such as, the frequency (scales) of the imposed upstream perturbations, the presence of imposed perturbations with different frequency (range of scales) and the energy content of perturbations. The response of turbulent mixing layers to 2D excitations (single frequency and dual frequency) directly affecting the dynamics of large coherent vortices, is already investigated extensively.
4 Laboratory experiments

This chapter deals with the laboratory experiments executed in this study. Two experiments are executed which only differ in intensity of the turbulence upstream. An experiment (labelled experiment 1) is executed in which the turbulence intensity level of the contiguous flows is raised using a bed of stones (rough upstream bottom) uniformly distributed over the width of the inlet section upstream of the apex of the splitter plate. This flow condition is compared with a second experiment (labelled experiment 2) without an extra source of upstream turbulence (smooth upstream bottom). In section 4.1 the experimental set-up is discussed. In section 4.2 measurement techniques and programmes are presented. In section 4.3 the analysis of data acquired with PTV and 2D LDA is described.

4.1 Experimental set-up

4.1.1 Shallow-water flume

The experiments are executed in a facility specially built for shallow-water flow research, the so-called shallow-water flume, which is located at the Laboratory for Fluid Mechanics of the Faculty of Civil Engineering of the Delft University of Technology. The flume has an effective flow length of 19 m, a width of 3 m and a height of 0.20 m. The relatively large width of the facility ensures that the flow is shallow without sidewall effects. Therefore, the development in downstream direction of characteristic properties of shallow mixing layers can be investigated.

The facility has smooth glass sidewalls and a smooth horizontal glass bottom which is positioned 1.8 m above the floor. These provisions make optical access for LDA-measurements from below possible. A top view and side view of the facility are presented in the figure underneath.

![Figure 4-1 The shallow-water flume at the Laboratory for Fluid Mechanics](image)

The inlet section is divided into two equal sections by means of a 3 m long splitter plate with a thickness of 8 mm. The inlet region has a sufficiently large length, which ensures that the bottom boundary layers are fully developed before the end of the splitter plate is reached.

The facility is connected to the water circulation system of the laboratory. The water supply to the facility is controlled with a main valve. The water supply to the inlet sections is controlled with a separate valve for each inlet section. The main valve is used to start and end an experiment. The flow conditions are imposed using the valves of the inlet sections. After suitable inlet conditions have been chosen, these
valves remain fixed. The outflow is controlled by means of a sharp crested weir at the end of the facility.

The inlet section has a vertical contraction that connects to the horizontal part of the facility. Screens are placed between the contraction and the entrance of the horizontal part of the facility to dampen recirculations in the inlet region in order to obtain a homogeneous inflow. Floating foam boards are placed just downstream from the screens to suppress surface waves. At the end of the channel the water flows into a storage bin of the circulation system.

4.1.2 Flow conditions

**Mean flow characteristics**

The mean flow conditions have to meet several requirements. First, in order to establish a fully turbulent flow the Reynolds number condition, which quantitatively expresses the condition of a turbulent flow regime, has to be satisfied. It is assumed that the Reynolds number should be larger than 4000 to establish a fully developed turbulent free surface flow. This condition is readily satisfied by the real world prototype flow, but may pose some difficulties in laboratory experiments with respect to other requirements, which have to be met.

Second, the facility is considered to be a model of the confluence of two rivers. Most river flows are subcritical. Therefore a subcritical flow is required in the facility. The Froude number quantitatively expresses the condition of a subcritical free surface flow (Fr < 1). Moreover, the Froude number has to be sufficiently low (Fr < 0.5) ensuring the flow not to be affected by surface disturbances.

The conditions concerning turbulent flow and subcritical flow restrict the possible inlet flow conditions. The condition of turbulent inflow requires a high flow velocity while the condition of subcritical flow requires a low flow velocity. So, the subcritical flow condition gives a maximum value for the inlet velocity of the fast stream and the turbulent flow condition gives a minimum value for the inlet velocity of the slow stream. Both conditions are presented in the figure underneath.

![Figure 4-2 Conditions concerning turbulent and subcritical flow](image)

A third requirement, which restricts the mean flow conditions, is the mixing layer width. If the mixing layer width is too large the sidewalls of the facility may influence the dynamics of the mixing layer flow. To prevent such conditions the mixing layer should not be too large, a mixing layer width of approximately 1 m should not be exceeded in the measuring plane located furthest downstream. From equation 2.10, with increasing water depth the relative velocity difference should decrease in order to prevent such conditions.
A fourth requirement is directly related to the shallowness of the flow. The bottom friction affects the downstream development of the velocity difference across the mixing layer, the mixing layer width, the mixing layer shift and the large horizontal coherent vortices. A typical length scale (equations 2.3 and 2.10) related to the influence of the bottom friction is:

\[ L_f = \frac{H}{c_f} \]  

(4.1)

If this length scale becomes too large, stages of development characteristic for shallow mixing layers may not be captured in this facility because these phenomena occur at larger distances (multiples of this length scale). So, this length scale more or less controls the length of the area to be measured.

**Turbulence characteristics**

In this study emphasis is put on the development of large horizontal vortices in downstream direction in shallow mixing layers. Turbulence in shallow mixing layers is characterised as highly anisotropic, which means that distinct separate turbulence time and length scales are identified in this type of shear flow. Length scales associated with the bottom-induced 3D large coherent structures are of the order of the water depth and the length scales associated with the large horizontal vortices are of the order of the mixing layer width. Although the 3D coherent vortices are considered to be of the order of the water depth their detailed structure and development are 3D and highly complex. The same is valid for the downstream and instantaneous development of the large horizontal vortices in the mixing layer, which can be entirely different with regard to the downstream development of the mixing layer width.

In order to estimate length and time scales of the large coherent 3D structures, Nezu & Nakagawa (1993) have proposed a streamwise turbulence macroscale \( L_{x,w} = 0.77 \, H \) for the region near the free surface \( (z/H > 0.6) \). This length scale corresponds to a streamwise time scale of \( T_{x,w} = 0.77 \, H/U \). Previous investigations conducted in the shallow flume at the TU Delft (Uijttewaal & Booij, 2000) show time scales \( (T_{x,v}) \) of the developing large horizontal vortices up to 10 s \( (\approx 2.21 \, \delta/\Delta U) \) whereas time scales \( (T_{x,v}) \) of the 3D coherent structures are of the order 0.1 s \( (\approx \frac{1}{2} \, T_{x,v}) \).

In this study the PTV measurement technique is used to obtain turbulence data. The PTV measurement technique can produce more reliable results if the contributions of the large horizontal vortices to the turbulence properties (e.g. the Reynolds stress components) dominate over the contributions of the bottom turbulence. Therefore, the ratio between the mixing layer width and the water depth has to be sufficiently large. However, this ratio should not be increased by choosing the water depth too small. There appears to be a critical point where the bottom friction becomes dominant, corroding the large horizontal vortices that can no longer be sustained by the lateral shear (Uijttewaal & Booij, 2000). The large horizontal vortices initially present in the mixing layer disappear completely. The water depth can be increased in order to reduce the damping influence of the bottom friction on the large horizontal vortices. However, this will increase the influence of disturbances that originate from the splitter plate. Boundary layers developing at both sides of the splitter plate and secondary currents may affect the PTV measurements and may affect the initial development of the large horizontal vortices present in the mixing layer relatively more.

**Inlet conditions**

The inlet conditions were ultimately chosen by trial and error in compliance with the requirements mentioned in this paragraph. A different flow condition is chosen compared to previous shallow mixing layer research conducted in the shallow-water flume (Uijttewaal & Booij, 2000). A larger water depth is chosen to reduce the damping influence of the bottom friction on the large horizontal vortices and to obtain vortices with larger horizontal dimensions compared to previous investigations. The mean flow...
conditions at the apex of the splitter plate for both experiments are presented in the table 4-1.

<table>
<thead>
<tr>
<th>$H_0$ [mm]</th>
<th>$U_{1,0}$ [m/s]</th>
<th>$U_{2,0}$ [m/s]</th>
<th>$U_2$ [m/s]</th>
<th>$Re_{1,0}$</th>
<th>$Re_{2,0}$</th>
<th>$\lambda_0$</th>
<th>$Fr_{1,0}$</th>
<th>$Fr_{2,0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>0.11</td>
<td>0.31</td>
<td>0.21</td>
<td>24800</td>
<td>8800</td>
<td>0.48</td>
<td>0.35</td>
<td>0.12</td>
</tr>
</tbody>
</table>

*Table 4-1 Flow conditions at the end of the splitter plate ($x = 0.05$ m and $z/H = 2/3$) from LDA measurements for experiment 2*

### 4.1.3 The turbulence forcing mechanism

**Motivation**

There are several reasons to start an experiment involving a forcing of the shallow mixing layer to upstream bottom turbulence:

- First, a study involving linear and non-linear analysis (Van Prooijen & Uijtewaal, 2002a) indicates that the intensity of perturbations representing the bottom turbulence has consequences for the downstream development of coherent vortices formed in mixing layers. This hypothesis is not yet confirmed experimentally.
- Second, it can be verified whether linearized analysis (Van Prooijen & Uijtewaal, 2002b) is an applicable tool to analyse this type of shear flows. This can be evaluated by means of implications that result from the sequence and type of modelling proposed by Van Prooijen & Uijtewaal (2002b). These implications, such as equation 2.13, are presented in section 2.3.
- Third, a study on the subject of an excitation of the turbulent mixing layer to 3D-bottom turbulence has not been conducted yet and is essentially different with respect to an excitation involving 2D perturbations. Bottom turbulence affects all the components of turbulence kinetic energy but the bottom turbulence does not directly affect the transverse component of the large coherent vortices in the plane of the mixing layer, which is in contrast to 2D excitations described in section 3.3. Moreover each component of the total turbulence kinetic energy is distributed over a continuum of frequencies (scales).
- Fourth, the high practical relevance of such an experiment with regard to the modelling of this type of shallow shear flows. In shallow-water flows the bottom-induced turbulence serves as a disturbance, which is always present in hydraulic and environmental engineering practice. Nowadays, a new generation of 2D numerical models is used for exploratory investigations in hydraulic and environmental engineering practice: the depth-averaged LES. These numerical models can simulate the large horizontal vortices in the flow and model the bottom-induced turbulence exclusively as a dissipative term. Moreover, due to integration over the water depth 3D effects, such as the production of 3D-bottom turbulence, are omitted. An experiment as proposed in section 1.4 could give insight in the validity of this type of modelling, and data obtained from this experiment can be of use to improve the subgrid modelling of the bottom turbulence in these numerical models.

**Set up**

The research presented in appendix B indicates that a rough bottom, using a bed of stones, increases the turbulence intensities in comparison with a smooth bottom. This is a natural and practical method to impose an extra source of 3D-bottom turbulence. A densely packed bed of stones effectively raises the bottom level thereby disturbing the mean flow conditions. Therefore the stones are placed in a staggered pattern on a 0.04 m mesh grid in order not to disturb the mean flow too much. Moreover, within a certain range of the interparticle distance the bottom shear stress becomes saturated (Kurose and Komori, 2001). So, maximum turbulence intensities are not achieved with a most densely packed bed of stones given a certain stone size. The stones are placed
from the screens at the beginning of the inlet sections to the apex of the splitter plate (figure 4-3).

*Figure 4-3 The turbulence forcing mechanism; the stones are placed in a staggered grid pattern*

It is noted here that a rough bottom with relatively low submergence may affect the vertical profile of the streamwise velocity, causing deviations from the logarithmic profile of the streamwise velocity, which is considered to be valid for stationary uniform open channel flows. Consequently, the vertical profile of the streamwise velocity may need a distance of 20 to 50 times the water depth from the end of a rough bottom with relatively low submergence to recover to a logarithmic profile of the streamwise velocity. Therefore a rough bottom should not extend to the apex of the splitter plate. However, it is expected that the extra turbulence produced over a rough bottom will decay as it is advected downstream from the rough bottom by the mean flow. The advected turbulence will decay until a turbulence kinetic energy level is reached that can be sustained by smooth bottoms. So, in order to raise the turbulence intensity level at the origin of the mixing layer sufficiently, the turbulence forcing mechanism must be located at a relatively small distance from the origin of the mixing layer even though the vertical profile of the mean streamwise velocity might be affected. It is hypothesised that the length scale of turbulence decay is much smaller than the length scale needed for the vertical profile of the mean streamwise velocity to recover (appendix C).

