Aeration Performance of Low Drop Weirs[a]

Discussion by Hubert Chanson[4]

The authors should be congratulated for their interesting work. The work is a significant addition to the study of drop structure aeration. The discusser wishes to comment on the incomplete work on rough chute weirs.

AERATION PERFORMANCE OF OPEN CHUTES

In open chutes, supercritical turbulent flows are often characterized by large quantities of air entrained across the free surface (Fig. 4). The high level of turbulence and the air entrainment process enhance the air-water transfer of atmospheric gases and modify the downstream water quality. For example, the downstream dissolved oxygen content is significantly higher (e.g., Rindels and Gulliver 1989). In some cases, nitrogen supersaturation could cause ''gas bubble disease'' and high fish mortality for salmonids and steelheads, as in the Columbia and Snake rivers (in the United States) (Boyer 1971; Smith 1973). Some researchers have proposed empirical correlations to predict the oxygen content downstream of chutes (e.g., Department of Environment 1973).

Recently, the discusser's work (Chanson 1995, 1997) emphasized that the aeration performances of chutes are directly related to the presence or absence of free-surface aeration. Along a chute, the upstream flow is clear until the outer edge of the developing turbulent boundary layer reaches the free surface (Fig. 4). Downstream of the inception point, the entrained air contributes significantly to an increased air-water interface area and high gas transfer rates.

Rindels and Gulliver (1989) reported several measurements of dissolved oxygen content upstream, downstream, and along spillways and weirs. Their photographs showed clearly the existence of free-surface aeration. The discusser (Chanson 1995) compared their data with a crude numerical model of free-

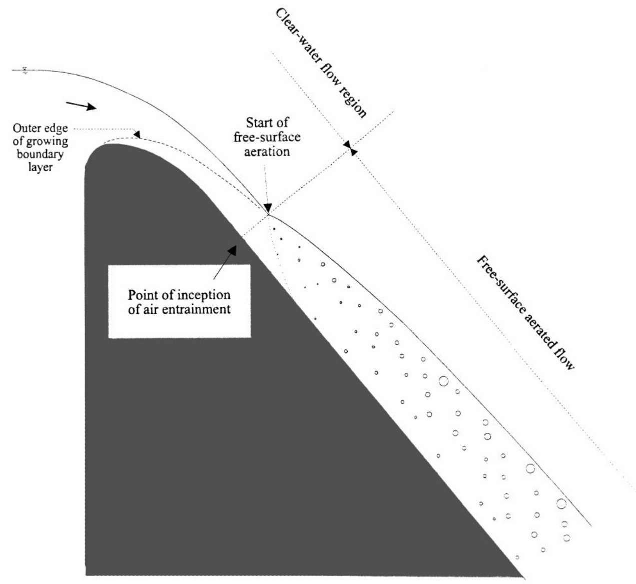

FIG. 4. Longitudinal Flow Pattern of Self-Aerated Chute Flows

[a]January 1998, Vol. 124, No. 1, by Chester C. Watson, Richard W. Walters, and Scott A. Hogan (Paper 6349).

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TABLE 7. Examples of Reaeration Stepped Cascade

