Modern Environmental Science and Engineering (ISSN 2333-2581)
April 2019, Volume 5, No. 4, pp. 293-300
Doi: 10.15341/mese(2333-2581)/04.05.2019/004
Academic Star Publishing Company, 2019
www.academicstar.us

Comparison of Theoretical and Experimental Results from the Operation of An Aerator in A Chute

Javier Osnaya Romero, Víctor M. Ortíz Martínez, Jesús Gracia Sánchez, and Eliseo Carrizosa Elizondo

Instituto de Ingeniería, Universidad Nacional Autónoma de México, México

Abstract: In this work, the results of the measurements made in a physical model of a chute with two-phase aerated flow are presented. The aim is to compare the results of an existing theoretical criterion, with the results measured in the laboratory by means of updated measurement equipment, which allows better corroboration of the reliability of the theoretical criterion. To measure the air content in an air-water biphasic flow a physical model was used that simulates the Huites dam, Mexico, where, to diminish the effects of scale, it was built at 1:21 scale. Given the difficulties of making measurements in prototypes and the restrictions to represent the behaviour of the air with the current techniques of CFD, a conductivity probe was designed to measure the air content in a reliable, easy-to-manufacture way that allows measurement in models. The air measurements were processed using the technique of adaptable thresholds to obtain reliable records and these were compared with the equation proposed by Kramer [10]. This study focuses on the concentration of air near the bottom which is a site where a minimum concentration is required to avoid damage by cavitation. In addition to the agreement between measurements and calculations, the results show that there are difficulties in defining the thickness of the bottom layer which need to be considered to avoid cavitation.

Key words: cavitation, spillways, biphasic flow

1. Introduction

When the speed of spillways is higher than 22 m/s, cavitation damage may occur when the absolute pressure within the fluid drops below the vaporization pressure of the fluid. The variables causing this are the flow velocity, local atmospheric pressure, local pressure on the spillway, amplitudes of pressure fluctuations and fluid vapor pressure. There is an equation for the cavitation index that relates the parameters involved which is expressed by the following equation

$$k = \frac{(p - p_v)}{\rho_w u^2/2} \quad [1]$$

Where p is the pressure load, p_v is the vaporization pressure of the fluid, p_w is the density of the fluid and u is the velocity. Falvey [7] recommends a cavitation index greater than 0.25 with a smooth finish which would represent a velocity close to 29 m/s, however, it is recommended to take measures to avoid cavitation by ensuring velocities in the range of 22-26 m/s [20].

Another important factor to avoid cavitation damage is the air content near the spillway template. One of the first investigators to perform measurements on physical models to determine the air content in channels was Viparelli [20] in 1953. He developed a device to determine the velocity load in air water flows and the air content using a modified a pitot tube connected to a reservoir, where it extracted a sample of the flow and measured the amount of water and air taken. This method shows acceptable results with low air content, but shows uncertainty when the air concentration is high [1]. Later this instrument was modified to determine the air content in a staggered spillway [12] and in a hydraulic jump [3] with the disadvantage that for proper operation it is required to know the direction of the dominant flow, which is

Corresponding author: Javier Osnaya-Romero, M. en I.; research areas/interests: hydraulics, physical models, rivers. E-mail: jor@pumas.iingen.unam.mx.

difficult to determine in a hydraulic jump. Subsequently, numerous investigations have been carried out to determine the minimum air content to prevent cavitation. One of the first to investigate this was Petarka [16] who performed tests with velocities of 35 m/s and observed that when the air content was between 1 to 2% the cavitation was reduced. Incrementing this between 6 to 8%, close to the template, cavitation was completely avoided. Russel and Sheehan [18] conducted studies at velocities greater than 46 m/s and determined that in order to avoid cavitation a concentration of 3 to 5% is required. In addition, Chanson [5] analyzed several experiments and found that with an air content between 4 to 8% close to the template, and even with speeds greater than 45 m/s, damage by cavitation is avoided.

