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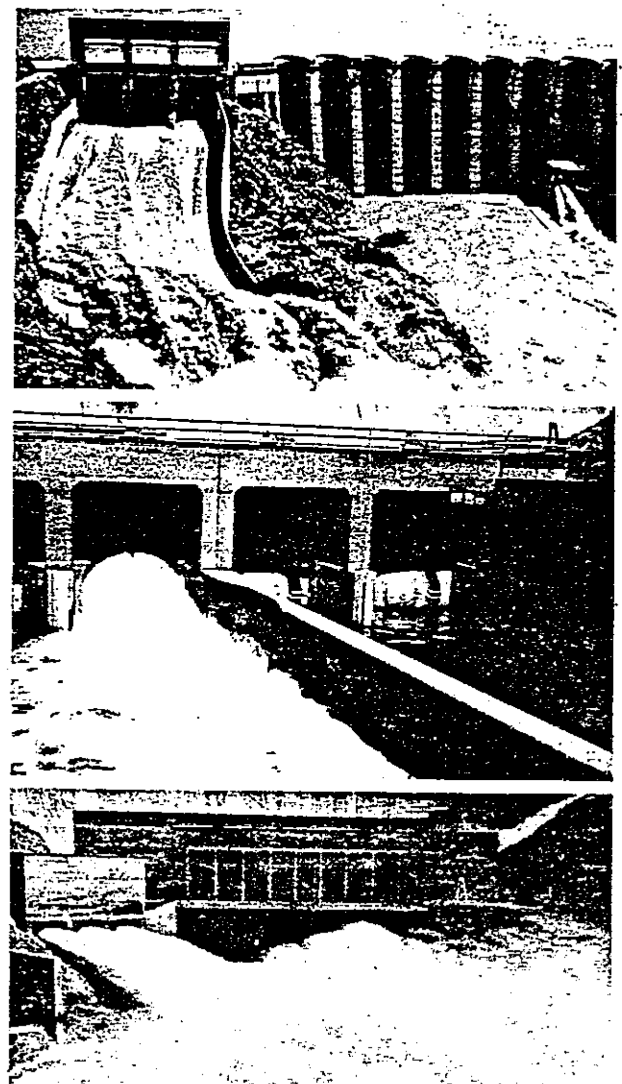

EXCERPT FROM

# AIR-WATER FLOW IN HYDRAULIC STRUCTURES

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UNITED STATES DEPARTMENT OF THE INTERIOR
WATER AND POWER RESOURCES SERVICE

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# Preface

The material assembled in this report is the result of studies extending over many years by a large number of engineers. Ellis Picket at the U.S. Army Engineer Waterways Experiment Station in Vicksburg, Mississippi, supplied a reference list dealing with air-water problems. Personnel of the Water and Power Resources Service E&R Center. Water Conveyance Branch made their files and drawing on air design criteria in pipelines available for publication in this report. Prior to publication, the report was reviewed by Ellis Pickett and Ted Albrecht with the U.S. Army Engineers; and by engineers in the Dams, Mechanical, and Water Conveyance Branches, E&R Center, Water and Power Resources Service. The many constructive comments by these individuals and the assistance of Richard Walters who provided continuity and technical editing is greatly appreciated.



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# Letter Symbols and Quantities

