Turbulent mixing layers in shallow water

J. Tukker

report no. 10-94

August 1994

Laboratory of Hydromechanics
Hydraulic and Geotechnical Engineering Division
Department of Civil Engineering
Delft University of Technology

Contents

1. Introduction 2
  1.1 Background 2
  1.2 Aim of the study on shallow mixing layers 2

2 Adjustments of the mixing layer flow in the shallow-water flume 4
  2.1 The shallow-water test flume 4
  2.2 Conditions for the investigated mixing layer flow 4
  2.3 Choice of flow adjustments 6
    2.3.1 Limitations 6
    2.3.2 Mixing layer flow A 8
    2.3.3 Water level 8

3. Start of experiments 10
  3.1 Preparation of the flume 10
  3.2 Preliminary measurements 11
  3.3 LDA measurements 12

4. Analysis of the measured data 14

References 16

Table of figures

figure 1 A lateral mixing layer in the shallow-water test flume.
figure 2 The turbulent-flow and the subcritical-flow condition on the mixing layer flow.

1. Introduction

1.1 Background

A mixing layer is a flow between two adjacent streams with different current velocities. Mixing layers are present in the entrances of harbours situated on a river (Langendoen, 1992) and between two confluent streams in natural junctions (Biron et al., 1993). Large horizontal eddies with dimensions larger than the water depth are formed in mixing layer flows in shallow water. These large eddies are also sometimes present behind islands (Wolanski et al., 1984; Ingram and Chu, 1987).

A research program was started to study a developing lateral mixing layer in a shallow water flow in the Laboratory of Hydromechanics, Delft University of Technology two years ago. A new wide, glass-bottom flume has been built for this project. This flume is suitable for investigations on shallow water flow.

1.2 Aim of the study on shallow mixing layers

This investigation on shallow mixing layers has two main objectives:

To gain insight in the influence of the depth on the evolution of large, horizontal eddies in a lateral mixing layer in a shallow free-surface flow and

To gain insight in the contribution of these eddies to the entrainment into the layer and to the mixing and to the transport of momentum and passive substances in and through the layer.

Remarks:

Influence of the depth:

The shallowness of the flow restricts large-scale motion to basically two-dimensional, horizontal motions and large, horizontal coherent structures are formed. The turbulent phenomena of vortex stretching of these large eddies is presumably suppressed and an inverse-energy-cascade is presumably present. Small-scale 3D-turbulent motions are produced by small-scale vortex-stretching at the bottom. Chu and Babarutsi (1988) have assumed that this small-scale 3D-turbulence acts as a direct energy sink for the large-scale motions, without the intervention of a continuum of intermediate scales.

Mixing and transport:

Momentum and passive substances are transported by random 3D-turbulent motion and by large-scale coherent structures. This last contribution to the transport in a shallow lateral mixing layer is presumably the most important contribution.

Areas

A mixing layer in shallow free-surface flow is divided in three regions (comparable with the division of a shallow plane jet flow proposed by Giger (1987)):

- Near field

  The flow behind the partition is characterized by formation of eddies due to the horizontal velocity-gradient (Kelvin-Helmholtz- instability). The width of the mixing layer is smaller than the water depth, so this part of the flow will be considered as a two-dimensional mixing layer. The direct influence of the bottom friction is negligible.

- Middle field

  The bottom resistance directly influences the development of eddies with dimensions equal to and larger than the water depth. The growth of the eddies is also influenced by the horizontal lateral velocity gradient. The structure of the flow is three dimensional, particularly in the first part of the middle field. Large-scale motions are restricted to basically two-dimensional motions and large horizontal coherent structures are being formed. The spreading rate decreases downstream due to the bottom friction.

- Far field

  The transverse spreading rate is small. The dimensions of the horizontal coherent structures are larger than the water depth. Large-scale turbulent energy are transferred to small-scale eddies without the intervention of intermediate scales, due to the bed friction.

The most interesting areas of a shallow mixing layer flow are the last part of the middle field and the far field. In this part of the flow horizontal eddies are larger than the water depth. A proposed lack of intermediate length-scales in the energy-cascade will be observable if length-scales of the horizontal coherent structures are an order of magnitude larger than the water depth. The large horizontal motion are scaled with the width of the mixing layer and the dimensions of the small eddies are proportional to the water depth.

