Combined Planar Measurements of Flow Velocity and Mass Concentration in Shallow Turbulent Flow
Part 1: Development of a Planar Concentration Analysis (PCA) System

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Abstract : For the experimental investigation of the transfer of mass concentrations in shallow turbulent flows an time/cost efficient and easy-to-use measuring technique will be presented. The Planar Concentration Analysis (PCA) technique allows to evaluate the depth-averaged concentration of a soluble conservative tracer, namely food coloring. Since PCA is based on video image analysis, the spatial and temporal resolution is high, depending on the optical components and on the digitalisation and storage capacity. Details will be given to the algorithm for the conversion of light intensity to concentration, which also accounts for the non-linear relation. This extension significantly increases the measurement range for mass concentrations.

Finally the PCA system will be applied to the spreading of a tracer plume for a continuous point-source in a shallow turbulent laterally unbounded flow.

Introduction

Due to the large length-to-width ratio of horizontally sheared shallow turbulent flows, the transport equations can often be simplified using 2D depth-averaging. In order to observe depth-averaged concentration fields, we developed a Planar Concentration Analysis (PCA) system based on video image analysis. The concentration of dye, introduced into the flow as a soluble tracer, is evaluated using a video image analysis algorithm, which accounts for non-linear light attenuation.

PCA is a planar non-intrusive measurement system which belongs to the class of scalar measurement systems. Other planar non-intrusive measurement systems are PLIF and remote sensing (scalar) or PIV (non-scalar). Measurement systems for scalar quantities are methods for measuring e.g. mass concentration, temperature, conductivity or pH-value.

Experimental setup and measurement technique

Experiments were made in a shallow water basin with horizontal dimensions of 13.5 x 5.5 m and a regular water depth of a few centimeters (Fig. 1). The water flow is provided by a system of tubes and a smoothly adjustable pump which is controlled by a frequency converter. The flow rate is measured by a magnetic-inductive flow meter, installed inside the tube system, the water depth is observed with a set of ultrasonic probes. The experimental equipment is controlled by FLAMES, a process control software using LabView.

Four photo headlights each with 1000 Watt are set up outside the basin to get a good illumination of the observation field. To improve this four-point-illumination a light diffuser of cotton fabric is used (see Fig. 1b). The main benefit of it is to get an uniform distribution of the illumination, reducing shadows behind obstacles in the water flow and minimising reflections on the water surface. Through the upper aperture of the light diffuser a video camera observes a measurement area of 1.4 m x 1.0 m from above.

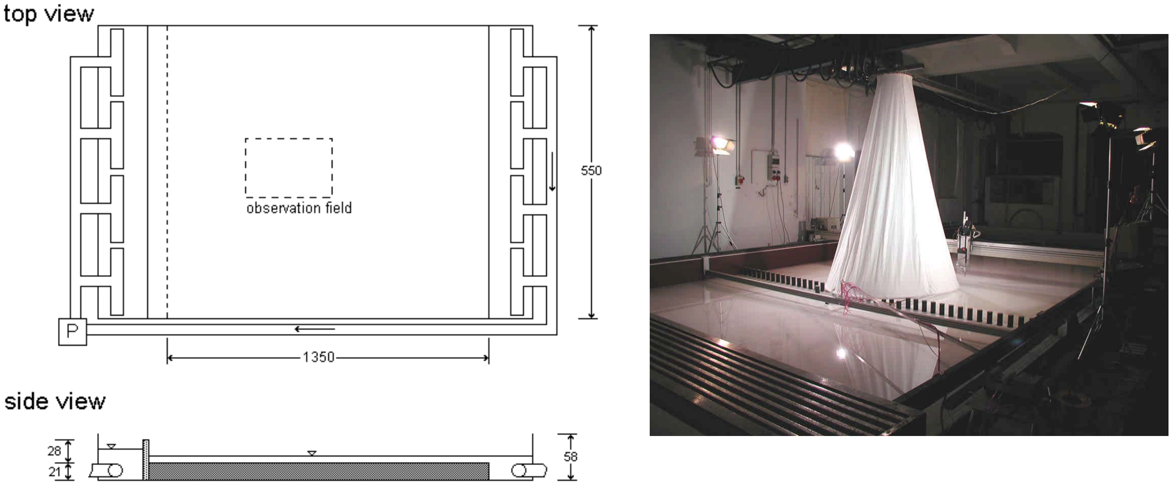

Fig 1: a) top view and side view of the shallow water basin with the observation area; P = pump; b) view of shallow water basin from upstream with light diffuser, four photo headlights, tracer injection device and a row of cylinders to get a higher, grid generated turbulence

