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Total pressure fluctuations and two-phase flow turbulence in self-aerated stepped chute flows

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ABSTRACT

Current knowledge in high-velocity self-aerated flows continues to rely upon physical modelling. Herein a miniature total pressure probe was successfully used in both clear-water and air-water flow regions of high-velocity open channel flows on a steep stepped channel. The measurements were conducted in a large size facility (θ=45°, h=0.1 m, W=0.985 m) and they were complemented by detailed clear-water and air-water flow measurements using a Prandtl-Pitot tube and dual-tip phase-detection probe respectively in both developing and fully-developed flow regions for Reynolds numbers within 3.3×10^5 to 8.7×10^5. Upstream of the inception point of free-surface aeration, the clear-water developing flow was characterised by a developing turbulent boundary layer and an ideal-flow region above. The boundary layer flow presented large total pressure fluctuations and turbulence intensities, with distributions of turbulence intensity close to intermediate roughness flow data sets: i.e., intermediate between d-type and k-type. The total pressure measurements were validated in the highly-aerated turbulent shear region, since the total pressure predictions based upon simultaneously-measured void fraction and velocity data agreed well with experimental results recorded by the total pressure probe. The results demonstrated the suitability of miniature total pressure probe in both monophase and two-phase flows. Both interfacial and water phase turbulence intensities were recorded. Present findings indicated that the turbulence intensity in the water phase was smaller than the interfacial turbulence intensity.

1. Introduction

Dams and reservoirs are man-made hydraulic structures built across rivers and streams to provide water storage. During major rainfalls, the large inflows into a reservoir induce a rise in water level associated with the risk of dam overtopping, unless a spillway system is designed. Most dams are equipped with an overflow system, consisting of a crest, a steep chute and a downstream energy dissipator [31,37,46]. On the steep chute, the flow is accelerated by gravity and a turbulent boundary layer develops at the upstream end. When the outer edge of the boundary layer interacts with the free-surface, the turbulent shear stresses next to the air-water interface may overcome both the surface tension and buoyancy effects, and free-surface aeration takes place [14,24]. This location is called the inception point of free-surface aeration [34,49]. Fig. 1 illustrates the overflow down a steep chute, and the inception point of free-surface aeration is clearly seen in Figs. 1A and B. Downstream self-aeration is commonly observed and the process is called 'white waters' [7,23,43,48] (Fig. 1). The physical processes are basically identical for smooth-invert and stepped spillways, although the latters are characterised by a greater rate of energy dissipation [11].

Current knowledge in high-velocity self-aerated flows relies heavily upon physical modelling and measurements, because of the large number of relevant equations and parameters [5,22,30]. Traditional monophase flow metrology may be used in the developing flow region, although velocity measurements are difficult close to the free-surface [1,36,38]. Accurate measurements in the air-water flow region rely upon intrusive phase-detection probes and hot-film probes. Review papers include Cain and Wood [8], Chanson [13], Chang et al. [10] and Chanson and Carosi [15].

In the present study, it is shown that a miniature total pressure probe may provide detailed informations in both clear-water and air-water flow regions. The metrology was applied to high-velocity open channel flows on a steep stepped channel. The measurements were conducted in a large size facility (θ=45°, h=0.1 m, W=0.985 m) in which detailed turbulent flow properties were recorded systematically in both developing and fully-developed flow regions for several discharges, corresponding to Reynolds numbers within 3.3×10^5 to 8.7×10^5.

