Turbulence at free surface in hydraulic jumps

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TURBULENCE AT FREE SURFACE IN HYDRAULIC JUMPS

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ABSTRACT

In the context of recent work by Brocchini & Peregrine [1,2], this paper aims to document free surface elevations, and free surface length scales in hydraulic jumps with Froude numbers between 1.98 and 4.82. Although information on bubble size, frequency and velocities in hydraulic jumps is available in the literature, there is not much data on the features of the free surface, or on mixing layer thickness. In the present case, measurements at the free surface have been realized with two miniature resistive wire gauges made of two parallel 50 micron diameter wires 1mm apart. These instruments were calibrated dynamically over a range of frequencies up to 20 Hz. Furthermore optical probes were used to measure properties of the air phase within the jump, including void fractions (up to 98%).

The present results extend the range of Froude numbers for which two-phase measurements in hydraulic jumps are available, and, in most respects, confirm earlier results obtained with different experimental techniques. Length scales at the free surface are deduced from cross-correlation analysis of wire gauge measurements, and are compared with similar data obtained from images of the surface.

INTRODUCTION

Hydraulic jumps often occur in open channels when the transition from a super-critical to a sub-critical flow is reached. It is then characterized by a strong free surface motion leading to air entrainment. The same process is important in a number of situations and applications, notably in the air-sea exchange of mass, momentum and heat. Indeed on the upper ocean, this mechanism has a major influence on the regulation of the global environment. It is then relevant to investigate how the processes involved in this particular multi-phase flow are affected by turbulence, bubble features, free-surface and their interactions.

Previous studies were mainly performed with Pitot tubes and conductivity probes (Chanson, [3]), Laser Doppler Velocimetry (Waniewski et al., [4]), or Acoustic Doppler Velocimetry (Liu et al., [5]). Intrusive probes clearly suffer the disadvantage that they could affect the flow, but the non-intrusive techniques (LDV and ADV) also face strong technical limitations in such aerated conditions.

The goal of this paper is to present some properties (void fraction essentially) of the aerated flow in a hydraulic jump, obtained by an optical probe, and measurements of features of the free surface of the jump made by means of miniature resistive wires. The space delimitation of a mixing-layer will be deduced from the interpretation of the 'wire' and the 'optical' techniques. This work presents also a comparison of free surface length scales deduced either from correlation free surface measurements or from spectral image analysis of the hydraulic jump.

The investigations were performed for four different Froude numbers ($1.98 < Fr < 4.82$) in a partially-developed hydraulic jump.

EXPERIMENTAL SET-UP

Instrumentation and data processing

The experiments were conducted in a 12m long recirculating channel at the University of Southampton. The flow rate can be controlled by a regulating valve. The flume is 0.3m wide, 0.4m high and the roughness height of the flat bottom was measured at 0.3mm. The jump was generated by a sluice gate whose elevation above the channel bottom could be adjusted between 3cm to 9cm with in fixed steps of 1cm (Fig. 1a).

Figure 1b represents the sketch of the experiment, the position of the axis and the parameters definition. X_{foot} is defined as the mean position of the foot of the jump.

Void fraction measurements

Void fraction distributions were recorded using a dual-tip optical probe. The measurements rely on the optical detection of the change in the refractive indices between the phases air/water in a fibre optic. The probe consists of two sensitive tips with an external diameter of 10µm, and separated by 1mm. Data from each fibre was sampled at a rate up to 1MHz to provide measurements on void fractions. The data collection duration was set to 2 minutes.

The void fraction, C, is calculated as the ratio of the total of the time intervals during which air was detected τ_i to the whole measurement duration T:

$$C = \frac{\sum_{i=1}^{n} \tau_i}{T} \tag{1}$$

Free surface measurements

Free surface elevations were measured with resistive probes. Each probe consists of two wires of 50µm diameter, 1mm apart. A static calibration gives a direct relationship between the surface elevation and the output voltage from a wave monitor. A dynamic calibration of these wire gauges has been made with a vibrometer in order to estimate their frequency response. The results established a cut-off frequency (-3dB) of 12Hz which is quite reasonable considering previous studies. Liu et al. [6] found a cut-off frequency of 7Hz. During the hydraulic jump measurements 640 samples were collected at a rate of 128Hz.for each position,

The free surface turbulence length scales are determined from the correlation between the signals S_i coming from two wire gauges separated in the transverse direction. The separation, r, between the wire gauges was adjusted from 3mm to more than 100mm to follow the decrease of the correlation coefficient R_i :

$$R_i(AB = r) = \frac{\overline{s_{iA} \cdot s_{iB}}}{\sqrt{\overline{s_{iA}^2}}\sqrt{\overline{s_{iB}^2}}} \tag{2}$$

The free surface transverse length scale L_g is then defined by :

$$L_g = \int_0^{r_{max}} R_i(r)\, dr \tag{3}$$

where r_{max} is the distance r for which R_i fells to 0.