2 Adjustments of the mixing layer flow in the shallow-water flume

2.1 The shallow-water test flume

The new test flume of the Laboratory of Hydromechanics has a width of 3 m and a length of 20 m and the height of the side-walls is 0.20 m. The inlet-section is divided in two equal parts by a partition. At the end of the partition the fast stream contacts the adjacent slow stream and the mixing layer flow develops (see figure 1). The horizontal flume bottom is about 1.7 m above the floor. The flume has been connected to the water-supply-system of the laboratory.

2.2 Conditions for the investigated mixing layer flow

The mixing layer flow in the flume have to obey the following conditions:

1. Two turbulent adjacent flows
2. A subcritical flow in the whole flume
3. The presence of large, horizontal eddies in the far field region
4. A minimal influence of the outlet on the mixing layer
5. No influence of the side-walls on the mixing layer
6. No wake flow behind the partition
7. No lateral slope of the water level
8. A laterally uniform mean-velocity profile at the end of the partition.

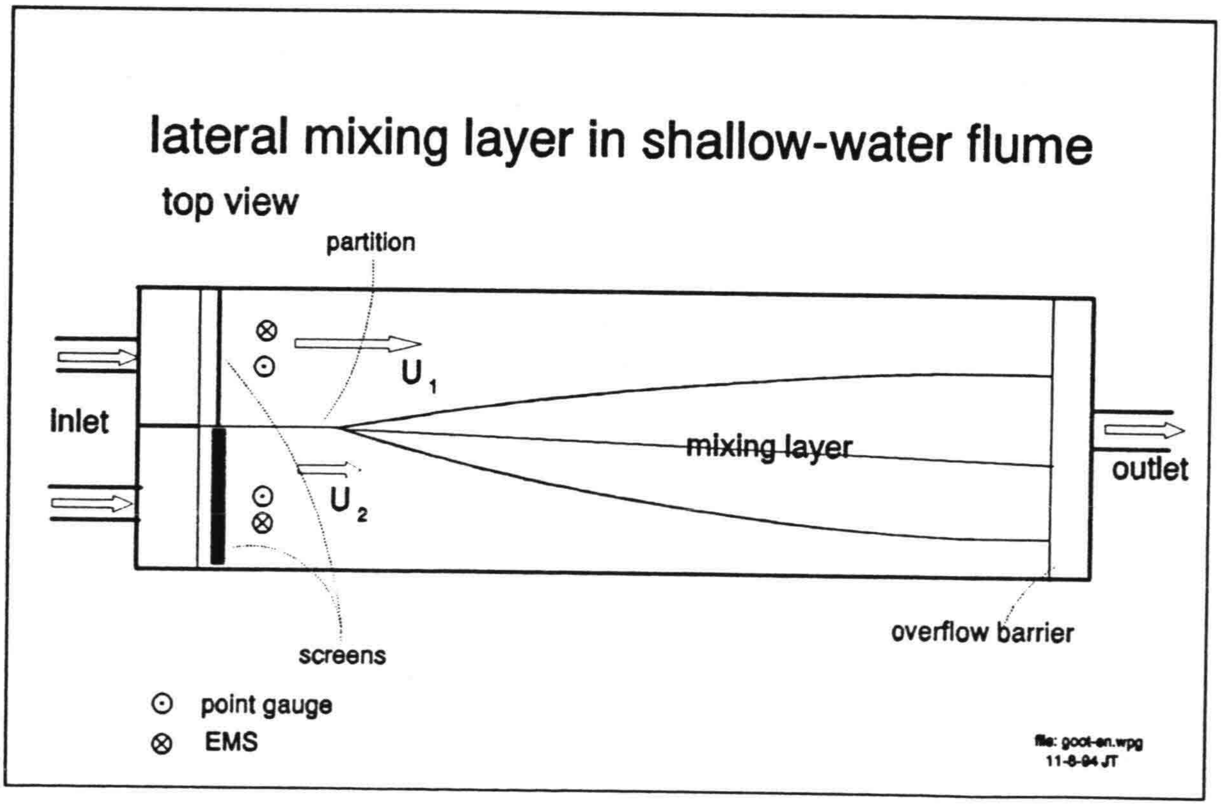

Figure 1. A lateral mixing layer in the shallow-water test flume.