A digital CCD camera (Siemens SICOLOR C810) is positioned perpendicular to the water surface recording the intensity images. The camera has a pixel resolution of 768 x 576 and a color depth of 3 x 8 bit (red-green-blue), the signal-to-noise ratio is $\geq 46\,dB$. The camera operates in European Video Standard (PAL) with a frame rate of 25 Hz. For a later digitalisation and for storage conservation the video signal is recorded to a digital video tape (Mini-DV®) using a Mini-DV-recorder (Sony GV-D 900 E). For the transfer of the image data from tape into a PC system a digital video card “Studio DV” (Pinnacle Systems) is in use. The connection is FireWire or IEEE-1394 which as a digital connection works without any loss. The output of the employed software “Studio 7” is a digital video AVI-file with a resolution of 720 x 576 pixel. This AVI-file is cut into single pictures by MainActor. The last step of the digitalisation is to convert the coloured images into greyscaled ones using an image editing software with batch conversion (Ulead Photo Impact). So, raw images (8-bit greyscale, 720 x 576 pixels) in a standard image file format (BMP or TIFF), with no loss due to compression, are finally provided by the measuring system.

Converting light intensity to mass concentration

To get the mass concentration from the scattered light of the soluble dye a program using MATLAB® is developed. This program converts a greyscale image (intensity) into the relevant concentration with a transfer function. In this process, the intensity matrix (i.e. series of images) has to undergo several steps of digital image processing to improve the quality of the image data. A linear 2D - averaging filter is applied to get spatial averaging (cf. JÄHNE 1991). This is necessary due to the high signal-to-noise ratio (see above). To save storing capacity the image data is scaled to a smaller matrix.

In order to calculate concentrations from intensity values, a calibration of the transfer function (see (1)) is needed. Therefore at least 20 images of different known concentrations are taken before each experiment. To get a statistical mean value for every element of the intensity matrix the images for the different concentrations are averaged in time. Due to the non-linear light attenuation at least four calibration steps to reproduce the curvature of the transfer function are needed.

To convert the given intensities into concentrations a fitting curve for the calibration points has to be found. Because the illumination is not completely uniform, every element of the intensity matrix has its own characteristic trait in curvature. So all coefficients of the transfer function have to be calculated for each element of the matrix. From optical grounds a functional relation between concentration c and intensity I is used:

$$I = f(c) = A + (Bc + C)e^{-Dhc} + Ec \tag{1}$$

where A, B, C, D and E = coefficients of transfer function; h = water depth; I = intensity matrix; c = concentration matrix.

The sum of coefficient A and C represents the light intensity when c=0. Coefficient A corresponds to saturation of dye which means no further scattering of incident light. The exponential term $exp(-Dhc)$ reflects the attenuation of incident light assuming a homogeneous concentration along the optical path. Coefficient D denotes the dye property of scattering incident light. Reflection at the water surface is embedded in Ec. Coefficient E stands for the reflectivity of the water surface and is introduced for a better curve fitting in the interesting range of the transfer function, i.e. concentrations lower than 50 mg/l.

From sensitivity analysis it turned out, that not all coefficients have to be calculated iteratively with this equation, but coefficient D and E can be excluded. For coefficient D an almost constant value for every element of the matrix appears to be appropriate. In case of E, representing mathematically the behaviour of the curve for infinite c (i.e. high concentration), the coefficient can directly be estimated from the slope between the values of the two highest concentrations.

For these estimates, only the coefficients A, B and C remain to be determined iteratively. The coefficient B yields a value of zero, unless the distribution of the calibration points is not at an optimum, thus it represents the error compensation. As an example for the described iteration, figure 2 shows the calibration points, the calculated transfer function and the related plot for a selected pixel.