Cascade (1)	Reference (2)	Purpose (3)	Characteristics (4)
		(a) Reoxygenation cascade	
Calumet water cascades, Chicago	Cargill (1994); Robison (1994)	Five reaeration cascades. Designed to reoxygenate depleted waters of Columet waterway.	Cascades with pooled steps: Station 1: 11.6 m^3/s, 4 steps (h = 1 m); Station 2: 1.59 m^3/s, 4 steps (h = 1 m); Station 3: 13.7 m^3/s, 3 steps (h = 1.5 m); Station 4: 13.7 m^3/s, 3 steps (h = 1.5 m); Station 5: 16.4 m^3/s, 4 steps (h = 1 m).
Canyon weir, USA	Hauser and Morris (1995)	Reaeration weir downstream of hydropower station. Designed to reoxygenate turbined waters.	Labyrinth weir (crest length: 118 m). Single drop (h = 1 m). Plunge pool depth: 1.9 m. Design flow conditions: 0.14 m^2/s.
Chatuge weir, USA	Hauser et al. (1992); Hauser and Morris (1995)	Reaeration weir downstream of Chatuge hydroproject in Hiwasse river (North Carolina). Designed to reoxygenate turbined waters.	Hollow broad-crested weir. Single drop (h = 2.9 m). Plunge pool depth: 1.1 m. Design flow conditions: 1.2 m^2/s.
Petit-Saut reaeration cascade, French Guyana		Reaeration weir downstream of Petit-Saut dam (French Guyana). Designed to reoxygenate turbined waters.	Labyrinth weir. Two drops (h = 2 m each). Design flow conditions: 110 m^3/s.
South Holston weir, USA	Rizk and Hauser (1993); Hauser and Morris (1995)	Reaeration weir downstream of hydropower station. Designed to reoxygenate turbined waters.	Labyrinth weir (crest length: 640 m). Single drop (h = 2.3 m). Plunge pool depth: 0.91 to 1.37 m. Design flow conditions: $q_w \leq 0.185$ m^2/s (0.11 m^2/s during turbine operation).
		(b) Nitrogen removal cascade	
Montferland demonstration plant, The Netherlands	van der Hoek et al. (1992)	Nitrate removal from ground water by sulphur/limestone denitrification: aeration cascade to reoxygenate depleted water at end of process.	3 weirs with 3 steps each (h = 0.7 m). Design flow conditions: 9.72 L/s.

Note: h = cascade step height.

surface aerated flow. The results indicated some agreement between measurements and rough calculations, and they highlighted that the gas transfer is substantial in self-aerated flows. More, for a given chute length, the aeration efficiency decreases when the discharge increases until no aeration takes place, and the gas transfer efficiency increases with the temperature.

COMMENTARY

For the authors' experiments, a reanalysis of the flow conditions suggests that no substantial free-surface aeration took place. The chute model was too short to experience free-surface aeration, and the data in Table 6 are not representative of self-aerated chute aeration.

A related geometry, which was not investigated by the authors, is the stepped cascade. Stepped cascades are characterized by a large amount of ''white water,'' and they are an efficient means to reoxygenate depleted waters. In rivers, artificial stepped cascades and weirs have been introduced to enhance the DOC of polluted or eutrophic streams (e.g., Avery and Novak 1978; Nakasone 1987). In-stream stepped cascades are also built downstream of large dams to reoxygenate water, e.g., the Chatuge weir built by the Tennessee Valley Authority and the two-step labyrinth drop structure built by the French Electricity Commission downstream of the Petit-Saut dam (Table 7). (Note that the Petit-Saut dam is an RCC construction, equipped with an overflow stepped spillway. The downstream stepped cascade is designed to reoxygenate the turbined waters depleted in oxygen.) Another example is the series of five aeration cascades built along the Calumet waterway in Chicago. The waterfalls are designed to reoxygenate the polluted canal, and they are landscaped as leisure parks, combining flow aeration and aesthetics.

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Discussion by Pavel Novak[5]

The authors presented interesting results concerning the aeration performance of low drop weirs achieved using a novel enhanced-oxygen testing facility. From their reported results, some additional conclusions can be reached, but further clarification may also be required.