Remarks:

1. The Reynolds number in shallow channel flow

$$Re = \frac{Uh}{\upsilon} \tag{1}$$

U : *depth-averaged velocity*
h : *water depth*
υ : *kinematic viscosity*

should be larger than 4000 for flows dominated by turbulent motions.

2. The Froude number

$$Fr = \frac{U}{\sqrt{gh}} \tag{2}$$

g : *gravity constant (9.81 m/s^2)*

is smaller than 1 in subcritical flows. Downstream the water level decreases and the mean velocity increases, due to the friction gradient and the conservation of mass. This results in an increase of the Froude-number. To ensure a subcricital flow at the outlet the Froude-number at the inlet should be smaller than 0.5.

3. According to present theory the far field region begins where the gradient-stability number S, defined as

$$S = \frac{c_f \delta}{4h\lambda} \tag{3}$$

with

$$\lambda = \frac{U_1 - U_2}{U_1 + U_2} \tag{4}$$

S : *gradient-stability number*
c_f : *bottom-friction coefficient*
δ : *width of the mixing layer*
λ : *relative-velocity difference between the adjacent streams*
U_1, U_2 : *depth-averaged velocities of the adjacent streams with $U_1 > U_2$*

reaches the value of 0.09.
The horizontal dimensions of large eddies have to be an order of magnitude larger than their vertical dimensions in the far field to investigate the supposed lack of intermediate length-scales in the energy-cascade. This results in the following condition of the ratio between the layer width and the water depth:

$$\frac{\delta}{h} \geq O(10) \tag{5}$$

4. The flow is not influenced by the outlet at a distance of ten water depths.
5. In the central area of the flume the side walls do not influence the flow. The width of this central area is estimated with an approximation of Nezu & Nakagawa (1993) for wide channels:

   $$\text{for} \quad \frac{B}{h} > \alpha_c \quad : \quad \frac{b}{h} = \frac{B}{h} - \alpha_c \tag{6}$$

   B : *width of the flume*
   b : *width of the central area*
   α_c : *critical ratio between the channel width and the water depth*

   The critical ratio has the value α_c of 5. The width of the mixing layer should be smaller than the width of the central area. The centre of the mixing layer moves to the slow stream. This displacement y_c is estimated with the relation

   $$y_c = -\delta\left[\frac{2\lambda + 1}{6(\lambda + 1)}\right] \tag{7}$$

   deduced from the conservation of momentum transport applied to a mixing layer with a constant lateral streamwise-velocity gradient. Outside the mixing layer the streamwise-velocity profile is uniform.
6. To prevent a domination of the wake effect in the near region the end of the plate has to be sharp and the velocity difference between the adjacent flows has to be sufficiently large. From the measurements of Miau and Hsu (1988) the following condition for the stream velocities in a mixing layer flow is proposed:

   $$\frac{U_1}{U_2} \geq 0.4$$

7. The slope of a flow is dependent on the bed friction, the water depth and the flow rate. The slope of the adjacent streams will be different, because the flow rates differ. The inlet flow has to be manipulated to minimize the lateral variation of water level between the parallel streams, particularly in the near region of the mixing layer. Lateral long waves generated by the lateral slope of the water level will presumably smooth the lateral differences of the water level.
8. Flow disturbances due to the inlet configuration and fluctuations of the rate of inflow are damped by fine screens. These screens are also used for the adjustment of a laterally uniform mean velocity profile .

2.3 Choice of flow adjustments

2.3.1 Limitations

Assuming a constant spreading rate in the near and the middle region the spreading rate is estimated with the following relation (Brown and Roshko, 1974; Chu and Babarutsi, 1988):

$$\frac{d\delta}{dx} = 0.18\,\lambda \tag{9}$$

x : *streamwise position starting at the end of the partition*

The layer grows proportional to the distance to the partition:

$$\delta = 0.18\,\lambda x \tag{10}$$

The middle region stops where the gradient-stability number reaches the critical value S_{crit} of 0.09. The transition position in the far field x_{far} is related to the water depth accordingly

$$x_{far} = 22.2\,S_{crit}\frac{h}{c_f} \tag{11}$$

Remarkably the position x_{far} is independent of the velocity ratio. A calculation of the bottom-friction coefficient c_f has resulted in the value of $6.0 \cdot 10^{-3}$ using the smooth-wall approximation and the log-law. The total length of the flume is 20 m and the length of the partition is 3 m and the outlet-length is about 0.5 m. A length of the far region of 1.5 m is minimally necessary to investigate large eddies in the far field. Then the starting point of the far field region has to obey the condition: $x_{far} < 15$ m. This condition results in a maximum water depth of 0.045 m.