Cavitation is the formation of vapor cavities in a liquid. In the rapids of a spillway the cavitation occurs in the flow at high velocity, where the water pressure is reduced locally due to an irregularity in the surface of the bottom. As the vapor cavities move into a higher pressure zone, they collapse, sending high-pressure shock waves and if the cavities collapse near the bottom, there will be damage to the concrete. Cracks, displacement, and surface roughness may also increase the potential for cavitation damage. The extent of cavitation damage will be a function of cavitation indices in key places in the spillway and the duration of flow. This mode of failure will normally only be a concern in fast spillways, since cavitation damage is less likely to occur in tunnels and conduits where there are changes in flow direction and confinement. In most cases, this mode of failure is unlikely to progress to dam failure as long flow durations are required to cause major damage to concrete liners.

Kramer [11] studies the development of the distribution of air concentration in the hydraulic depth in a channel (straight model). The slope was adjustable between 0% and 50% and therefore allowed the study of the influence of the slope in the phenomenon. These detailed studies were possible mainly because new measurement techniques appeared. Kramer used an optical fiber measurement system. This system allows measurement of the local air concentration, flow velocity and bubble size. His work highlights a number of results, such as the air drag on the underside of the downstream jet of a deflector was large, however rapidly downstream of its point of impact, most of the air dragged is absorbed into the jet. The measured air concentrations at the bottom of the canal were much lower than those established by other authors. Even in these cases though there is no cavitation damage. It is also shown that the air-drag mechanism influences the air-absorption process. Using his results one can estimate air transportation to the flow.

There have only been a few studies concerning the axial distribution of the water-air mixture in spillways and even less focused on the concentration of air in the template. In order to protect this type of structure from cavitation Kramer [11] developed an equation to determine the air content near the template downstream of the aerator, which is presented below

$$C_b = C_{b0} exp[-(7{,}2 * 0{,}006^{S_0} + 6{,}6) F_0^{-2.5} * X_{90u}]$$
$$for \quad 5 \le F_0 \le 12 \, , S_0 \le 50\% \qquad [2]$$

Where the air content close to the template is expressed C_b as a function of the air concentration at the bottom upstream C_{b0}, the number of arrival Froude F_0, channel slope S_0, and the distance where it is required to know the air. X_{90u}, which is dimensionless, is represented by the distance where one wants to know the air content between the hydraulic depth and where the air concentration is 90%. To use this equation, measurements were made using an optical fiber probe manufactured by RBI. It is noted that although the device used by Kramer [12] to introduce the air is not identical to the one utilized in this study, the phenomenon of air exhaustion in the rapid itself is the same as the one which is presented here.

At the Institute of Engineering, UNAM tests were performed to identify the air content downstream of the aerator of the rapid using a physical model with scale 1/21 of the exceeded spillway of the Huites hydroelectric power plant. Eight transversal sections were located upstream of the aerator and 7 were located downstream from the aerator. The air content was measured at 2 mm from the template as well as at each centimeter of hydraulic depth and at 5 sites for each cross section (i.e., a total of approx. 8 × 5 × 7 = 280 points). This was done for three different flows (0.5, 1.0 and 1.5 m^3/s). In this paper, only the results of the template (2 mm) and 1cm of the bottom are presented. This is to analyze the behavior of the air concentration in the bottom layer, which is where one needs to know the air content to avoid cavitation.

This paper compares the measurements made at the Institute of Engineering, UNAM, with the equation developed by Kramer [12]. For the measurement of the concentration of air a conductivity probe developed in the Institute of Engineering, UNAM, was used. The data obtained was processed using the technique of adaptive thresholds, and with these results the concentration of air close to the template was obtained. Once the air content is known the measurements are compared with the results of the criterion proposed by Kramer [11].

2. Physical Model

To achieve a correct reproduction in physical models of hydraulic phenomena where air-water flows intervene is complicated and impossible if the same fluid is used in the prototype and model. This is because the behavior of the air bubbles is directly affected by the forces expressed by the dimensionless numbers of: Froude F_b, Reynolds R_b and Weber W_b of the bubbles. The importance of these numbers was validated by Haberman and Morton [9] who showed that if the numbers of R and Weber W_b are below a minimum value, then the fluid is affected by the characteristics of the bubbles. The scale effects are considerably reduced if certain limits related to the number of Morton M are observed that relates, R and W [11]. Pfister and Hager [8] recommend working with numbers of $W^{0.5} > 140$ or $R > 2.2\,x\,10^5$. If the characteristics of the turbulence model and the water-free surface are maintained within this range, then the characteristics of the air concentration is similar to those of the prototype.