So a matrix (size: 720 x 576 x 5), representing the calibrated transfer function, is generated including all of the five coefficients. Using this coefficient matrix, the system of transfer functions is solved iteratively for the full intensity matrix using Newton's tangent method

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \text{ with } f(x) = 0 \tag{2}$$

The distributions of the different concentrations can easily be calculated. To speed up this converging process, initial values will be determined with the following inverted transfer function:

$$c = \frac{\ln\left(\frac{I - A}{B}\right)}{C} \tag{3}$$

where A, B and C = coefficients of simple transfer function; I = intensity matrix; c = concentration matrix.

The resulting concentration matrix will be saved on hard disc in a MATLAB binary file format (*.mat). This matrix can be loaded for post processing.

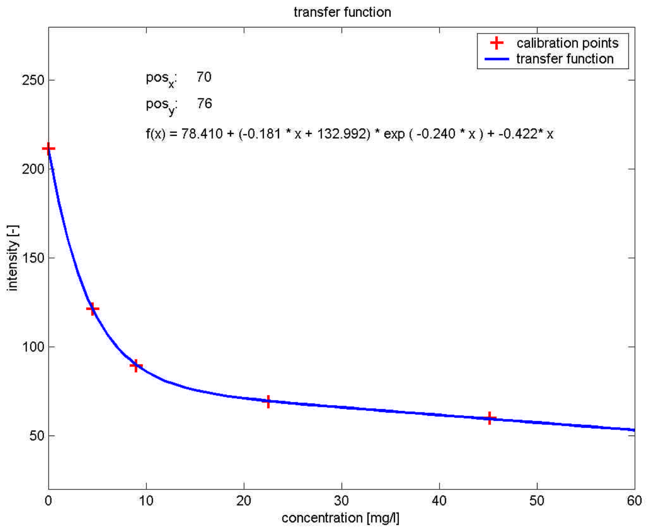

Fig 2: plot of measured calibration points (red crosses) for a single pixel, representing the different calibration levels, and the transfer function for the same pixel (blue line) adjusted iteratively to the calibration points.

Special attention is needed to get a uniform and time constant illumination. Therefore a reference frame inside the observation area is used. Comparing the mean value of intensity in this frame with the same frame in the calibration image ensures that fluctuations in illumination play no roll in evaluating the images. In case of a difference between these values, this difference has to be added or subtracted to all elements of the intensity matrix in the way that the experimental image is adapted to the calibration image.

In order to take into account the background concentration, a second reference frame is in use. This frame has to be located outside the dyed flow region, because tracer from the actual run must not be considered. In case of a background concentration from former experiments, its value has to be reduced from the concentration matrix after the conversion.

Calibration procedure of PCA

Basically the experiments are split-up in two parts. First, a set of calibration images from homogeneously coloured water body for different concentrations is taken in order to calibrate the non-linear transfer function, then the experiment itself is conducted.

For the calibration, a frame of transparent perspex is placed into the basin. This frame is larger than the observation field to avoid any shadow from the frame to influence the region of interest, observed by the camera. To pay special attention to the non-linear light attenuation at least four concentration steps have to be recorded (see above). To guarantee the same experimental conditions it is important that the experiment is done with the same water depth and illumination. During the experiment tracer is injected into the flow as a continuous single point source at mid-depth with a peristaltic pump either directly with a thin brass tube (inner diameter 1 mm) or from the shoulder of an obstacle.

As a tracer material, food dye (Amaranth 85, E 123) is in use. This has a very intense red colour and provides a very stable aqueous solution, i.e. conservative and passive to the flow. No deposition or resorption of dye occurs during the experiments.

Application

As a test case, we applied the PCA procedure on a continuous plume to determine the turbulent transverse diffusion coefficient of the base flow in the shallow water basin.

Since we employ a depth-averaged measurement technique, we exclude the near-field, where fully vertically mixed conditions have not yet established, from our analysis. As the flow is very shallow (comparing depth to width) and thus laterally unbounded, the plumes does not spread over the whole width of the basin during the experiment. Therefore, the mass transport takes place in the mid-field of the plume. Following RUTHERFORD (1994), a good approximation for the beginning of the mid-field is 50 times the water depth downstream of the source.

