surfaces has been completed, and analysis is underway. The writer concurs with Novak's opinion that width may be more important than depth, and subsequent testing has been completed to define the importance of depth. Novak also suggests an approach to analysis of the chute aeration data presented. Some additional data is available, and his approach will be investigated.

Chanson offers numerous references for chute, weir, and multiple cascading aeration features. Many of these higher energy aeration features were initially considered (Houck et al. 1992) and rejected because of possible danger to recreational boaters. The writer thanks this discusser for reference to his recent publications.

TURBULENT OPEN-CHANNEL FLOWS: DROP-GENERATION AND SELF-AERATION[a]

Discussion by Hubert Chanson[2]

The author presented an original approach of the problem of self-aeration in a spillway chute. He should be congratulated for his challenging development. The work is helpful in gaining a better understanding of the spillway chute aeration. The discusser wishes to add further information for completeness. Important references are missing, and large-scale data were omitted.

BIBLIOGRAPHY

Self-aeration down open chutes has been investigated for nearly a century. The discusser retraced recently the historical development of this study (Chanson 1997a), highlighting in particular the significant contributions of three researchers and their teams: R. Ehrenberger in Austria, L. G. Straub in the United States, and I. R. Wood in New Zealand.

The bibliography on self-aerated flows is broader than suggested by the author. For example, some important progress was made in the 1980s, e.g., Kobus (1984) and Wood (1985). Recent comprehensive reviews include the books of Wood (1991) and Chanson (1997a).

SELF-AERATED FLOW STRUCTURE

Several large-scale experiments were performed with self-aerated chute flows (Table 1). The experimental results provide information that was not taken into account by the author, and are discussed below.

Downstream of the critical point (or the inception point of air entrainment), a dominant feature of high-velocity chute flow is the homogeneous nature of the air-water mixture. Between 0 and 90% of air content, the air-water flow properties (void fraction, mean velocity, air bubble frequency) exhibit smooth variations with distance from the invert (e.g., Chanson 1997b). There is no discontinuity between a "drops" region and a "bubbles" region, and the author's Fig. 1 could be misleading.

The discusser's experience with air-water flows suggests that self-aerated chute flows consist of a bubbly flow region for low air contents and a highly-aerated flow mixture for $C > 0.3–0.4$ [Fig. 3; Chanson (1997a)]. At large air contents, the air-water mixture consists of air-water projects and foam. Both air-water projections and foam structures are instantaneous structures, which constantly evolve in shapes and sizes.

Indeed, the concept of "free surface" is arbitrary in self-aerated chute flows. In clear-water flow, the air-water interface is well marked, and the free surface may be accurately measured with a pointer gauge. In self-aerated flow, the exact location of the interface between the flowing fluid and the above atmosphere becomes undetermined. Several researchers have proposed various criteria. Chanson (1997a) defined the interface between the air-water mixture flow and the atmosphere as the iso-air concentration line $C = 90\%$. The choice of 90% air content as the "free surface" can be justified, because it satisfies the continuity equation for water, as demonstrated by Cain (1978) and Chanson (1988). That is:

$$\frac{Q}{W} = \int_0^{Y_{C=0.9}} (1 - C)*V*dy \qquad (1)$$

where Q is known, and the air content and velocity are measured between $y = 0$ (invert) and the distance y normal to invert where $C = 0.9$.

EXPERIMENTAL DATA: MAXIMUM DROP HEIGHT

The discusser would like to add new information on maximum drop height observations. Recent experiments were performed in a large flume [Chanson (1997b); Table 1]. The char-

