Description of the data base: Plane turbulent mixing layer from C.E.A.T. Poitiers

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June 1995 rev 2 (October 1997)

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Chapter 1

Brief description of the data base

convention: In this data base the main directory is noted: `SHL04`

1.1 Quick overview

This data base of a plane turbulent mixing layer contains two levels of data. The main features of the flow, the turbulent quantities and energy balance are contained in the following directories

- `SHL04/facility` **: wind tunnel and notations**
- `SHL04/ic` **: initial longitudinal velocity profile**
- `SHL04/turb` **: interesting turbulent quantities**
- `SHL04/balance` **: turbulent energy balance**

More detailed data, including spectra and Probability Density Functions are also available.

To get a quick overview of what this data base contains, type `SHL04/mkovrvw` **this script file will display on your X terminal the main quantities available.**

1.2 Flow under study

This data base presents results concerning a **plane turbulent incompressible mixing layer: air-air**. The mixing layer flow is generated from the confluence of two air streams merging from the trailing edge of a thin flat plate. The boundary layers over this plate are turbulent. The velocity ratio is of the order of 0.6. The mean velocity of the high speed stream is noted U_a and the corresponding velocity for the low speed part is U_b.

In the region where similarity is achieved the mean velocity can be expressed in a normalized form as :

$$\Phi(\eta) = \frac{U - U_b}{U_a - U_b} = \frac{1}{2}\big(1 + \mathrm{erf}\sigma.(\eta - \eta_0)\big)$$

where erf() is the error function:

$$\mathrm{erf}x = \frac{2}{\sqrt{\pi}} \int_0^x \exp(-t^2)\, dt$$

and η is the normalized spatial variable: $\eta = \frac{Y - Y_0}{X - X_0}$, where $\eta = \eta_0$ on the mixing layer axis and (X_0, Y_0) is the virtual origin of the mixing layer.

1.3 Quantities provided

Three experiments are performed by using hot wire anemometry (constant temperature anemometers). Single wire probes and X wires are used. From this set of experiments the following quantities are provided.

- Mean an MS longitudinal velocity profiles measured at more than 20 downstream location
- High order moments of the velocity fluctuations (up to order 4) measured at 6 downstream locations
- spectra of velocity
- Probability density function of velocity
- balance of kinetic energy and of the shear stress uv
- velocity profile close downstream of the trailing edge

1.4 Structure of the data base

All the data are saved in ASCII format, in a way compatible with the Gnuplot package.

The directories hierarchy is as follows:

```
./data
./balance
./turb
./doc
./figures/rawdata
./figures/facility
./figures/balance
./figures/spectra
./figures/pdf
./pdf
./spectra
./ic
./flow
```

```
./prog
./ps
./tex
./PDF2
```

where `./` is the home directory `SHL04`

1.4.1 Directory `data`

Contains the data files. Generated by the measurements. The units used are metric.

1.4.2 Directory `balance`

Contains data files where a few quantities have been calculated, and that are useful for the momentum balance. This quantities are properly normalized. See section 3.3.

1.4.3 Directory `turb`

This directory contains the turbulent quantities properly normalized. See section 3.3.

1.4.4 Directory `doc`

Contains Files describing the data base. Three versions are available: LaTeX files, plain ASCII or ps files.

1.4.5 Directory `figures`

This directory and the different subdirectories contains Gnuplot scripts `*.gp` allowing to generate the plots. Three kinds of scripts are provided

- for viewing on a X terminal: first characters "`xt`"
- generating LaTeX files: first characters "`la`"
- generating Postscript files: first characters "`ps`"

When ran these scripts will fill the subdirectories `ps` and `tex`

Subdirectory `rawdata`

Contains Gnuplot scripts to plot the raw data.

Subdirectory `facility`

Contains a few figures that describe the flow configuration.

Subdirectory `balance`

Contains Gnuplot scripts to plot the balance of the turbulent kinetic energy

Subdirectory `pdf`

Contains Gnuplot scripts to plot the Probability Density Function of u

Subdirectory `spectra`

Contains Gnuplot scripts to plot the Spectra of u

1.4.6 Directory `pdf`

Contains the PDF of u

1.4.7 Directory `spectra`

Contains the Spectra of u

1.4.8 Directory `ic`

Contains the initial conditions of the flow. A velocity profile measured downstream close to the trailing edge of the plate.

1.4.9 Directory `flow`

Contains files summarizing the main features of the flow.

1.4.10 Directory `PDF2`

Contains PDF of velocity differences.

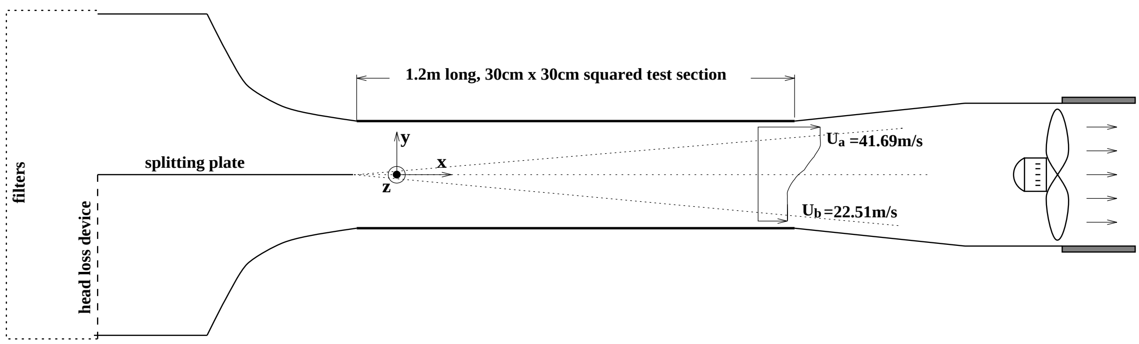
Chapter 2

Experimental facility

2.1 Wind Tunnel

The experiments are performed in the E300 open loop wind tunnel of the C.E.A.T. Poitiers (see Fig- 2.1 for a description). It is composed of the following parts, from upstream to downstream:

- filters to avoid probes contamination
- a converging part (contraction ratio 16) with a square section.
- the test section. The lower and upper walls can be slanted to adjust pressure gradients
- a diffuser
- an axial fan
- a silencer



WIND TUNNEL	E300 of the C.E.A.T. Poitiers France
Type:	open loop
Test section:	square - 300mm×300mm - length : 1.2 m
Contraction ratio:	16
Motor and fan:	power : 4.2 kW up to 3,200 rpm
Rotation of the fan :	can be varied in a ratio of 10 (for probe calibration purposes)
Temperature:	regulated ±0.5 degrees Celcius
Probe holder:	motions along 3 orthogonal axis via stepping motors - accuracy 1/100mm

Figure 2.1: Wind tunnel

2.2 Generation of the flow

A duraluminium flat plate separates the converging part of the wind tunnel in two symmetrical parts. Head loss filters are located at the entrance of one of the halves. The characteristics of this plate are:

- length: 1m
- thickness: 3mm
- sand paper is glued on the upstream sides of the plate in order to stabilize the boundary layers on this plate
- downstream edge: slanted symmetrically with a slope of about 3% - length of the beveled edge 50mm.

The head loss filters create a velocity difference between the upper and lower part of the test section entrance. This velocity difference creates a plane mixing layer.

The roof and floor of the test section are slanted in order to get a zero pressure gradient.

2.3 Measurement Configuration

2.3.1 Hot-wires and Constant Temperature Anemometry

The experiments are performed by using hot wire anemometry and constant temperature anemometers. Two kinds of probe are used

- a single probe : home modified DANTEC 55P11 - wire W-Pt length 0.5 mm ; diameter 2.5 μm
- a 2 wires miniature end flow “X” probe : standard TSI 1248 - spacing between wires 0.5mm - wires length 1mm ; diameter 5 μm

Anemometers are built from TSI 1750.

2.3.2 Temperature measurement

Temperatures are measured by using a K-type thermocouple and an Omega cold junction compensator

2.3.3 Data Acquisition

Two data acquisition systems are used for the present experiments

- The first one is devoted to measurements of Temperature, mean and RMS voltages. It is built from a Keithley 705 10 channels scanner and a Keithley 195A digital multimeter. These devices are controlled via a GPIB bus by a PC micro-computer. This configuration is used for experiment I only (see 4.1)
- The second one is devoted to the data acquisition of instantaneous signals. It presents the following characteristics:
  - signal conditioning by analog separation of mean and fluctuating voltages
  - programmable amplification for gains up to 10240
  - programmable anti-aliasing filters (-36dB/octave)
  - Analog Digital Converters - 12 bits - Voltage range $\pm$5V
  - simultaneous sampling up to 100 kHz
  - maximum continuous record size 512k samples
  - these devices are controlled by a PC micro-computer via a GPIB bus, and a CAMAC crate controller.

2.4 Calibrations

2.4.1 Single wire probe

The calibration law which is used is:

$$e^2(t) = (T_w - T_f) \times (a + bu(t)^n) \tag{2.1}$$

$e(t)$	is	the instantaneous output voltage from the anemometer
$u(t)$	is	the instantaneous streamwise velocity
T_w	is	the wire constant temperature
T_f	is	the flow temperature
a, b, n	are	calibration coefficients

The calibration is performed in the non turbulent high speed side of the wind tunnel. During the calibration the temperature of the mean flow T_f and the global velocity U_c of the wind tunnel are varied in an uncoupled way. This allows to determine the coefficients a, b, n and the temperature of the wire via a regression procedure.

2.4.2 "X" wires probe

The calibration law used is for a wire i:

$$e_i^2(t)/(T_{w_i} - T_f) = C_{a_i}(\alpha(t)) + C_{b_i}(\alpha(t)) \cdot u_{n_i}(t)^{n_i}. \tag{2.2}$$

where

$e_i(t)$	is	the instantaneous output voltage from the anemometer
T_{w_i}	is	the constant temperature of wire i
$u_{n_i}(t)$	is	the instantneous velocity normal to wire i
$\alpha(t)$	is	the instantaneous angle between the velocity vector and the probe axis in the plane defined by the wires.
n_i	is	a calibration coefficient chosen independent of α
$C_{a_i}(\alpha)$, $C_{b_i}(\alpha)$	are	calibration coefficients

The calibration is performed is a small jet facility. During this calibration, the mean velocity, the temperature of the flow and the yaw of the probe are varied. The coefficients T_{w_i}, n_i and the laws $C_{a_i}(\alpha)$ and $C_{b_i}(\alpha)$ are calculated by a regression procedure. The calibration is performed for a range of ±30 degrees for the angle α.

For the experiments involving X-wires (experiments 3, 4, 5), we use **non linearized** calibration laws. In the single wire experiments (experiments 1 and 2) we use a linearized version of the calibration law (equation 2.1) then the output fluctuating voltage of the anemometer is supposed to be linearly related to the fluctuating part of the velocity.

Chapter 3

Flow feature and notations.

3.1 Coordinates

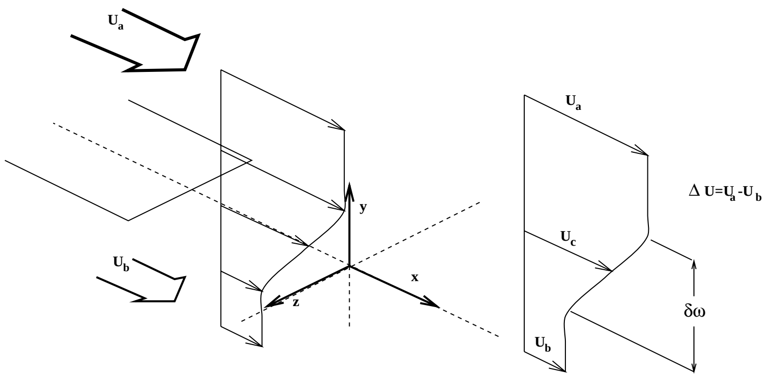


Figure 3.1: Coordinates and notations in the mixing layer

The frame of reference is described on figure 3.1. The coordinates are:

Ox	streamwise direction starting from the trailing edge of the plate
Oy	normal to the plate starting from trailing edge
	$y > 0$ for the high velocity side
Oz	spanwise direction

3.2 Notations

U_a	mean velocity (high speed side)
U_b	mean velocity (low speed side)
U_c	average convection velocity $U_c = (U_a + U_b)/2$
ΔU	velocity difference: $\Delta U = U_a - U_b$
δ_ω	conventional vorticity thickness (see Fig-3.2)
X_0, Y_0	virtual origin of the mixing layer (see Fig-4.4)
θ	momentum thickness
σ	expansion factor

3.3 Data reduction.

When plotting normalized data, the velocity difference ΔU and the vorticity thickness δ_ω will be used.

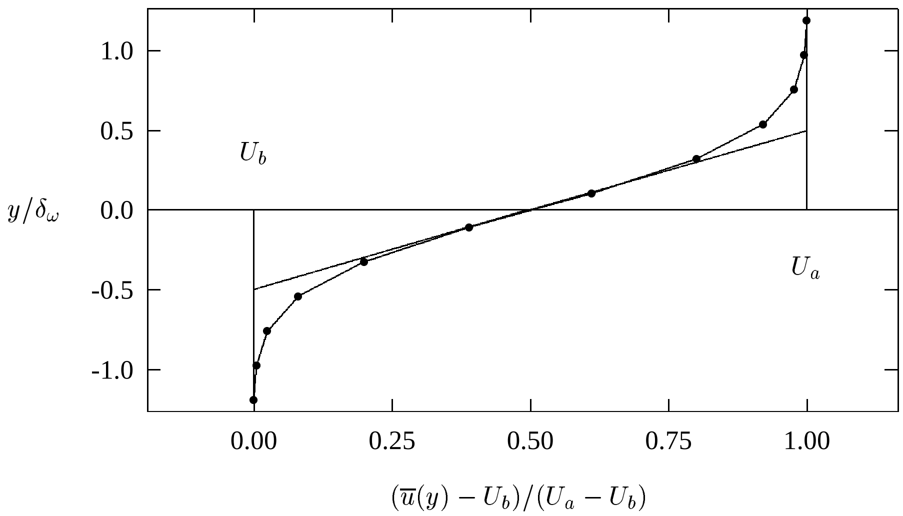


Figure 3.2: Typical mean velocity profile in a plane mixing layer.

3.4 Pressure gradient

The pressure gradient $\partial \overline{p}/\partial x$ is adjusted as close to zero as possible. This is performed by achieving a divergence between the roof and the floor of the test section.