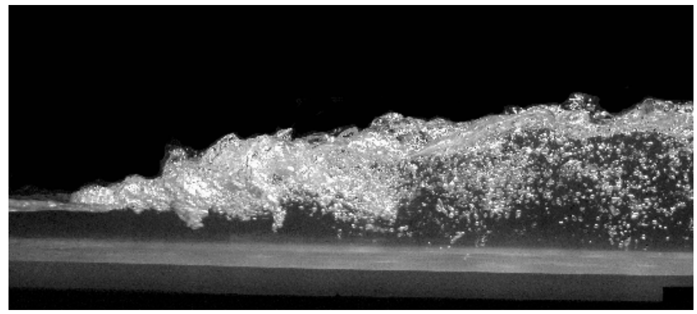

Fig. 1a) Hydraulic jump in the recirculating tank (Fr = 3.65)

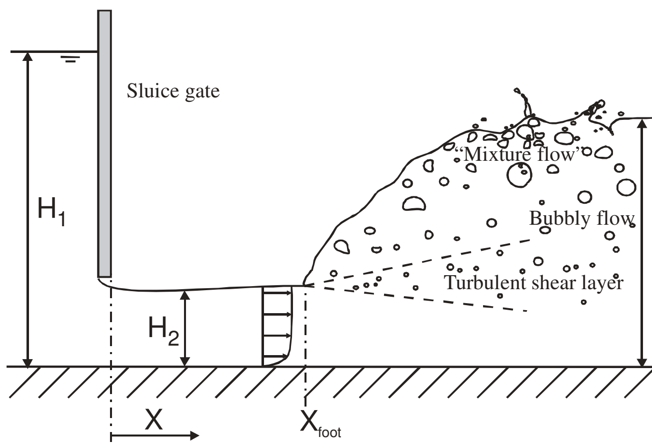

Fig. 1b) Sketch of the hydraulic jump set-up

Free surface visualization

A high speed monochrome camera has been used to record the water surface of the hydraulic jump. The video acquisition rate was 120 frames per second at a frame size of 648 x 484 pixels. For each flow condition, the images were collected over 2 to 4 seconds. The grey levels (256) of a transverse scanning line (over 500 pixels) were collected using the Matlab image processing toolbox (Fig. 2). The grey levels along this line were recorded in a matrix for all the images. A one-dimensional wavenumber spectrum was calculated for each image. An averaged spectrum of the whole image set exhibits a serie of 3 to 4 peaks which identify the characteristic wavelengths of the flow. These length scales will be compared with the free surface length scales obtained by the wire gauge correlation technique.

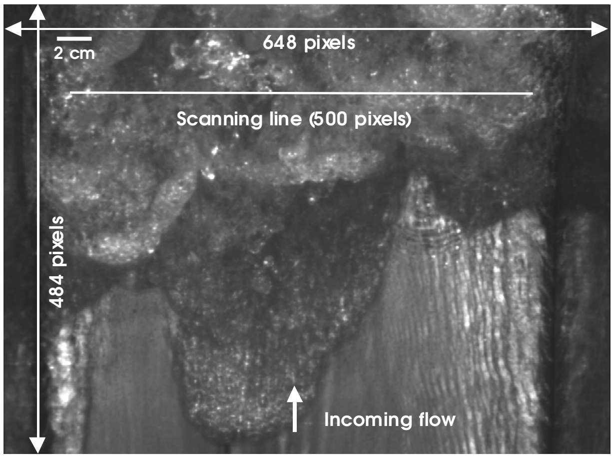

Fig.2 Scanning line position

Experimental conditions

The incident velocity U upstream of the foot of the jump and the Froude number (Fr) were estimated from the measurements of the elevations H_2 and H_3:

$$\frac{H_3}{H_2} = -\frac{1}{2} + \sqrt{\frac{1}{4} + 2Fr^2} \tag{4}$$

and $$Fr = \frac{U}{\sqrt{gH_2}} \tag{5}$$

Four set of experiments are presented in this paper, characterized by four different Froude numbers. The following table presents the flow conditions:

Test	H_1(m)	H_2(m)	H_3(m)	U (m/s)	Fr
1	0.186	0.059	0.138	1.50	1.98
2	0.200	0.046	0.137	1.64	2.43
3	0.280	0.032	0.150	2.05	3.65
4	0.320	0.021	0.133	2.19	4.82

Table 1. Experimental conditions

EXPERIMENTAL RESULTS

The experiments were performed for a maximum incident velocity U of 2.19m/s. An estimate of the bed boundary layer at the foot of the jump suggested a maximum thickness of $0.36H_2$. Hence the hydraulic jump can be considered as partially-developed for all flow conditions.

Void fraction measurements

Air entrainment at the foot of the jump leads to the creation of bubbles. The distribution of air in the jump, obtained from the optical fibre probes, can be plotted against the elevation z at different positions downstream of the foot, as shown in Fig. 3.

In the turbulent shear region, Chanson and Brattberg [7] approximated the void fraction C through the solution of a diffusion equation:

$$C = C_{\max} \exp\left[-\frac{1}{4} \frac{UH_2}{D_t} \frac{(z/H_2 - z_{C_{\max}}/H_2)^2}{(x - x_{foot})/H_2} \right] \tag{6}$$

for $\frac{z}{z_{shear}} < 1$, and where C reaches a maximum C_{max} at the position (x, z_{Cmax}).

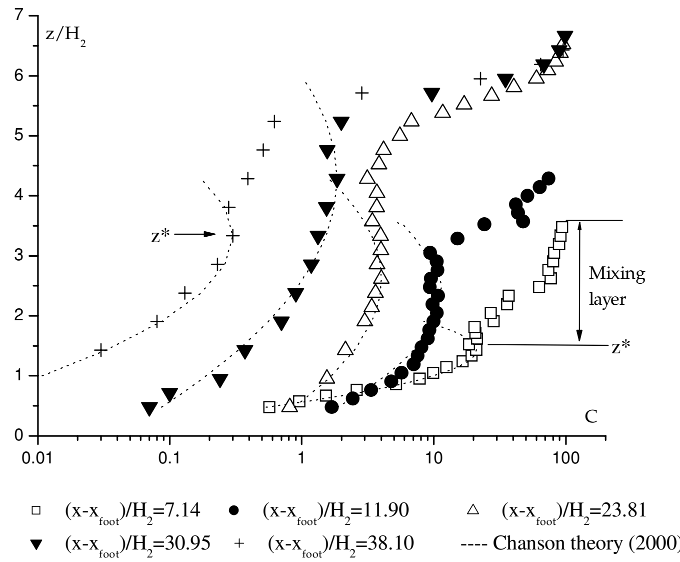

Fig.3 Void fraction profiles (Fr = 4.82)

The void fraction profiles show clearly two distinctive regions. In the lower region (including the turbulent shear layer), the bubbles are relatively small and round. Furthermore the void fraction profiles follow the expression of C established by Chanson and Brattberg [7]. At a certain elevation z^*, the void fraction distribution diverges from Eq. (6) as the flow at higher elevations is dominated by the interface (roller region). In this region, the flow is not only bubbly but also contains a mixture of splashes, droplets and air inclusions (see Fig.1b). In this region, the void fraction is found to follow an error function distribution [8]. The region between z* and the highest air concentration measurements (C~98%) is defined as a 'mixing layer' (Fig. 3). The next section presents the dimension and position of the mixing layer superimposed to the free surface profiles along the jump.

Free surface measurements

Time averaged free surface elevations (η) and their standard deviations (η') are plotted against streamwise position relative to that of the foot of the jump $(x\text{-}x_{\text{foot}})/H_2$ on Fig. 4 and on Fig. 5.