In the facilities of the Institute of Engineering of the UNAM, the physical model of the spillway corresponding to the hydroelectric Huites dam was used (Fig. 1), which is located on the Fuerte river in the

Fig. 1 Physical model of the hydroelectric spillway Huites, Mexico.

state of Sinaloa in northwestern Mexico. The objective of model was to understand the behavior of the air along the spillway and thus know where to position aerators to reduce the risks of cavitation. For this purpose the model was built to 1:21 scale in order to decrease the scale effects. It was decided to try low flows in the discharge of the spillway because they are more likely to be presented in the prototype. Those used in the physical model were 0.5, 1.0 and 1.5 m^3/s, and it should be noted that the design flow in the prototype of the spillway is 9500 m^3/s.

In the model the height of the crest to the lowest section of the spillway is 4.13 m, the chute has a total length of 11.8 m, and the flow is supplied by two 100 hp pumps each with a maximum flow of 2.2 m^3/s. The chute of the spillway has two aerators one at 4.7 m and another at 8.6 m measured from the crest as shown in Fig. 1. Only the first aerator was used in the tests performed and described in this work.

3. Instrumentation

To carry out the tests it was decided to develop an easy to manufacture instrument based on a conductivity probe whose principle has been used for some time by different authors Cain [2], Chanson [4], as well as being used to measure velocities in biphasic flows by Matos et al. [14]. The probe is made up of two sensors built of 0.8 mm diameter needles installed inside a cylindrical stainless steel body that facilitates the realization of the measurements as it provides rigidity for the instrument. An electric current is circulated through the sensor which shows variations depending on the electrical conductivity of the environment in which it is immersed. In this case there is a difference between the conductivity of two sources that are the water with a conductivity of 5 ms/s and the air which is almost nil. The sensors thus detect well the presence of water or air which is associated with the passage of an air bubble through the probe.

Conductivity probes have been used since the sixties with different measurement purposes such as detection of the air fraction, frequency of the bubbles and their size giving reliable results, for instance, in a mercury-nitrogen system, Neal and Bankoff [15]. Subsequently they have been perfected and used in a large number of investigations and it is currently possible to measure with them the volume of air, bubble velocity, distribution of the number of bubbles, concentration of interfacial area, bubble size Chanson [6], and in some cases one can estimate the velocity of the bubble in two, Yang et al. [22] and three directions, Shen et al. [19]. The probe used in this work and the additional equipment was manufactured at the Institute of Engineering (II), UNAM. The signal obtained from the probes in this work allows the capturing of up to 40,000 samples per second. A picture of the probe and the equipment used is shown in Fig. 2.

Fig. 2 Conductivity probe manufactured by the II, UNAM.

The signal processing method utilized was the adaptive threshold technique (Fig. 3), commonly used to detect faults in signal analysis processes, Höfling and Isermann [10].

4. Tests

The objective of these measurements is to determine the air content found in the flow, with the main interest being in the concentration near the template to identify and avoid cavitation problems. In the physical model it was decided to measure the air content on the spillway making measurements in 8 different cross sections which were 13.0 cm before the aerator and 0.15, 0.45, 1.20, 1.60, 2.00 and 2.40 cm after the aerator. These 8 sections were divided into 5 equidistant points across the width of the cross section, to measure within 2 mm of the template, and then at each centimeter until the free surface is reached which is calculated from the bottom to where the air concentration is less than 0.9, Pfister [17]. Tests were performed on the physical model with three flows 0.5, 1.0 and 1.5 m^3/s. The measurements were carried out with a sample frequency of 20,000 Hz, in each of the two reading channels for an average duration of 35 s. After this, the signals where analyzed using an adaptive thresholding technique to obtain the air content of each sensor. Finally, the average of both records was used to determine the average air content in each cross section, which is presented in Figs. 4, 5 and 6. The results were compared with Eq. (2) proposed by Kramer [11].