3.5 Boundary layers on the plate

The use of the sand paper and of a long plate allows both boundary layers to be fully turbulent at the trailing edge of the plate. Table 3.1 summarizes the main features of these boundary layers

Characteristic quantity measured at X=-10mm	Notation	High velocity side boundary layer	Low velocity side boundary layer
Velocity	U_∞	$U_a = 41.54$m/s	$U_b = 22.40$m/s
thickness (99%)	δ	9.6 mm	6.3 mm
displacement thickness	δ_1	1.4mm	1.0mm
momentum thickness	Θ	1.0mm	0.73mm
shape factor	H	1.35	1.37
Reynolds number based on θ	R_θ	2900	1200
turbulence level	u'/U_∞	$\sim$ 0.3%	$\sim$ 0.3%

Table 3.1: Main features of the boundary layers of the separating plate (measured at the trailing edge).

Some velocity characteristics just downstream the trailing edge can be found in Fig-3.3, Fig-3.4, where profiles of mean value and variance of the streamwise component of the velocity are plotted respectively.

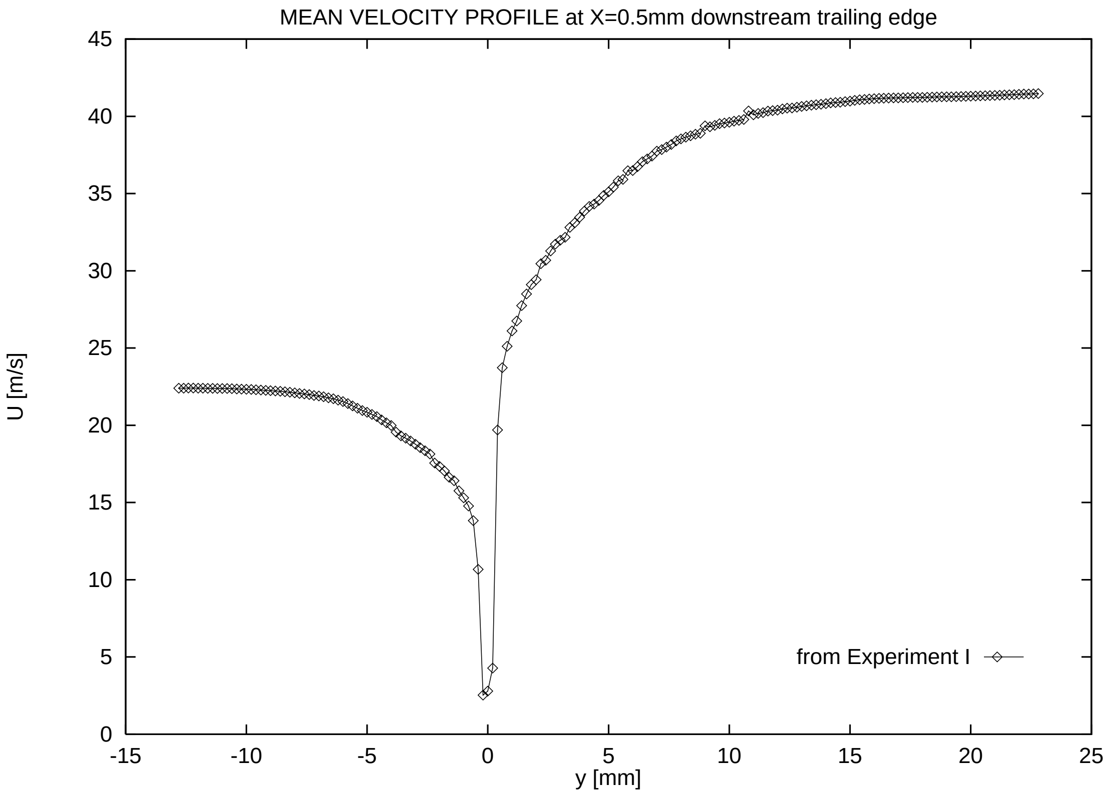


Figure 3.3: Mean velocity profile at $x = 0.5mm$ from the trailing edge. Experiment I

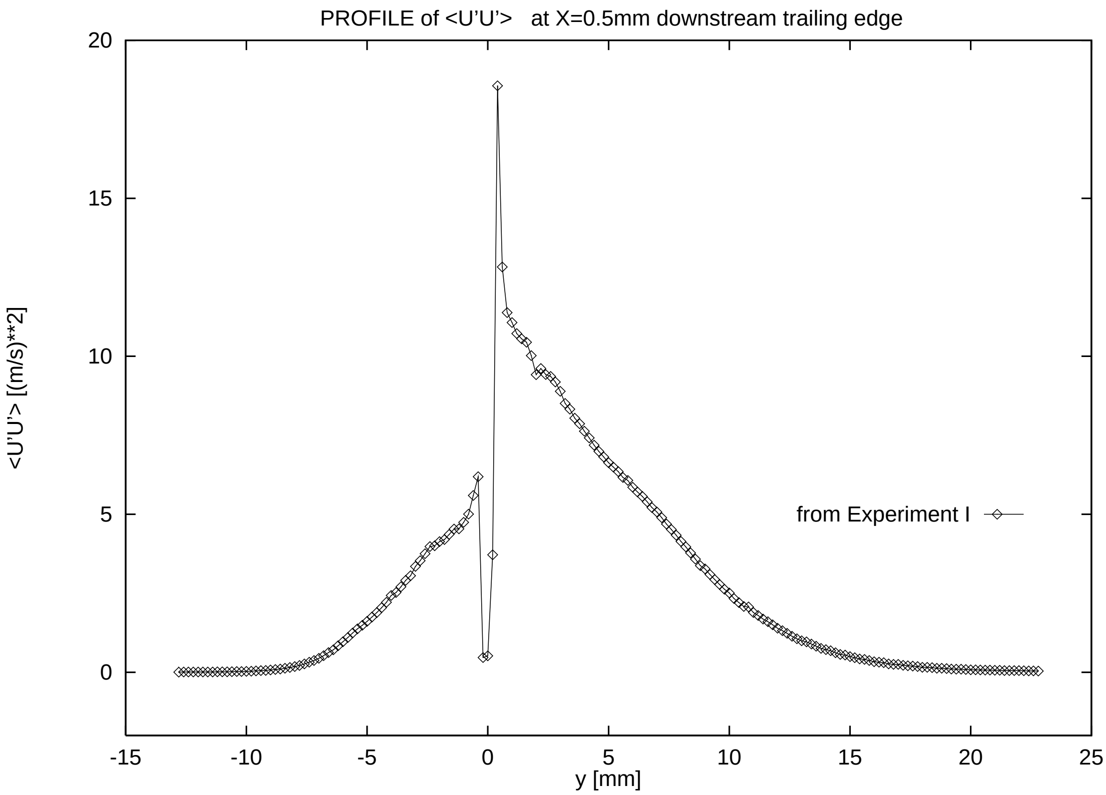


Figure 3.4: RMS velocity profile at $x = 0.5mm$ from the trailing edge. Experiment I

Chapter 4

Description of experiments

The aim of the experiments provided in this data base was to check an experimental procedure allowing to obtain the balance of turbulent kinetic energy. The use of this procedure on a well documented flow: the plane mixing layer seemed to be a reasonable check.

To perform this check 3 sets of experiments are used

- Experiment I : single wire - analogic treatment: main qualification of the flow
- Experiment II : single wire - sampled data: estimation of dissipation
- Experiment III : "X" wire - sampled data: estimation of various turbulent quantities, useful for checking the energy balance.
  - Experiment III-a or (3)- wires in the xy plane
  - Experiment III-b or (4)- wires in the xz plane
  - Experiment III-c or (5)- wires in a 45 degrees plane

During all these experiments, the temperature of the flow, and a reference velocity (lower side velocity) are continuously measured. The mean temperature of the flow is kept close to 20^{o}C

4.1 Experiment I : single wire - analogic treatment

This experiment has been performed in order to characterize the main features of the flow. The measurements provide:

- The mean velocity
- the variance value of the fluctuating velocity

4.1.1 Measurement grid

The following X locations are investigated (measured from the trailing edge of the plate):
X = 30.0, 40.0, 50.0, 70.0, 100.0, 130.0, 170.0, 200.0, 250.0, 300.0, 350.0, 400.0, 450.0, 500.0, 550.0, 600.0, 650.0, 725.0, 750.0, 800.0, 850.0, 900.0, 950.0, 1000.0 mm

For each X location, 201 measurement locations are used in the Y direction. The extent of the measurement domain is adapted to the mixing layer size.

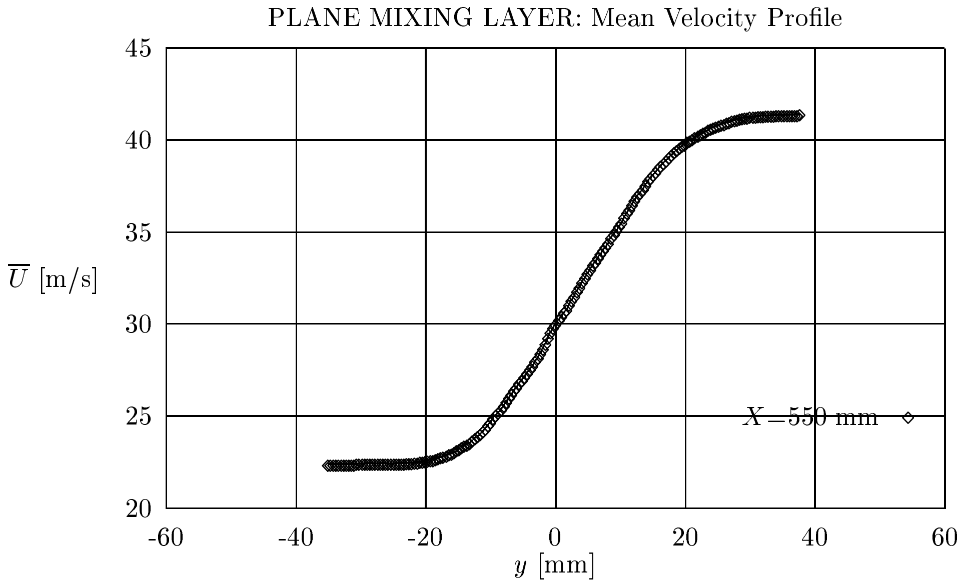


Figure 4.1: Typical mean velocity profile measured in the mixing layer.

4.1.2 Files

The corresponding files are in the directory `SHL04/data`.

file names `DDDD.ml1`, where `DDDD` is the X location written using 4 digits and leading zeros. (ie. `0005.ml1`).

A header of 4 lines describes the file contents. Then the data follow organized in 4 columns:

1. X location [mm]
2. Y location [mm]
3. U mean velocity [m/s]
4. $\overline{u'^2}$ [m^2/s^2]

Example of file content:

```
# FILE 0030.mls
#SINGLE WIRE MEASUREMENTS IN PLANE MIXING LAYER
#data taker: J. Delville CEAT Poitiers - France
#       X  [mm]        Y [mm]          <U> [m/s]    <u'u'> [(m/s)**2]
0.300000E+02   -0.118200E+02    0.223847E+02    0.478949E-02
0.300000E+02   -0.116080E+02    0.223880E+02    0.606776E-02
 ....
```

4.1.3 Visualizing the raw data

The raw data can be visualized by using the Gnuplot file `SHL04/figures/rawdata/xtml1.gp`

The script file `SHL04/figures/rawdata/makefigs` creates

- LaTeX files (stored in `SHL04/tex`), names: `ml1DDDDm.tex` for mean velocity and `ml1DDDDf.tex` for fluctuating part. `DDDD` is the X location written using 4 digits and leading zeros.

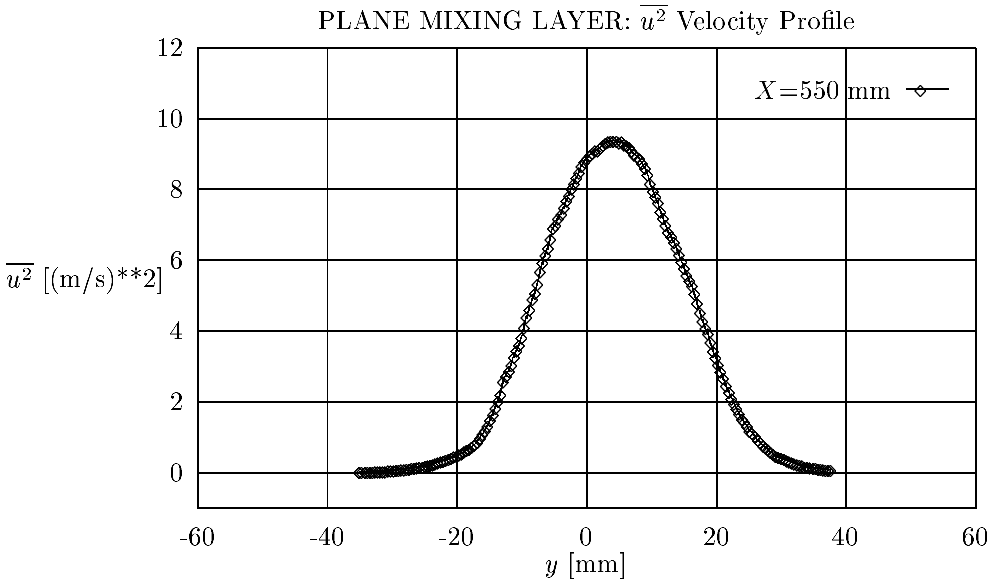


Figure 4.2: Typical $\overline{u^2}$ velocity profile in the plane mixing layer.

- a single Postscript file (stored in `SHL04/ps`), named `psuml1.ps` that contains all the plots directly printable.
- Encapsulated Postscript files (stored in `SHL04/ps`), names with the same rules as the LaTeX ones, but the extension is now `.eps`.

Figure 4.1 and 4.2 gives examples of such plots.

4.1.4 Related data

From the mean velocity profiles the following quantities have been computed

- downstream evolution of U_a and U_b
  The corresponding data file is `SHL04/flow/uaub.ml1`
- vorticity thickness $(U_a - U_b)/(\partial U/\partial y)$ on the mixing layer axis
  The corresponding data file is `SHL04/flow/delom.ml1`
- momentum thickness $\Theta = \int_{-\infty}^{+\infty} \frac{U-U_b}{U_a-U_b}(1 - \frac{U-U_b}{U_a-U_b})\, dy$
  The corresponding data file is `SHL04/flow/theta.ml1`
- expansion factor of the mixing layer σ
- iso-velocity lines $\Phi(x,y)$=Cte
  The corresponding data file is `SHL04/flow/thephis.ml1`
- virtual origin of the mixing layer

Visualizing related data

These related data can be plotted by using `SHL04/figures/rawdata/xtscales.gp`. Figure 4.3 shows the downstream evolution of the vorticity thickness and momentum thickness.