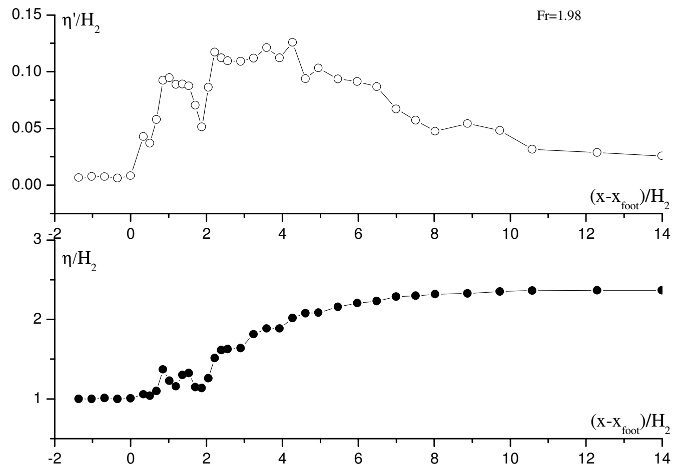

Fig. 4 Free surface and fluctuations profile for Fr=1.98

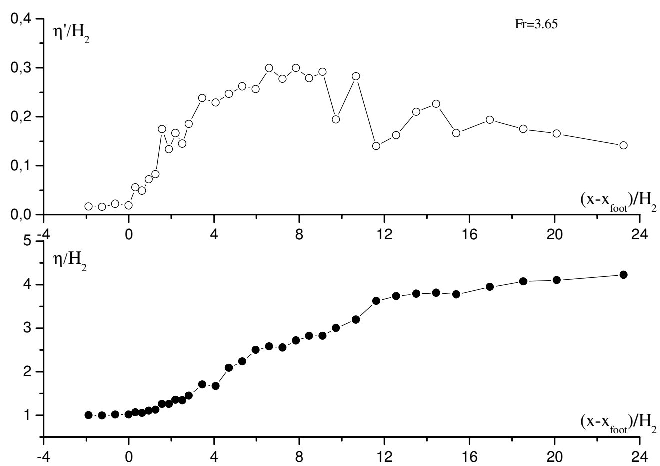

Fig. 5 Free surface and fluctuations profile for Fr=3.65

These plots show three distinctive regions according to $(x - x_{\text{foot}})/H_2$:

Upstream of the foot of the jump, the free surface is flat and there is no visible sign of turbulence.

At the position of the foot $((x\text{-}x_{\text{foot}})/H_2 = 0)$, the free surface profile is growing slightly while the fluctuations profile shows a sudden strong gradient revealing the formation of the jump. The fluctuations reach a maximum and reveal an area of intensive turbulence. The bubbles generated at the foot of the jump are entrained in the shear layer and in the roller, which is characterized by large recirculation vortices. Coherent structures, reaching the free surface, are revealed by the undulations of the free surface plots and strong variations of η'. The length of this intensive turbulent area represents 25% to 30% of the total length of the jump.

Lastly, a large dissipative zone takes place downstream as the free surface fluctuations decrease quickly and as the free surface elevation approaches the horizontal.

Mixing layer

The previous measurements (of void fraction and free surface elevations) allow us to identify and to quantify a mixing layer. z* is taken as the lower part of this mixing layer and the position where C=98 % is defined as its upper limit. The position and thickness of the mixing layer are presented in Fig. 6 along the axis *x* for all the test conditions.

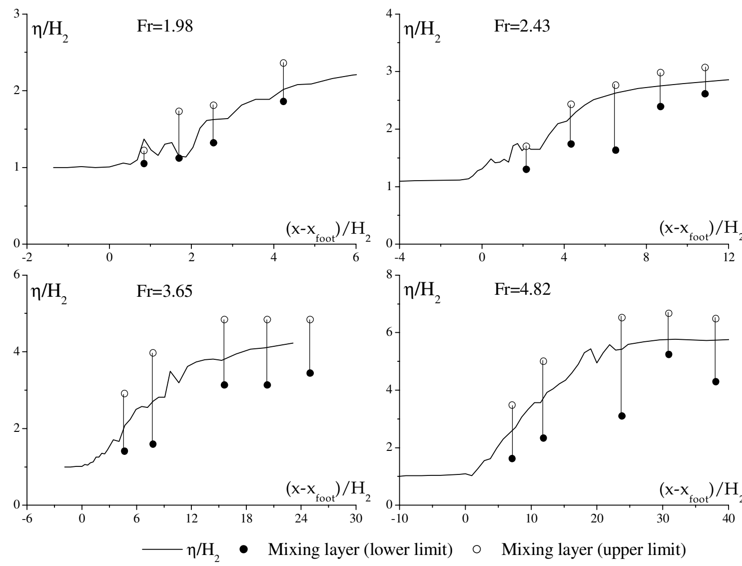

Fig. 6 Mixing layer thickness

For all test conditions, the mixing layer increases from a zero value at the foot of the jump to a maximum value inside the ‘roller area’, and then decreases slightly downstream to the jump.