The stone grading used in this study is chosen of those available at the Laboratory with the requirement that the stones remain stable in the flow. A \( D_{50} \) of approximately 0.03 m defines the stone grading used in this study. The ratio defined by equation B.5 (Appendix B) can be calculated by means of equation B.2, equation B.3, the depth integrated Prandtl-Von Karman logarithmic profile, an equivalent roughness height of \( k_s/30 \) and an estimate of \( k_s \). An upper limit estimate of \( k_s \) is \( 6 \, D_{50} \) and a lower limit estimate of \( k_s \) is \( 2 \, D_{50} \). The ratio defined by equation B.5 is then of the order \( 9 – 26 \).

### 4.2 Measurement techniques and programmes

Methods used to measure turbulence in water flows can be classified into two categories:

- Single point measurements.
- Flow visualisation techniques.

Single point measurement techniques are useful for the accurate determination of velocity fluctuations at one or more measurement points in order to acquire detailed temporal information about turbulence properties. Flow visualising techniques are effective in revealing the presence, dimensions and structure of large 2D vortices. Because of the quasi-2D properties of large horizontal vortices, the large-scale motions

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near the free surface are considered to be a measure for the large-scale motions beneath the free surface.

In this study both categories are used. Visualisations of large-scale quasi-2D structures are carried out by means of Particle Tracking Velocimetry (PTV). Detailed information about the turbulence properties is acquired with point measurements by means of 2D Laser Doppler Anemometry (LDA). The main advantages of the LDA-system with respect to the PTV measurement technique are:

- A higher spectral (temporal) resolution.
- A longer measuring period (10 minutes or 120000 bursts).
- The ability to measure over the water depth allows for the influence of the complex 3D structure of turbulence on the measured turbulence properties in the horizontal plane.

It is noted that the validity of the data obtained with PTV increases if the characteristic time and length scales of the quasi-2D vortices are much larger than those of the bottom induced turbulence. Thus, at relatively small distances from the apex of the splitter plate data obtained with the LDA-system is considered more reliable than data obtained with PTV, because the turbulence structure is considered to be more 3D at relatively smaller distances from the apex of the splitter plate.

Flow properties presented in table 4-2 have to be determined in order to analyse the flow and to validate the models described in chapter 2. Data acquired by means of PTV are used to investigate the influence of an extra source of upstream turbulence on the mean flow evolution of the shallow mixing layer (the velocity field, the width of the mixing layer and the centre of the mixing layer) and the Reynolds tensor components. Moreover it was intended to use PTV-data to investigate the development in size and intensity of the large coherent vortices. However, this is not carried out due to a lack of time. Data obtained by means of LDA are used to investigate the structure of the mean base flow and turbulence by means of transverse en vertical profiles of the streamwise velocity and the components of the Reynolds stress tensor. Furthermore, data obtained with the LDA-system are used to investigate the spectral distribution of the turbulence kinetic energy.

<table>
<thead>
<tr>
<th>Flow evolution</th>
<th>Properties</th>
<th>Measurement technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean flow development</td>
<td>Velocity difference</td>
<td>PTV</td>
</tr>
<tr>
<td></td>
<td>Mean convection velocity</td>
<td>PTV</td>
</tr>
<tr>
<td></td>
<td>Vertical velocity profiles</td>
<td>LDA</td>
</tr>
<tr>
<td></td>
<td>Width of the mixing layer</td>
<td>PTV</td>
</tr>
<tr>
<td></td>
<td>Centre location of the mixing layer</td>
<td>PTV/LDA</td>
</tr>
<tr>
<td>Turbulence characteristics</td>
<td>Reynolds stress tensor components</td>
<td>PTV/LDA</td>
</tr>
<tr>
<td></td>
<td>Energy density spectrum</td>
<td>PTV/LDA</td>
</tr>
<tr>
<td></td>
<td>Weiss function (visualising vortices)</td>
<td>PTV</td>
</tr>
</tbody>
</table>

Table 4-2 Flow properties measured

4.2.1 PTV measurement technique and programme

Particle Tracking Velocimetry (PTV) is used to acquire sequences of velocity maps of the instantaneous surface velocity. This method tracks the paths of the individual particles and calculates the velocity, resulting in an unstructured velocity vector map. The unstructured velocity vector map is interpolated to a regular grid of 51 * 51 mesh points using linear interpolation. Interpolation of the velocity vectors yields a sequence of velocity vector maps on a structured grid.

Figure 4-4 shows the sequence of analysing PTV data. Data obtained from measurement area 9 (centre location at x = 9.935 m) have been used to construct figures 4-4. In order to show the presence of large horizontal vortices relative velocity vectors are plotted in figures 4-4d and 4-4e. Therefore the mean convection is subtracted from the streamwise velocity component and the transverse velocity component is doubled $[\bar{u} (u-U_w, 2v)]$. 
Sensitivity of shallow mixing layers to upstream turbulence

a. Particles

b. Unstructured velocity vector map

c. Structured velocity vector map

d. Relative velocity vector map

e. Time averaged (2/3 sec) relative velocity vector map
**Figure 4-4 Sequence of analysing PTV data**

The PTV measurement equipment consists of a digital camera mounted on a bridge over the flume at some distance above the water surface, which recorded the positions of the particles during the course of an experiment. The camera, a Kodak ES1.0, has a resolution of 1008 × 1018 pixels with 256 grey levels and a maximum frame rate of 30 Hz. Due to a lack of spatial resolution and the relatively low sampling frequency only the large-scale motion can be captured; the small-scale motion is not fully recorded. Time series of images are stored directly on the hard disc of a PC with a maximum storage capacity of 10,000 frames for a single continuous sequence.

Measurements are performed at eight overlapping measurement areas (numbered 3 to 10) covering the mixing layer over a length of 12 m (figure 5). The centres of the measurement areas are located at \( x = 1.235 \) m, \( x = 2.685 \), \( x = 4.135 \) m, \( x = 5.585 \) m, \( x = 7.035 \) m, \( x = 8.485 \) m, \( x = 9.935 \) m and \( x = 11.385 \) m (apex of the splitter plate \( x = 0 \) m). The measurement areas overlap 0.20 m and have dimensions of 1.65 m × 1.65 m, which is considered to be sufficient to record the development of the mixing layer width and the large coherent vortices.

During the second experiment (smooth upstream bottom) it was noticed that the screens placed between the contraction and the horizontal part of the facility were non-uniformly obstructed over the width resulting in non-negligible transverse gradients of the streamwise velocity within the inlet sections which continued to exist downstream of the splitter plate. Therefore, the second experiment was executed once more for a limited number of PTV measurement areas (3,6 and 8).

**Figure 4-5 Measurement areas and experimental set-up**

Floating polypropylene particles with a diameter of 2 mm are used as tracers. These particles are relatively small so the flow can be accurately followed. Since the dimensions of the particles are small with respect to the dimensions of the vortices, the vortices contain a lot of particles, allowing an accurate description of the vortices. The particles are 90% immersed which prevents clustering of particles. However, it is observed that when the particles are moist at the start of a measurement, clustering cannot be avoided. In order to present a good contrasting background for the particles white foil is attached to the glass bottom from below. The particles are more or less homogeneously distributed over the water surface by hand. It turned out to be difficult to get particles into the mixing layer region at measurement area 3 (centre location at \( x = 1.235 \) m) for both experiments as a result of strong upflow. Secondary currents might have caused this strong upflow.

In this study, on average 3500 particles are detected at each time step with a minimum of 2600 particles and a maximum of 5000 particles. The relatively large range can be ascribed to the distribution of the particles by hand. Consequently, the number of particles differs for each measurement area.
The PTV scheme developed at the TU Eindhoven is used (Zoeteweij et al., 2001). The PTV algorithm tracks individual particles in successive images. A velocity vector at each particle position is determined on the basis of finding the most likely relations between the particle images of three successive frames. The most important modules of the PTV algorithm are:

- Background filtering.
- Particle image localisation.
- Mapping.
- Matching and prediction.
- Post-processing.

First, the images are filtered to remove background intensity variations (background filtering). This procedure is performed using dedicated software (jasc image robot). It is remarked that it was difficult to find appropriate filters because the fast stream and slow stream differed in intensity level. Moreover, during the course of an experiment the weather conditions varied, consequently the intensity level varied. Second, the image frames are processed to obtain the particle image coordinates using prescribed criteria for size (maximum and minimum) and brightness of the particles (particle image localisation). Next, a matching algorithm links successive particle images. This matching algorithm takes the likelihood into account that one particle image in one frame and another particle image in the next frame correspond to the same particle in the flow. A maximum matching distance is used to solve the matching algorithm more easily. The maximum matching distance determines the searching area in which a match can be made. Reliable matching occurs when the maximum matching distance is smaller than mean minimum interparticle distance:

$$ \Delta s_{\text{max}} < \frac{1}{2} \sqrt{A N} \quad (4.2) $$

with $A$ the pixel area and $N$ the number of particles. When $\Delta s_{\text{max}}$ is too large there are many candidates to match with one particle. However, if $\Delta s_{\text{max}}$ is too small some candidates will not be within the searching area to match with one particle. The particles are tracked by predicting their positions from previous frames. Two predictions are applied: a temporal extrapolation and a spatial extrapolation. First, a temporal extrapolation of the particle path is calculated to estimate the new position. However, if there is no previous matching, spatial interpolation is applied based on the neighbouring matched particles. If the amount of information in a specified area is not sufficient, a spatial interpolation using velocities from a specified file, is executed. Finally, the post-processing mode calculates the particle velocities from the stored particle path.

![Figure 4-6 Maximum matching distance and prediction](image)

The particle displacement and the mean minimum interparticle distance influence the performance of the PTV scheme. If the average particle displacement is smaller than the mean minimum interparticle distance the majority of the particles will be matched correctly even if no prediction scheme is employed.
A high value of the maximum particle displacement compared to the mean minimum interparticle distance will mean a high number of erroneous candidates for matching, especially if the maximum particle displacement is larger than the mean minimum interparticle distance.

From data, in which the tracking ability of the flow behind a heated cylinder using PTV and HPV is experimentally evaluated, it was concluded that for an optimal tracking ability the ratio of mean minimum interparticle distance to maximum particle displacement should be of the order 3 (Zoeteweij et al., 2001). If this ratio is smaller than 3 the quality drops quickly and if this ratio is higher than 3 the quality drops less quickly. This ratio is 1.3 for the fast stream and 4.5 for the slow stream. This indicates that particle tracking in the fast stream can be affected by erroneous matching.

4.2.2 LDA measurement technique and programme

In this study 2D Laser Doppler Anemometry is used to perform turbulence measurements. Laser Doppler Anemometry requires optical access to the flow, a transparent medium and the presence of tracer particles. All of these conditions are satisfied. The glass bottom of the shallow-water facility is positioned 1.8 m above the laboratory floor which enables optical access from underneath. Due to the presence of small suspended particles no seeding was necessary.

The Laser Doppler system used is based upon the backscatter technique. A measurement volume is formed where two beams intersect. For a measurement a particle has to travel through the measurement volume and scatter light back. The system detects only the backscattered light. In order to separate the component of each signal from the scattered light, two-colour laser light with different wavelengths is used. The 2D probe measures directly two components of the velocity in the horizontal plane. The 2D probe was mounted on a traversing system, which allows longitudinal, transverse and vertical transpositions of the probe. The measurements were executed automatically. A PC controlled the traversing system and was also used to store data. For a detailed description of the LDA measurement technique and the LDA system, the reader is referred to Nezu & Nakagawa (1993) and Tukker (1997).