The iso-Φ are plotted by using `SHL04/figures/rawdata/xtthephi.gp`. (Figure 4.4)

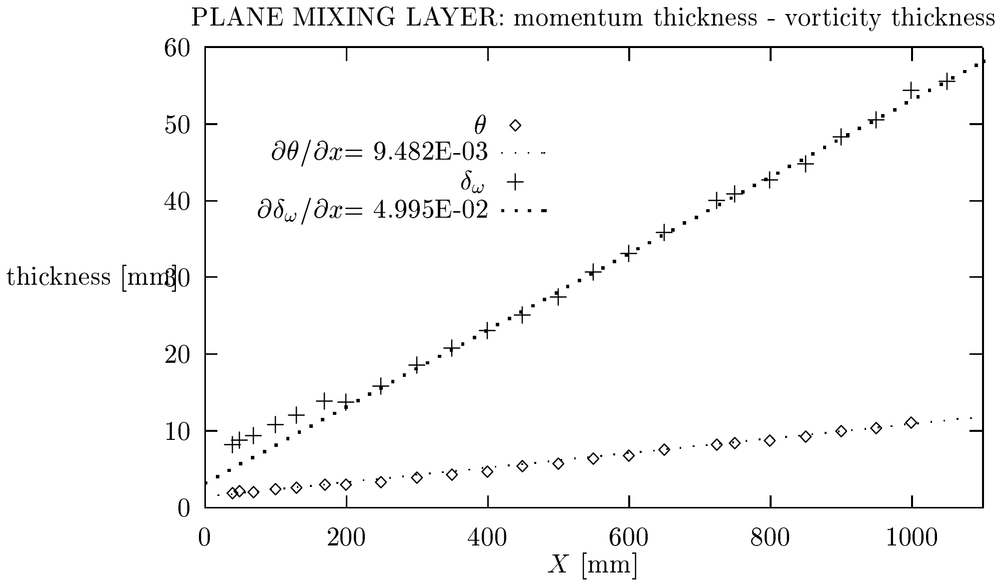


Figure 4.3: downstream evolution of the vorticity thickness and momentum thickness

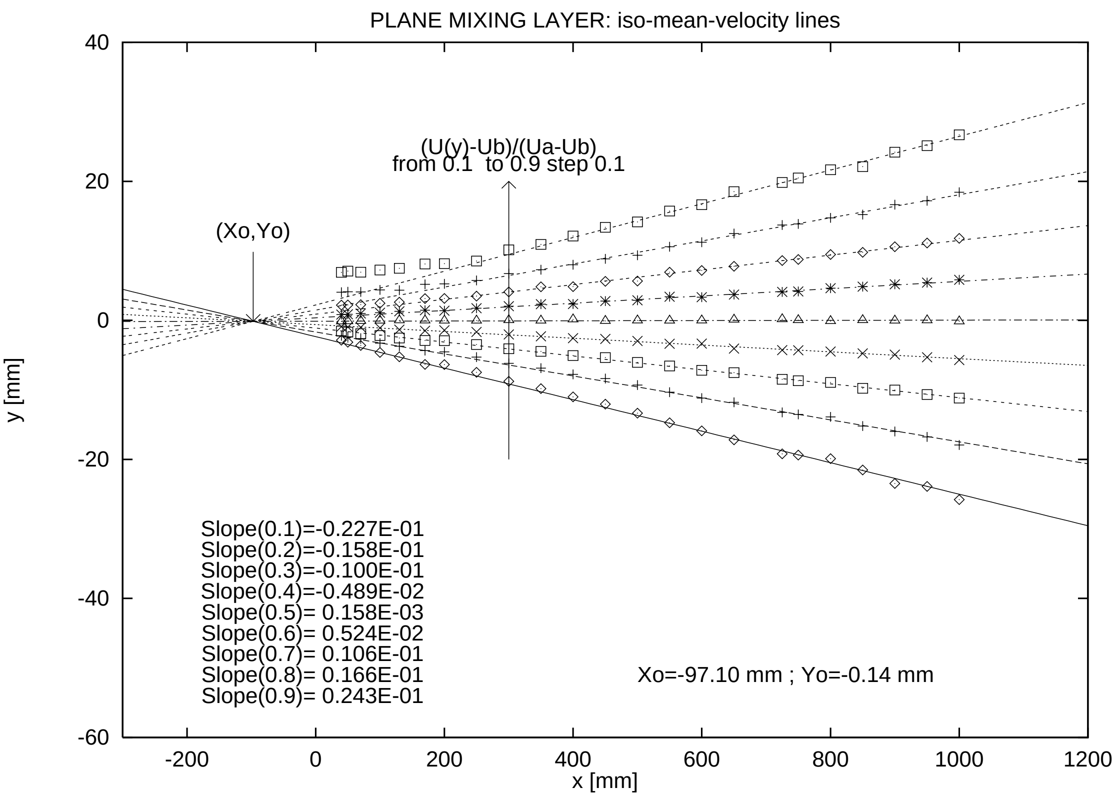


Figure 4.4: Iso-$\overline{u}$ velocity lines.

4.1.5 Measurement at the trailing edge of the plate

Experiment I has also been performed close downstream the trailing edge ($X \sim 0.5$mm) the corresponding data file is `SHL04/data/0001.ml1` the corresponding plot file is: `SHL04/figures/rawdata/xtprofin` (cf Fig. 3.3 and 3.4)

4.2 Experiment II : single wire - sampled data

In this experiment we are mainly interested in the determination some statistics concerning the longitudinal component of the velocity:

- higher moments
- spectra from which an estimation of the dissipation term $epsilon$ can be provided

4.2.1 Measurement grid

This experiment has been performed at two X locations : X=200mm and X=800mm from the trailing edge. In the Y direction, 41 positions are explored.

- for X =200mm the measurement step is δy= 1.575 mm
- for X =800mm the measurement step is δy= 2.15 mm

4.2.2 data acquisition configuration

At each Y location, two samples of 512k instantaneous conversions are stored. The sampling frequency is 50kHz. An anti-aliasing filter is used with a cut-off frequency f_c=20kHz.

4.2.3 Files

Higher moments

The data corresponding to the higher moments can be found in `SHL04/data`. These files are: `0200.ml2` and `0800.ml2`. In these files, are found 4 lines of header, followed by 41 lines of 6 columns.

1. X location [mm]
2. Y position [mm]
3. $\overline{u'^2}$ [m^2/s^2]
4. $\overline{u'^3}$ [m^3/s^3]
5. $\overline{u'^4}$ [m^4/s^4]
6. an estimation of the dissipation $epsilon$ obtained from spectra [m^2/s^3]. This dissipation is obtained by assuming isotropy of small dissipative scales and by using a Taylor hypothesis. Following these assumptions:

$$\epsilon = \frac{15.\nu}{\overline{U}^2}.\overline{(\frac{\partial u'}{\partial t})^2} \tag{4.1}$$

$$\epsilon = \frac{60.\nu.\pi^2}{\overline{U}^2}.\int_0^{+\infty} f^2.E_{u'}(f)df \tag{4.2}$$

Example of file content:

```
# FILE 0200.ml2
#SINGLE WIRE MEASUREMENTS IN PLANE MIXING LAYER
#data taker: J. Delville CEAT Poitiers - France
# X [mm]  Y [mm]  <u**2> [(m/s)**2] <u**3> [(m/s)**3] <u**4> [(m/s)**4]  eps
0.200000E+03   -0.295600E+02    0.766937E-02    0.499922E-03    0.662172E-03 ....
0.200000E+03   -0.279850E+02    0.153935E-01    0.410928E-03    0.115059E-02 ....
```

Spectra

The spectra files are in the directory `SHL04/spectra`. The generic name is `s0200ml2.DDD` for the location X=200mm. Where `DDD` is a three digits representation of the probe location varying from `001` to `041`.

A header of 4 lines describes the file content. 1024 frequencies are available. Then the data follow organized in 3 columns:

1. f frequency [Hz]
2. Y location [mm]
3. $S(f)$ energy at frequency f. The data are normalized in such a way that $\sum_1^{1024} s(f_k) = \overline{u'^2}$

Example of file contents:

```
# File s0200ml2.016
#SINGLE WIRE MEASUREMENTS IN PLANE MIXING LAYER
#data taker: J. Delville CEAT Poitiers - France
# f  [Hz]    y    [mm]         S(f)
     6.10352   -5.93500    11.2115
     30.5176   -5.93500    11.2115
```

Data visualization

- Spectra plots are generated by using the script file `SHL04/figures/spectra/makefigs`. These plots can be viewed by using: `gnuplot xtspml2.gp` Figures 4.5 and 4.6 show two typical spectra obtained during this experiment.
- Higher moments plots can be obtained by using the script-files described in section 4.4.2

4.3 Experiment III : "X" wire - sampled data

This experiment is performed with a X-wires probe. Three configurations of probe orientation are used:

- wires in the xy plane: experiment IIIa (3). The probe provides $u(t), v(t)$. By this way one can measure the turbulent quantities $\overline{u'^p}$, $\overline{v'^p}$, $\overline{u'^q v'^r}$ for $p = 1, 2, 3, 4$ and $q + r < 4$. (eg. $\overline{u'^3 v'}$)
- wires in the xz plane: experiment IIIb (4). The probe provides $u(t), w(t)$. By this way one can measure the turbulent quantities $\overline{u'^p}$, $\overline{w'^p}$, $\overline{u'^q w'^r}$ for $p = 1, 2, 3, 4$ and $q + r < 4$. (eg. $\overline{u'^2 w'^2}$). The moments involving odd powers of w' have been checked to be close to zero, as it should be due to the homogeneity in the Z direction.
- wires in the xt plane: experiment IIIc (5). In this configuration, the probe is rotated 45 degrees on its axis. The probe provides $u(t), (v(t) - w(t))$. This experiment is performed in order to get an estimation of the moment $\overline{v'w'^2}$.

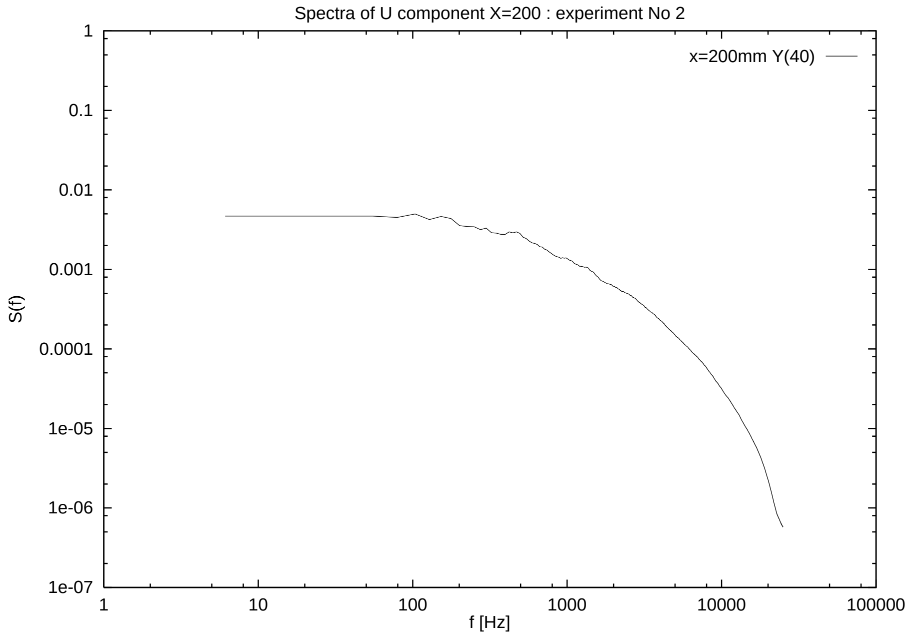


Figure 4.5: Sample of spectrum measured during experiment 2. For a probe location in the high velocity side of the mixing layer. X=200mm

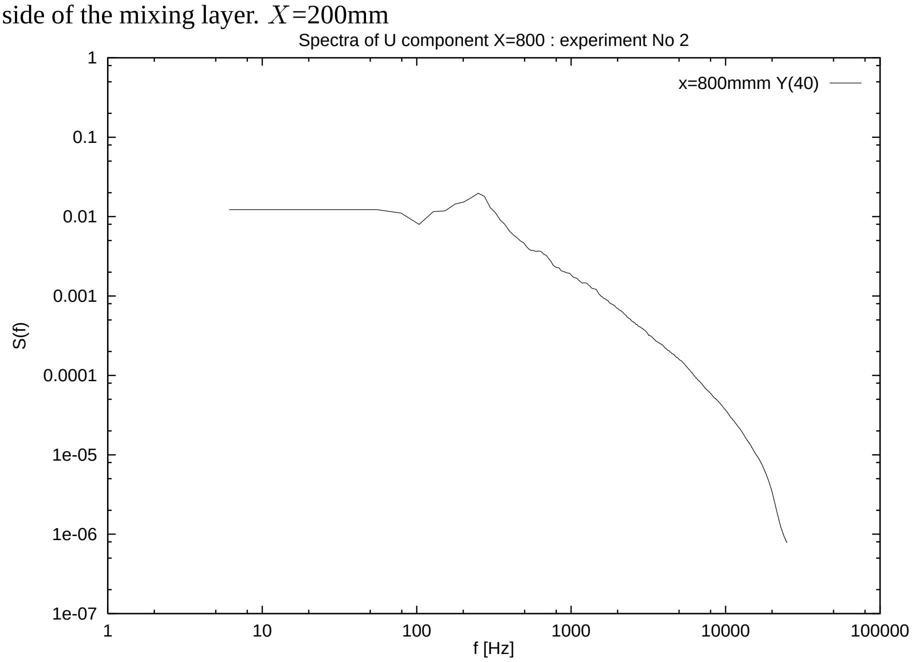


Figure 4.6: Sample of spectrum measured during experiment 2. For a probe location in the high velocity side of the mixing layer. X=800mm

4.3.1 Measurement grid

Experiments IIIa (3) and and IIIb (4) are performed at 6 downstream locations: X=150, 200, 250mm and X=650,800,950mm. The first three are located upstream of the self similar region of the flow, while the last are located in the self similar region. Experiment IIIc (5) is only performed at locations X=200 and 800mm.

4.3.2 data acquisition

At each Y location, two samples of 512k instantaneous conversions are stored for each velocity component. The sampling frequency is 50kHz. An anti-aliasing filter is used with a cut-off frequency f_c=20kHz.