A choice of basic velocities is also limited on the high side by the condition of subcritical flow and on the low side by the turbulent flow condition. These two conditions combined result in a minimum water depth of 0.019 m (then $U_1 = U_2 = 0.21$ m/s, $Fr_1 = Fr_2 = 0.5$, $Re_1 = Re_2 = 4000$ with $\upsilon = 1.0 \cdot 10^{-6}$ m^2/s (water)). The combination of these two conditions is presented in figure 2. This figure shows the region which obey these two conditions A large velocity-difference between the adjacent streams can be chosen if the water depth is maximal. If the maximal water depth is 0.045 m (see above) the maximal possible velocity is 0.33 m/s ($Fr_1 = 0.5$), the minimum one is 0.09 m/s ($Re_2 = 4000$) and the maximal velocity ratio λ is 0.57.

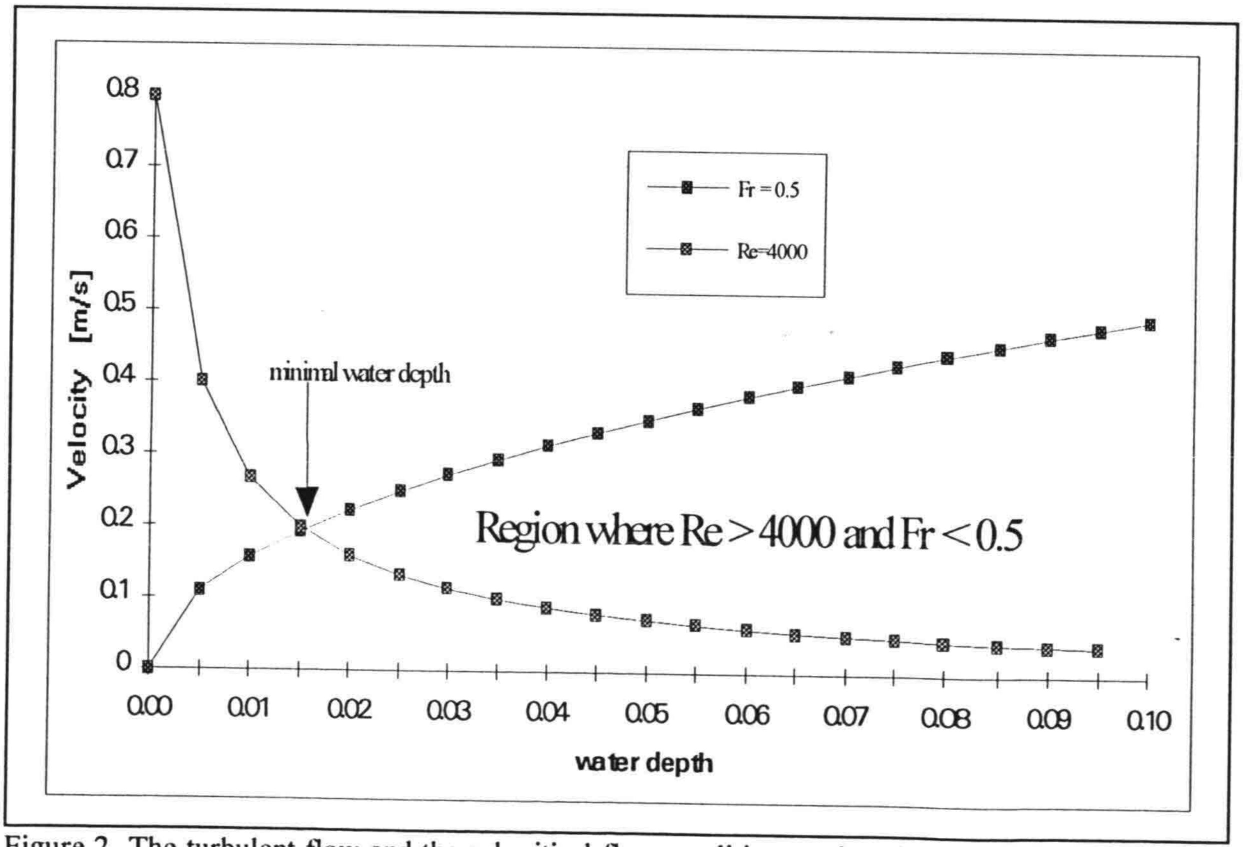

Figure 2. The turbulent-flow and the subcritical-flow condition on the mixing layer flow.