A relative short measurement programme was executed with the LDA-system. Three cross-sections (transverse profiles) are measured for both experiments. In a cross section vertical profiles are measured at a location in the slow stream. The fast stream and the mixing layer centre. It is chosen to measure at \( x = 0.05 \) m, \( x = 0.40 \) m and \( x = 5 \) m. At \( x = 0.05 \) m the inflow boundary conditions of the mixing layers are investigated. At \( x = 0.40 \) m the width of the mixing layers is of the order of the water depth, therefore the effects of an extra source of bottom turbulence on the initial development of the mixing layer dynamics, which are more 3D, can be investigated. Furthermore, a cross-section was chosen at \( x = 5 \) m. Here the mixing layer width is much larger than the water depth, therefore the effect of an extra source of bottom turbulence on the development of the mixing layer dynamics, which are more quasi-2D, can be investigated. At \( x = 5 \) m, it is expected that the large quasi-2D vortices dominate over the bottom turbulence due to the restricted water depth. The LDA measurement locations are presented in appendix D. In this study the measurement time was 10 minutes and the data rate varied from approximately 100 Hz to 300 Hz.

4.3 Data processing and analysis

The turbulence velocity signals obtained with PTV and LDA are considered to be stochastic signals, which can be analysed with standard statistical techniques. Here attention is paid to the more sophisticated techniques.
4.3.1 Spectral analysis

A more detailed description of the flow conditions is provided by the variance (energy) density spectrum. It distributes the variance (energy) over the frequencies. The concept of variance can be extended to energy. The variance (energy) density spectrum can be obtained from turbulence velocity signals by means of spectral analysis. This allows the detection of large-scale fluctuations in turbulent flows. In mixing layer flows, even in the absence of the turbulence forcing mechanism, a peak appearing in the low-frequency range of the energy density spectrum can be identified with the presence of large coherent vortices.

PTV data consist of equidistantly sampled data. LDA data consist of non-equidistantly sampled data, because the acquisition of a sample depends on the presence of a particle in the measurement volume. In order to compute energy density spectra, the LDA data are resampled at equidistant times using the piecewise cubic Hermite polynomial interpolation method (second order interpolation). The resample frequency is chosen equal to the mean data rate of the corresponding time series.

Spectral analysis is based on Fourier transformations of the measured velocity data. Fourier analysis breaks down a signal into constituent sinusoids of different frequencies. It transforms the signal from the time domain to the frequency domain. For sampled data, Fourier analysis is performed using the discrete Fourier transform (DFT). Practical problems arise when computing a DFT of a velocity signal. The finite duration of the velocity signal limits the frequency resolution. The discrete character of the velocity signal causes the occurrence of the Nyquist frequency (mirror frequency). Because the DFT assigns information to the wrong carrier the spectrum above the Nyquist frequency is mirrored onto the spectrum below the Nyquist frequency. The availability of only one record of a certain flow condition causes a limited reliability of the spectral estimates, because only one sample of the variance per frequency can be obtained. This would give a rather noisy spectrum.

In this study the spectral resolution is more or less fixed by the sample frequency and measurement duration. So, only the reliability of the spectral estimates can be optimised. However, an increase in reliability of the estimate of the variance yields a decrease of the low spectral resolution. By dividing the record into a number of half-overlapping segments (20) of shorter duration the reliability of the spectral estimates is increased. Each segment is Fourier analysed to obtain a sample of the variance. By averaging the estimates obtained from the different samples a more reliable estimate of the variance is obtained. Furthermore, a spectral moving-average filter is used to suppress the spectral noise.

Time scales of the large coherent vortices can be estimated from the 1D energy density spectra of the transverse velocity fluctuations. Using Taylor’s hypothesis of frozen-turbulence these time scales can be transformed to length scales by multiplying the mean convection velocity with the periods of the coherent vortices (\(T_{x,v} = 1/f_{\text{dominant},v}\)):

\[
L_{x,v} = \frac{U_c}{f_{\text{dominant},v}}
\]

Taylor’s hypothesis is applicable if the mean convection velocity is much larger than the streamwise turbulence intensity (Nezu & Nakagawa, 1993).

4.3.2 Visualising vortices

Single point measurement techniques are inadequate to observe the detailed spatial structure of coherent vortices. Coherent vortices such as quasi-2D horizontal vortices in mixing layers and bursting phenomena near the wall were first discovered by means of flow visualisation. Flow visualisation made it possible to observe the spatial structure of coherent motions qualitatively. Nowadays, new measurement techniques such
as PIV, PTV (paragraph 4.2.1) and HPV in association with data processing techniques make it possible to obtain quantitative information about the spatial structure of coherent vortices as well.

In numerical studies, the second invariant of \(\nabla u\) or Weiss function \((Q)\) is used for a first impression of the presence of large-scale horizontal vortices. The Weiss function uses expressions related to the kinematics of the flow and is effective to discriminate between the coherent vortex cores and the turbulent background in regions of strongly sheared flow:

\[
Q = S^2 - \omega^2 = \left( \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \right)^2 + \left( \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right)^2 - \left( \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right)^2 \tag{4.4}
\]

\(S\) is a measure for the rate of strain (deformation) in a particular area of the flow and \(\omega\) is the vorticity (rotation). Regions with \(Q < 0\) are rotation dominated (\(|\omega| > |S|\)) and have elliptic or neutral character: two fluid particles initially near each other in an elliptic region will stay close together. Regions where \(Q > 0\) the flow is strain-dominated (\(|\omega| < |S|\)) and has a hyperbolic or turbulent character: the distance between the fluid particles in these regions increases exponentially in time. Vortex cores are found in regions with \(Q < 0\), that are surrounded by regions with \(Q > 0\).

In figure 4-7 vortices are visualised by means of colourmaps of the Weiss function. Another method which can be applied for a first impression of the presence of large-scale horizontal vortices uses the transverse velocity component. In figure 4-8 vortices are visualised by means of colourmaps of the transverse velocity component. As a guide to the eye relative velocity vectors are plotted in figures 4-7 and 4-8 as well. Therefore the mean convection is subtracted from the streamwise velocity component and the transverse velocity component is doubled \([\hat{u}(u-U_x, 2v)]\). Time averaged \((2/3\ s)\) data obtained from PTV measurement area 6 (centre location at \(x = 5.585\ m\)) experiment 2 (smooth upstream bottom) have been used to construct figures 4-7 and 4-8.

\[\text{[Time filtered PTV-vectorfield and Weiss function \([1/s^2]\)]}\]

\[\text{[Time filtered PTV-vectorfield and Weiss function \([1/s^2]\)]}\]

\(\text{Figure 4-7 Visualising vortices by means of colourmaps of the Weiss-function (Q) \([1/s^2]\)}\]

From figure 4-7 it can be concluded that the vortex visualisations by means of the Weiss-function are rather unsatisfactory. For instance, it is difficult to estimate a length scale. The Weiss function uses gradients of the velocity components, which are subjected to noise.

From figure 4-8 a length scale can be estimated from the distance between a maximum and a minimum transverse velocity. Length scale estimates from figure 4-8 appear to give more satisfactory results in comparison with length scale estimates from figure 4-7.
Although data used to construct figures 4-7 and 4-8 are time averaged (2/3 s), noise is still visible in both figures. Figures 4-7 and 4-8 illustrate the need for ensemble-averaged vortices.

Figure 4-8 Visualising vortices using the transverse velocity component [m/s]

In this study it was intended to reveal the presence, spatial structure (dimensions) and intensity of quasi-2D large horizontal vortices. For this purpose an ensemble average has to be determined in which the large coherent vortices are conditionally averaged in order to gather appropriate statistics and length scales. This analysis is rather labour-intensive. Due to a lack of time this is not carried out.
5 Experimental results

In this chapter it is investigated whether or not a difference in intensity level of the perturbations imposed at the mixing layer inflow boundary results in different mixing layer dynamics. From previous investigations (chapter 2 and 3) the mixing layer length scale, the Reynolds stress tensor components and the spectral distribution of the spanwise turbulence kinetic energy are considered to be identifiers for different mixing layer dynamics. Differences in downstream development of these identifiers are ascribed to a different downstream development of the large coherent vortices present in mixing layers.

Two experiments are executed in this study that differ only in intensity of the upstream turbulence. In this chapter the experiment in which the intensity of the upstream turbulence is increased using a rough upstream bottom is labelled experiment 1 and the experiment without an extra source of upstream turbulence (smooth upstream bottom) is labelled experiment 2.

5.1 Development of the mean flow

In this section emphasis is put on differences between both experiments in downstream development of the mean flow properties obtained from PTV measurements and LDA measurements. These properties are the velocity difference across the mixing layer, the mean centre or convection velocity, the mixing layer width and the mixing layer centre location. It is noted that the mean flow in both parallel streams must be the same for both experiments. Therefore the downstream development of the mean velocities in both parallel streams is also investigated. Furthermore, properties calculated using PTV measurements are compared to the models described in section 2.1. The model results are calculated using an initial velocity difference of 0.26 m/s, a mean convection velocity of 0.225 m/s, a water depth of 0.08 m and a bed friction coefficient of 0.0026. For experiment 1, PTV data from measurement areas 3 to 10 are used to analyse the flow and for experiment 2, PTV data from measurement areas 3, 6 and 8 are used to analyse the flow. For both experiments LDA data at x = 0.05 m, x = 0.40 m and x = 5 m are used to analyse the flow.

Development of the mean velocity field

Figure 5-1 shows scaled mean streamwise dimensionless velocity profiles for both experiments. The mean streamwise velocity is scaled with the local velocity difference. The self-similarity coordinates are determined by subtracting the local transverse coordinate y_{0.5} where (U-U_i)/\Delta U = 0.5 from the transverse coordinates, the differences are scaled using the local width of the mixing layer.

The modelling proposed by Van Prooijen and Uijttewaal (2002b) uses a profile function of the form of a hyperbolic tangent (equation 2.7). In order to model the mean streamwise velocity field by means of a profile function it is required that the transverse profile the streamwise velocity is self-similar. It is observed from figure 5-1 that PTV data from measurement area 6 (centre location at x = 5.585 m) and measurement area 8 (centre location at x = 8.485 m) collapse better on a hyperbolic tangent profile than data obtained from measurement area 3 (centre location at x = 1.235 m). Deviations from the hyperbolic tangent profile are ascribed to the three-dimensionality of the flow, which affects the transverse profiles of the streamwise velocity at relatively shorter distances from the apex of the splitter plate. Moreover, for experiment 1 the rough bed also affects the transverse profiles and vertical profiles (figure 5-2) of the streamwise velocity as a result of the placement of the roughness elements in a staggered pattern and the relatively small submergence of the roughness elements.

Thus, the transverse profile of the streamwise velocity is not well approximated by a hyperbolic tangent profile at the origin of the mixing layer. However, at a distance several times the water depth (x > 20H) downstream the transverse profiles of the
streamwise velocity fit a hyperbolic tangent fairly well. It is concluded that the transverse profile of the streamwise velocity is self-similar for both experiments.

Figure 5-1 Dimensionless transverse profiles of the streamwise velocity obtained with PTV at a. $x = 0.87 \text{ m and } 1.60 \text{ m}$ b. $x = 5.22 \text{ m and } x = 5.95 \text{ m}$ c. $x = 8.12 \text{ m and } x = 8.85 \text{ m}$
Figure 5-2 shows vertical profiles of the streamwise velocity at three locations (fast stream, mixing layer centre and slow stream) in cross-sections at $x = 0.05$ m, $x = 0.40$ m and $x = 5$ m from the apex of the splitter plate.

*Figure 5-2 Vertical distributions of the streamwise velocity a. experiment 1 $x = 0.05$ m b. experiment 2 $x = 0.05$ m c. experiment 1 $x = 0.40$ m d. experiment 2 $x = 0.40$ m e. $x = 5$ m experiment 1 f. $x = 5$ m experiment 2*
For experiment 1, vertical profiles of the streamwise velocity obtained at \( x = 0.05 \) m and \( x = 0.40 \) m deviate from the logarithmic profile of the streamwise velocity that is expected for stationary uniform open channel flows. For experiment 1 the vertical profile of the streamwise velocity is logarithmic at \( x = 5 \) m and for experiment 2 the vertical profile of the streamwise velocity is logarithmic with exception of the mixing layer centre at \( x = 0.05 \) m and \( x = 0.40 \) m.