4.4 Comparison of moments obtained by the different experiments.

4.4.1 Files

Directory `SHL04/data`

File names: `DDDDX.mlY` where

- `DDDD` is the X location with leading zeros (`DDDD`=0150, 0200, 0250, 0650, 0800 or 0950)
- `X` corresponds to the order of the moment:
  - `a`: second order moments
  - `b`: third order moments
  - `c`: fourth order moments
  - `m`: first order moment
- `Y`: index of experiment:
  - `Y`=3 : experiment IIIa
  - `Y`=4 : experiment IIIb
  - `Y`=5 : experiment IIIc

Files description Here are the headers of the different files involved in this experiment for X=200mm

```
# FILE 0200a.ml3
# X WIRE MEASUREMENTS IN PLANE MIXING LAYER
# data taker: J. Delville CEAT Poitiers - France
# X [mm]    Y [mm]      <u**2> [(m/s)**2]  <v**2> [(m/s)**2]  <uv> [(m/s)**2]
0.200000E+03   -0.295600E+02    0.957454E-02    0.113029E-01   -0.202307E-02
```

```
# FILE 0200b.ml3
# X WIRE MEASUREMENTS IN PLANE MIXING LAYER
# data taker: J. Delville CEAT Poitiers - France
# X [mm] Y [mm] <u**3> [(m/s)**3] <v**3> [(m/s)**3] <u**2v> [(m/s)**3] <uv**2> [(m/s
0.200000E+03  -0.295600E+02   0.156138E-02  -0.339162E-02  -0.152548E-02   0.158487E
```

```
# FILE 0200c.ml3
# X WIRE MEASUREMENTS IN PLANE MIXING LAYER
# data taker: J. Delville CEAT Poitiers - France
# X [mm]  Y [mm]   <u**4>[(m/s)**4]   <v**4>    <u**2v**2>    <u**3v>   <uv**3>
0.200000E+03 -0.295600E+02 0.147914E-02 0.265662E-02 0.951231E-03 -0.824148E-03 ....
```

```
# FILE 0200m.ml3
# X WIRE MEASUREMENTS IN PLANE MIXING LAYER
# data taker: J. Delville CEAT Poitiers - France
# X [mm]    Y [mm]  <U> [m/s] <V> [m/s]
   200.    -29.560  22.605499  -0.953397
```

```
# FILE 0200a.ml4
# X WIRE MEASUREMENTS IN PLANE MIXING LAYER
# data taker: J. Delville CEAT Poitiers - France
# X [mm]    Y [mm]      <u**2> [(m/s)**2]  <w**2> [(m/s)**2]
 0.200000E+03   -0.295600E+02    0.143306E-01    0.683822E-02
```

```
# FILE 0200b.ml4
# X WIRE MEASUREMENTS IN PLANE MIXING LAYER
# data taker: J. Delville CEAT Poitiers - France
# X [mm]    Y [mm]      <u**3> [(m/s)**3]  <uw**2> [(m/s)**3]
 0.200000E+03   -0.295600E+02    0.163858E-02    0.850425E-03
```

```
# FILE 0200c.ml4
# X WIRE MEASUREMENTS IN PLANE MIXING LAYER
# data taker: J. Delville CEAT Poitiers - France
# X [mm]    Y [mm]      <u**4> [(m/s)**4]  <w**4> [(m/s)**4]  <u**2w**2> [(m/s)**4]
 0.200000E+03   -0.295600E+02    0.189589E-02    0.147619E-02    0.694260E-03
```

```
# FILE 0200m.ml4
# X WIRE MEASUREMENTS IN PLANE MIXING LAYER
# data taker: J. Delville CEAT Poitiers - France
# X [mm]    Y [mm]  <U> [m/s]
   200.    -29.560  22.409800
```

```
# FILE 0200a.ml5
# X WIRE MEASUREMENTS IN PLANE MIXING LAYER
# data taker: J. Delville CEAT Poitiers - France
# X [mm]    Y [mm]      <u**2> [(m/s)**2]
 0.200000E+03   -0.295600E+02    0.160760E-01
```

```
# FILE 0200b.ml5
# X WIRE MEASUREMENTS IN PLANE MIXING LAYER
# data taker: J. Delville CEAT Poitiers - France
```

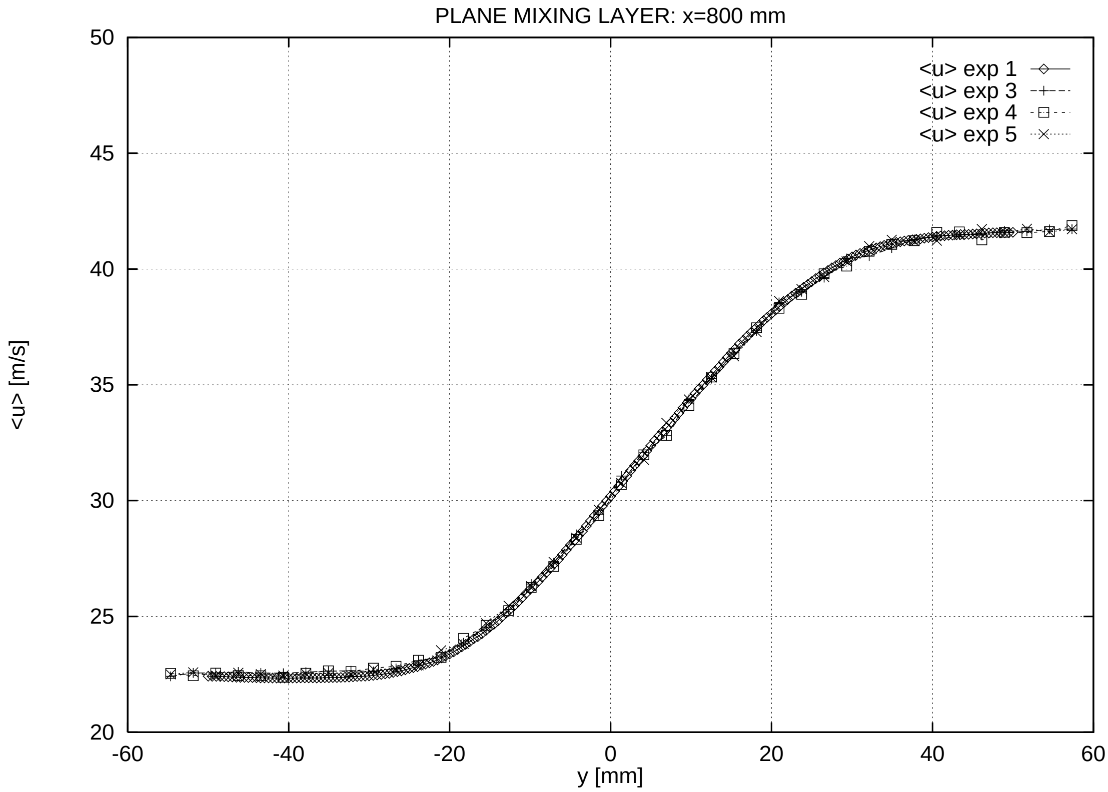


Figure 4.7: Comparison of $\overline{U}$ obtained from the different experiments

```
# X [mm]    Y [mm]      <u**3> [(m/s)**3]      <v**3+ 3 v w**2> [(m/s)**3]
 0.200000E+03   -0.295600E+02   -0.188325E-02   -0.743583E-04


# FILE 0200c.ml5
# X WIRE MEASUREMENTS IN PLANE MIXING LAYER
# data taker: J. Delville CEAT Poitiers - France
# X [mm]    Y [mm]      <u**4> [(m/s)**4]
 0.200000E+03   -0.295600E+02    0.114488E-02


# FILE 0200m.ml5
# X WIRE MEASUREMENTS IN PLANE MIXING LAYER
# data taker: J. Delville CEAT Poitiers - France
# X [mm]    Y [mm]  <U> [m/s] <V> [m/s]
  200.    -29.560  22.538000
```

4.4.2 Drawing and comparison of measured quantities

The data measured via experiments I to III can be compared by using the Gnuplot script: `SHL04/figures/rawdata/xtprof.gp`.

Figures 4.7 to 4.10 shows selected examples of these comparisons for X=800mm

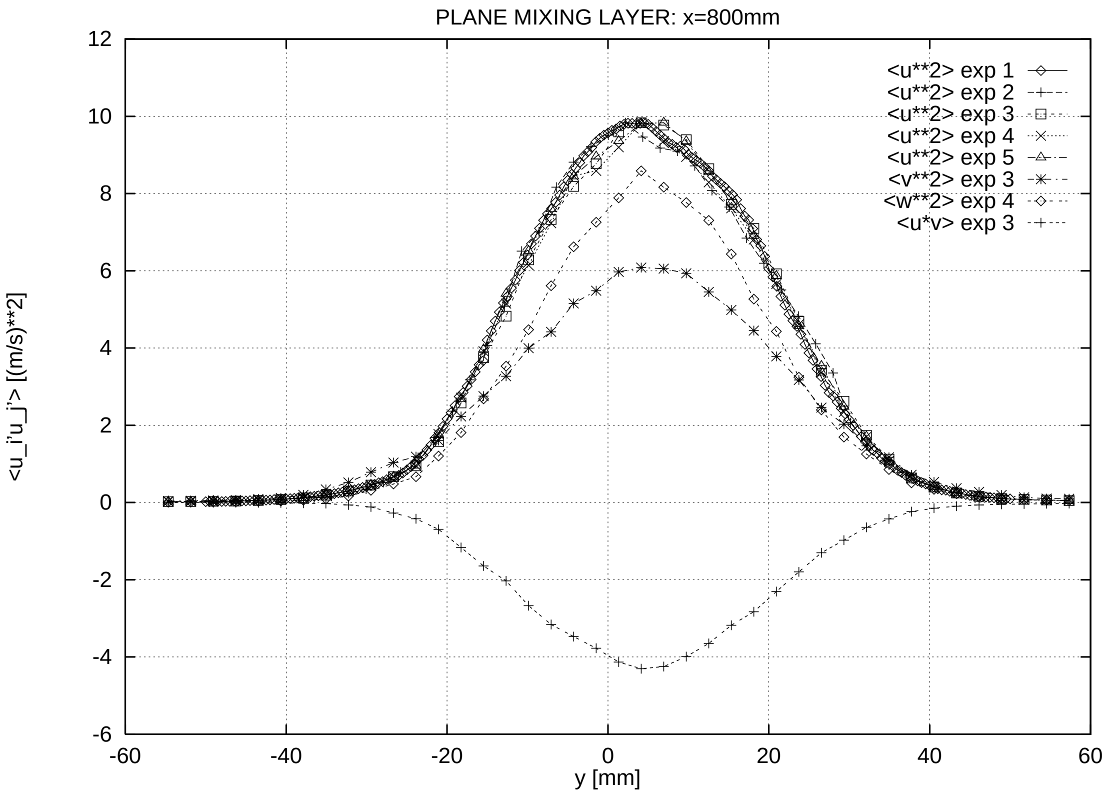


Figure 4.8: Comparison of second order moments obtained from the different experiments

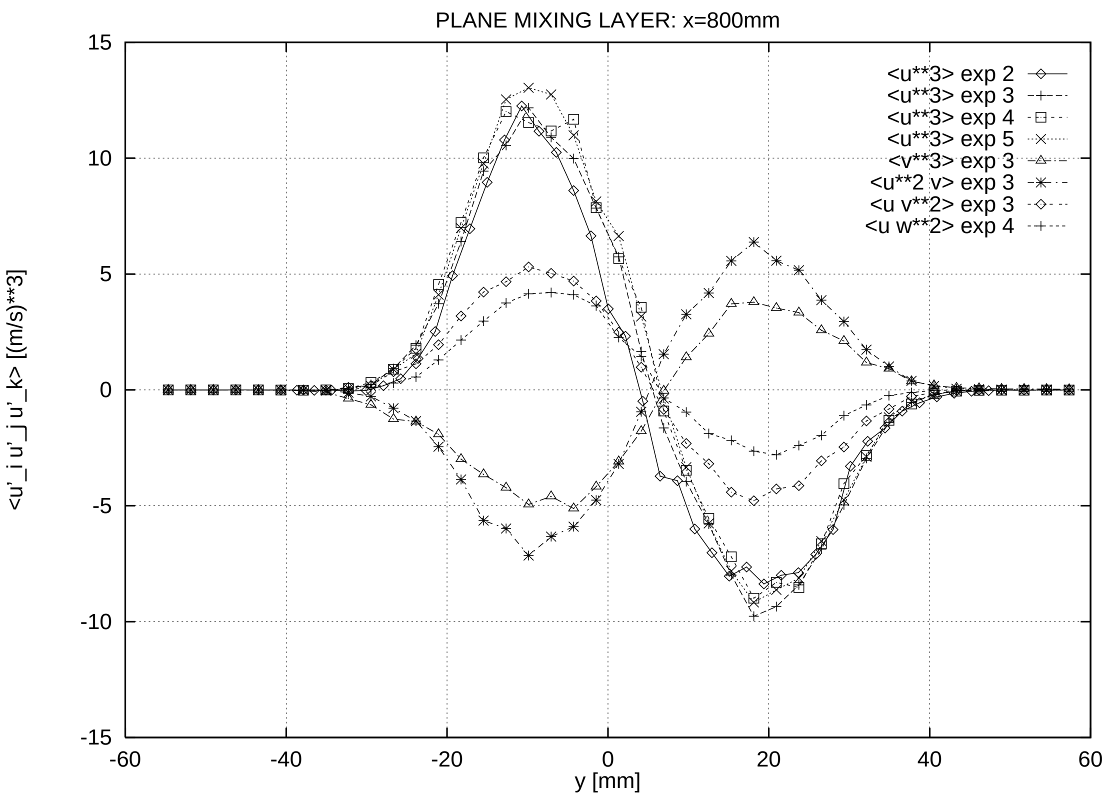


Figure 4.9: Comparison of third order moments obtained from the different experiments

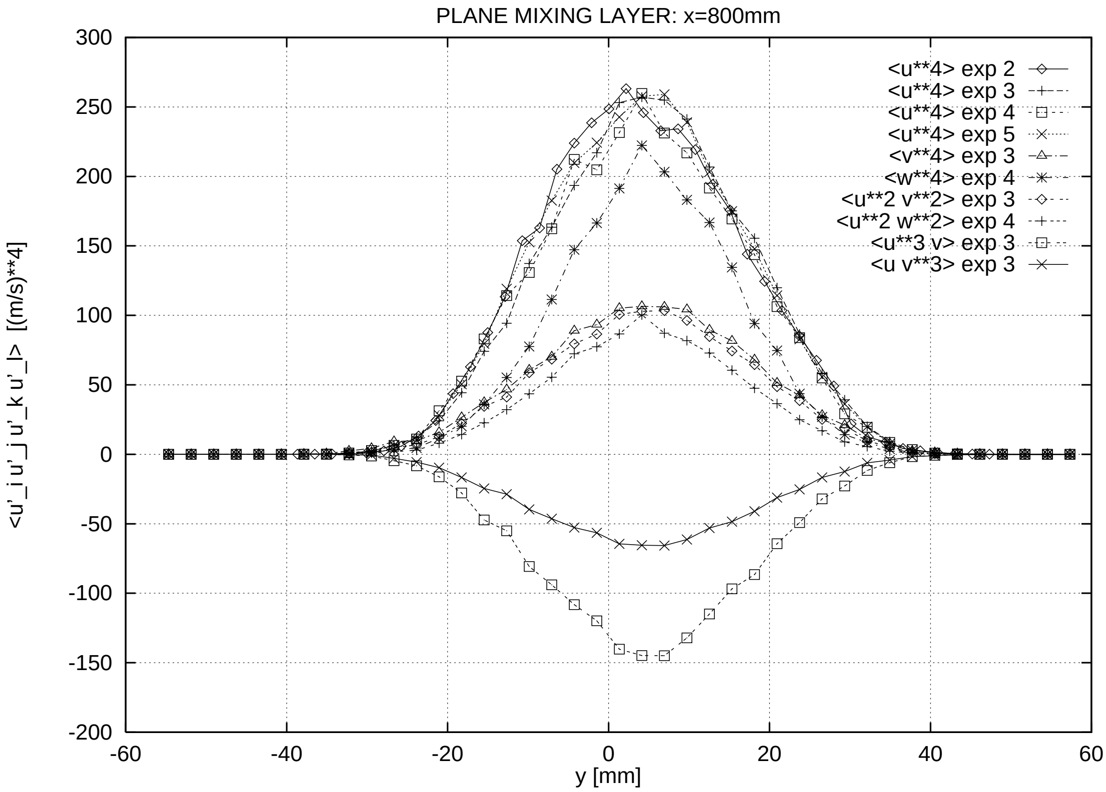


Figure 4.10: Comparison of fourth order moments obtained from the different experiments

4.5 Spectra

4.5.1 Files

The spectra files are in the directory `SHL04/spectra`. The generic name is `s0200mlu.DDD` for the location X=200mm, u component ; `s0200mlv.DDD` and `s0200mlw.DDD` for components v and w. Where `DDD` is a three digits representation of the probe location varying from `001` to `041`.