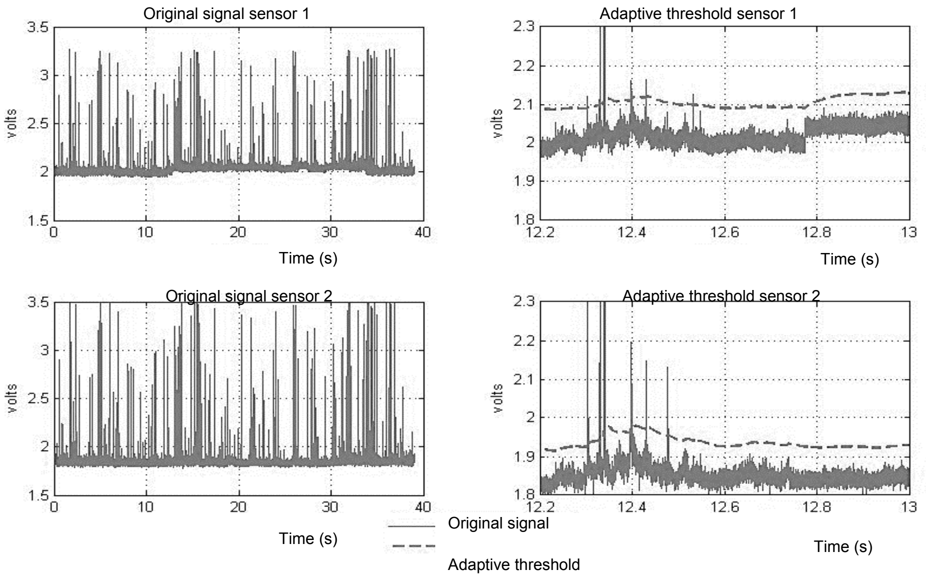

Fig. 3 Example of the use of the adaptive threshold technique.

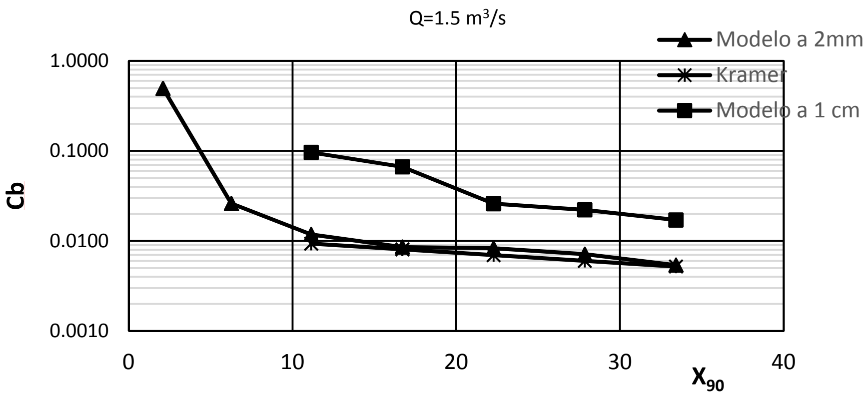

Fig. 4 Air concentrations with 0.5 m^3/s.

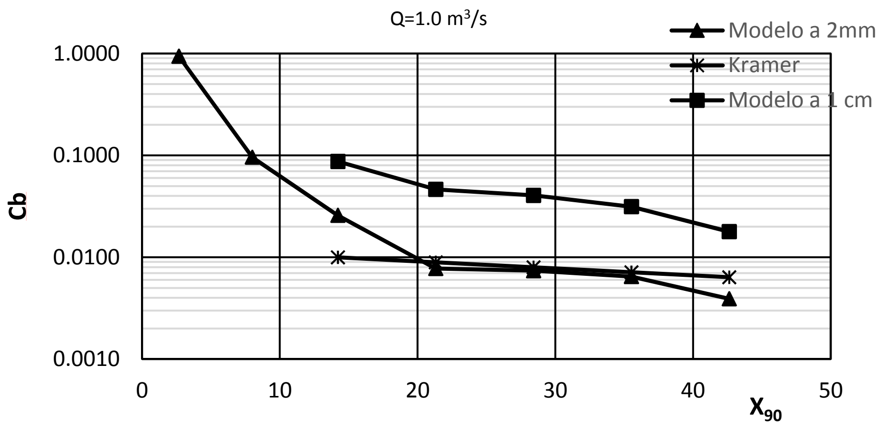

Fig. 5 Air concentrations with 1.0 m^3/s.