The vertical profiles of the streamwise velocities at \( x = 0.5 \) m and \( x = 0.40 \) m in the fast stream and slow stream show a more or less linear distribution of the streamwise velocity over the vertical from \( z/h = 0.08 \) to \( z/h = 0.85 \). Thus, more streamwise momentum is located in the upper part of the velocity profile in compared to a logarithmic profile. As a result larger vertical gradients of the streamwise velocity occur in the upper part of the water column and smaller gradients of the streamwise velocity occur in the lower part of the water column in comparison with a logarithmic distributed streamwise velocity. Transverse distributions of the streamwise velocity (figures 5-3a,b and 5-4a) indicate that the vertical distributions vary in transverse direction. The linear like vertical profiles of the streamwise velocity ultimately recover to logarithmic profiles of the streamwise velocity at approximately 20 to 50 times the water depth (1.6 m – 4 m) from the end of the splitter plate. This phenomenon is confirmed by the observation of logarithmic profiles of the streamwise velocity at \( x = 5 \) m in the whole cross-section for both experiments.

Figure 5-3 shows the transverse distributions of the streamwise velocity for both experiments obtained with the LDA system at \( z = 2/3 \) H and figure 5-4 shows transverse distributions of the streamwise velocity for both experiments obtained with PTV. The solid lines in figure 5-4 represent the model, equation 2.7, described in section 2.1.

Comparing streamwise velocities obtained with LDA and PTV quantitatively is not straightforward, because the downstream coordinates differ and for experiment 1 the vertical profile of the streamwise velocity needs a certain distance to recover to a logarithmic streamwise velocity profile. The vertical distribution of the streamwise velocity is considered to be logarithmic at \( x = 0.4 \) m (LDA data) and \( x = 0.87 \) m (PTV data) for experiment 2 and at \( x = 5 \) m (LDA data) and \( x = 5.22 \) m (PTV data) for both experiments. At these locations the difference between streamwise velocities obtained with PTV and LDA is on average 10 % and the shapes of the transverse distributions more or less compare although the spatial density of measurement-locations in transverse direction is lower for LDA measurements compared to PTV measurements.

![Graphical representation of mean streamwise velocities vs lateral distance at x = 0.05 m and z/h = 2/3](image.png)
Figure 5-3 Transverse distributions of the streamwise velocity obtained with LDA at a. $x = 0.05$ m b. $x = 0.40$ m c. $x = 5$ m and $z/H = 2/3$

From figures 5-3 and 5-4 it is observed that with the exception of the region near the end of the splitter plate [$x < (20 - 50)H$] the streamwise velocities for both experiments do not significantly differ (Appendix E).

It is observed from figures 5-3a, 5-3b and 5-4a that the transverse velocity profiles of the streamwise velocity for experiment 1 appear to be broadened more in the mixing layer region with respect to experiment 2, which might be the consequence of a stronger three-dimensionality of the flow in the region near the end of the splitter plate due to the presence of the forcing mechanism. Figures 5-3 and 5-4 show that the fast stream of experiment 2 appears to be broader and the slow stream appears to be narrower in comparison with experiment 1 which implies that the transverse profiles of the streamwise velocity are shifted more towards the fast stream in comparison with experiment 2, which indicates that the position of the mixing layer centre location differs for both experiments.
Figure 5–4 Transverse distributions of the streamwise velocity obtained with PTV at a. $x = 0.87$ m and $1.60$ m b. $x = 5.22$ m and $x = 5.95$ m c. $x = 8.12$ m and $x = 8.85$ m

In detail, from figures 5-3a,b and 5-4a it is observed that the transverse distributions of the streamwise velocity appear to be affected by the presence of the splitter plate at a relatively small distance from the apex of the splitter plate. LDA measurements and PTV measurements show for both experiments a wake-like profile formed by
boundary layers, which emerge at both sides of the splitter plate. Furthermore, in figures 5-3a, b and 5-4a the distortion of the transverse profile of the streamwise velocity for experiment 1 due to the presence of the forcing mechanism is clearly visible. This distortion continues to exist up to 3 m from the end of the splitter plate.

The observation from figures 5-3, 5-4 and appendix E that the mean streamwise velocity does not significantly differ for both experiments, with the exception of the region near the end of the splitter plate, is examined further by investigating the downstream development of the streamwise velocities in both parallel streams, the velocity difference across the mixing layer, the mean centre or convection velocity, the mixing layer width and the mixing layer centre location.

Figure 5-5a shows the downstream development of the velocities in both parallel streams outside the mixing layer for both experiments. The solid lines represent the model, equation 2.7, described in section 2.1. From overlapping measurement areas it is concluded that with the exception of measurement area 3 (centre location at x = 1.235 m), the experiments do not show significant differences in the development of the streamwise velocities in both parallel streams (Appendix E). Both experiments show that the fast stream decelerates and the slow stream accelerates in downstream direction. The model predicts the downstream deceleration relatively well but the acceleration of the slow stream is overestimated.
Streamwise velocity in the mixing layer centre vs downstream distance

Figure 5-5 Downstream development of the a. streamwise velocities in both parallel streams b. velocity difference across the mixing layer and c. mean convection velocity

In figure 5-5b the downstream development of the velocity difference across the mixing layer for both experiments is presented. The solid line represents the model, equation 2.3, described in section 2.1. From measurement data it is concluded that the experiments do not show significant differences (Appendix E). Figure 5-5b shows that for both cases the velocity difference decreases in downstream direction, which is a logical consequence of a horizontal bottom and a free surface. It is noted that the model does not fully apply to the development in downstream direction of the velocity difference measured for experiment 2.

Figure 5-5c shows the downstream development of the mean convection velocity or the streamwise velocity in the mixing layer centre. Several methods can be used to determine this property. For example, velocities at positions in a cross-section where dU/dy has a maximum can be used when the transverse profile of the streamwise velocity can be approximated by a hyperbolic tangent profile. However, centre velocities determined with this method are subjected to scatter and therefore not presented. In this study a simple method is applied; $U_c = \frac{1}{2}(U_1+U_2)$. The solid lines represent the model, equation 2.7, described in section 2.1. From measurement data it is concluded that with the exception of measurement area 3 (centre location at $x = 1.235$ m), the experiments do not show significant differences in the development of the streamwise velocity in the mixing layer centre (Appendix E).

Figures 5-5b and 5-5c show significant differences between both experiments at measurement area 3 (centre location at $x = 1.235$ m), which confirm that the streamwise velocity at the free surface for experiment 1 is not the same measure for the depth-averaged velocity when compared to experiment 2 (figure 5-2). Thus, the mean velocity field for both experiments does not show significant differences (Appendix E) with the exception of the region near the end of the splitter plate [$x < (20 – 50)$H].

Development of the mixing layer width and centre location
Figure 5-6a shows the downstream development of the mixing layer width for both experiments. The solid line represents the model, equation 2.10, described in section 2.1. It is concluded that the experiments do not show significant differences in development of the mixing layer width in downstream direction (Appendix E). Both experiments show a decreasing mixing layer growth rate in downstream direction as a result of the decrease of the velocity difference across the mixing layer caused by the bottom friction.

The model predicts the development of the mixing layer width in downstream direction for both experiments rather well. However, the measurements show that in both
experiments the growth rate decreases further downstream despite the presence of a significant velocity difference across the mixing layer. This is ascribed to the damping influence of the bottom friction on the large coherent vortices. The model does not capture this mechanism. Consequently the model overestimates the mixing layer width in the far field \((x > 10 \, \text{m})\).

![Mixing layer width vs downstream distance](image)

![Mixing centre vs downstream distance](image)

**Figure 5-6 Downstream development of the a. mixing layer width b. mixing layer centre location**

Figure 5-6b shows the shift of the mixing layer centre location with respect to the apex of the splitter plate. The solid line represents the model, equation 2.11, presented in section 2.1. The transverse displacement of the mixing layer centre location towards the slow stream is characteristic for shallow mixing layers.

Two methods have been used to determine the mixing layer centre location. A first method labelled method 1, uses equation 2.11 described in section 2.1. This method does not give satisfactory results for the region near the end of the splitter plate for experiment 1, because the vertical profile of the streamwise velocity is affected by the forcing mechanism. Therefore a second method is used which locates the transverse position in a cross-section where \((U-U_0)/\Delta U = 0.5\). Mixing layer centre locations obtained with both methods show significant differences for experiment 1 but for experiment 2 the mixing layer centre locations obtained with these methods more or less compare. The second method indicates that the mixing layer centre location for experiment 1 is shifted more towards the fast stream in comparison with experiment 2. Moreover, the calculated transverse coordinates of the mixing layer centre indicate that the mixing layer centre location for experiment 1 initially shifts towards the fast
stream (upto y = 0.10 m) in the region near the end of the splitter plate (figures 5-3a,b and 5-6b). This explains the observation from figures 5-3a,b and figure 5-4a of a broader fast stream for experiment 2 in comparison with experiment 1. It is hypothesised that the mixing layer dynamics in the region near the end of the splitter plate for experiment 1 are affected by the three-dimensionality of the flow. The three-dimensionality in the region near the end of the splitter plate for experiment 1 is characterised by the presence of vertical gradients and transverse gradients of the streamwise velocity due to the forcing mechanism, the presence of boundary layers that develop at both sides of the splitter plate and the presence of secondary currents. As a result exchange of mass and momentum between the parallel flows can occur which might explain this initial development of the mixing layer centre location for experiment 1.

Taking the observations mentioned above into account, the second method is used to determine the positions at which the spectral distribution of the spanwise turbulence kinetic energy will be computed. The model overestimates the shift of the mixing layer as a consequence of an overestimation of the acceleration of the slow stream. It is noted here that the model does reproduce the downstream development of the mixing layer centre for an experiment (case with a water depth of 0.067 m) conducted by Van Prooijen & Uijttewaal (2002b).

From transverse profiles of the streamwise velocity (figure 5.3) measured with the LDA system it is concluded that for experiment 1, x = 0.05 m, x = 0.40 m and x = 5 m the mixing layer centre is located at respectively y = 0.05 m, y = 0.075 m and x = -0.15 m. For experiment 2, x = 0.03 m, x = 0.40 m and x = 5 m the mixing layer is located at respectively y = 0 m, y = 0 m and y = -0.20 m.

It is concluded from figure 5-5 that the mixing layer width does not show significant differences between both experiments (Appendix E). The mixing layer centre for experiment 1 is shifted more towards the fast stream in comparison with experiment 2. Moreover, the mixing layer centre for experiment 1 initially shifts towards the fast stream in the region near the splitter plate.

### 5.2 Development of the turbulence characteristics

In this section emphasis is put on differences between both experiments in evolution of the turbulence characteristics in transverse and longitudinal direction of the most important turbulence properties obtained from PTV measurements and LDA measurements. The most important turbulence properties with respect to the evolution of the turbulence characteristics are the components of the Reynolds stress tensor and the spectral distribution of the spanwise turbulence kinetic energy. Furthermore, implications that result from the modelling proposed by Van Prooijen & Uijttewaal (2000b) discussed in section 2.3 are verified. For experiment 1, PTV data from measurement areas 3 to 8 are used to analyse the flow and for experiment 2, PTV data from measurement areas 3, 6 and 8 are used to analyse the flow. For both experiments LDA data at x = 0.05 m, x = 0.40 m and x = 5 m are used to analyse the flow.

**Development of the transverse distributions of the Reynolds stresses**

Figures 5-7, 5-8 and 5-9 show transverse distributions of the Reynolds stresses for both experiments at x = 0.05 m, x = 0.40 m and x = 5 m from the apex of the splitter plate at z/H = 0.67 measured with the LDA system. Figures 5-10, 5-11 and 5-12 show transverse distributions of the Reynolds stresses for both experiments measured with PTV.