2.3.2 Mixing layer flow A

Following from the limitations calculated above
a water depth of 0.045 m and
current velocities of U_1 *= 0.30 m/s and* U_2 *= 0.15 m/s at the end of the transition*
have been chosen. The flow with this flow adjustments is called mixing layer flow A.

The corresponding velocity-difference ratio and the Reynolds-numbers and Froude-numbers are (with equations: 4, 2 en 1): $\lambda = 0.33$, $Re_1 = 1.4 \cdot 10^4$, $Fr_1 = 0.45$, $Re_2 = 6.8 \cdot 10^3$, $Fr_2 = 0.23$. The estimated layer width is 0.89 m at the transition position x_{far} (= 15 m) and the ratio between the layer width and the water depth δ/h is there 20. The displacement y_c of the centre of the mixing layer is 0.50 m (equation 7). A flume with a width of 3 m and a water depth of 4.5 cm has a central area with a width of about 2.9 m (equation 6). From these calculations it follows that the mixing layer is not influenced by the side-walls.

2.3.3 Water level

The slope of the water surface can be estimated by

$$i_f = \frac{c_f U^2}{2gh} \tag{12}$$

i_f : *slope of the water surface due to bottom friction*

If the slope varies slightly over a distance l the decrease of the water level over this distance is calculated with the following relation:

$$\Delta h = i_f l \tag{13}$$

Δh : *decrease of the water level*
l : *distance downstream*

The water depth is controlled by an sharp overflow barrier with an adjustable height at the outlet. At the top of this barrier the flow will be critical (Fr = 1). With the mass-preservation law the flow barrier height is calculated with the following relation:

$$h_b = h_o - \left(\frac{U_i h_i}{\sqrt{g}}\right)^{\frac{2}{3}} \tag{14}$$

h_b : *height of the overflow barrier*
h_o : *water depth at the outlet*
U_i : *dept-averaged velocity at the inlet*
h_i : *water depth at the inlet*

The distance between the end of the transition and the outlet is 17 m. The decrease of the water level over the whole flume have been calculated with equation 13 in two steps: l = 10 m and 7 m. If U is equal to the averaged velocity of U_1 and U_2 (= 0.225 m/s) this yields in a water depth and a velocity at the outlet of 0.039 m and 0.26 m/s, with a Froude-number of 0.42 (equation 2). This results in a barrier height of 0.017 m (equation 14).

A remark: If $U = U_1$ the water depth and the current velocity at the outlet will be 0.035 m and 0.42 m/s ($Fr = 0.72$). If U is equal to the slow current velocity U_2 the water depth and the current velocity at the outlet will be 0.042 m and 0.16 m/s ($Fr = 0.25$). The effects of different slopes will presumably be smoothed by surface waves.

3. Start of experiments

3.1 Preparation of the flume

Aim

The aim of preparation of the flume is:

To adjust the desired mixing layer in the shallow water flume obeying the proposed conditions

To determine the accuracy of the flow adjustments.

Work

The preliminary work is devided in:

1. The placing of a partition (made of glass) with a sharp side at the end.
2. The placing of iron rails at both sides of the flume.
3. The adjustment of the velocities and lateral profiles in the inlet region.
4. The adjustment of the water depth at the outlet barrier.
5. The determination of the accuracy of the flow adjustments and of the adjustment possibilities.