1. The chute produced the lowest results, and the authors did not present a predictive relationship. Assuming that the flow on the chute remained without air entrainment, the resulting deficit ratio could be computed by using the Avery-Novak equation, (5), with $q_J = q$, as at impact into the downstream pool, air is entrained on one side only. Comparing the results in Table 4 with those in Table 6 (neglecting any tailwater effects; see later) seems to suggest that such an approach is possible [e.g., for a smooth weir with $q = 0.0469$ and $h = (0.635 + 0.673)/2 = 0.654$, $r = (1.39 + 1.38)/2 = 1.335$; and for a chute with $q = 0.0939$ and $h = (0.638 + 0.706)/2 = 0.672$, $r = (1.19 + 1.24) = 1.215$].
2. In their 1978 paper, Avery and Novak correlated successfully their equations with results given by van der Kroon and Schram (1969) for multiple jets, assuming no interference by neighboring jets and using a Froude number $N^{1/4}\mathsf{F}_J$ where N = number of jets. The authors used 66.5 mm cobbles on a 1.22 m wide weir. Thus, assuming multiple noninterfering jets, this would result in $N = 1{,}220/130 = 9 - 10$ (assuming more or less equal spacing of cobbles, which, however, were randomly placed) with $N^{1/4} = 1.75$. Using the design curves presented by the authors for rough and smooth weirs results in a ratio of the deficit ratios between 1.15 and 1.45 (depending on the drop height), suggesting a more complicated mechanism (e.g., flow over as well as between cobbles, as was the case in the reported experiment); nevertheless, an analysis along the suggested lines taking into account the shape of jet(s) at impact into the pool is possible.
3. In the authors' work, the width of the downstream pool was equal to the weir length, thus avoiding any recirculation in the downstream pool. In the discusser's opinion, the shape (width) of the downstream pool compared with the crest width is possibly more important than the depth of the pool, always assuming that this is at least equal to or bigger than the optimum, (9) [see also Novak and Gabriel (1997)].

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Closure by Chester C. Watson[6]

The writer thanks the discusser for their interest in the topic and for their comments.

Novak's suggestion for additional analysis of the rough weir incorporating van der Kroon and Schram's (1969) investigation of multiple jets is appreciated. Since the original testing, new testing of roughened weirs using three different uniform

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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).

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

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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:

$$\frac{Q}{W} = \int_{0}^{y_{C=0.9}} (1 - C) * V * dy \tag{1}$$

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.