| Symbol | Quantity |
|---|---|
| $A$ | Cross sectional area of water prism |
| $A_a$ | Cross sectional area of airflow passage |
| $A_c$ | Cross sectional area of air core in a vertical shaft |
| $A_d$ | Cross sectional area of conduit |
| $A_o$ | Orifice area |
| $A_p$ | Cross sectional area of penstock |
| $A_v$ | Cross sectional area of vent |
| $a$ | Ratio of bubble terminal velocity in turbulent flow to terminal velocity in still water |
| $a_0$ | Mean air distribution function |
| $a_1$ | Mean air distribution constant |
| $B$ | Width of rectangular chute |
| $b$ | Width of flow channel |
| $b_n$ | Nappe width |
| $b_s$ | Empirical coefficient accounting for sand grain roughness |
| $C$ | Air concentration |
| $C_a$ | Actual air concentration |
| $C_b$ | Drag coefficient on a bubble |
| $C_d$ | Discharge coefficient based on 100 percent gate opening |
| $C_f$ | Local loss coefficient |
| $C_l$ | Air concentration at $d_t/2$ |
| $C_m$ | Air concentration measured by a pitot tube sampler |
| $C_o$ | Orifice discharge coefficient |
| $C_s$ | Drag coefficient on a sphere |
| $C_t$ | Air concentration at the bottom of the mixing zone |
| $\overline{C}$ | Mean air concentration |
| $c$ | Waterhammer wave celerity |
| $D$ | Conduit diameter |
| $D_b$ | Smaller dimension of a rectangular conduit |
| $D_d$ | Diameter of water drop |
| $D_e$ | Equivalent bubble diameter |
| $D_s$ | Larger dimension of a rectangular conduit |
| $d$ | Flow depth |
| $d_b$ | Bulked flow depth |
| $d_e$ | Deflector height |
| $d_n$ | Nappe thickness |
| $d_o$ | Orifice diameter |
| $d_t$ | Total depth of underlying and air free zones |
| $d_{95}$ | Bubble diameter for which 95 percent of the air, by volume, is contained in bubbles of this diameter or smaller |
| $E$ | Relative width of the frequency spectrum |
| exp | Napierian logarithm equal to 2.71828, approximately |
| $f$ | Darcy-Weisbach friction factor |
| $G$ | Gate opening |
| $G_g$ | Mass velocity of gas |
| $G_l$ | Mass velocity of liquid |
| $g$ | Gravitational constant (acceleration) |
| $H$ | Hydraulic radius of prototype air vent |
| $H_f$ | Fall height of a water jet |
| $H_m$ | Head across orifice |
| $H_n$ | Net head across turbine |
| $H_o$ | Distance from channel invert to energy grade line |
| $H_t$ | Total potential and kinetic energy |
| $h$ | Mean wave height |
| $h_a$ | Height of airflow passage |
| $h_f$ | Distance from inlet to the water level in the vertical shaft |
| $h_l$ | Head loss per unit length |
| $h_m$ | Head across manometer |
| $h_w$ | Allowable head rise in penstock |
| $K_e$ | Entrance loss |
| $K_s$ | Singular (form) loss |
| $k$ | Von Karman universal constant equal to 0.4 |
| $k_r$ | Coefficient of roughness |
| $k_s$ | Sand grain roughness |

## LETTER SYMBOLS and QUANTITIES—Continued

| Symbol | Quantity |
|---|---|
| $L$ | Length of conduit or vent |
| $L_c$ | Distance to start of self-aeration |
| $L_r$ | Prototype to model scale ratio |
| $L_s$ | Distance between stiffener rings |
| $M$ | Unit mass |
| $M_o$ | Maximum difference in elevation between a wave crest and the mean water level |
| $m$ | Air concentration distribution coefficient |
| $N$ | Safety factor |
| $n$ | Manning's roughness coefficient |
| $n_v$ | Velocity distribution power-law coefficient |
| $P$ | Energy dissipated |
| $P_g$ | Normal distribution function |
| $P_h$ | Probability that the wave height is equal to given height |
| $P_w$ | Probability that the water surface is equal to or greater than the given elevation |
| $p$ | Pressure intensity |
| $p_a$ | Allowable internal pressure |
| $p_{atm}$ | Atmospheric pressure |
| $p_c$ | Collapse pressure |
| $p_{in}$ | Internal pressure |
| $p_n$ | Nappe perimeter |
| $Q$ | Discharge |
| $Q_a$ | Volume flowrate of air |
| $Q_c$ | Critical discharge |
| $Q_r$ | Discharge from reservoir |
| $Q_w$ | Volume flowrate of water |
| $q$ | Unit discharge |
| $q_a$ | Insufflation rate of air per unit surface area |
| $R$ | Bubble radius |
| $R_b$ | Equivalent bubble radius |
| $R_c$ | Radius of curvature of the bubble cap |
| $R_j$ | Thickness of annular jet |
| $r$ | Water jet radius |
| $r_s$ | Relative roughness of conduit (rugosity to diameter ratio) |
| $S$ | Submergence depth |
| $S_o$ | Pipe slope |
| $S_f$ | Slope of energy grade line |
| $s$ | Root-mean-square value of wave height distribution |
| $s_w$ | Root-mean-square value of water surface distribution |
| $T$ | Top width of flow passage |
| $t$ | Pipe wall thickness |
| $U$ | Free stream velocity |
| $U_d$ | Velocity of water drop relative to air velocity |
| $U_j$ | Water jet velocity |
| $u$ | Local air velocity |
| $V$ | Mean flow velocity |
| $V_f$ | Terminal velocity of bubbles in turbulent flow |
| $V_i$ | Nappe velocity at impact |
| $V_m$ | Minimum velocity required to entrain air |
| $V_o$ | Maximum water surface velocity |
| $V_s$ | Terminal velocity of bubbles in slug flow |
| $V_t$ | Terminal velocity of bubbles in still water |
| $W$ | Wetted perimeter |
| $x$ | Distance from start of boundary layer growth |
| $y$ | Distance normal to channel bottom (flow depth) |
| $y_a$ | Distance from water surface |
| $y_c$ | Conjugate depth |
| $y_e$ | Effective depth |
| $y_k$ | Critical depth |
| $y'$ | Normal distance to the bottom of the mixing zone |
| $z$ | Elevation |