A header of 4 lines describes the file content. 1024 frequencies are available. Then the data follow organized in 3 columns:

1. f frequency [Hz]

2. Y location [mm]

3. $S(f)$ energy at frequency f. The data are normalized in such a way that $\sum_1^{1024} s(f_k) = \overline{u'^2}$

4.5.2 Figures

The spectra can be plotted by using `SHL04/figures/spectra/xtspml*.gp` Gnuplot script files. Examples of spectra are plotted figures 4.11 to 4.13.

4.6 Probability Density Function

The PDF are estimated for the 3 components of the velocity. 201 bins are used regularly spaced between $\pm 5\times$ the standard deviation.

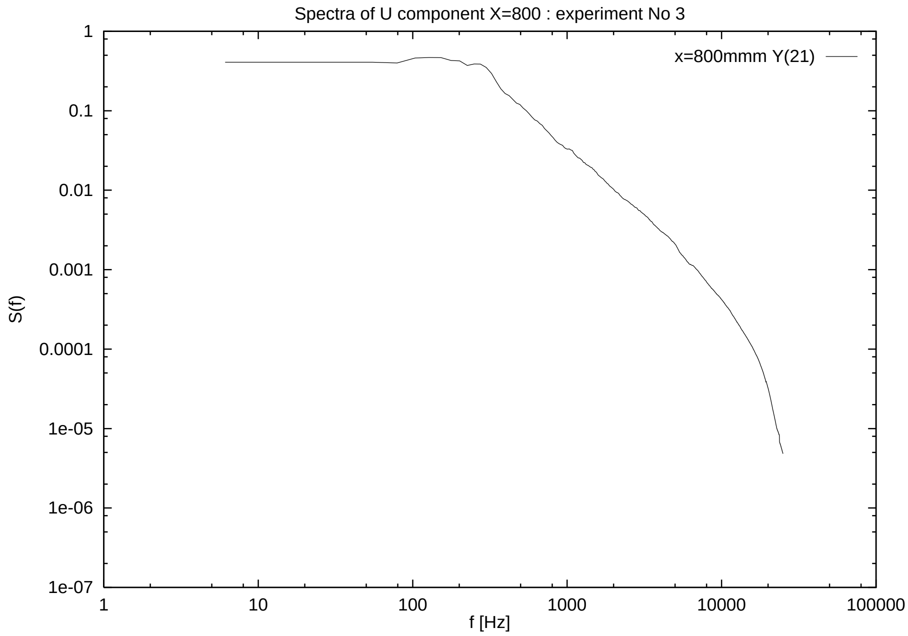


Figure 4.11: Sample of spectrum of u measured during experiment 3. For a probe near the mixing layer axis. X=800mm

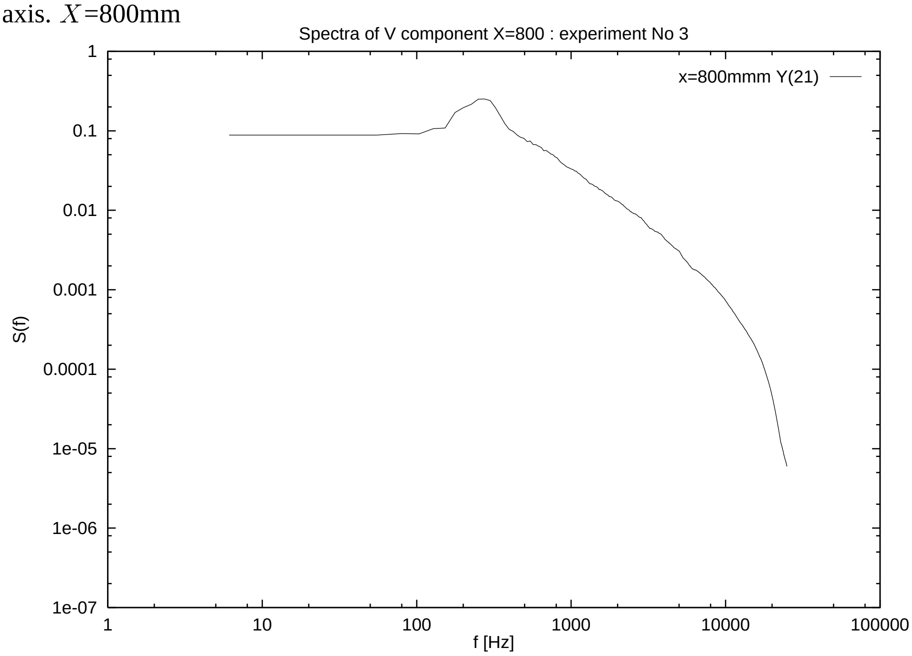


Figure 4.12: Sample of spectrum of v measured during experiment 3. For a probe near the mixing layer axis. X=800mm

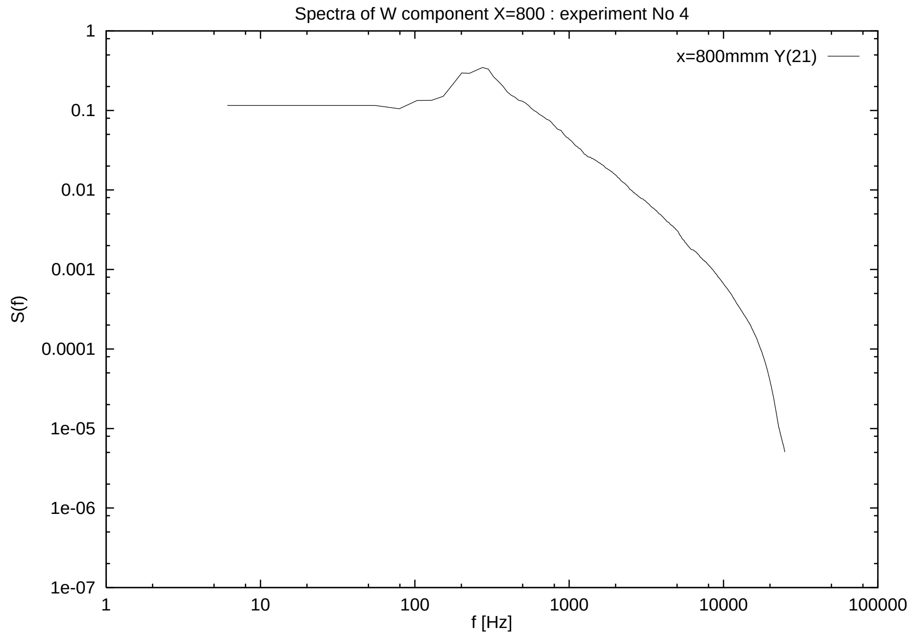


Figure 4.13: Sample of spectrum of w measured during experiment 4. For a probe near the mixing layer axis. X=800mm

4.6.1 Files

The PDF files are in the directory `SHL04/pdf`. The generic name is `p0200mlu.DDD` for the location X=200mm, u component ; `p0200mlv.DDD` and `p0200mlw.DDD` for components v and w. Where `DDD` is a three digits representation of the probe location varying from `001` to `041`.

headers

```
# File p0200mlw.003
# X WIRE MEASUREMENTS IN PLANE MIXING LAYER
# data taker: J. Delville CEAT Poitiers - France
# w/sigma      y    [mm]        sigma P(w/sigma)
    -5.00000   -26.5600    1.31225E-02
```

4.6.2 Figures

The PDF can be plotted by using `SHL04/figures/spectra/xtpdf*.gp` Gnuplot script files. Examples of spectra are plotted figures 4.14 to 4.16.

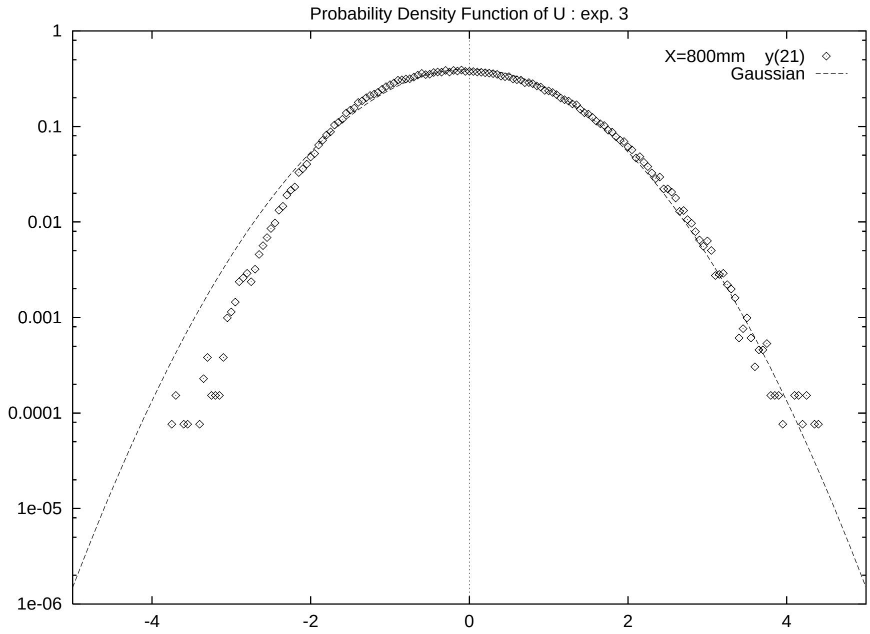


Figure 4.14: Sample of PDF of u measured during experiment 3. For a probe near the mixing layer axis. X=800mm

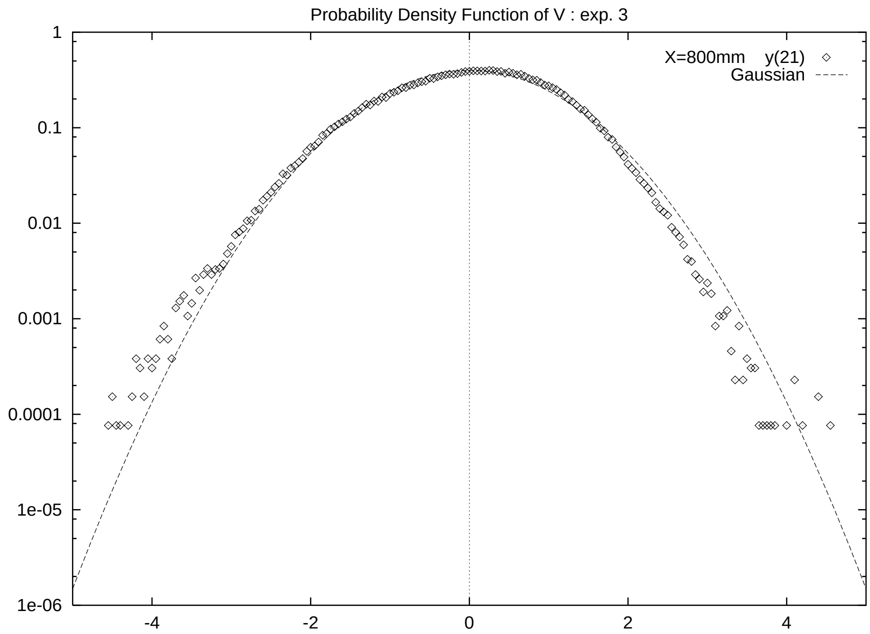


Figure 4.15: Sample of PDF of v measured during experiment 3. For a probe near the mixing layer axis. X=800mm

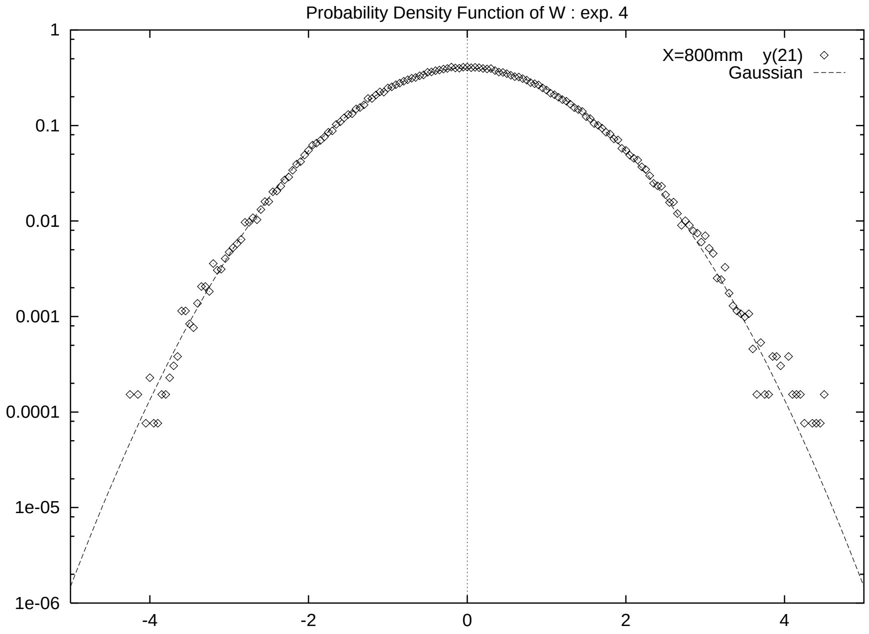


Figure 4.16: Sample of PDF of w measured during experiment 4. For a probe near the mixing layer axis. X=800mm

Chapter 5

Energy, Shear-stress and Momentum balance

The flow is supposed to be homogeneous in the Z direction. The balances are written:

ENERGY:

$$CONVECTION + DIFFUSION + PRODUCTION + DISSIPATION = 0$$

where:

$CONVECTION = -\overline{U}\dfrac{\partial k}{\partial x} - \overline{V}\dfrac{\partial k}{\partial y}$

$DIFFUSION = -\frac{1}{2}.\dfrac{\partial}{\partial x}(\overline{u'^3} + \overline{u'.v'^2} + \overline{u'.w'^2}) - \frac{1}{2}.\dfrac{\partial}{\partial y}(\overline{u'^2.v'} + \overline{v'^3} + \overline{v'.w'^2})$

$PRODUCTION = -(\overline{u'^2} - \overline{v^2}).\dfrac{\partial \overline{U}}{\partial x} - \overline{u'v'}.\dfrac{\partial \overline{U}}{\partial y}$

$DISSIPATION =$estimated through the spectrum see equation 4.2; or by difference.