It is difficult to compare data obtained with LDA to data obtained with PTV in the region near the end of the splitter plate because the downstream coordinates differ and the forcing mechanism affects the vertical structure of the flow thereby increasing the three-dimensionality of the flow in the region near the end of the splitter plate. It is observed qualitatively that the shape of transverse distributions of the normal stresses in the mixing layer region obtained from PTV data at measurement area 3
Sensitivity of shallow mixing layers to upstream turbulence

... (centre location at \( x = 1.235 \) m) differs in comparison with the shape of the transverse distributions of normal stresses obtained from LDA data at \( x = 0.40 \) m. This might be attributed to strong upwelling, which prevented the systematic entrainment of particles into the mixing layer. This observation and the arguments presented in section 4.2 with regard to the validity of the PTV measurement technique near the end of the splitter plate indicate that the components of the Reynolds stress tensor obtained from PTV measurement area 3 (centre location at \( x = 1.235 \) m) are not a proper measure for the turbulence characteristics of the flow for both experiments. So, the turbulence characteristics at a relatively small distance from the end of the splitter plate are investigated using LDA measurements.

From figures 5-7c, 5-8c and 5-9c and E-2 (Appendix E) it is observed that the differences between the peak Reynolds normal stresses obtained with the LDA and PTV measurement technique at \( x = 5 \) m for experiment 1 are of the order 10 % and for experiment 2 of the order 50 %. The difference between the peak Reynolds shear stresses obtained with the LDA and PTV measurement technique at \( x = 5 \) m for experiment 1 is of the order 35 % and the difference for experiment 2 is of the order 100 %. This might be ascribed to the shorter measuring time and the lower measuring frequency used for the PTV measurement technique or sources of inaccuracy described in appendix E. This observation implies that relatively large errors can be made with the PTV measurement technique.

![Graph of streamwise turbulence kinetic energy vs lateral distance at x = 0.05 m and z/H = 2/3](image)

![Graph of streamwise turbulence kinetic energy vs lateral distance at x = 0.40 m and z/H = 2/3](image)
Figure 5-7 Transverse distributions of the streamwise turbulence kinetic energy obtained with LDA at a. $x = 0.05$ m b. $x = 0.40$ m c. $x = 5$ m

LDA and PTV measurement data presented in figures 5-7, 5-8, 5-9a,c, 5-10b,c, 5-11b,c and 5-12b,c show that the peak values of the Reynolds normal stresses in the mixing layer region for experiment 1 are always higher in comparison with experiment 2. This is expected from linear stability analysis and non-linear analysis when it is assumed that the forcing mechanism raises the spectral distribution of the turbulence kinetic energy.

It is noted that the LDA data is considered to be more reliable than data obtained with PTV. LDA data obtained at $x = 5$ m (figures 5-7c, 5-8c and 5-9c) show that peak values of the streamwise turbulence kinetic energy differ approximately 70 %, peak values of the spanwise turbulence kinetic energy differ approximately 100 % and peak values of the Reynolds shear stress differ approximately 70 %.

Thus, the downstream development of the large coherent vortices formed in the mixing layer is different for both experiments. The large coherent vortices formed in the mixing layer are considered to be stronger for experiment 1 in comparison with experiment 2. This will be investigated further by evaluating the spectral distribution of the turbulence kinetic energy.
Sensitivity of shallow mixing layers to upstream turbulence

Figure 5-8 Transverse distributions of the spanwise Reynolds normal stresses obtained with LDA at a. \( x = 0.05 \) m b. \( x = 0.40 \) m c. \( x = 5 \) m

From measurement data (Appendix E) it is concluded that the differences between the Reynolds stresses for both experiments obtained from PTV data are not significant. However, LDA measurements have confirmed that the Reynolds stresses are always higher for experiment 1 in comparison with experiment 2.

A distinct peak in the transverse distributions of the components of the Reynolds stress tensor locates the mixing layer region with high turbulence kinetic energy as a result of a strong transverse gradient of the streamwise velocity and the quasi-2D vortices. This distinct peak is clearly visible for the transverse distributions of the Reynolds stresses for experiment 2 and is less visible for experiment 1 at \( x = 0.05 \) m and \( x = 0.4 \) m. It is observed from figures 5-7a,b and 5-8a,b that for experiment 1 relatively higher values for the Reynolds stresses are measured in the fast stream in comparison with the mixing layer region, which indicates that the 3D bottom turbulence produced by the rough bed is more intense than the quasi-2D turbulence produced in the mixing layer region. The Reynolds normal stresses measured in the slow stream seem to decrease in the mixing layer region (-0.10 m < \( y < 0 \) m). Figures 5-7a,b and 5-8a,b show that the Reynolds normal stresses for experiment 2 are amplified in the mixing layer region, which is expected from linear stability analysis. This indicates that the 3D bottom turbulence produced by a smooth bottom is less intense than the quasi-2D turbulence produced in the mixing layer region. The difference in amplifica-
tion of Reynolds normal stresses between both experiments is ascribed to the stronger three-dimensionality of the flow for experiment 1 in comparison with experiment 2, which might disturb this amplification mechanism by stronger dissipation.

Figure 5-9 Transverse distributions of the Reynolds shear stress obtained with LDA at a. $x = 0.05$ m b. $x = 0.40$ m c. $x = 5$ m
Figures 5-9a and 5-9b show positive and negative Reynolds shear stresses outside the mixing layer region in the fast stream. These positive and negative Reynolds shear stresses might have been caused by the bottom turbulence that in the presence of transverse gradients of the streamwise velocity can work as a horizontal viscosity. The transverse gradients of the streamwise velocity are a result of the in transverse direction oscillating streamwise velocity (figures 5-3a, 5-3b and 5-4a).

This can be verified by using a simple gradient type transport model with a constant turbulence viscosity (Appendix C, equation C.4). It is concluded that the positive value of the Reynolds shear stress at \( x = 0.05 \, \text{m} \) and \( y = 0.15 \, \text{m} \) can fairly well be approximated with this method but the positive value of the Reynolds shear stress at \( x = 0.40 \, \text{m} \) and \( y = 0.20 \, \text{m} \) would require a horizontal turbulence viscosity which is four times larger than the eddy viscosity found at \( x = 0.05 \, \text{m} \) and \( y = 0.15 \, \text{m} \). This might indicate that large-scale fluctuations contribute to the turbulence diffusion of momentum in the horizontal plane. It is hypothesised that the forcing mechanism might induce large-scale fluctuations as a result of the presences of transverse gradients of the streamwise velocity and instabilities in the flow.

Figure 5-9c shows larger Reynolds shear stresses for experiment 1 in comparison with experiment 2. This indicates that the turbulence transport of momentum is larger for experiment 1 in comparison with experiment 2. Thus, the vortices formed in the mixing layer further downstream are for experiment 1 stronger in comparison to experiment 2. As a result the mixing layer width is expected to be larger for experiment 1 in comparison with experiment 2. However, from figure 5-6a it is observed that this is not the case. This is ascribed to the relative large inaccuracy in estimating the mixing layer width (Appendix E).
Figure 5-10 Transverse distributions of the streamwise Reynolds normal stresses obtained with PTV

Figures 5-6, 5-7, 5-8, 5-9b,c, 5-10b,c, 5-11b,c and 5-12b,c show that the maxima of the Reynolds stress components of experiment 1 are shifted more towards the fast stream in comparison with experiment 2, which corresponds with the observation that the mixing layer centre for experiment 1 is shifted more towards the fast stream (figure 5-5b).

From figures 5-10b,c 5-11b,c and 5-12b,c it is observed that the downstream evolution of the transverse distributions of the Reynolds stress tensor components for both experiments show a strong broadening of the transverse distributions obtained at measurement area 8 (centre location at x = 8.485 m) and lower maxima in comparison with the transverse distributions of the stresses obtained at measurement area 6 (centre location at x = 5.585 m). The broadening of the distributions can be ascribed to the growth of large coherent vortices in size and might be ascribed to differences in lateral displacement. The transverse distributions of the components of the Reynolds stress tensor for both experiments do not show distinct differences in broadening of the transverse profiles.
Figure 5-11 Transverse distributions of the transverse Reynolds normal stresses obtained with PTV

From figures 5-10b,c 5-11b,c and 5-12b,c it is observed that the maxima of the Reynolds tensor components decrease in downstream direction. The decrease of the maxima indicates that the large vortices become less intense in downstream direction.
as a result of the damping influence of the bottom friction on the large coherent vortices.

However, the initial decrease of the maxima observed from figures 5-7a,b and 5-8a,b cannot be explained by evaluating the Reynolds normal stresses, the spectral distribution of the turbulent kinetic energy has to be taken into account. This decrease is caused by the initial amplification of the energy density levels of the whole frequency range for both experiments at $x = 0.05$ m and the decay of the energy density levels of the high frequencies ($f > 1 - 2$ Hz) in downstream direction.

![Reynolds shear stress vs lateral distance](image)

*Figure 5-12 Transverse distributions of the Reynolds shear stresses obtained with PTV*
Spectral analysis

In this study the implications that result from sequence and type the modelling proposed by van Prooijen & Uijttewaal (section 2.3) are verified, by evaluating the evolution of the quasi-2D vortices using spectral analysis. In section 2.2 it is noted that linear stability analysis seems to be valid for length scales larger than 10 times the water depth. This corresponds for both experiments with frequencies lower than approximately 0.28 Hz.

Figures 5-13, 5-14, 5-15 and 5-16 show one-dimensional energy density spectra of the spanwise velocity fluctuations. These spectra are computed from LDA time signals with measurement periods of 10 minutes measured in the fast stream and centre of the mixing layer. The mixing layer centre is defined by \( y_c = y_{0.5} \), where \( (U-U_2/\Delta U) = 0.5 \) is satisfied. Figure 5-13 shows spectra of the spanwise velocity fluctuations in the fast stream for both experiments. In general, the forcing mechanism raises the spanwise turbulence kinetic energy levels for the higher frequencies more with respect to the lower frequencies. In more detail, the frequency range 0.6 Hz < \( f \) < 1.6 Hz is raised most and the spanwise turbulence kinetic energy levels for lower frequencies (\( f < 0.6 \) Hz) are raised less with lower frequency. However, the energy density levels for these lower frequencies (\( f < 0.6 \) Hz) are always higher for experiment 1 in comparison with experiment 2.

Figure 5-13 Spectra obtained with LDA in the fast stream for both experiments at \( x = 0.05 \) m, \( x = 0.40 \) m and \( z/H = 2/3 \) a. logarithmic b. linear

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For experiment 1, a bulge on the spectra can be associated with a characteristic length scale. This characteristic length scale is of the order of 3 – 4 times the water depth, which indicates that the forcing mechanism might also induce large-scale fluctuations (see also figure 5-9b). It is hypothesised that the transverse gradients and instabilities present in the flow might organise horizontal vortices. However, Nikora et al (2001) claim that the flow above roughness elements with relatively small submergence appears to be influenced by vortices generated in the wakes of roughness elements, which scale with the roughness height of the elements. These vortices strongly dominate over vortices that scale with the water depth.

It is observed from figure 5-14 that a peak in the energy density spectrum occurs at 1.2 Hz for experiment 1 and at 5.2 Hz for experiment 2. The peak energy density level for experiment 1 is higher in comparison with experiment 2. Figure 5-15 shows that for both experiments the peak energy density levels are approximately the same and occurs approximately at the same frequency. Figure 5-16 shows that the energy density level for experiment 1 is higher in comparison with experiment 2 and the peak energy density occurs approximately at the same frequency. These observations indicate that the energy density levels at the low frequency range (f < 0.3 Hz) determine the energy density levels of the quasi-2D vortices further downstream.

Figure 5-14 Spectra obtained with LDA in the mixing layer at x = 0.05 m and z/H = 2/3 for both experiments a. logarithmic b. linear
The peak shifts for both experiments towards the low frequency range moving in downstream direction. However, this shift is larger between $x = 0.05 \text{ m}$ and $x = 0.40 \text{ m}$ for experiment 2 in comparison with experiment 1. This corresponds to a larger rate of growth of the large coherent vortices for experiment 2 in comparison to experiment 1 between $x = 0.05 \text{ m}$ and $x = 0.40 \text{ m}$.

