Experimental Thermal and Fluid Science 83 (2017) 19–36

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Scale effects in microscopic air-water flow properties in high-velocity free-surface flows

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ARTICLE INFO

Article history:
Received 15 August 2016
Received in revised form 9 December 2016
Accepted 11 December 2016
Available online 16 December 2016

Keywords:
Scale effects
Air-water flow properties
Chord sizes
Cluster properties
Interparticle arrival time
Stepped spillway

ABSTRACT

Experiments of high-velocity air-water flows were conducted on two scaled stepped spillways with step heights of h = 0.05 and 0.1 m to investigate scale effects in terms of air-water flow properties for a wide range of discharges in transition and skimming flows. The investigation comprised the complete range of macroscopic and microscopic two-phase flow properties including basic air-water flow parameters, interfacial turbulence properties, as well as cluster properties based upon the near-wake criterion and interparticle arrival time. For both undistorted Froude and Reynolds similitudes, the comparative analysis highlighted scale effects in terms of several gas-liquid flow properties, demonstrating that an extrapolation to full-scale prototype conditions may not be possible. These properties comprised the interfacial area, the turbulence properties and the particle sizes and grouping, affecting any scaling of air-water mass transfer processes. Other key air-water parameters were scaled accurately including the void fraction, interfacial velocity and flow bulking. The present investigation was the most comprehensive to date providing clear guidance on air-water flow properties which may be affected by scale effects. The present results may be also applicable to other types of air-water flows. However detailed testing of air-water flow properties at the prototype scale is needed for final confirmation.

1. Introduction

With the development of faster computers the interest in numerical modelling in hydraulic engineering and fluid mechanics increased significantly. While a number of complex turbulent flow processes can be computed today, the numerical modelling of stepped spillway flows is still in its infancy despite first attempts [21,35,6,41]. Successful physical experimental studies have led to a better knowledge of stepped spillway flows and physical modelling is still the most reliable means to enhance the understanding of the micro- and macroscopic air-water flow properties and its complex interactions (Fig. 1). Stepped spillway experiments are performed with a geometric scaling ratio of the prototype stepped chute trying to reproduce the air-water flows in laboratory which would occur at full-scale (e.g. Fig. 1A). A true dynamic similarity between laboratory and prototype is not possible unless working at full scale and scale effects must be considered. In particular the scaling of air-water flows is difficult and scale effects have been reported in a variety of air-water flows in hydraulic engineering applications [34,44].

Recently Heller [33] provided a literature overview about the scaling criteria and physical modelling approaches to minimise scale effects in hydraulic engineering. While the guideline provides basic advice, the developments in terms of air-water flow scaling were restricted to void fraction and interfacial velocity. Using these two parameters Boes [5] provided earlier limited guideline of maximal scaling proportion for stepped spillway flows based upon a Froude similitude (Appendix A). Appendix A lists a number of relevant experimental studies of scale effects in stepped spillway flows. Both the instrumentation and range of investigated parameters are listed in the last two columns. In air-water flows, viscous and gravity forces are important and the assessment of scale effects cannot be limited to void fraction and interfacial velocity only. Further air-water flow properties must be considered at the time scale of air-water flow interactions, rather than the time-averaged period. The general need for large size facilities in physical modelling of air-water flows and the limitations were emphasised recently [13,37]. Indeed the results of recent experimental investigations emphasised that the selection of the criteria to assess scale affects is critical [11,16,40]. These results showed that some parameters, such as bubble sizes and turbulent scales,

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http://dx.doi.org/10.1016/j.expthermflusci.2016.12.009
0894-1777/

(A) Prototype scale: Paradise dam, h= 0.62 m, θ = 57.4°, d_c/h = 2.85, q = 7.4 m^2/s, Re = 2.9×10^7 (Flow from top to bottom)

(B) Laboratory scale: Present study, h= 0.05 m, θ = 26.6°, d_c/h = 2.22, q = 0.116 m^2/s, Re = 4.6×10^5 (Flow from top to bottom)

Fig. 1. Air-water flows on stepped spillways.

are likely to be affected by scale effects, even in relatively large-size laboratory models (e.g. 2:1 to 3:1). These studies comprised aerated flows in hydraulic jumps [11,16,42] and air-water flows on stepped spillways [5,17,7,25,24]. No scale effect can only be observed at full scale, when using the same fluids in prototype and model.