SHEAR STRESS:

$$CONVECTION + DIFFUSION + PRODUCTION + PRESSURE\,STRAIN = 0$$

where:

$CONVECTION = \overline{U}\dfrac{\partial \overline{u'v'}}{\partial x} + \overline{V}\dfrac{\partial \overline{u'v'}}{\partial y}$

$DIFFUSION = \dfrac{\partial \overline{u'v'^2}}{\partial y}$

$PRODUCTION = \overline{v^2}\dfrac{\partial \overline{U}}{\partial y}$

$PRESSURE - STRAIN =$ can be obtained by difference

MOMENTUM:

$$\overline{U}\frac{\partial \overline{U}}{\partial x} + \overline{V}\frac{\partial \overline{U}}{\partial y} = \frac{\partial \overline{u'v'}}{\partial y} - \frac{\partial \overline{u'^2} - \overline{v'^2}}{\partial x}$$

These balances are established at two downstream locations : X=200 and X=800mm.

The first step is to select among the data the ones given the best estimation of the turbulent quantity:

order	turbulent quantity	experiment used	files
1	$\overline{U}$	3	`*m.ml3`
1	$\overline{V}$	3	`*m.ml3`
2	$\overline{u'u'}$	3	`*a.ml3`
2	$\overline{v'v'}$	3	`*a.ml3`
2	$\overline{u'v'}$	3	`a.ml3`
2	$\overline{w'w'}$	4	`a*.ml4`
3	$\overline{u'u'u'}$	3	`*b.ml3`
3	$\overline{u'u'v'}$	3	`*b.ml3`
3	$\overline{u'v'v'}$	3	`*b.ml3`
3	$\overline{v'v'v'}$	3	`*b.ml3`
3	$\overline{u'w'w'}$	4	`*b.ml4`
3	$\overline{v'w'w'}$	3, 4, 5	`b.ml5`

To obtain the $\overline{v'w'w'}$ correlation, the following formula has to be used:

$$\overline{v'w'^2} = \frac{1}{3}(2^{1.5}\overline{m'^3} - \overline{v'^3})$$

where $\overline{m'^3}$ is the quantity measured in experiment 5 (files `*b.ml5`).

The partial derivatives are performed by a second order finite different scheme. Before applying the derivatives, the data are smoothed in the Y direction by a FFT procedure: Fourier transform of size 128 of the profiles then rejection of the 20 highest Fourier modes.

5.1 Files

The data corresponding to this part of the study are located in the directory `SHL04/balance`.

The selected moments are in the directory `SHL04/turb`. In this directory can be also found the data corresponding to the profiles of k and $\overline{u'v'}$. These profiles are plotted figure 5.1 and 5.2 for the two X locations retained.

All data are stored normalized:

- by $1/\delta_\omega$ for the y position
- by $\delta_\omega/\Delta U^3$ for the terms of the balance

5.2 Energy balance

5.2.1 Convection

Figure 5.3 shows for X=800 mm the contribution of the two terms involved in the convective part of the balance of energy: $\overline{U}\dfrac{\partial k}{\partial x}$ and $\overline{V}\dfrac{\partial k}{\partial y}$, showing the dominant contribution of the first term.
Files: `convk.200` and `convk.800`

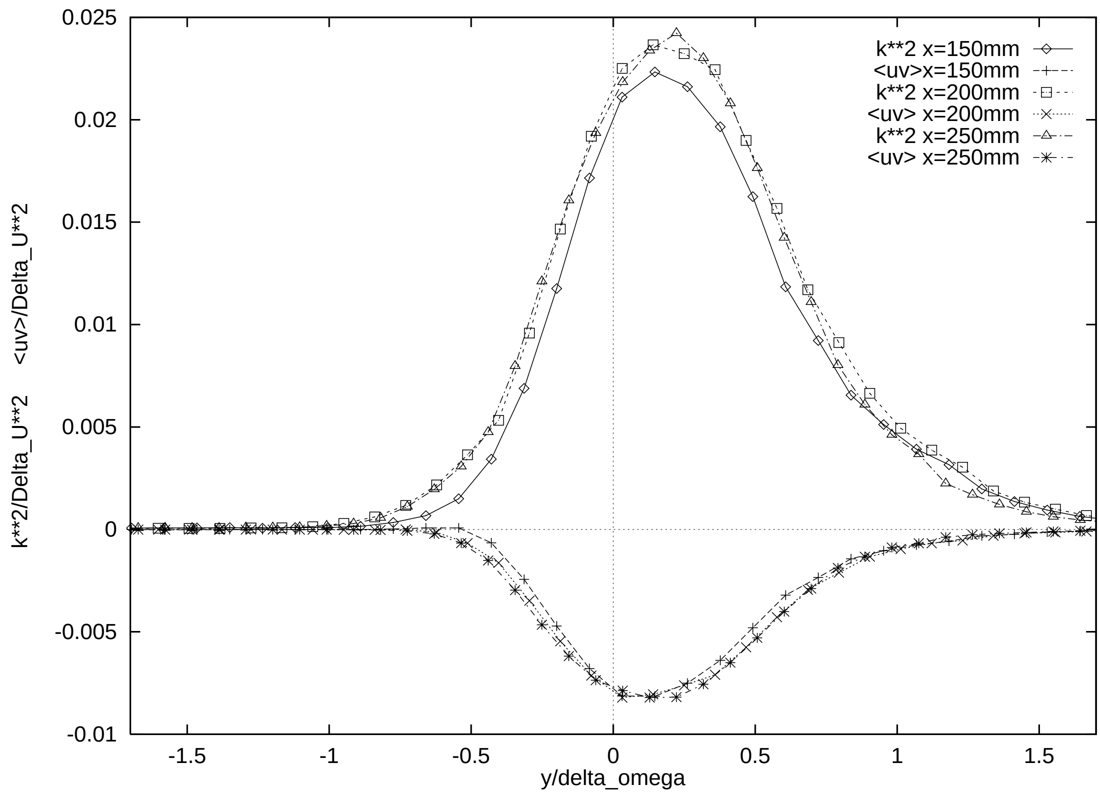


Figure 5.1: Evolution of k and $\overline{u'v'}$ around $X = 200$mm

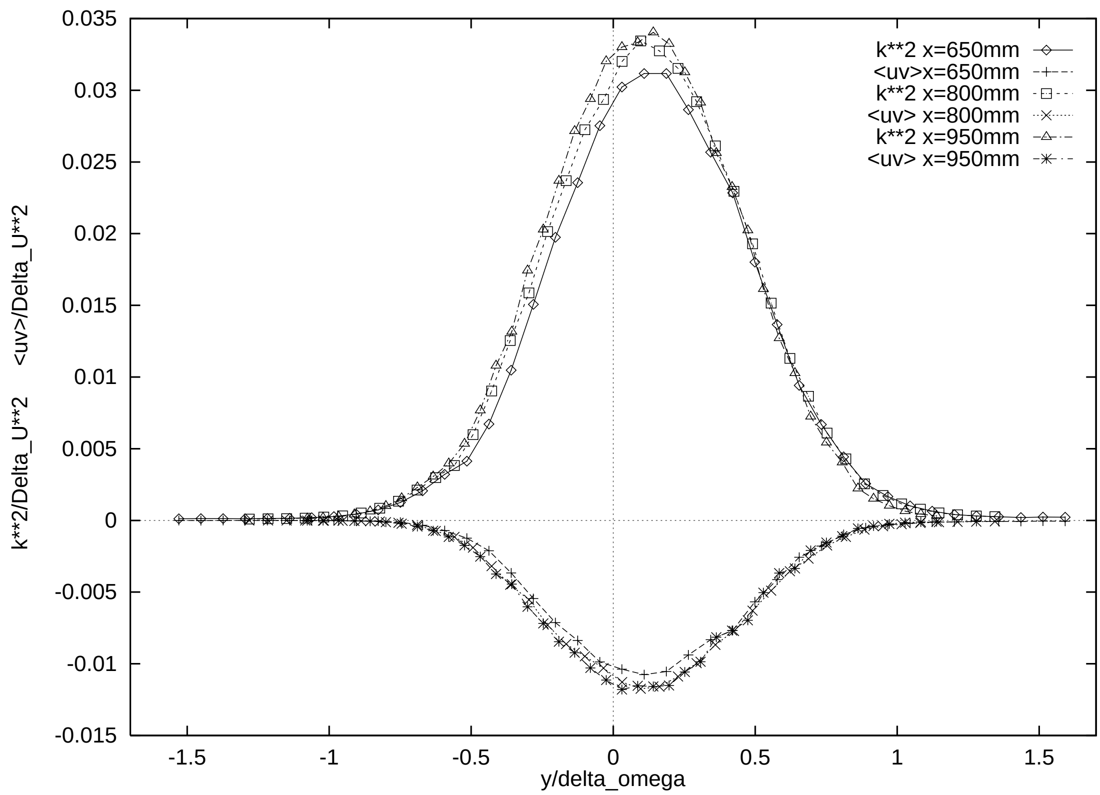


Figure 5.2: Evolution of k and $\overline{u'v'}$ around $X = 800$mm

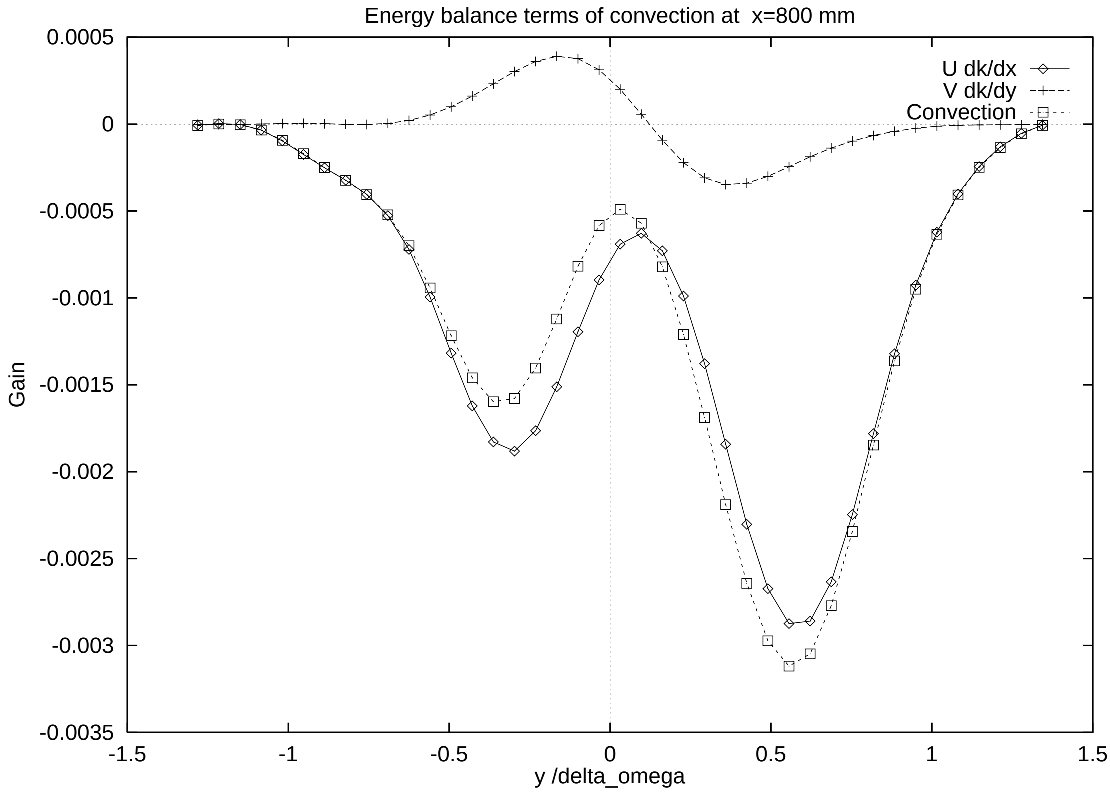


Figure 5.3: Evolution of the terms involved in the convective part of the balance of k ; $X = 800$mm

```
#  File convk.200
#  Terms appearing in k convection
#
#      y          u* dk/dx      v *dk/dy      convection
```

5.2.2 Diffusion

Figure 5.4 shows for X=800 mm the contribution of the two terms involved in the diffusive part of the balance of energy: $-\frac{1}{2}.\frac{\partial}{\partial x}(\overline{u'^3}+\overline{u'.v'^2}+\overline{u'.w'^2})$ and $-\frac{1}{2}.\frac{\partial}{\partial y}(\overline{u'^2.v'}+\overline{v'^3}+\overline{v'.w'^2})$, showing the dominant contribution of the second term.
Files: `diffk.200` and `diffk.800`

```
# File diffk.200
# Terms appearing in diff of k
#
#  y     -.5*d/dx(u3+uv2+uw2)  -.5*d/dy(u2v+v3+vw2)  diffusion
```