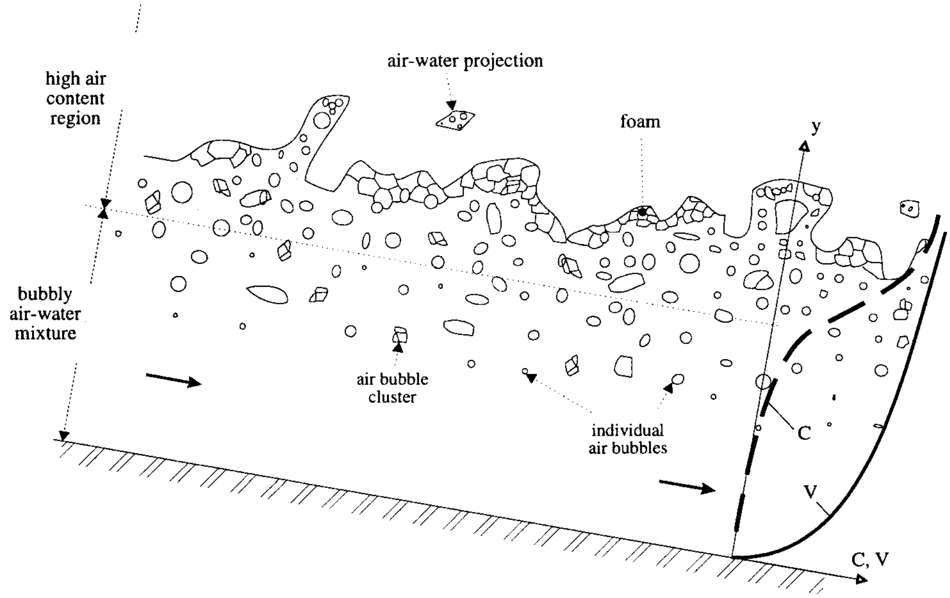

FIG. 3. Air-Water Flow Structures in Self-Aerated Chute Flows

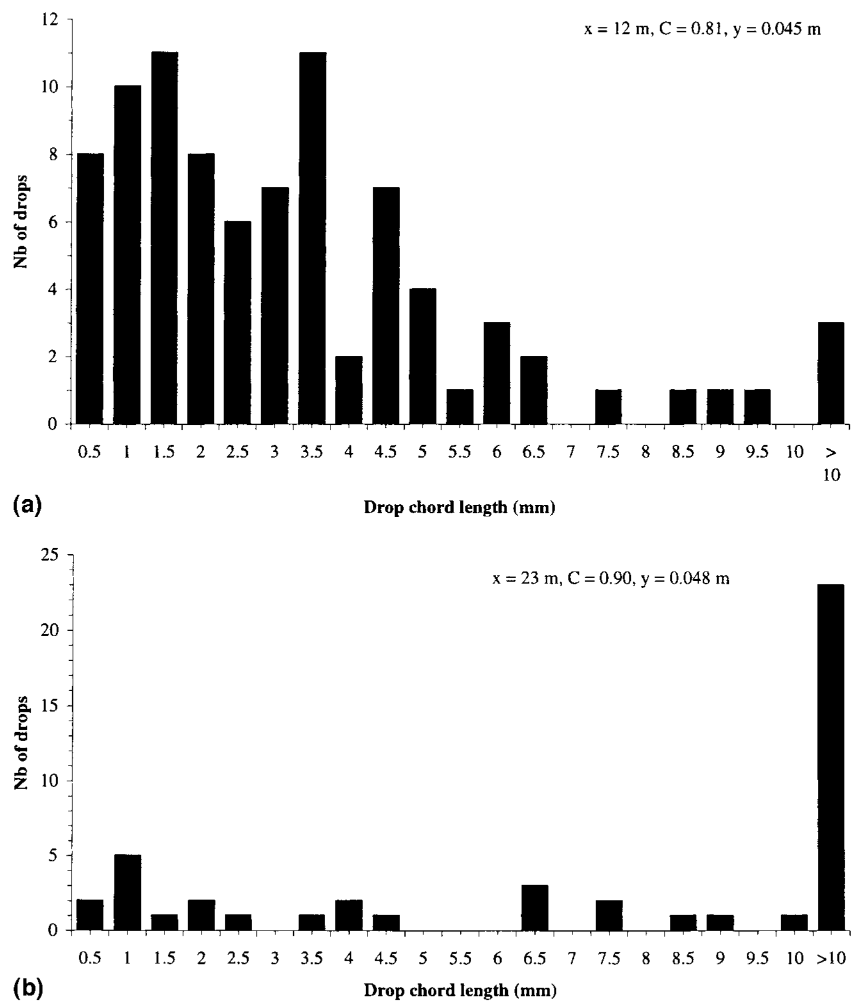

FIG. 4. Drop Chord Length Distributions (0.5 mm Drop Chord Length Intervals): (a) Flow Conditions: $x = 12$ m, $U = 3.56$ m/s, $y = 0.045$ m, $C = 0.81$, $V = 4.24$ m/s; Scanning Rate: 40 kHz; Duration: 1.638 s, 87 Water Drops; (b) Flow Conditions: $x = 23$ m, $U = 3.41$ m/s, $y = 0.048$ m, $C = 0.90$,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

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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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assumptions made in determining the net unit discharge q_t and the difficulty of measuring the depth d (the water surface elevation could not be measured directly), have the authors carried out an analysis of the accuracy of the results presented in Fig. 10?

Eq. (16) is in the traditional form

$$\frac{1}{\sqrt{f}} = A \log \frac{R}{D} + B \tag{17}$$

where A = function of K (the von Karman ''constant of turbulence'').

In their 1981 paper, Pyle and Novak analyzed the values of A and B as influenced by the roughness shape and concentration and presented a procedure for the computation of the friction coefficient in conduits with a large roughness. The data presented by the authors in their paper are not sufficient to use the method suggested in the 1981 paper, but a superficial comparison of, e.g., figure 2 in the Pyle and Novak paper for natural river stones and the authors' (16) suggests that it might be possible to pursue this line of investigation further and compare the authors' data with the 1981 paper. The results would be particularly interesting, as the authors worked with significantly smaller values of d/D than Pyle and Novak.

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Pyle, R., and Novak, P. (1981). ''Coefficient of friction in conduits with large roughness.'' *J. Hydr. Res.*, Delft, The Netherlands, 19(2), 119–140.