Figures 5-14 and 5-15 show that the energy density levels for experiment 1 are less amplified in comparison with experiment 2. However, the amplification of the low frequency range ($f < 0.4 \text{ Hz}$) for both experiments is difficult to evaluate. In more detail, from figures 5-13 and 5-14 it is observed that for experiment 1 the energy density levels for frequencies $f > 1 \text{ Hz}$ decay and the energy density levels are amplified for $0.4 \text{ Hz} < f < 1 \text{ Hz}$. For experiment 2, the energy density levels are amplified for the frequency range $0.4 \text{ Hz} < f < 1.6 \text{ Hz}$.

The difference in amplification and decay of the energy density levels for both experiments is ascribed to the stronger three-dimensionality of the flow for experiment 1 in comparison with experiment 2 in the region near the end of the splitter plate, which might disturb this amplification mechanism by stronger dissipation.

![Spectral distribution of the spanwise velocity fluctuations in the mixing layer (x = 0.40 m, z/h = 2/3)]

**Figure 5-15 Spectra obtained with LDA in the mixing layer at x = 0.40 m and z/H = 2/3 for both experiments a. logarithmic b. linear**

LDA measurements show that higher energy density levels of low frequency perturbations ($f < 0.3 \text{ Hz}$) result in higher energy density levels of the quasi-2D vortices formed in the mixing layer further downstream. Thus, the quasi-2D vortices formed
downstream are stronger for experiment 1 in comparison with experiment 2. In general, this confirms the concept of linear stability analysis (section 2.3) that perturbing the inflow determines the turbulence characteristics downstream.

\[
\begin{align*}
E_{vv}(f) \quad &\text{(m/s)}^2/\text{Hz} \\
Spectral \ distribution \ of \ the \ spanwise \ velocity \ fluctuations \ in \ the \ mixing \ layer \ (x = 5 \ m, \ z/h = 2/3) \\
\end{align*}
\]

---

**Figure 5-16 Spectra obtained with LDA in the mixing layer at x = 5 m for both experiments a. logarithmic b. linear**

In section 5.1 it is concluded that the mean velocity field for both experiments shows significant differences in the region near the end of the splitter plate \([x < (20 - 50)H]\) and is considered to be more 3D for experiment 1 in comparison with experiment 2 as a result of the presence of the forcing mechanism. Differences between both experiments in amplification and decay of energy density levels for frequencies higher than 0.4 Hz are observed from figures 5-14 and 5-15. However, differences between both experiments in amplification and decay of energy density levels for the frequencies lower than 0.4 Hz are difficult to observe from spectra presented in figures 5-14, 5-15 and 5-16. This can be ascribed to spectral noise and a different mean sample rate for each location and both experiments.

In order to determine the applicability of the linear theory quantitatively the LDA data at \(x = 0.40 \text{ m}\) and \(x = 5 \text{ m}\) is resampled by means of the interpolation method described in paragraph 4.3.1 and a sampling frequency of 150 Hz. The LDA data obtained at \(x = 0.05 \text{ m}\) for experiment 1 is considered to be more affected by the three dimensionality of the flow and is therefore not used. The resampled data is used to
calculate equations 2.13 and 2.14 (section 2.3) which result from sequence and type the modelling proposed by van Prooijen & Uijttewaal.

Figure 5-17 a. Amplification factors defined by equation 2.13 b. Ratios defined by equation 2.14

The amplification factors plotted for both experiments in figure 5-17a are determined from the ratio between the energy density spectrum at x = 5 m in the centre of the mixing layer and the energy density spectrum at x = 0.40 m in the centre of the mixing layer (equation 2.13). Figure 5-17a indicates that the initial energy density levels at the low frequency range for both experiments are considerably amplified further downstream, which is expected from linear stability theory. Similar amplification factors for both experiments are found at the low frequency range. However, considerable differences between the amplification factors for both experiments are also observed at the low frequency range as a result of scatter.

In figure 5-17b the ratio between the energy density spectra of both experiments at a certain streamwise position is plotted (equation 2.14). This ratio should be the same for the low frequency range at every streamwise position. However, figure 5-17b shows that this ratio at the low frequency range f < 0.3 Hz increases in downstream direction. This might confirm the initial difference in amplification and decay of the energy density levels for both experiments as a result of the stronger three-dimensionality of the flow for experiment 1 in comparison with experiment 2 in the region near the end of the splitter plate. This three-dimensionality might disturb this
amplification mechanism by stronger dissipation. However, the spectral noise is too large to claim this phenomenon. It is noted that the ratio between the initial energy spectra of both experiments in the mixing layer at $x = 0.05$ m is much smaller than the ratio between the energy density spectra of both experiments in the fast stream (figure 5-13).

In order to establish the applicability of the linear theory quantitatively more evidence is needed. Therefore energy density spectra need to be evaluated at relatively large distances from the end of the splitter plate [$x > (20 - 50)H$]. For this purpose energy density spectra are calculated from PTV data at $x = 5.59$ m and $x = 8.49$ m.

Spectra obtained from PTV data at $x = 5.59$ m, presented in figure 5-18, confirm the observation of higher peak energy density levels at the low frequency range ($f < 0.3$ Hz) further downstream for experiment 1 in comparison with experiment 2.

Figure 5-18 Spectra obtained with PTV in the mixing layer at $x = 5.59$ m for both experiments a. logarithmic b. linear

However, figure 5-19 shows that the peak energy density levels of the spectra obtained from PTV data at $x = 8.49$ m are comparable and the peak energy density levels do not appear at the same frequency. Linear stability analysis does not give an explanation for this event. It is noted that the energy content at the low frequency range ($f < 0.3$ Hz) is larger for experiment 1 in comparison with experiment 2. These observations might be related to the decay of the quasi-2D vortices far downstream, nonetheless the spectra obtained from PTV measurements may not be accurate enough.
Figure 5-19 Spectra obtained with PTV in the mixing layer at $x = 8.49$ m for both experiments a. logarithmic b. linear

The accuracy of the spectra obtained from PTV data is evaluated by comparing them to LDA spectra. Spectra obtained from LDA data are considered to be more reliable than spectra obtained from PTV data.

Figure 5-20 shows spectra obtained from LDA data and PTV data in the mixing layer for experiment 1 at $x = 5$ m. It is observed that the peak energy density levels differ approximately 11% if the energy density spectrum obtained from LDA data at $y = -0.15$ m is used for comparisons. The peak frequencies differ approximately 28%.
Figure 5-20 Spectra in the mixing layer at $x = 5$ m obtained from LDA and PTV data for both experiments

Figure 5-21 shows spectra in the mixing layer obtained from LDA and PTV data for experiment 2 at $x = 5$ m. The peak energy density levels differ approximately 200%. The peak frequencies are more or less comparable if the energy density spectrum obtained from LDA data at $y = -0.15$ m is taken into account (figure 5-16).

Thus, a relative large error in the approximation of the peak energy density level from PTV measurement data can occur. These spectra are therefore not used for further analysis.
Figure 5-21 Spectra in the mixing layer at x = 5 m obtained from LDA and PTV data for both experiments

Thus, LDA measurements show that higher energy density levels of low frequency perturbations (f < 0.3 Hz) imposed at the mixing layer inflow result in higher energy density levels of the horizontal vortices formed in the shallow mixing layer further downstream. The vortices formed in the mixing layer further downstream are stronger for the experiment with a rough upstream bottom in comparison with the experiment with a smooth upstream bottom. In general, this confirms the concept of linear stability analysis (section 2.3) that perturbing the inflow determines the turbulence characteristics downstream.

Figure 5-17a indicates that the initial energy density levels at the low frequency range for both experiments are considerably amplified further downstream, which is expected from linear stability theory. Similar amplification factors are found for both experiments at the low frequency range. However, the spectral noise is large which complicates the determination of the applicability of the linear stability theory quantitatively. The differences between the amplification factors found for both experiments might be ascribed to the stronger three-dimensionality of the flow in the region near the end of the splitter plate [x < (20 – 50)H] for experiment 1 in comparison with experiment 2, which might disturb this amplification mechanism initially for experiment 1 by stronger dissipation. The increase of the ratios between the energy density spectra of both experiments in downstream direction might confirm this phenomenon, but the spectral noise is too large to claim an increase of this ratio in downstream direction. It
is noted that the ratio between the initial energy spectra of both experiments in the mixing layer at $x = 0.05$ m is much smaller than the ratio between the energy density spectra of both experiments in the fast stream (figure 5-13).

In this study the applicability of the linear stability theory (Van Prooijen & Uijtte-waal, 2002b) can be established qualitatively but not quantitatively. For this purpose more detailed and more accurate experiments are needed.
6 Conclusions and recommendations

The objective of this study is to provide an experimental investigation concerning the consequences of upstream turbulence for the development of a shallow mixing layer and the large horizontal vortical structures, in size and intensity.

For this purpose two experiments are executed which only differ in intensity of the imposed upstream turbulence. A first experiment is executed in which the turbulence intensity of the parallel flows is increased using a rough upstream bottom and a second experiment is conducted with a smooth upstream bottom.

Turbulence data are obtained by means of 2D Laser Doppler Anemometry (LDA) and Particle Tracking Velocimetry (PTV).

By means of standard statistical and spectral analyses it is investigated whether or not a difference in intensity of the upstream turbulence conditions results in different mixing layer dynamics.

Due to technical and experimental set backs, the rather labour-intensive technique of vortex visualisation is not executed. So, the evolution of the quasi-2D vortices is only evaluated using spectral analysis.

From the results of the experiments conclusions are drawn in section 6.1 and recommendations are made in section 6.2.

6.1 Conclusions

From results of the experiments, the following conclusions can be drawn:

**Time averaged flow field**

1. The velocity field for both experiments does not significantly differ with the exception of the region just downstream of the apex of the splitter plate. In the region \( x < (20 - 50)H \) the velocity field is more 3D for experiment 1 in comparison with experiment 2. Transverse gradients and vertical gradients are present as a result of the presence of the turbulence forcing mechanism, although that the roughness elements are uniformly distributed over the widths of the inlet sections. The positioning of the roughness elements in a staggered pattern and a relatively low submergence of the roughness elements are the cause of these phenomena.

2. The experimental results indicate that the mixing layer centre location for experiment 1 is shifted more towards the fast stream in comparison with experiment 2. Moreover, the mixing layer centre location for experiment 1 initially shifts towards the fast stream (upto \( y = 0.10 \) m) in the region near the end of the splitter plate which is not expected. It is hypothesised that the mixing layer dynamics in the region near the end of the splitter plate for experiment 1 are affected by the three-dimensionality of the flow. This three-dimensionality can be characterised by the presence of transverse and vertical gradients of streamwise velocity, the presence of boundary layers that develop at both sides of the splitter plate and the presence of secondary currents. As a result exchange of mass and momentum between the parallel flows can occur which might explain this initial development of the mixing layer centre location for experiment 1.

3. The Reynolds normal and stresses for experiment 1 are always higher in comparison with experiment 2. The Reynolds stresses can be considered as identifiers of a different downstream evolution of the large horizontal vortices for different upstream turbulence conditions.
4. The different upstream turbulence properties have no measurable consequences for the downstream development of the mixing layer width.

**Forcing mechanism**

5. Energy density spectra of the transverse velocity fluctuations calculated from LDA measurements for both experiments show that the forcing mechanism raises the energy density levels over the whole frequency range. However, the levels at higher frequencies are raised more in comparison to the lower frequencies.

6. A distinct bulge on the spectra obtained in the fast stream for experiment 1 identifies a characteristic length scale several times the water depth and relative large Reynolds shear stresses are observed in the fast stream, which indicates that the forcing mechanism induces large-scale fluctuations.

**Evolution of the coherent vortices**

7. LDA measurements show that higher energy density levels of low frequency perturbations imposed at the mixing layer inflow result in higher energy density levels of the horizontal vortices formed in the shallow mixing layer further downstream. These vortices are stronger for the experiment with a rough upstream bottom in comparison with the experiment with a smooth upstream bottom. In general, this confirms the concept of linear stability analysis (section 2.3) that perturbing the inflow determines the turbulence characteristics downstream.