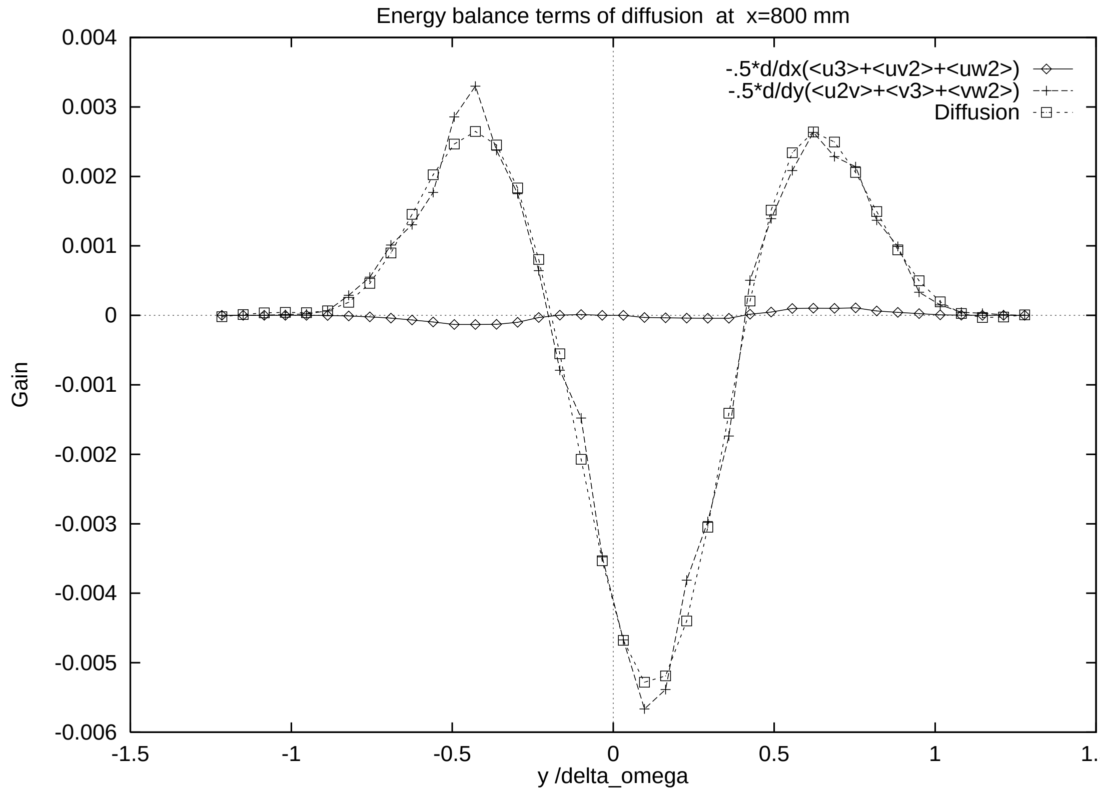


Figure 5.4: Evolution of the terms involved in the diffusive part of the balance of k ; $X = 800$mm

5.2.3 Production

Figure 5.5 shows for X=800 mm the contribution of the two terms involved in the productive part of the balance of energy: $-(\overline{u'^2} - \overline{v^2}).\dfrac{\partial \overline{U}}{\partial x}$ and $-\overline{u'v'}.\dfrac{\partial \overline{U}}{\partial y}$, showing the dominant contribution of the second term.

Files: `prodk200` and `prodk.800`

```
# File prodk.200
# Terms appearing in production of k
#
#  y        -(u2-v2)*dudx      -uv*dudy      production
```

5.2.4 Dissipation

Figure 5.6 shows for X=800 mm the dissipation ϵ estimated from the balance of k and the one directly measured by assuming isotropy of the small dissipative scales and applying Taylor hypothesis (equation 4.2). The dissipation obtained by the second approach is largely underestimated.

: Files `epsl.200` and `epsl.800`

```
# file epsl.200
# dissipation from experiment 2
#
#    y         epsilon
```

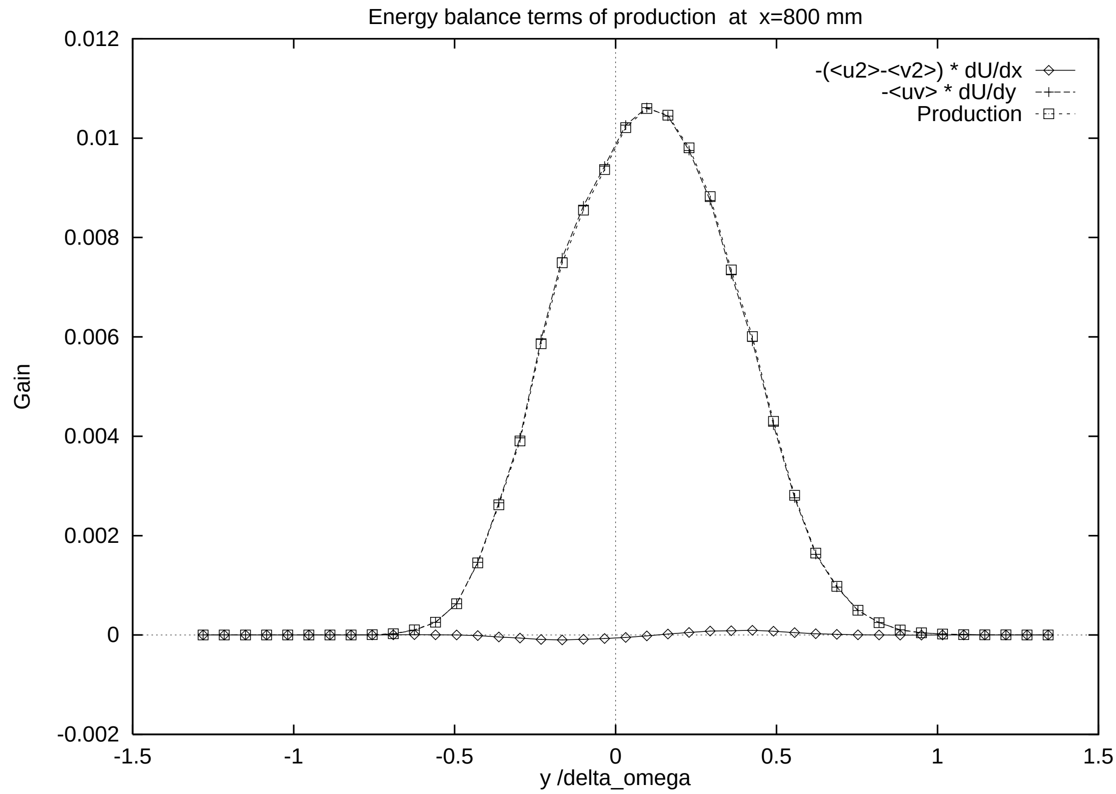


Figure 5.5: Evolution of the terms involved in the productive part of the balance of k ; $X = 800$mm

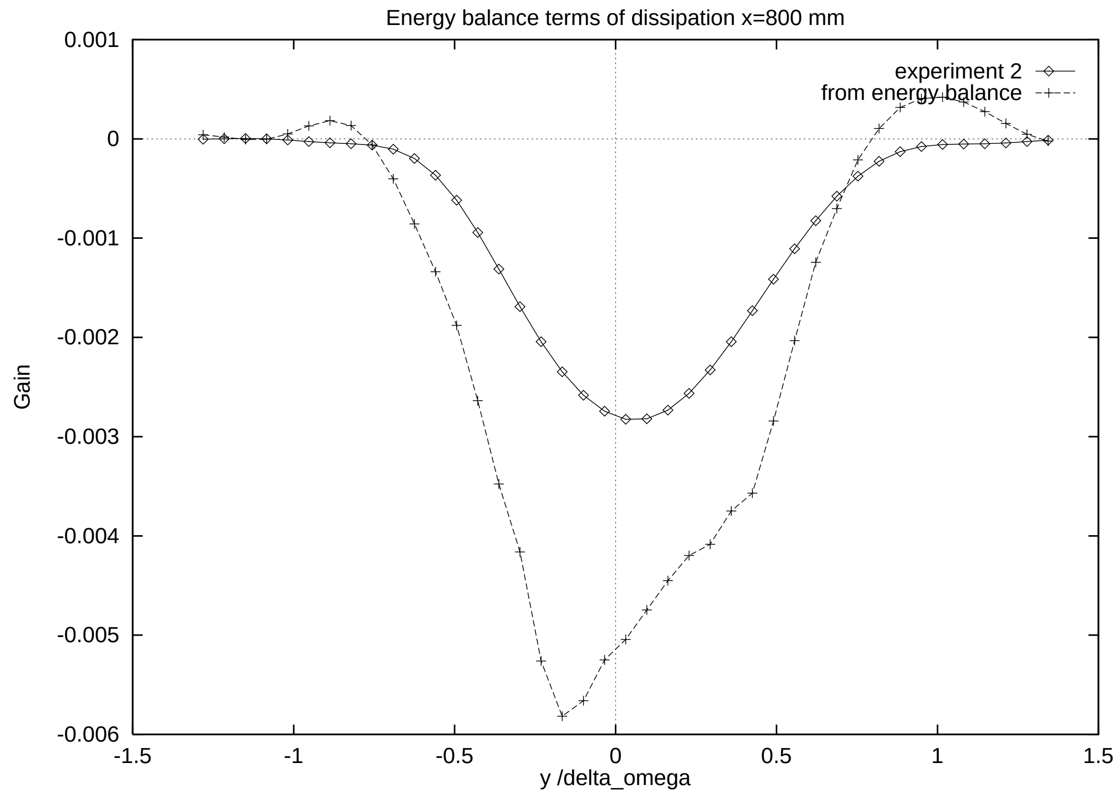


Figure 5.6: Evolution of the dissipation (experiment 2 and balance of k) ; $X = 800$mm

5.2.5 Balance

The turbulent kinetic energy balance is plotted on figures 5.7 and 5.8.

Files `balancek.200` and `balancek.800`

```
# File balancek.200
# Terms appearing in the balance of k
#       y       remainder     dissipation      dissipation
#               of balance   by difference     from exp 2
```

5.3 Shear stress balance

5.3.1 Files

Files: `balancuv.200` and `balancuv.800`

```
# File balancuv.200
# Terms appearing in the balance of shear stress
#
#   y    u*duvdx   v*duvdy    convection   diffusion   production  press_strain
```

5.3.2 Balance

The shear-stress balance is plotted on figures 5.9 and 5.10.

5.4 Momentum balance

5.4.1 Files

Files: `momentum.200` and `momentum.800`

```
# File momentum.200
# Terms appearing in the momentum equation
#
# y  u*dudx  v*dudy  -duvdy  -d(u2-v2)dx  u*dudx+v*dudy -duvdy-d(u2-v2)dx\
  should_be_0  v_from_mom._bal.
```

5.4.2 balance

On Figures 5.11 and 5.12, the two terms of the momentum balance: $\overline{U}\dfrac{\partial\overline{U}}{\partial x}+\overline{V}\dfrac{\partial\overline{U}}{\partial y}$ and $\dfrac{\partial\overline{u'v'}}{\partial y}-\dfrac{\partial\overline{u'^2}-\overline{v'^2}}{\partial x}$ are compared.