The analytical mid-field solution of the depth-averaged governing advective-diffusion equation is

$$C(x,y)=\frac{q'}{\sqrt{4\pi\, xuD_t}}\exp\left[-\frac{uy^2}{4D_t x}\right] \tag{4}$$

where q' = time rate of mass injection per unit length; x,y = spatial coordinates; u = mean flow velocity in x-direction; D_t = transverse turbulent diffusion coefficient.

From semi-empirical grounds FISCHER ET AL. (1979) or RUTHERFORD (1994) reported the average transverse turbulent diffusion coefficient in a uniform channel to be

$$D_t = 0.15hu_* \tag{5}$$

where h = water depth; u_* = bottom shear velocity.

The accuracy of (5) is estimated to be $\pm 50\%$ for a straight rectangular open channel flow.

The experiment is conducted at a water depth of $h = 25mm$, a main flow velocity of $u = 0.16\,{}^{m}\!/\!_{s}$ and a Reynolds number of $\mathrm{Re}_h = 4000$. The Darcy-Weisbach bottom friction coefficient is $\lambda = 2c_f = 0.0142$.

Because of the small observation field it is necessary to repeat the experiment while observing three different downstream positions. These steps are evaluated separately and after that the concentration matrices are averaged in time and concatenated to one big matrix.

The centre line concentration C_C and the plume width $W_C = \sigma_C$ are calculated from the distribution of the time-mean concentration (see fig. 3). For the 2D-analytical model (4) the transverse distribution of the vertically well mixed tracer is assumed to be Gaussian. Therefore the concentration at the plume boundary $C(\pm\sigma_C)$ is

$$C(\pm\sigma_C) = 0.61C_C(x) \tag{6}$$

The relation between the plume width, standard deviation and the transverse turbulent diffusion coefficient is defined as

$$W_C = \sigma = \sqrt{2Dt} \tag{7}$$

With the characteristic time scale $t = \frac{x}{u}$, the transverse turbulent diffusion coefficient is given as

$$D_t = \frac{{W_C}^2 u}{2x} \tag{8}$$

With this procedure of evaluation the transverse turbulent diffusion coefficient is calculated to be

$$D_{t,\mathrm{exp.}} = 0.14hu_* \tag{9}$$

in the mid-field of the plume.

The transverse turbulent diffusion coefficient, obtained from the PCA system, corresponds remarkably well with literature (see above).

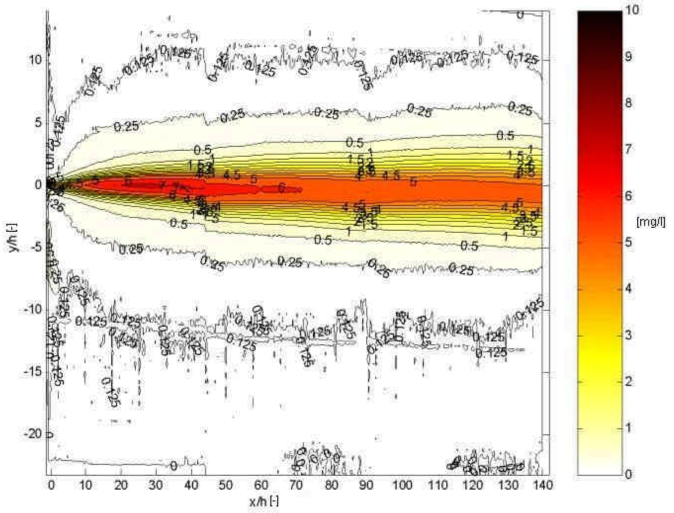

Fig 3: distribution of the time-mean concentration of a continuous plume in [$^{mg}/_{l}$], evaluated with the PCA system.

Conclusions

The Planar Concentration Analysis (PCA) technique provides a fast, low-cost and flexible tool to evaluate the transfer of depth-averaged mass concentrations in shallow turbulent flow. Because of its sensitivity to changes in the illumination, it is restricted to indoor laboratory investigations. The applicability was demonstrated for a continuous tracer release from a single point-source into shallow flow, a more sophisticated flow will be addressed in Part 2 of this paper (CARMER ET AL. 2002). Further improvement of the PCA system can be achieved by using a high-quality optical system (e.g. lower signal-to-noise ratio, higher colour depth, larger size of ccd chip) and by optimizing the digitalisation and storing of the video frames.

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