8. Similar amplification factors (equation 2.13) are found for both experiments at the low frequency range. However, the scatter is too large to conclude linear behaviour quantitatively.

**Measurement techniques**

9. The PTV measurement data used to meet the objective formulated in this study require a substantial effort to process and analyse.

10. In this study 2D LDA measurement data proved to be valuable to meet the objective formulated for this study and to further interpret the data obtained with PTV.

### 6.2 Recommendations

From results of the experiments, the following recommendations can be made:

**Time averaged flow field**

1. For experiment 1 the amplification mechanism seems to be affected by the three-dimensionality of the flow just downstream of the end of the splitter plate. It is recommended to study the effect of a strong 3D velocity field on the downstream development of the quasi-2D vortices. In practice, the vertical profile of the streamwise velocity can deviate from the logarithmic streamwise velocity profile, for instance in compound channels at the interface between the main channel and the flood plain as a result of groynes, submerged vegetation or irregularities in bed topography.

**Forcing mechanism**

2. The forcing mechanism appears to induce large-scale fluctuations in the fast stream outside the mixing layer region. This phenomenon could be studied more extensively.
3. The roughness elements used to raise the turbulence intensities have a relative small submergence (H/k = 2.67). As a result the velocity field in the region near the end of the splitter plate and the structure of the turbulence in the parallel streams are affected by this configuration. For future investigations, it is recommended to use roughness elements which are more comparable with roughness elements found in nature. It is however questionable whether the large increase in turbulence intensity can be reached in this way.

**Evolution of the coherent vortices**

4. In this study a relatively limited LDA measurement programme is executed. Just three downstream locations are used to verify the consequences of upstream turbulence for the development of the quasi-2D vortices further downstream. It is recommended to measure with the LDA system at a few locations downstream in order to reveal more satisfactorily the differences in downstream development of the quasi-2D vortices. Moreover, in order to confirm linear behaviour for this flow configuration spectra have to be obtained from LDA data measured at distances x > (20 – 50)H from the end of the splitter plate.

5. It is recommended to compute ensemble-averaged vortices for both experiments in order to acquire appropriate statistics to evaluate the consequences of bottom turbulence for the size and the detailed structure of the quasi-2D vortices. Standard statistical analysis can be used to characterise the acquired length scales in a statistical sense.

**Consequences for numerical modelling**

6. From linear stability analysis and the experiments conducted in this study it is concluded that energy density distribution of the low frequency perturbations at the mixing layer inflow determine the turbulence characteristics downstream. It is concluded from the 1D energy density spectra that these perturbations have length scales exceeding the water depth. Questions arise. What are these low frequency perturbations? How do they behave? What kind of intensity levels can they attain in practice? How do we model or simulate them? For example, a depth averaged LES with a spatial resolution of the computational grid of the order of the water depth can simulate low frequency perturbations because these structures have length scales several times the water depth. However, depth averaging suppresses details which are important for the proper simulation of these structures. For instance, the production term of 3D-bottom turbulence disappears, which means that the energy density levels can only decay in absence of transverse shear. This implies that the modelling in a depth averaged LES has to be adapted.

**Measurement techniques**

7. It is recommended to investigate the origin of the observed discontinuities at overlapping PTV measurement areas.

8. It is recommended to control the number of particles per frame and the light intensity to allow for reliable and “all weather” Particle Tracking Velocimetry.

9. It is recommended to increase the LDA measurement period in order to reduce the spectral noise present in spectra calculated from LDA measurements, which might be beneficial for the comparison of the energy density levels between both experiments.
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M.A.J. de Nijs
Appendix A

Flow stability

Linear stability analysis is a useful tool to determine the conditions for which a flow becomes unstable given the mean flow field. In every stability analysis the following steps are taken. Small finite non-stationary perturbations are superimposed on the stationary base flow. The small amplitude wave like disturbances and the base flow are substituted in equations of motion. Because the amplitudes of the imposed disturbances are small, higher order terms and quadratic terms can be neglected. Linearization of the equations yields a set of differential equations for the perturbations. This set of equations is an eigenvalue problem. The development of the perturbations can be evaluated by using the new set of equations to obtain growth rates for the wave numbers of the imposed perturbations. If the growth rates are positive the amplitudes of disturbances grow, the solution is unstable. If the growth rates are negative the amplitudes of the disturbances decreases, the perturbations decay, the solutions are stable. Linear stability analysis does not give an explanation for the origin of the imposed perturbations.

Using simplified base flow solutions and simplified equations of motion, conditions can be determined which give more insight into mixing layer flow instability. The development of large coherent structures present in mixing layers is attributed to a Kelvin Helmholtz type instability process. The Kelvin Helmholtz instability is related to a discontinuous base flow and equations of motion without viscous terms. However base flows with a continuously varying velocity profile in one dimension with a point of inflection is also unstable. The existence of an inflection point is a necessary condition for instability and is called Rayleighs condition for instability. Using the theorem of Fjortoft, which states that a vorticity maximum is a necessary and sufficient condition for instability, it is clear that Rayleighs condition for instability is a generalisation of the Kelvin Helmholtz instability criterion (Nieuwstadt, 1988). The instability analyses related to the Kelvin Helmholtz instability and Rayleighs condition for instability are called inviscid linear stability analyses, because the viscous terms are neglected in the equations of motion.

Figure A-1 Kelvin Helmholtz stability criterion and Rayleigh stability criterion

The imposed perturbations can be interpreted as the onset of large coherent structures that are a product of the hydrodynamic instability process in an inflectional mean flow. This instability process can physically be interpreted as a process, which extracts energy from the main inflectional mean flow to the large coherent structures present in this type of shear flow.
The linear stability theory should not be used to calculate the development of a fully turbulent shallow mixing layer flow, because in turbulent flows the quadratic and higher order terms in the equations for the perturbations cannot be neglected. However, Van Prooijen & Uijttewaal (2002b) have demonstrated that linear stability analysis, is a useful tool to describe and interpret the development of quasi-2D vortices in turbulent shallow water mixing layers. Even though the linear stability analysis is used beyond its limit of application. The modelling and the implications of the modelling used by Van Prooijen & Uijttewaal (2002b) is discussed in more detail in section 2.2 and section 2.3.
Appendix B

Turbulent flows over rough beds

Turbulent flows over rough beds are important in hydraulic and environmental engineering practice. For instance, most riverbeds are composed of sand grains or granular material. Moreover, fluvial open channel flows have complicated bed configurations. Thus, these beds can be characterised as rough. In practice, the bottom turbulence produced over rough bottoms can attain a wide range of intensities depending on the roughness. Knowledge of the detailed turbulence structure of flows over rough bottoms is limited.

Nakagawa and Nezu (1977) have studied the turbulence structure over a rough wall, where the particles where densely fixed on a smooth wall. They showed that the Reynolds stress and turbulence intensities become larger for a rough wall compared to a smooth wall. They concluded that the production of the turbulent structure is different for smooth walls compared to rough walls.

Nezu (1977a) has examined the effects of bottom roughness on the streamwise macroscale. The streamwise macroscale decreases near the bottom with increasing roughness size, but this effect is smaller in the outer region. It is thought that the large vortices are broken up by the roughness elements consequently decreasing the streamwise macroscale.

Nezu and Nakagawa (1993) have proposed semi-empirical functions for the vertical distributions of the turbulence intensities for stationary uniform flows over a smooth bottom:

\[
\frac{u_j^2}{u_*} = D_j \exp \left(-C_k \frac{z}{H} \right)
\]  

(B.1)

where \(D_j = 2.30\), \(D_v = 1.63\), \(D_w = 1.27\) and \(C_k = 1.0\) are empirical constants. The equations presented above need additional validation, because the data to validate these equations for flows over rough walls has been limited.

Flows with relatively large ratios of water depth to characteristic size of the roughness elements show that the flow structure at distances from the wall greater than the roughness elements is similar to the flow structure over smooth walls. Nonetheless, the turbulence structure over irregular rough beds with relatively small submergence is still unclear.

Kurose and Komori (2001) investigated the effects of the particle roughness with various inter particle distances on the turbulence structure and examined the validity of the Townsend’s similarity hypothesis. The Townsend’s similarity hypothesis states that for sufficiently large Reynolds numbers turbulent motions outside the roughness sublayer are independent of the wall roughness. They proved that this hypothesis is valid, so the distributions of the turbulence quantities normalised by the wall shear stress should be the same for smooth and rough surfaces. They showed that components of the Reynolds stress tensor and spectra in the outer region normalised by the friction velocity coincide with each other independent of the type of particle roughness. Moreover, they showed that within a certain range of the inter particle distance the friction stress reaches a saturated state. This means that a maximum friction stress is not reached with a most densely packed bed of particles. The research described above indicates that the turbulence intensities scale with the friction velocity. Subsequently, increasing the bottom roughness can raise the turbulence intensities. The friction velocity is directly related to the bottom friction coefficient. Writing the bottom shear stress as:
\[ \tau_b = -\rho u_*^2 \]  

(B.2)

with \( u_* \) the friction velocity. For stationary turbulent depth averaged flows the bottom shear stress is normally assumed to be proportional to the squared depth averaged velocity:

\[ \tau_b = -\rho c_f U^2 \]  

(B.3)

in which \( U \) is the depth averaged velocity and \( c_f \) the bottom friction coefficient. In case of a stationary uniform flow over a completely rough bottom, the bottom friction coefficient depends on the roughness height and the water depth. Relation B.1 from Nezu & Nakagawa (1993) and research performed by Kurose and Komori (2001) support the following relation:

\[ \bar{u}_j^2 \propto c_f U^2 \]  

(B.4)

The ratio between components of the turbulence kinetic energy of an experiment with an extra source of 3D bottom turbulence (rough upstream bottom) and an experiment without an extra source of 3D bottom turbulence (smooth upstream bottom) can be estimated with the following relationship for otherwise equal mean flow conditions:

\[ \frac{\left( \bar{u}_j^2 \right)}{\left( \bar{u}_j^2 \right)_{2D}} \propto \frac{c_{f1}}{c_{f2}} \]  

(B.5)

Equation B.4 does not show how the bottom roughness affects the spectral distribution of the turbulence kinetic energy. Moreover, the equation does not show how roughness affects the distribution of the turbulence kinetic energy among the different components of the Reynolds tensor. This means that the roughness can affect the empirical constants in equation B.1. The ratio (equation B.5) can be calculated for a stationary uniform flow assuming a logarithmic velocity profile, an equivalent roughness length of the order of the size of the Nikuradse roughness \( k_s \) for a rough bottom and an equivalent roughness length that is of the order of the size of the viscous length scale for a smooth bottom. Nikuradse concluded that for a rough bed, which consists of densely packed granular material with a uniform diameter glued on the bottom, the diameter of grains could be used for \( k_s \). Other research shows that for flat beds, which consist of granular material (sand, pebbles etc.) with a non-uniform diameter as found in nature, the Nikuradse roughness \( k_s \) can be expressed as several times a characteristic diameter. For instance, Lammers (1997) and Bortovski (1998) found for a flat bed that \( k_s = 6 \ D_{n50} \). Van Rijn (1986) proposed \( k_s = 4 \ D_{n50} \) and Schiereck (2001) suggests that a practical choice would be \( k_s = 2 \ D_{n50} \).
Appendix C

3D turbulence decay

It is hypothesised that the length scale of turbulence decay is much smaller with respect to the length scale needed for the vertical profile of the mean flow to recover. This implies that the forcing mechanism must be located at a relative small distance from the apex of the splitter plate even though the rough bottom might affect the vertical profile of the mean streamwise velocity.

Analysis using the turbulence energy equation of the single-length-scale turbulence model of Rastogi and Rodi (1978) supports this hypothesis. The model of Rastogi and Rodi (1978) is derived from the standard k-ε model by averaging the model equations over the water depth. The turbulence energy equation:

\[
\frac{DK}{Dt} = P_{ro} + D_K - \varepsilon
\]  

with K the depth averaged total turbulence kinetic energy, \(P_{ro}\) the production of turbulence kinetic energy, \(D_K\) the diffusion of turbulence kinetic energy and \(\varepsilon\) the turbulence energy dissipation rate term.