## LETTER SYMBOLS and QUANTITIES—Continued

| Symbol | | Quantity |
|---|---|---|
| $\alpha$ | alpha | Angle chute invert makes with horizontal |
| $\beta$ | beta | Ratio of volumetric airflow rate to waterflow rate |
| $\gamma$ | gamma | Specific force of water |
| $\delta$ | delta | Boundary layer thickness |
| $\varepsilon$ | epsilon | Mass transfer coefficient of bubbles |
| $\zeta$ | zeta | Air concentration distribution constant |
| $\eta$ | eta | Normalized wave height |
| $\theta$ | theta | Void fraction |
| $\varkappa$ | kappa | Gas constant |
| $\lambda$ | lambda | Density ratio |
| $\mu$ | mu | Dynamic viscosity |
| $\mu_a$ | | Dynamic viscosity of air |
| $\mu_w$ | | Dynamic viscosity of water |
| $\nu$ | nu | Kinematic viscosity |
| $\nu_f$ | | Water viscosity |
| $\pi$ | pi | Ratio of the circumference of any circle to its radius, 3.14159... |
| $\varrho$ | rho | Density |
| $\varrho_a$ | | Air density |
| $\varrho_w$ | | Water density |
| $\varrho_g$ | | Gas density |
| $\varrho_l$ | | Liquid density |
| $\varrho_m$ | | Density of manometer fluid |
| $\sigma$ | sigma | Interfacial surface tension |
| $\tau_o$ | tau | Wall shear stress |
| $\tau_j$ | | Shear stress at water jet |
| $\upsilon_{atm}$ | upsilon | Specific volume of air at atmospheric pressure |
| $\upsilon_*$ | | Shear velocity |
| $\psi$ | psi | Multicomponent flow parameter |
| $\omega$ | omega | Volume of gas bubble |
| $\omega_a$ | | Volume of air |
| $\omega_w$ | | Volume of water |
| $\infty$ | | Infinity |

| Symbol | Quantity | | |
|---|---|---|---|
| E | Eötvös number | = | $\frac{\gamma D^2}{\sigma}$ |
| $E_u$ | Euler number | = | $\frac{\Delta p}{\varrho V^2/2}$ |
| F | Froude number | = | $\frac{V}{(gD)^{1/2}}$ |
| P | Prandtl velocity ratio | = | $\frac{V}{(\tau_o/\varrho)^{1/2}}$ |
| $P_o$ | Poiseuille number | = | $\frac{h_a^2\,(dp/dx)}{2\mu V}$ |
| R | Reynolds number | = | $\frac{VD}{\nu}$ |
| $R_x$ | Distance Reynolds number | = | $\frac{Vx}{\nu}$ |
| W | Weber number | = | $\frac{V}{(\sigma/\varrho D)^{1/2}}$ |

# Contents

## FIGURES—Continued



## APPENDIX

# Introduction

In many engineering projects a strong interaction developes between the water flowing through a structure and the air which is adjacent to the moving water. Sometimes the interaction produces beneficial effects. However, more often than not, the effects are not beneficial and the remedial action required to reduce the effects can be costly.