Remarks:

1. The partition has been placed in the centre of the flume at the inlet side. The total length of this wall is 3 m, the height of it is 0.11 m and the width is 4 mm. The sharp point at the end can be made or PVC of other material. The plate will be attached at the bottom and maybe supporting beams on the top will be needed.
2. An iron rail will be used for supporting other rails over the flume (for placing measuring apparatus) and is necessary to protect the glass walls against collisions.
3. Velocities on both sides of the plate will be simply measured by two Electromagnatic- velocity meters (EMS). Velocity profiles will be measured with a lateral row of floats. Deviations of an uniform profile will be seen directly. A video camera will be used to record the movements of the floats. The input flow and the velocity-profile will be controlled with screens at the inlet.
4. The water depth will be controlled by the overflow barrier at the outlet. A barrier with a adjustable height is needed. The profile and the height of the barrier should be experimentally determined. The water depth will be measured with point gauges.
5. The flow in the flume has to be reproducible. The accuracy of the reproduction depends on the accuracy of the flow adjustments. These adjustments must be constant. The current velocities and the water depth have to be measured at the inlet. Therefore, an EMS and a point gauge will be installed in both inlet streams.

Instruments needed:

- Three Electromagnetic velocity meters with A/D-converter and computer.
- Floats (about 30)
- Construction for putting floats in a row into the flow.
- A net for catching the floats in the outlet section.
- Three point gauges.
- Video camera (or CCD-camera)
- The moveable platform of the laboratory

Program

Preparation of the flume:
When? August-September 1994
Who? H. Tas, technical staff, J. Tukker.

3.2 Preliminary measurements

Aim

The aims of the preliminary measurements are:

To obtain a rough impression of the behaviour of a mixing layer in a free-surface shallow flow by visualising the developing horizontal coherent structures

To determine the three regions (near, middle and far) of the investigated flow.

Aspects

Different aspects are distinguished:

1. The downstream growth of the layer width and the vertical variation of the layer width.
2. The formation of horizontal eddies in the near field and in the first part of the middle field.
3. The dimensions and life-times of large, horizontal eddies
4. The downstream variations of the water depth and mean velocities.
5. The mean-velocity profiles inside and outside the mixing layer.

Visualization

The large structures of the flow will be visualized by floats and dye (potassium permanganate). A video camera or CCD-camera will be used to record the visible eddies and the positions of the floats. The horizontal velocities and the water depth are measured with EM-velocity meters. Depending on the interesting region of the flow variation of the he position putting floats into the flow or injecting dye should be possible.

Measurements

The development of the layer width will be measured from images of the flow visualized with dye. The width will also be calculated from the lateral profiles of the streamwise velocity measured by an EMS The horizontal velocity field will be measured using an EMS with a proposed grid of a streamwise distance of 50 cm and a lateral distance of 10 cm inside the layer and a distance of 25 cm outside the layer. Around the centre of the mixing layer 5 points with a lateral distance of 1 cm are placed. The measuring period in each point will be 10 minutes with a sample frequency of 10 Hz. This job will require three to four weeks. The water level will be measured using a point gauges with proposed grid of a streamwise distance of 100 cm and lateral distance of 50 cm.

The video images will be analyzed with a simple computer programm (written by A.M. den Toom) calculating the float positions in the different images. Some reference points have to be visible in the images to calculate the scale of the images. With this information horizontal velocities and particle paths are calculated.

Instruments needed:

- Three Electromagnetic velocity meters with A/D-converter and computer.
- Floats (about 30) and a construction putting floats in a row into the flow.
- Three point gauges.
- Video camera or CCD-camera
- Computer program determining float positions (written by A.M. den Toom).
- Computer program to process float positions (if the amount of data is too big to process it in other way).
- Computer program to process the data measured by an EMS (written by P.J. de Wit)
- Potassium permanganate.
- 1D-traversing system with a length of 3 meter (has to be built).

Program

Preliminary experiments:

When?	September-October
Who?	H. Tas, J. Tukker, a guest researcher or a student.

3.3 LDA measurements

Aim

The aims of the measurements with a Laser-Doppler-Anomometry-system (LDA) are

To measure in detail some parts of a mixing layer

To analyze how the large, horizontal coherent structures are formed and evolve in a free-surface shallow mixing layer.

Grid

Four positions of the vertical lateral measuring planes are proposed:

A. in the near field
B. in the begin area of the middle field
C. in the middle of the middle field
D. in the far field.

In the mixing layer about 10 to 30 measuring points in a horizontal line are chosen. The number of points depends on the width of the mixing layer and the dimensions of coherent structures. Outside the layer velocities will be measured in few points with a horizontal distance of 10-25 cm. In the vertical direction velocities will be measured in about 5-10 points. More points can be chosen for detailed measurements.