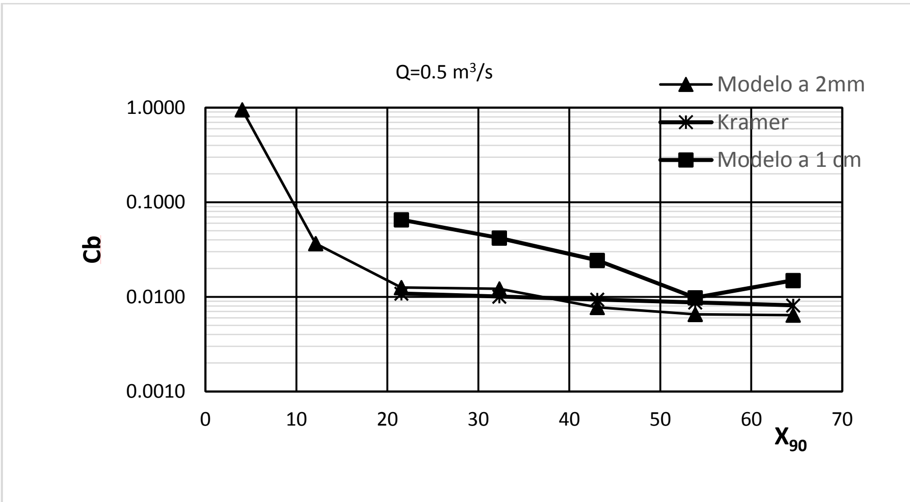

Fig. 6 Air concentrations with 1.5 m^3/s.

From the measurements taken, the Reynolds and Weber numbers were obtained for each test, with the purpose of corroborating the scale effects. The values are presented in Table 1 and it is observed that they are in the range of the criteria established earlier.

In the Figs. 4 to 6, the air content close to the template is shown. For this, the results of the measurements of the right, left and center margin were measured at the points closest to the template (2 mm) which are those of the bottom. In addition, the results were compared with those obtained with the Kramer equation [11].

Table 1 Values of reynolds and weber.

Q [m^3/s]	Re $\times 10^5$	$W^{0.5}$
0.5	2.89	159.73
1.0	5.77	247.46
1.5	8.66	313.71

From the measurements of air content, it is observed that for the three flows and at 2 mm, there is an air concentration of less than 1%, which is below the recommended values so that cavitation damage can be prevented. However, when observing the values of air content at 1 cm in the model, these are between the 2 and 10% recommended values to prevent cavitation in the bottom.

In addition, according to the measurements and the comparison with the calculated value using the expression of Kramer [12] it is observed that both values are similar, so the use of this expression to determine the concentration of air in the template is reliable.

5. Conclusions

It is possible to reliably measure the air content in large physical models by means of conductivity probes and corresponding post-processing with an adaptive thresholding technique. The use of the conductivity probe in this application is reliable with the added benefit that they are also easy to manufacture. Additionally, an advantage of the equipment used is that it can be deployed in any type of cross-section, such as in circular-section tunnels, etc.

When comparing the measurements made in the laboratory with those calculated using the equation proposed by Kramer [11] it is observed that the there is a reliable correlation in obtaining the air concentration at the bottom. The use of this equation to estimate the air concentration is thus also recommended in prototypes.

The measurements made in the model show that there is a difference between the values at the bottom (2 mm) and those obtained at 1 cm, so one has to make a decision in each case, on the distance from the template that is considered representative to predict the possible cavitation. In the test case, the distance of 2 mm indicates that the air concentrations are in the order of 1% or less, whereas the amount of air at 1.0 cm from the bottom varies between 10 to 2%. Therefore, no cavitation problems were detected in the prototype.