The present investigation extends previous findings by analysing the full range of air-water flow properties in terms of scale effects for a broad range of discharges in transition and skimming flows. The particular focus is on the microscopic air-water flow properties. The aim of this manuscript is to provide general guidance for all available air-water flow properties where scale effects may be expected in both undistorted Froude and Reynolds similitudes. Among the investigated microscopic flow properties are interparticle arrival times and cluster properties. In a detailed comparison of cluster analysis criteria, the near-wake criterion was identified as the most suitable cluster criterion and the near-wake criterion was used for the analysis of scale effects in terms of a range of cluster properties. The present results provide a clearer guidance regarding which air-water flow properties may be affected by scale effects. The outcomes may be also applicable for other types of air-water free-surface flows such as hydraulic jumps, breaking waves and drop structures.

2. Physical modelling and experimental configurations

2.1. Dimensional considerations

High-velocity air-water flows are complex two-phase turbulent flows (Fig. 1). The gas-liquid flow motion is characterised by a significant number of parameters and properties describing the dynamic processes in the high-velocity flows including the fluid properties, physical constants, two-phase flow conditions, boundary conditions and initial flow properties. A dimensional analysis of the relevant parameters can identify the most relevant dimensionless properties and parameters, including Froude, Reynolds and Weber numbers, to achieve kinematic and dynamic similarities in a geometrically-similar stepped spillway flow. Considering a steady skimming flow down a rectangular prismatic stepped chute, a simplified dimensional analysis yields a series of relationships between the air-water flow properties at a location (x, y, z) and a number of relevant dimensionless numbers:

$$\begin{aligned}&\mathrm{C}, \mathrm{F}\times\frac{\mathrm{d_c}}{\mathrm{V_c}}, \frac{\mathrm{V}}{\sqrt{\mathrm{g}\times\mathrm{d_c}}}, \mathrm{Tu}, \mathrm{T_{int}}\times\sqrt{\frac{\mathrm{g}}{\mathrm{d_c}}}, \frac{\mathrm{L_{xz}}}{\mathrm{d_c}}, \mathrm{T_{xx}}\times\sqrt{\frac{\mathrm{g}}{\mathrm{d_c}}}, \mathrm{a}\\&\quad\times\mathrm{d_c}, \frac{\mathrm{d_{ab}}}{\mathrm{d_c}}, \frac{\mathrm{ch_{cl}}}{\mathrm{d_c}}, \mathrm{P_{cl}}, \mathrm{N_{cl}}, \mathrm{F_{cl}}\times\frac{\mathrm{d_c}}{\mathrm{V_c}}, \mathrm{t_{ipa}}\times\sqrt{\frac{\mathrm{g}}{\mathrm{d_c}}}, \ldots\\&\quad=\mathrm{f}\left(\frac{\mathrm{x}}{\mathrm{d_c}}, \frac{\mathrm{y}}{\mathrm{d_c}}, \frac{\mathrm{Z}}{\mathrm{d_c}}, \frac{\mathrm{d_c}}{\mathrm{h}}, \mathrm{Re}, \mathrm{Mo}, \theta, \mathrm{k}_s', \ldots\right)\end{aligned} \tag{1}$$

where C is the local void fraction, F is the bubble count rate, d_c and V_c are the critical flow depth and velocity respectively: $d_c = (q_w^2/g)^{1/3}$ with q_w the specific discharge and g the gravity acceleration and $V_c = (g \times q_w)^{1/3}$, V is the interfacial velocity, Tu is an air-water flow turbulence intensity, T_{int} is an integral turbulent time scale, L_{xz} is a turbulent length scale, T_{xx} is an auto-correlation time scale, a is the specific interface area, d_{ab} is a chord size of entrained particles, ch_{cl} is the average chord size of particles in clusters, P_{cl} is the percentage of particles in clusters, F_{cl} is the number of clusters per second, t_{ipa} is the interparticle arrival time, x, y and z are the longitudinal, normal and transverse directions respectively, h is the step height, Re is the Reynolds number defined in terms of the hydraulic diameter, Mo is the Morton number, θ is the chute slope and k_s' is the step surface roughness height. More details about the definition of the air-water flow properties in Eq. (1) can be found in Felder [24] and Felder and Chanson [27]. In Eq. (1), d_c/h is the dimensionless discharge proportional to a Froude number defined in terms of the step height since: $d_c/h = (q_w^2/(g \times h^3))^{1/3}$, and Mo is the Morton number: $Mo = g \times \mu^4/(\rho \times \sigma^3)$, with ρ and μ the water density and dynamic viscosity, and σ the surface