TABLE 1. Large-Scale Experiments in Self-Aerated Chute Flows

Reference (1)	Slope (degrees) (2)	U (m/s) (3)	h (m) (4)	$U*h/v$ (5)	Location (6)	Comments (7)
			(*a*) Prototypes			
Cain (1978)	45.0	15.6 to 18.5	0.126 to 0.191	2.2E + 6 to 3.2E + 6	Aviemore dam, New Zealand	Concrete spillway
			(*b*) Large models			
Chanson (1988)	52.3	8.8 to 12.4	0.021 to 0.034	2E + 5 to 5E + 5	Clyde model, New Zealand	Perspex flume, $W = 0.25$ m.
Arreguin and Echavez (1986)	0	14.9 to 24.1	0.14 to 0.23	1.3E + 6	Mexico Lab., Mexico	Galvanised tin, $W = 0.2$ m.
Xi (1988)	52.5	8.3 to 11.1	0.029 to 0.038	3E + 5	Meishan Hydraulic Lab., China	Timber, $W = 0.6$ m.
Chanson (1997b)	4.0	3.4 to 5.5	0.030 to 0.044	1.3E + 5 to 1.45E + 5	Univ. of Queensland, Australia	Painted timber, $W = 0.5$ m.

Note: W = channel width.

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[a] January 1998, Vol. 124, No. 1, by Martin Rein (Technical Note 12234).

[2] Sr. Lect. in Fluid Mech., Hydr., and Envir. Engrg., Dept. of Civ. Engrg., The Univ. of Queensland, Brisbane QLD 4072, Australia.