According to the free surface measurements, the position where the thickness of the mixing layer is maximum corresponds to the area where large eddies are reaching the interface. In that place, the large undulations of the free surface and the steep gradients of the turbulent fluctuations are generating a large growth of splashes and air inclusions inside the jump.

Free surface length scales

The following plots show a superposition of the free surface length scale estimations deduced either from the wire gauge measurements or from the video analysis.

The transverse length scale L_g grows linearly with distance downstream from the foot of the jump (Fig. 7). As the behavior of L_g does not show any obvious dependence with the Froude number, the length scale is mostly governed by the upstream water depth H_2.

For the same position $(x\text{-}x_{foot})/H_2$, each cross sign on Fig. 7 refers to a peak revealed by the video spectral analysis (see the section above on Experimental set-up).

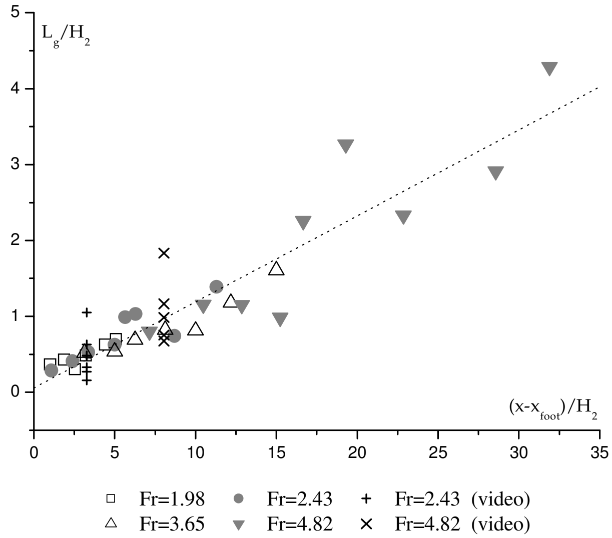

Fig.7 Transverse free surface length scales

The calculations of L_g based on the integral of the cross-correlation coefficient R_i provides only one measure of the surface roughness scale over the whole acquisition duration at each position (120s). The video analysis gives a range of scales over a very short time, but the averaged results presented in Fig. 7 show a reasonable agreement with those obtained from the correlation technique.

CONCLUSION

Most previous studies in hydraulic jumps have been performed with intrusive techniques which are not necessarily well suited to aerated flow, and with which they could possibly interfere. Though it is also intrusive, the dual-tip optical probe provides an attractive technique for studying a bubbly flow thanks to its microscopic dimensions. In that context, the main objective of this work was to study the void fraction behavior in a hydraulic jump at low Froude numbers, as well as the surface properties in terms of mean/fluctuations profiles and characteristic length scales.

Concerning the void fraction measurements, the results show a good agreement in the lower part of the jump with the expression established by Chanson and Brattberg [7]. In the upper part of the aerated flow, the interface influences strongly the void fraction profiles which then follow a different distribution. The intersection of these profiles defines the limit of a mixing layer whose thickness has been quantified. The position where the mixing layer is the thickest corresponds to the area where large structures reach the interface.

The free surface elevations and turbulent fluctuations show three distinctive regions along the jump, including the region just downstream of the foot (high level of turbulence).

Free surface length scales obtained from wire gauges were in reasonable agreement with those computed from a series of images of the water surface made by high speed video from above.

Understanding the properties of the free surface turbulence is still a challenging topic. Therefore this study has been extended to the case of a jet flow beneath a free surface. Knowledge on the role of the surface tension, salinity or scale effects is still needed.

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NOMENCLATURE

ADV	Acoustic Doppler Velocimetry
C	Void fraction
D_t	Diffusion coefficient in the shear layer
Fr	Froude number
LDV	Laser Doppler Velocimetry
L_g	Free surface length scale (transversal)
r	Separation between the two wire gauges
R_i	Free surface correlation coefficient
S_i	Signal from the wire gauge
T	Total measurement duration
τ_i	Duration of the air phase
U	Incident velocity
X_{foot}	Mean position of the jump's foot
z_{Cmax}	Position where C reaches a maximum
z_{shear}	Upper limit of the turbulent shear region
z^*	Lower limit of the mixing layer

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