Profiles

At first 2D-measurements will be done with one LDA probe, because the adjustment of 3D-measurements are complicated and are time-absorbing. The three 2D-combinations between the streamwise velocity, the transverse one and the vertical one ask three different directions of the probe. Profiles of the first and second velocity moments measured inside the layer will be compared with profiles measured in the free streams outside the mixing layer. Horizontal and vertical momentum exchange will be analyzed with the help of these profiles.

Scales

Time-correlations will be calculated to estimate time-scales of coherent structures. Spacial correlation will be measured by two probes. Horizontal dimensions of large, horizontal eddies will be calculated based on a combination of streamwise correlations and lateral ones of the streamwise velocity and the lateral velocity. The vertical correlations will show information about the vertical variations of the horizontal coherent structures in the mixing layer. These results will be compared with results of the preliminary experiments.

Spectra

A turbulence spectrum of a velocity signal presents the distribution of energy over different frequencies in the flow. Transfer of energy from large scale to small one (the energy-cascade) or from small scale to large one (the inverse-energy-cascade) will be analyzed with the help of spectra. Measuring of spectra is be needed, because the transfer of energy between different scales is an important turbulent process in (shallow) mixing layers.

An accurate calculation of a spectrum requires a high data rate and a correct calculation algorithm. The height of the data rate depends on the energy-distribution about small scales. The standard spectra-calculation algorithms (by example: Fast Fourier Transform) assume a constant period between two samples. In LDA measurements the samples are randomly detected depending on the passing particles. Continuous-time information can be obtained with a reconstruction scheme. The required data rate for reconstruction should at least be 2π times the highest frequency present in the turbulence (Van Maanen, 1994). If eddies with a scale smaller than 1/10 of the water depth have negligible amount of energy the required data rate have to be 420 Hz (with $U = 0.3$ m/s and $h = 0.045$ m).

Instruments needed:

- LDA-measuring system with two back-scatter probes
- Three Burst Spectrum Analyzers
- 4-Watt-Argon-laser
- Traversing system DMC-704
- Alignment tools
- Computer

Program

Building of a covered area around a part of the shallow-water flume:
    When?   October-November
    Who?   Technical staff
Writing of a report about the laser safety in this experiment
    When?   October
    Who?   J. Tukker
Preparing LDA apparatus and testing new configurations of the probes:
    Where?   Laser-room
    When?   September-October
    Who?   J. Tukker
Installation of LDA apparatus:
    When?   December.
    Who?   J. Tukker
LDA measurements
    When?   Januari-May 1995
    Who?   J. Tukker, H. Tas, a student or a guest researcher

4. Analysis of the measured data

Data-processing

The data measured with a Electromagnectic velocity meter will be processed with a program 'Edfnc', written by P.J. de Wit. LDA data will be processed with programs written by H. Klaasman. At this moment (August 1994) first, second and third moments can be calculated from LDA-raw-data files. Programs for calculations of third and fourth moments, time correlations, space correlations and spectra will be written in Autumn. Profiles and other figures can be made with Exel.

The analysis of the experimental data is divided in some aspects:

- The lateral growth of the mixing layer
- The dimensions of large, horizontal eddies
- Vertical turbulent structure of large eddies
- The (inverse)-energy-cascade

Lateral growth of the mixing layer

The width of the layer has been defined in various manners. The definition on the basis of the velocity-difference and the velocity-gradient in the centre of the layer

$$\delta = \frac{U_1 - U_2}{\left(\frac{\partial U}{\partial y}\right)_{max}} \tag{15}$$

has been preferably used. The velocities U_1 , U_2 and the lateral-velocity gradient are derived from measured horizontal profiles of the streamwise velocity. In visualization-experiments with potassium permanganate the layer width has to be estimated in other way. The evolution of the growth rate of the layer will be compared with results of others investigations on mixing layers written in the literature (by example: Chu and Babarutsi, 1988).