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Nomenclature

C	time-averaged void fraction defined as the volume of air per unit volume of air and water;
D_H	hydraulic diameter (m) also called equivalent pipe diameter;
d	clear water flow depth (m) measured normal to the pseudo-bottom formed by the step edges;
d_c	critical flow depth (m) : $d_c = \sqrt[3]{Q^2/(g\ W^2)}$;
F	bubble count rate (Hz) or bubble frequency defined as the number of detected air bubbles per unit time;
g	gravity constant: g=9.80 m/s^2 in Brisbane, Australia;
H_1	upstream head above crest (m);
h	vertical step height (m);
L_{xx}	air-water advection integral length scale (m): $L_{xx}=V_x T_{xx}$;
$(L_{xx})_{max}$	maximum advection air-water length scale (m) in a cross-section;
k_s	step cavity roughness height (m): $k_s = h \times \cos\theta$;
k_s'	equivalent sand roughness height (m);
L_{crest}	crest length (m);
l	horizontal step length (m);
N	power law exponent;
P_k	kinetic pressure (Pa);
P_s	static pressure (Pa);
P_t	total pressure (Pa): $P_t=P_k+P_s$;
p_k	kinetic pressure fluctuation (Pa);
p_s	static pressure fluctuation (Pa);
p_t	total pressure fluctuation (Pa);
$\overline{p_k^2}$	variance of kinetic pressure (Pa^2);
$\overline{p_s^2}$	variance of static pressure (Pa^2);
$\overline{p_t^2}$	variance of total pressure (Pa^2);
Q	water discharge (m^3/s);
Re	Reynolds number defined in terms of the hydraulic diameter;
R_{xx}	normalised auto-correlation function;
r_{pu}	correlation between static pressure and streamwise velocity fluctuations: $r_{pu} = \overline{p_s\,v_x}/\left(\sqrt{\overline{v_x^2}}\sqrt{\overline{p_s^2}}\right)$
Tu	interfacial turbulence intensity: $Tu = \sqrt{\overline{v_{aw}^2}}/V_{aw}$;
Tu_p	turbulence intensity in the water phase defined as: $Tu_p = \sqrt{\overline{v_x^2}}/V_x$;
T_X	integral turbulent time scale (s) characterising large eddies advecting the air bubbles;
T_{xx}	auto-correlation time scale (s): $T_{xx} = \int_0^{t_{Rxx=0}} R_{xx}(t)\,dt$
t	time lag (s);
V_{aw}	interfacial velocity (m/s);
V_c	critical flow velocity (m/s);
V_x	streamwise velocity component in water phase (m/s);
V_{90}	characteristic interfacial velocity (m/s) where C=0.90;
v_{aw}	fluctuation of interfacial velocity (m/s);
v_x	fluctuation of streamwise velocity component in water phase (m/s);
$\overline{v_{aw}^2}$	variance of longitudinal component of interfacial velocity (m^2/s^2);
$\overline{v_x^2}$	variance of longitudinal component of water phase velocity (m^2/s^2);
W	channel width (m);
x	distance along the channel bottom (m);
Y_{90}	characteristic depth (m) where the void fraction is 90%;
y	distance (m) measured normal to the invert (or channel bed);
z	transverse distance (m) from the channel centreline;

Greek symbols

δ	boundary layer thickness (m);
μ_w	water dynamic viscosity (Pa s);
θ	angle between the pseudo-bottom formed by the step edges and the horizontal;
ρ	density (kg/m^3);
ρ_w	water density (kg/m^3);
σ	surface tension between air and water (N/m);
τ	time lag (s);
$\varnothing$	diameter (m);

Subscript

aw	interfacial flow data;
p	total pressure data;
w	water properties;
xx	auto-correlation;
50	flow conditions where C=0.50;
90	flow conditions where C=0.90.

2. Physical modelling, experimental facility and instrumentation

2.1. Presentation

Steep chute flows are characterised by intense turbulence and interfacial interactions. Physical modelling is typically performed in a down-sized version of the prototype (Fig. 1). A full dynamic similarity is necessary for the laboratory model (Fig. 1B) to accurately predict a range of prototype characteristics (Fig. 1A). On a stepped chute, a simplistic dimensional analysis implies that the flow properties in the developing flow region must satisfy:

$$\frac{d}{d_c}, \frac{V_x}{V_c}, \frac{v_x}{V_c}, \frac{P_t}{\rho_w g\ d_c}, \frac{P_s}{\rho_w g\ d_c}, \frac{p_t}{\rho_w g\ d_c}\frac{p_s}{\rho_w g\ d_c}, \ldots = F_1\left(\frac{x}{d_c}, \frac{y}{d_c}, \frac{z}{d_c}, \frac{d_c}{h}, \frac{\rho_w V_x D_H}{\mu_w}, \frac{g\,\mu_w^4}{\rho\ \sigma^3}, \frac{W}{d_c}, \theta, \frac{k_s'}{d_c}, \ldots\right) \quad (1)$$

where d is the water depth, V_x is the mean streamwise water velocity, v_x is the streamwise water turbulent velocity fluctuation, P_t and p_t are the mean and fluctuating total pressure, P_s and p_s are the mean and fluctuating static pressure, g is the gravity constant, d_c is the critical depth: $d_c=(Q^2/(g\ W))^{1/3}$ with Q the water discharge and W the chute width, V_c is the critical velocity: $V_c=(g\ d_c)^{1/2}$, ρ_w is the water density, x, y and z are respectively the streamwise, normal and transverse coordinates, h is the step height, D_H is the hydraulic diameter, μ_w is the dynamic viscosity of water, σ is the surface tension of water, θ is the chute slope, and k_s' is the equivalent sand roughness of the step surface (Fig. 1C). In the fully-developed air-water flow region, dimensional analysis yields a different expression:

$$C, \frac{V_{aw}}{V_c}, \frac{v_{aw}}{V_c}, \frac{F\,d_c}{V_c}, \frac{P_t}{\rho_w g\ d_c}, \frac{P_s}{\rho_w g\ d_c}, \frac{p_t}{\rho_w g\ d_c}\frac{p_s}{\rho_w g\ d_c}, \ldots = F_2\left(\frac{x}{d_c}, \frac{y}{d_c}, \frac{z}{d_c}, \frac{d_c}{h}, \frac{\rho_w V_{aw} D_H}{\mu_w}, \frac{g\,\mu_w^4}{\rho\,\sigma^3}, \frac{W}{d_c}, \theta, \frac{k_s'}{d_c}, \ldots\right) \quad (2)$$