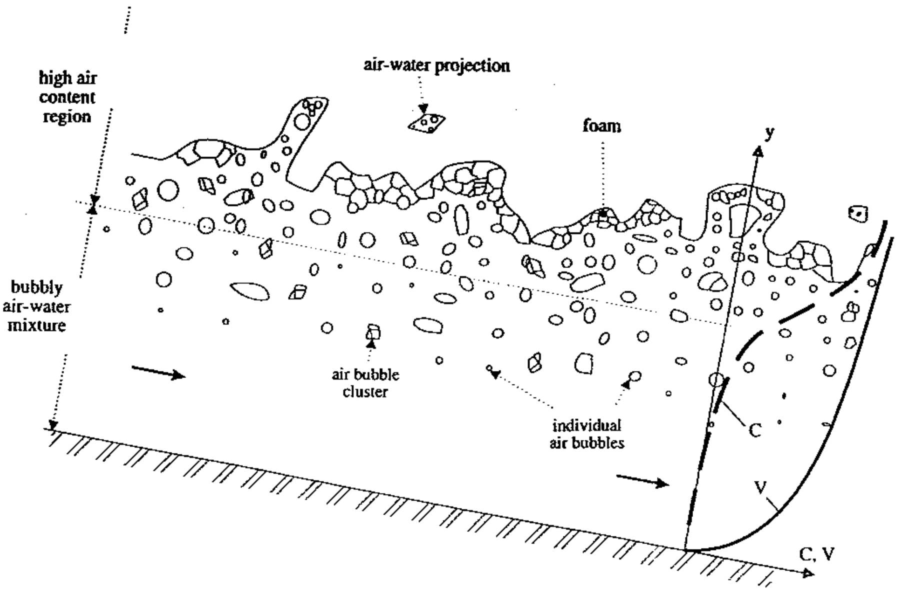

FIG. 3. Air-Water Flow Structures in Self-Aerated Chute Flows

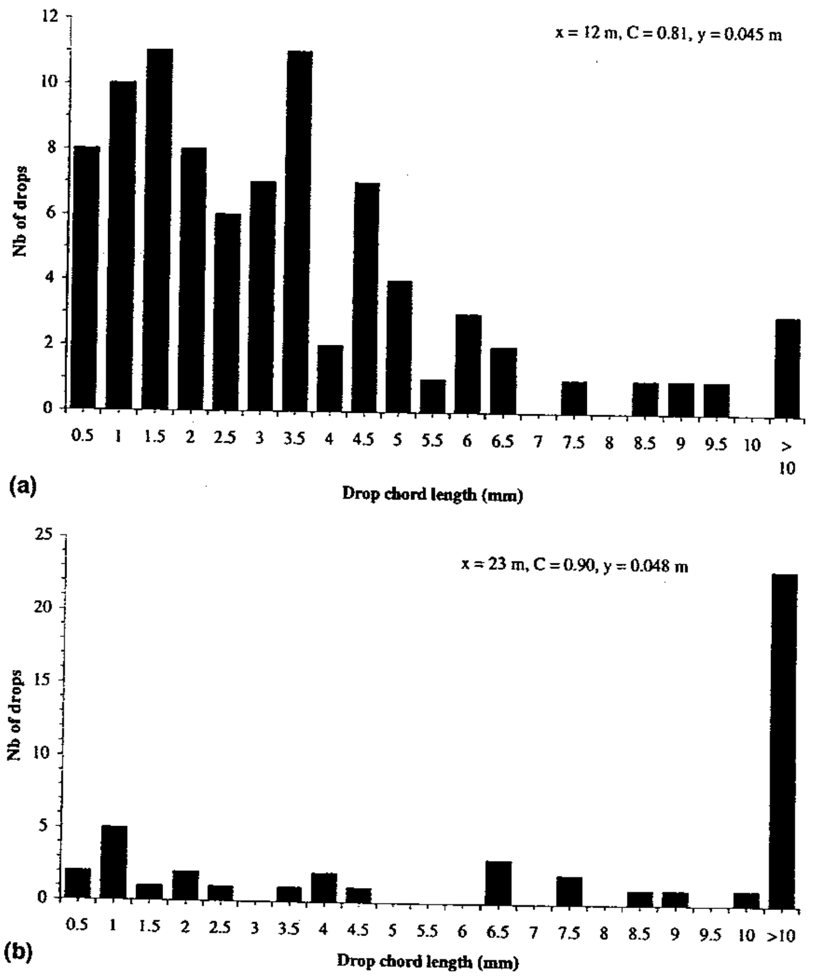

FIG. 4. Drop Chord Length Distributions (0.5 mm Drop Chord Length Intervals): (a) Flow Conditions: $x = 12$ m, $U = 3.56$ m/s, $y = 0.045$ m, $C = 0.81$, $V = 4.24$ m/s; Scanning Rate: 40 kHz; Duration: 1.638 s, 87 Water Drops; (b) Flow Conditions: $x = 23$ m, $U = 3.41$ m/s, $y = 0.048$ m, $C = 0.90$, $V = 3.76$ m/s; Scanning Rate: 40 kHz; Duration: 1.638 s, 46 Water Drops

acteristic flow velocity and flow depth were about 3.4–5.4 m/s and 30–44 mm, respectively. Droplet ejection heights were commonly observed to exceed 0.4 m (i.e., sidewall height).

Drop height observations were made also in stepped cascade flows. Chanson and Toombes (1997) observed maximum drop heights in excess of 0.6 m for the following flow conditions: $h \sim 0.03$ m, $U \sim 1.5$–3 m/s, step height = 0.14 m, longitudinal slope = 3.4°. More generally, droplet ejections and spray are common features of cascading waters.

EXPERIMENTAL DATA: DISTRIBUTIONS OF DROP CHORD LENGTH

A detailed study of the air-water flow structure in a large flume was performed by the writer (Chanson 1997b). The data analysis includes distributions of air bubble chord lengths and of water drop chord lengths. Bubble chord length data were presented elsewhere (Chanson 1997a and b).

Examples of drop chord length distribution are shown in Fig. 4. The data were recorded at various locations $\{x, y\}$, and the local air-water flow properties (C, V) are indicated in the caption, as well as the number of recorded drops during the scanning period. The histogram columns each represent the number of drops with chord length in a 0.5 mm interval; e.g., the number of drops with chord lengths between 2 and 2.5 mm is represented by the column labeled 2.5 mm.

The results (Fig. 4) indicate a broad spectrum of water drop chord lengths. The range of chord length extends over several orders of magnitude, e.g., from 0.5 to 82 mm in Fig. 4(a) and from 0.3 to over 40 mm in Fig. 4(b). Although the distributions appeared skewed, with a preponderance of small drop sizes relative to the mean in Fig. 4(a), the distributions are almost flat at a very large air content (i.e., $C \geq 0.9$), as illustrated in Fig. 2(b). For comparison, (7) would predict a minimum radius of water droplets of more than 25 mm. Such calculations are not accurate, as indeed noted by the author himself.

SUMMARY AND RECOMMENDATIONS

The discusser would recommend extending the author's analysis to large-scale and prototype data, e.g., the works of Cain (1978) and Chanson (1997b) (Table 1).