The dimensions of large, horizontal eddies

In visualizations with potassium permanganate of with floats horizontal eddies will be made observable and will be recorded with a camera. The dimensions of the eddies will be measured from the recorded images. Horizontal length-scales will also be measured with space correlations across horizontal distances. The results of these two methods will be compared. Time scales of the horizontal eddies will be determined from calculated time correlations of measured velocity signals.

Vertical structure of large eddies

In the centre of the mixing layer the flow is highly anisotropic and horizontal eddies dominates the flow. These large eddies influence the vertical profiles of the velocity moments. Some profiles of the first moments and of the second moments measured in the mixing layer will be compared with profiles measured outside the mixing layer. Based on this analysis insight in the vertical exchange of momentum in a mixing layer should be grained. The two-dimensionality of the large eddies will be checked with correlations of the different velocity components across vertical distances.

Energy transfer

Large, horizontal eddies are influenced by the shallowness of the flow. At first the eddies grow due to the lateral horizontal velocity gradient and presumably to an inverse-energy-cascade. Secondly, in the last area of the middle region the bottom friction is going to dominate the evolution of the eddies and the turbulent energy of the large, horizontal eddies will be transferred to small-scale turbulent motion. The evolution of the energy transfer between different scales will be made observable with spectra of the horizontal velocities. Therefore, spectra measured in the centre of the mixing layer at four different positions in the flow: in the near field, in the first part of the middle field, in the middle of the middle field and in the far field, will be analyzed.

Program

Writing of LDA-data-processing programs:

When?	August-November 1994
Who?	H. Klaasman

Processing of data preliminary experiments (Results in a report):

When?	October-December 1994
Who?	J. Tukker, a student or a guest researcher

Processing of LDA data (Results in a report):

When?	Januari-August 1995
Who?	J. Tukker, a student or a guest researcher

References

Biron, P., B. De Serres, A.G. Roy and J.L. Best, 1993, *Shear Layer Turbulence at an Unequal Depth Channel Confluence*, In: Clifford, N.J., J.R. French and J. Hardisty (editors), *Turbulence: Perspectives on flow andSedimetn Transport*, John Wiley & Sons Ltd, pp. 197-213.

Brown, G.L. and A. Roshko, 1974, *On density effects and large structure in turbulent mixing layers*; Journal of Fluid Mechanics, Vol. 64, part 4, pp. 775-816.

Chu, V.H. and S. Babarutsi, 1988, *Confinement and Bed-Friction Effects in Shallow Turbulent Mixing Layers*; Journal of Hydraulic Engineering, Vol. 114, No. 10, pp. 1257-1274.

Giger, M., 1987, *Der ebene Freistrahl in flachem Wasser* (The plane jet in shallow water); Institut für Hydromechanik und Wasserwirtschaft, Eidgenössische Techniscche Hochschule, Zürich (in German). Also: dissertation Eidgenössische Techniscche Hochschule, Zürich, No. 8308.

Langendoen, E.J., 1992, *Flow Patterns and Transport of Dissolved Matter in Tidal Harbours*; dissertation, Delft University of Technology, Department of Civil Engineering. Also: Communications on Hydraulic and Geotechnical Engineering, Delft University of Technology, Department of Civil Engineering, Report No. 92-8, 1992.

Maanen, H.R.E. van, and H.J.A.F. Tulleken, 1994, *Application of Kalman Reconstruction to Laser-Doppler Anemometry data for estimation of turbulent velocity fluctuations*, Proceedings of the Seventh International Symposium on Applications of Laser Techniques to Fluid Mechanics, July 11th to 14th 1994, Lisbon, Portugal, pp. 23-1-1-8.

Ingram, R.G. and V.H. Chu, 1987, *Flows Around Islands in Rupert Bay: An Investigation of the Bottom Friction Effect*, Journal of Geophysical Research, Vol. 92, No. C13, pp. 14521-14533.

Miau, J.J. & C.T. Hsu, 1988, *Concerning the Wake Effect on the Initial Instability Development of a Mixing Layer*; In: M. Hirato & N. Kasagi (editors) *Transport Phenomena in Turbulent Flows, Theory, Experiment and Numerical Simulation*; New York, pp. 363-376.

Wolanski, E., J. Imberger and M.L. Heron, 1984, *Island Wakes in Shallow Coastal Waters*, Journal of Geophysical Research, Vol. 89, No. C6, pp. 10553-10569.