References

[1] P. M. Borges, Free-surface flow interface and air-entrainment modeling using OpenFoam, thesis project in hydraulic, water resources and environment, Doctoral program in civil engineering, Coimbra, 2013.

[2] P. I. Cain and R. Wood, Instrumentation for aerated flow on spillways, *Journal of the Hydraulics Division*, ASCE.

[3] R. F. Carvalho, Acções Hidrodinâmicas em Estruturas Hidráulicas: Modelação Computacional no Ressalto Hidráulico, Ph.D. thesis, Universidade de Coimbra, Portugal, 2002.

[4] H. Chanson, Study of air entrainment and aeration devices on spillway model, Ph.D. thesis, Univ. of Canterbury, Christchurch, 1988.

[5] H. Chanson, Air entrainment in chute and spillways, Department of Civil Engineering, Research report series, The University of Queensland, 1992.

[6] H. Chanson, Hydraulics of aerated flows: quid pro? quo *Journal of Hydraulic Research* 51 (2013) (3) 223-243, doi: 10.1080/00221686.2013.795917.

[7] H. T. Falvey, Cavitation studies in tunnel spillways, in: *Symposium on Scale Effects in Modelling Hydraulic Structure*, Esslingen Germany, 1984.

[8] K. H. Frizell and J. F. Ruff, Air concentration measurements in highly-turbulent flow on a steeply-sloping chute, in: *Symposium on Hydraulic Measurements and Experimentation*, Buffalo, New York, 1994.

[9] W. L. Haberman and R. K. Morton, An experimental investigation of drag and shape of air bubbles rising in various liquids, rep. 802, David W. Taylor Model Basin, Berthesda, MD, 1953.

[10] T. Höfling and R. Isermann Fault, Detection based on adaptive parity equations and single-parameter tracking, *Control Engineering Practice* 4 (1996) 1361-1369.

[11] K. Kramer, Development of aerated chute flow, in: Vaw Mitteilung, H. E. Minor (Ed.), *Laboratory of Hydraulics, Hydrology and Glaciology*, ETH Zurich, Zürich, Switzerland, 2004, p. 183.

[12] K. Kramer, W. H. Hager and H. E. Minor, Development of air concentration on chute spillways, *Journal of Hydraulic Engineering* 132 (2006) (9) 908-915.

[13] J. Matos, Emulsionamento de ar e dissipação de energia do escoamento em descarregadores em degraus, Ph.D. thesis, Instituto Superior Técnico de Lisboa, Portugal, 1999.

[14] J. Matos, K. H. Frizell, S. André and W. Frizell, On the performance of velocity measurement techniqus in air-water flows, *Hudraulic Measurements and Experimental Methods*, 2002.

[15] L. G. Neal and S. G. Bankoff, A high resolution resistivity probe for determination of local void properties in gas-liquid flow, *A. I. Ch. E Journal*, 1963.

[16] A. J. Petarka, The effect of entrained air on cavitation pitting, Joint Meeting Paper, Minnesota, 1953.

[17] M. Pfister and W. H. Hager, Chute aerators I: Air transport characteristics, *J. Hydraulic Eng.* (2010) 352–359, doi: 10.1061/(ASCE)HY.1943-7900.0000189.

[18] S. O. Russel and G. J. Sheehan, Effect of entrained air cavitation damage, *Can. J. Civ. Engr. Canada* 1 (1974).

[19] X. Shen, Y. Saito, K. Mishima and H. Nakamura, Methodological improvement of an intrusive for-sensor probe for the multi-dimensional two-phase flow measurement, *International Journal of Multiphase Flow* (2005) 593-617.

[20] M. Viparelli, The flow in a flume with 1:1 slope, University of Napoli Italy, 1953.

[21] R. I. Wood, Air Entrainment in free-surface flows, University of Canterbury, Christchurch, New Zealand. A.A. Balkema/Rotterdam/ Brookfield, 1991, p. 142.

[22] R. Yang, R. Zheng, F. Zhou and R. Liu, Measurement of two-dimensional bubble velocity by using tri-fiber-optical probe, in: *The 6th International Symposium on Measurement Techniques for Multiphase Flows*, 2009.