It was shown that the distributions of air bubble chord sizes exhibit a broad spectrum and that the range of bubble chord length extends over several orders of magnitude (Chanson 1997b). Similarly, a reanalysis of the discusser's data (Fig. 4) suggests a broad range of water drop sizes. A study of both drop sizes and bubble sizes is required to gain a better understanding of the air-water flow mixture, and this would have direct applications in terms of water quality and air-water gas transfer at and downstream of hydraulic structures.

APPENDIX I. REFERENCES

Arreguin, F., and Echavez, G. (1986). "Natural air entrainment in high velocity flows." *Proc., Conf. on Advancements in Aerodyn., Fluid Mech. and Hydr.*, ASCE, Reston, Va., 186–192.

Cain, P. (1978). "Measurements within self-aerated flow on a large spillway," PhD thesis, Dept. of Civ. Engrg., University of Canterbury, Christchurch, New Zealand.

Chanson, H. (1988). "A study of air entrainment and aeration devices on a spillway model," PhD thesis, Dept. of Civ. Engrg., University of Canterbury, Christchurch, New Zealand.

Chanson, H. (1997a). *Air bubble entrainment in free-surface turbulent shear flows.* Academic Press, London.

Chanson, H. (1997b). "Air bubble entrainment in open channels: flow structure and bubble size distributions." *Int. J. of Multiphase Flow*, 23(1), 193–203.

Chanson, H., and Toombes, L. (1997). "Flow aeration at stepped cascades." *Res. Rep. No. CE155*, Dept. of Civ. Engrg., University of Queensland, Brisbane, Australia.

Kobus, H. (1984). *Proc., Int. Symp. on Scale Effects in Modeling Hydr. Struct.*, Balkema, Rotterdam, The Netherlands.

Wood, I. R. (1985). "Air water flows." *Proc., 21st IAHR Congress*, International Association for Hydraulic Research, Delft, The Netherlands, 18–29.

Wood, I. R. (1991). "Air entrainment in free-surface flows." *IAHR hydraulic structures design manual, No. 4: Hydraulic design considerations*, Balkema, Rotterdam, The Netherlands.

Xi, R. (1988). "Characteristics of self-aerated flow on steep chutes." *Proc., Int. Symp. on Hydr. for High Dams*, International Association for Hydraulic Research, Delft, The Netherlands, 68–75.

APPENDIX II. NOTATION

The following symbols are used in this paper:

C = local air concentration;
Q = water discharge (m^3/s);
V = local velocity (m/s);
W = channel width (m); and
y = distance (m) measured normal to invert.

Closure by Martin Rein[3]

The discussion presents interesting new experimental data obtained by the discusser that were not available at the time when the paper was written. In particular, a comparison of these data with Fig. 4 clearly shows that the energy of ejected drops can be much greater than the energy contained in turbulent eddies of the flow. The data of the discusser thus agree with the finding of the writer; drops actually rise to greater heights than can be explained by a model of drop formation based only on the energy of turbulent eddies. Furthermore, the discusser correctly notes that there is no discontinuity between a drops region and a bubbles region in self-aerated high-velocity chute flows. This was also discussed by the writer in the third paragraph of the Discussion section of the original paper. Finally, it should be emphasized that (7) does not determine a minimum radius of drops that can generally be formed. Actually, smaller drops can easily by pinched off, but they will not entrain air on succeeding impacts. The importance of (7) is that it defines a minimum radius of drops that can contribute to air entrainment during impact on liquid surfaces.

ROUGHNESS OF LOOSE ROCK RIPRAP ON STEEP SLOPES[a]

Discussion by Pavel Novak[4]

The authors, in their interesting paper, used an ingenious method to determine the "effective top-of-riprap" line, which, of course, is crucial for computation of the depth of free surface flow and relative roughness, which in turn influences the outcome of computations of f, (16), or n, (12). In view of the

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[a] February 1998, Vol. 124, No. 32 by C. E. Rice, K. C. Kadavy, and K. M. Robinson (Paper 13697).

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