Cases in which air-water interaction develop include:

- Open channels with fast flowing water that require depths adequate to contain the air which is entrained within the water
- Morning-glory spillways that must have a capacity to convey the design flood and its entrained air
- Vertical shafts that entrain large quantities of air at small water discharges
- Measuring weirs that need adequate ventilation to prevent false readings and to eliminate surging
- Outlet gates that require adequate aeration to prevent the development of low pressures—which can lead to cavitation damage
- Emergency gates at penstock entrances that require ventilation to prevent excessive negative internal pressures during draining or emergency gate closures
- Sag pipes (inverted siphons)[1] that can be damaged due to blowback of entrained air
- Long pipelines that require air release and vacuum relief valves

From these cases it is noted that air-water flows can be generalized into three basic flow types:

1. Air-water flows in open channels,
2. Air-water flows in closed conduits, and
3. Free-fall water flows.

The first type usually is called *air-entraining* flow because air is entrained into the water mass. The second basic flow type generally is referred to as *air-demand*. The term *air-demand* is both misleading and technically incorrect, since an air vent does not demand air any more than an open valve demands water. However, since the term has been in common use for over 20 years, efforts to improve the nomenclature seem rather futile. The third type is referred also to as *air-entraining flow*.

[1]"siphon, inverted—A pipe line crossing over a depression or under a highway, railroad, canal, etc. The term is common but inappropriate, as no siphonic action is involved. The suggested term, *sag pipe*, is very expressive and appropriate." *Nomenclature for Hydraulics*, Comm. on Hyd. Str., Hyd. Div., ASCE, 1962.

# Purpose and Application

The purpose of this report is to summarize the work that has been done on *air-entrainment* and *air-demand* regarding the most recent theories and to suggest ways in which the results can be applied to design. The intent was to produce a concise reference of material from which design manuals, nomographs, and charts for specific applications could be prepared.

Although many generalizations of the data can be made, some types of flow conditions that are encountered in practice can be treated only by individual studies with physical models. These cases are identified when they occur.

Additional studies are needed in many areas. Some of the most critical areas requiring further research include the following:

- Effects of turbulence and air concentration on bubble dynamics
- Fluid dynamics in the developing aeration regime of free-surface flow
- Effects of hydraulic and conduit properties on probabilistic description of water surface in free-surface, high-velocity flow
- Effect of pressure gradients on air flow in partially-filled, closed conduits
- Bubble motion in closed-conduit flows for conduit slopes exceeding 45-degrees
- Effects of ambient pressure levels on cavitation characteristics of gates and valves discharging into a closed conduit
- Interaction between the air and a free jet

# Summary and Conclusions

Methods have been developed to predict the mean air concentration and the concentration distribution with open channel flow. A new description of the free water surface in high velocity flow is proposed which more accurately represents actual conditions in high velocity flow. The effect of air entrainment on the performance of a stilling basin can be estimated using a bulked flow concept. A computer program (app. II) is presented with which the mean air concentration in steep chutes and spillways can be estimated.

With exception of a falling-water surface and decreasing flow in pipelines, closed conduit flows require model studies. When properly conducted and analyzed, model studies will yield accurate data for estimating air-flow rates. Experimental methods are discussed. A computer program (app. III) is presented which can be used to predict the airflow rate with a falling-water surface. Design charts are presented for sizing air relief valves and vacuum valves on pipelines.

The airflow rate in vertical shafts was found to be extremely dependent upon the flow conditions at the shaft inlet. Equations are included for estimating the airflow rate having various inlet conditions.

Factors influencing the airflow rate around free falling jets are discussed. This area is identified as one needing additional research. Equations are presented from which the air entraining characteristics of a jet entering a pool can be estimated.