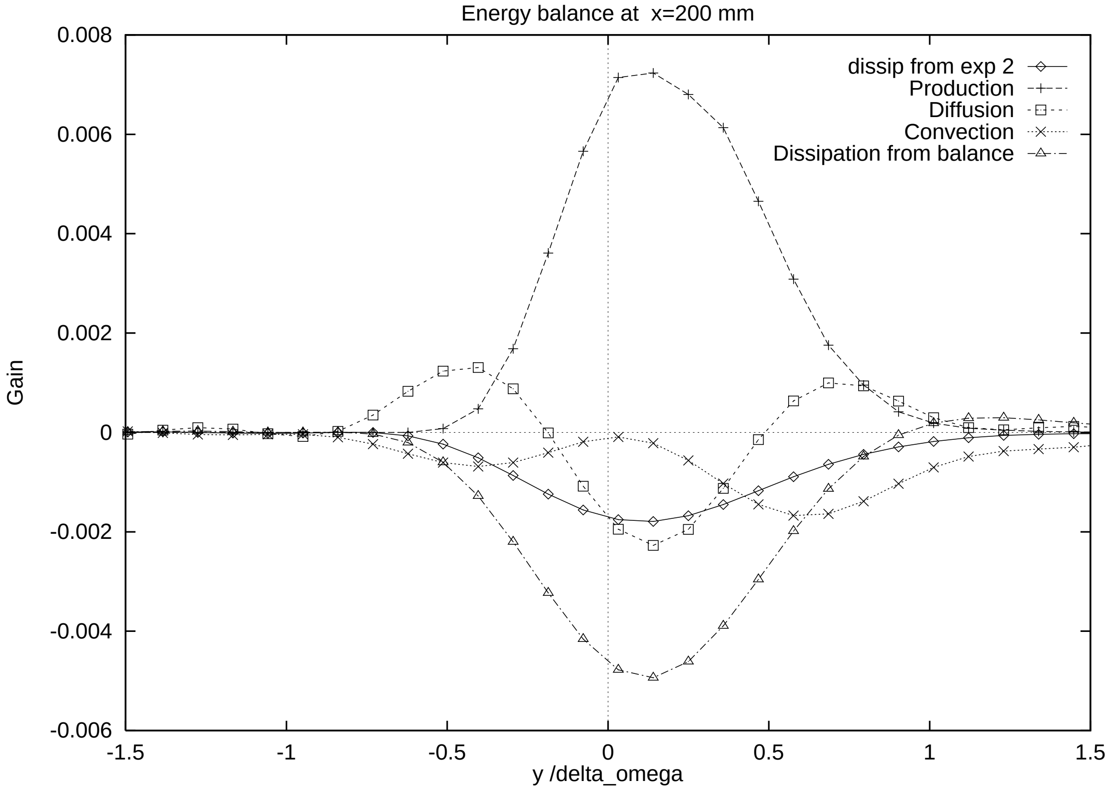


Figure 5.7: Energy balance at $X = 200$mm

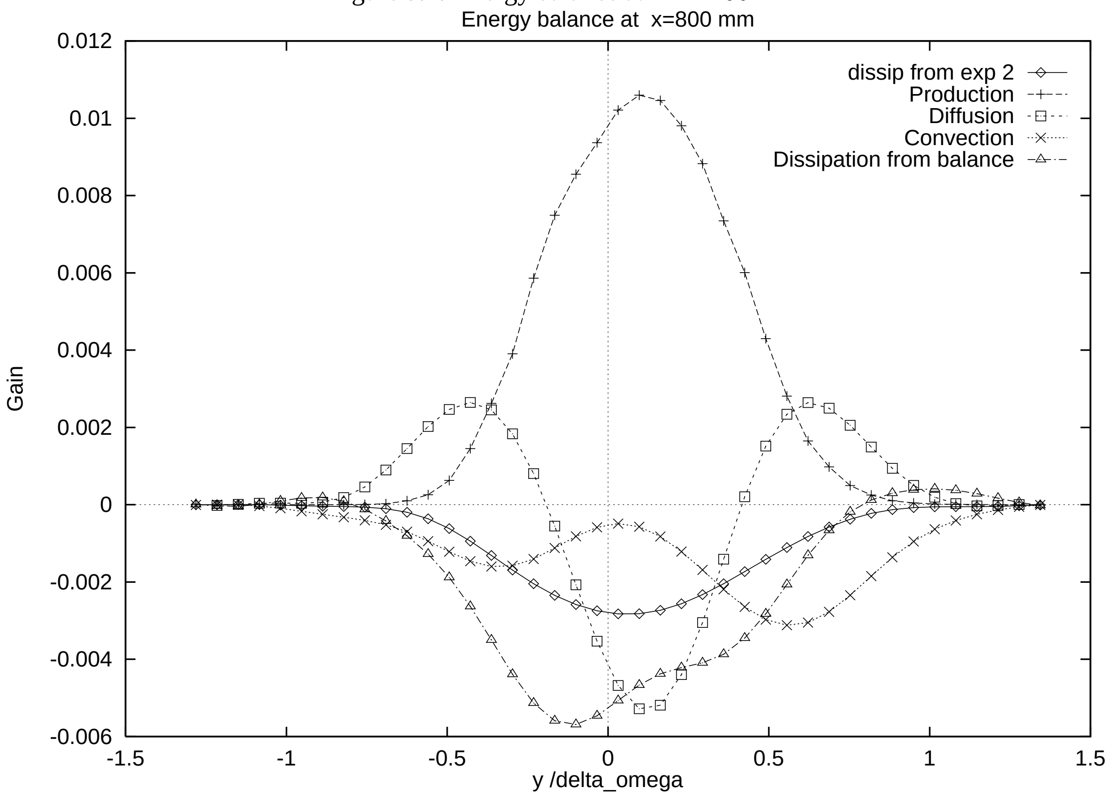


Figure 5.8: Energy balance at $X = 800$mm

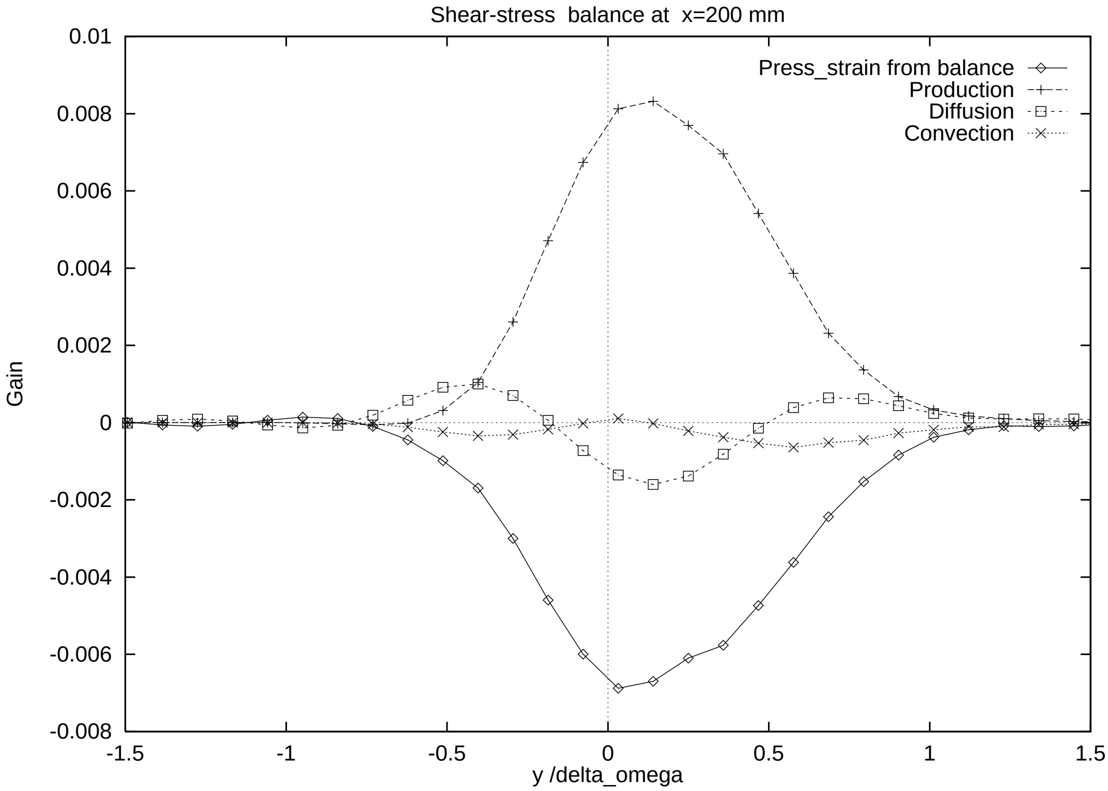


Figure 5.9: Shear-stress balance at $X = 200$mm

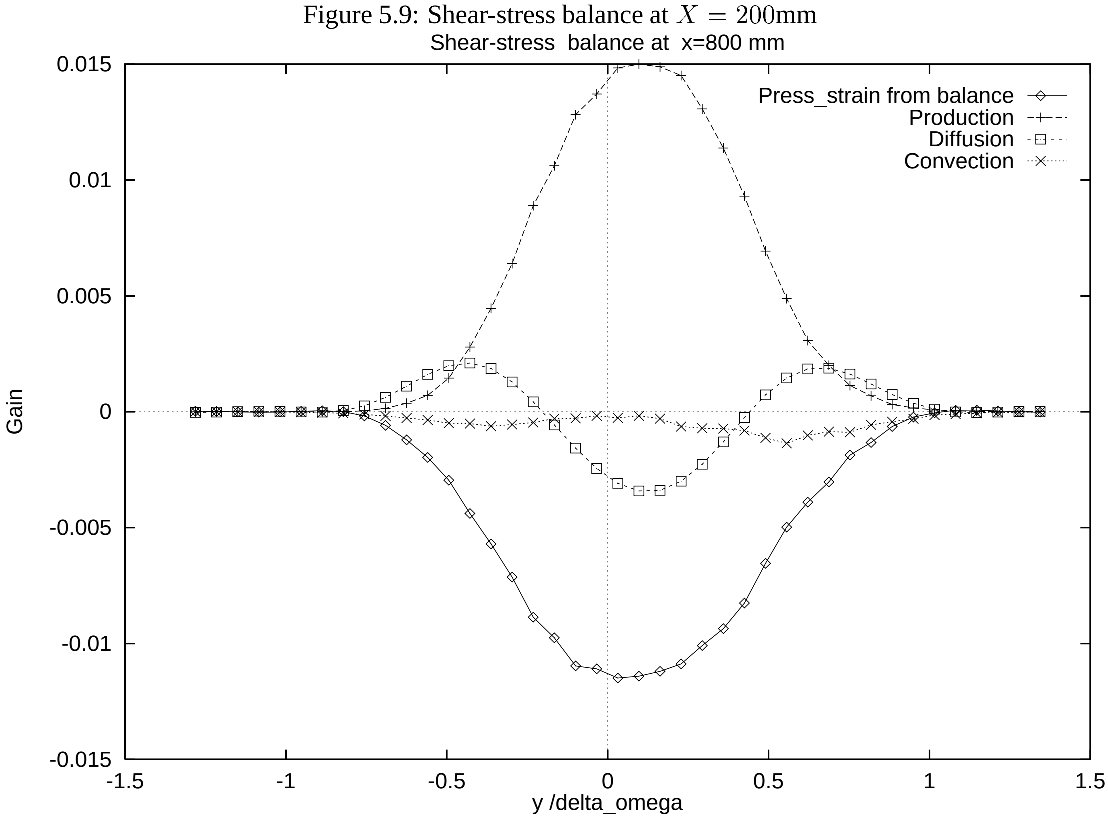


Figure 5.10: Shear-stress balance at $X = 800$mm

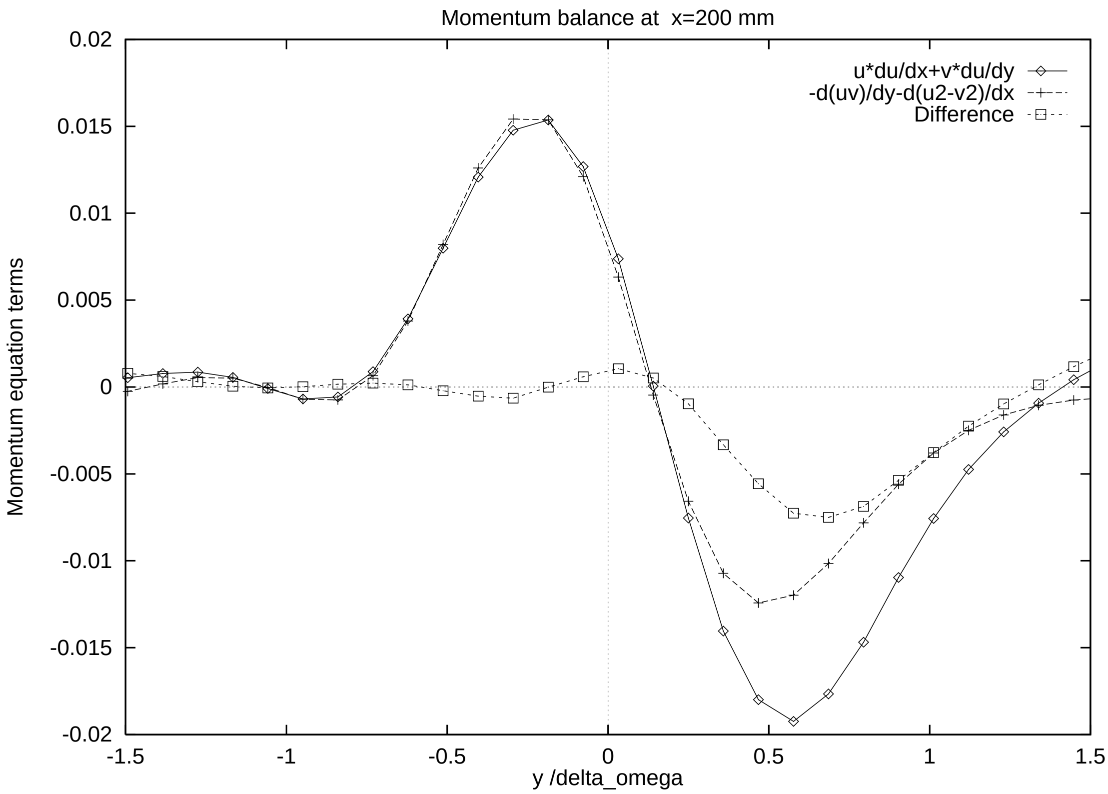


Figure 5.11: Momentum balance at $X = 200$mm

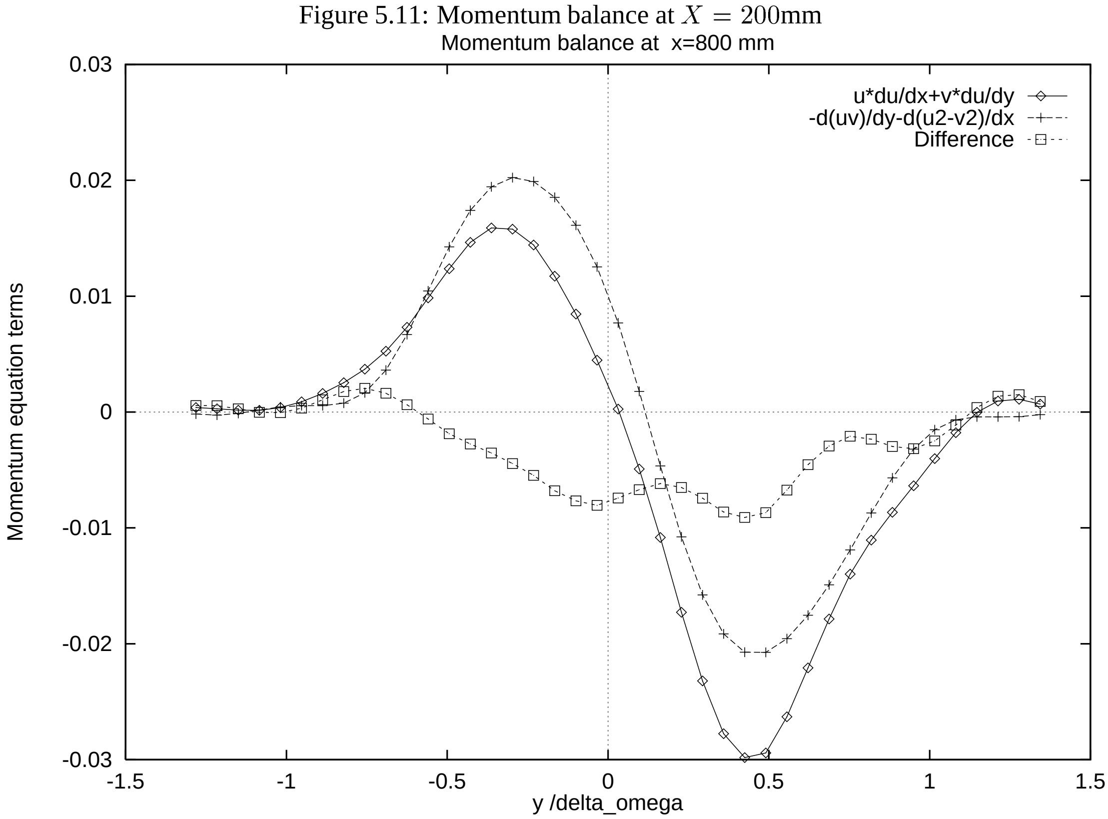


Figure 5.12: Momentum balance at $X = 800$mm

Bibliography

[1] DELVILLE, J., BELLIN, S., GAREM, J.H. & BONNET J.P. 1988 Analysis of structures in a turbulent a turbulent plane mixing layer by use of a pseudo-flow visualization method based hot-wire anemometry. *Advances in Turbulence II*, Fernholz and Fiedler eds., Springer, pp 251.

[2] DELVILLE J. 1995. La décomposition orthogonale aux valeurs propres et l'analyse de l'organisation tridimensionnelle des écoulements turbulents cisaillés libres. *Thèse Doctorat*, Université de Poitiers.

Appendix A

Characteristic quantities for the mixing layer

U_a	=	41.54 m/s
U_b	=	22.40 m/s
$\Delta U = U_a - U_b$	=	19.14 m/s
X_0	=	-97.10 mm
Y_0	=	-0.14 mm
$\partial\theta/\partial x$	=	9.482 10^{-3}
$\partial\delta_\omega/\partial x$	=	4.995 10^{-2}
$\sigma = \sqrt{\pi}/(\partial\delta_\omega/\partial x)$	=	35.48

X mm	δ_ω mm	θ mm
40.0	8.2349	2.11
50.0	8.8583	2.30
70.0	9.4703	2.28
100.0	10.833	2.58
130.0	12.100	2.79
170.0	13.958	3.14
200.0	13.771	3.17
250.0	15.827	3.51
300.0	18.577	4.11
350.0	20.822	4.51
400.0	23.148	4.93
450.0	25.124	5.55
500.0	27.429	5.90
550.0	30.730	6.61
600.0	33.100	7.00
650.0	35.894	7.74
725.0	40.059	8.43
750.0	40.895	8.62
800.0	42.687	8.88
850.0	44.780	9.45
900.0	48.302	10.18
950.0	50.547	10.55
1000.0	54.395	11.26