The mean flow within an inlet section is considered to be a stationary uniform 1D shallow flow. Thus only the streamwise advection of depth averaged turbulence kinetic energy by the mean flow is taken into account. The total turbulence kinetic energy produced over the rough bottom within an inlet section will decay as it is advected downstream over the smooth glass bottom to a turbulence kinetic energy level that can be sustained by a smooth bottom. So, the production term can therefore be omitted. The diffusion term is also omitted because the time scale of turbulence diffusion is much larger than the time scale associated with advection. The dissipation term is approximated using the Kolmogorov-Prandtl expression:

\[
\nu_t = c_\mu \frac{K^2}{\varepsilon}
\]

Equation B.1 results in an expression where the streamwise advection of depth averaged turbulence kinetic energy is balanced by the dissipation term of turbulence kinetic energy:

\[
U \frac{dK(x)}{dx} + c_\mu \frac{K(x)^2}{\nu_t} = 0
\]

with the calibration coefficient \(c_\mu = 0.09\), \(\nu_t\) defined as the turbulence viscosity and \(U\) defined as the depth and time averaged streamwise advection velocity. The turbulence viscosity needs to be specified in order to solve equation C.3. A parabolic distribution of the turbulence viscosity is considered to be valid for stationary uniform shallow flows. The viscosity term in equation C.3 is approximated by depth averaging the parabolic viscosity distribution:

\[
\nu_t = \frac{1}{6} \mu U H
\]
Integrating equation C.3 with respect to $x$:

$$K = \frac{K_0}{c_\mu K_0} \frac{1}{x + 1}$$  \hspace{1cm} (C.5)

$K_0$ in equation C.5 is approximated using equation B.1 (appendix B) proposed by Nezu & Nakagawa (1993) and the inlet conditions of the fast stream. The model predicts (figure C-1) that at approximately $x = 3H$ a total depth averaged turbulence kinetic energy level is reached equal to a total depth averaged turbulence kinetic energy level for a smooth bottom, if it is assumed that a rough bed raises the total turbulence kinetic energy over the entire water column with 800 %, 1600 % and 2500 % (appendix B).

![Figure C-2 Decay of an extra source of bottom turbulence](image)

**Figure C-2 Decay of an extra source of bottom turbulence**
Appendix D

LDA measurement locations

x is the transverse direction, y is the longitudinal direction and z is the vertical direction. Coordinates in mm. The z-coordinates have to be multiplied with 4/3 in order to determine the position in the water column.

The tables underneath represent input files for the traverse system. M2101W, M2201W and M2401W were used as input files for experiment 2 and M3001W, M3101W and M0302W were used as input files for experiment 1.

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Appendix E

Error analysis

To compare PTV results of the experiments, overlapping measurement areas for experiment 1 are used to estimate the error in mean flow and turbulence properties. These errors occur as a result of sources of inaccuracy related to the PTV measurement technique and the statistical uncertainty.

Systematic error
Sources of inaccuracy related to the PTV measurement technique are:

- **Optics.** The most important effects of optics which can influence the accuracy of the PTV output are distortion (deformation of the image by the lens system) and vignetting (non-uniform light intensity in the image) and the positioning of the camera.
- **Tracking algorithm.** The performance of the PTV scheme is influenced by the ratio of mean minimum interparticle distance to maximum particle displacement. This ratio should be of the order 3 (Zoeteweij et al., 2001). If this ratio is too small the particle tracking is affected by erroneous matching. In this study the ratio is 1.3 for the fast stream and 4.5 for the slow stream. This indicates that particle tracking in the fast stream can be affected by erroneous matching.
- **Physical processes.** Secondary currents and vortices can affect the distribution of the tracer particles over the image. This might result in areas without tracer particles. Thus, these areas lack information about the flow. For instance, it was noticed during measurements that particles are pushed relative more towards the edges of the vortices, which may result in a less accurate description of the vortices and subsequently less accurate velocity vectors are obtained.

Statistical error
The statistical error made in approximating time averaged flow properties in the mixing layer region will in general decrease when more large coherent vortices are measured. It can be shown by means of standard statistical analysis that the statistical error decreases with the square root of the number of large coherent vortices measured. The number of large coherent vortices measured depends on the measuring time and the periods of the large coherent vortices. It is noted that for a fixed measuring time the statistical error will increase with the development of the large horizontal vortices in size in downstream direction.

The statistical error in estimations of the Reynolds normal stresses is 26 % for a measuring time of 5 minutes (PTV), vortices with a characteristic timescale of 10 s (measurement area 8 centre location at x = 8.49 m) and a Gaussian probability distribution for the turbulence velocity fluctuations. From experimental results obtained with PTV transverse distributions of the normal Reynolds stresses were calculated for a measuring time of 5 minutes and a measuring time of 2.5 minutes. It was concluded that the peak Reynolds stresses did not significantly differ. This implies that a statistical error calculated using a Gaussian probability distribution for the turbulence velocity fluctuations overestimates the statistical error.

Uncertainty interval
Overlapping measurement areas of experiment 1 are used to estimate the error in mean flow and turbulence properties as a result of the PTV measurement technique and the statistical uncertainty. The obtained maximum errors are used to define an uncertainty interval. The uncertainty interval is assumed to be symmetrical expressed as two times the maximum error. If the differences between the two experiments are of the order of the uncertainty interval or smaller, than the uncertainty intervals for
both experiments will partly overlap indicating that these differences are not significant. However, the contribution to the error by the PTV measurement technique to the total error is determined by the quality of the pictures and can therefore be different for each measurement area. Subsequently, the validity of this method is disputable because the quality of the pictures differs for each measurement plane and therefore for each experiment.

**Velocity field**

Figure 5-5a shows the downstream development of the streamwise velocities in both parallel streams. Overlapping measurement areas of experiment 1 indicate that the mean streamwise velocity of the fast stream and slow stream is determined with a maximum error of approximately 5 % of the velocities outside the mixing layer. The errors do not show a preferred direction.

For measurement area 3 (centre location at \( x = 1.235 \) m) experiment 1 shows a 15 % higher fast stream mean streamwise velocity and a 14 % higher slow stream mean streamwise velocity in comparison with experiment 2. Measurement area 6 (centre location at \( x = 5.585 \) m), experiment 1 shows a 4 % lower fast stream mean flow velocity and a 9 % higher slow stream mean streamwise velocity in comparison with experiment 2. Measurement area 8 (centre location at \( x = 8.485 \) m), for experiment 1 the fast stream shows a 9 % lower mean streamwise velocity in comparison with experiment 2 and the mean streamwise velocity in the slow stream is comparable for both experiments.

Thus, it can be concluded from overlapping measurement areas that with the exception of measurement area 3 (centre location at \( x = 1.235 \) m), the PTV data do not show significant differences in mean streamwise velocity in both parallel streams for both experiments.

Figure 5-5b shows the downstream development of the velocity difference across the mixing layer. Overlapping measurement areas of experiment 1 indicate that the mean velocity difference is estimated with a maximum error of about 8 % of the mean velocity difference. The errors do not show a preferred direction.

For measurement area 3 (centre location at \( x = 1.235 \) m), experiment 1 shows a 10 % higher velocity difference in comparison with experiment 2. For measurement area 6 (centre location \( x = 5.585 \) m), experiment 1 shows a 10 % lower velocity difference in comparison with experiment 2. For measurement area 8 (centre location at \( x = 8.485 \) m), experiment 1 shows an approximately 14 % lower velocity difference in comparison with experiment 2. It is concluded that the differences between the two experiments are approximately of the order of the uncertainty interval. This implies that the PTV-data does not show convincing differences in downstream development of the velocity difference across the mixing layer.

Figure 5-5c shows the downstream development of the mean convection velocity. Overlapping measurement areas for experiment 1 indicate that the mean centre velocities are determined with a maximum error of approximately 5 % of the mean centre velocities. The errors do not show a preferred direction in downstream direction. For measurement area 3 (centre location at \( x = 1.235 \) m), the differences are approximately 15 % of the mean centre velocity, which are larger than the uncertainty interval. Other measurement areas show comparable differences, which are smaller than the uncertainty interval. This indicates that the PTV data shows significant differences in mean convection velocity between both experiments for measurement area 3 (centre location at \( x = 1.235 \) m), but the differences between both experiments in other measurement areas are not significant.

In figure E-1 is the downstream development of the maximum transverse gradient of the streamwise velocity presented. Overlapping measurement areas for experiment 1 indicate that the maximum transverse gradient of the streamwise velocity is determined with an maximum error of about 10 % of the maximum transverse gradient of the streamwise velocity. Measurement area 3 (centre location at \( x = 1.235 \) m), experiment 1 shows a 10 % higher maximum transverse gradient of the streamwise velocity in comparison with experiment 2. Measurement area 6 (centre location \( x = 6 \))
5.585 m), experiment 1 shows a 15 % higher maximum transverse gradient of the streamwise velocity in comparison with experiment 2. Measurement area 8 (centre location at x = 8.485 m), both experiments show comparable transverse gradients of the streamwise velocity. It is concluded that the differences between the measurement areas of both experiments are smaller than the uncertainty interval, which indicates that these differences are not significant.

![Maximum transverse gradient of the streamwise velocity vs downstream distance](image)

**Figure E-3 Downstream development of the maximum transverse gradient of the streamwise velocity**

**Mixing layer width**

Figure 5-6a shows the downstream development of the mixing layer width. Overlapping measurement areas of experiment 1 indicate that the mixing layer width is determined with a maximum error of about 8 % of the mixing layer width, however a preferred direction might be distinguished, which makes it difficult to estimate uncertainty intervals for the mixing layer width. Subsequently, the significance of the differences in mixing layer widths between both experiments is difficult to determine. Therefore a different approach is used, which takes into account the significance in differences in development of the velocity difference across the mixing layer and in development of the maximum transverse gradient of the streamwise velocity. These flow properties are used to determine the mixing layer width (equation 2.8). PTV data do not show significant differences in downstream development of the mean velocity difference across the mixing layer. Figure E-1 also shows that the differences in development of the maximum transverse gradient of the streamwise velocity in downstream direction obtained from PTV data are not significant. Therefore it is concluded that due to the relatively large uncertainty intervals the differences in downstream development of the mixing layer width calculated with equation 2.8 are not significant.

The mixing layer widths calculated with equation 2.8 for measurement area 3 (centre location at x = 1.235 m) compare for both experiments. This is due to a 10 % higher velocity difference for experiment 1 in comparison with experiment 2, which is balanced by a 10 % higher velocity gradient for experiment 1 in comparison with experiment 2. If the transverse velocity profiles (figure 5-4a) are examined in more detail a kink is observed in the mixing layer region for the transverse velocity profiles of experiment 1 resulting in a steeper velocity gradient although the mixing layer region is broader in comparison with experiment 2. The length scale definition used, equation

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2.8, may not be a suitable measure to predict the length scale development near the splitter plate, where the velocity profile is distorted in the mixing layer region.

Reynolds stress tensor components
From figures E-2, E-3 and E-4 uncertainty intervals are estimated for the components of Reynolds stress tensor. The uncertainty intervals of the normal stresses are approximately of the order of 50 % and the uncertainty interval of the shear stress is of the order of 60 %. The maximum difference in the downstream development of the maximum longitudinal normal stress between both experiments is of order 15 %, the maximum difference in downstream development of the maximum spanwise normal stress is of the order 25 % and the maximum difference in downstream development of the maximum shear stress is of the order 25 %. This indicates that the differences in components of the Reynolds tensor between both experiments are not significant.

![Graph showing maximum streamwise turbulence kinetic energy vs downstream distance](image)

*Figure E-4* Downstream development of the maximum streamwise normal Reynolds stress
**Figure E-5** Downstream development of the maximum spanwise normal Reynolds stress

**Figure E-6** Downstream development of the maximum Reynolds shear stress
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