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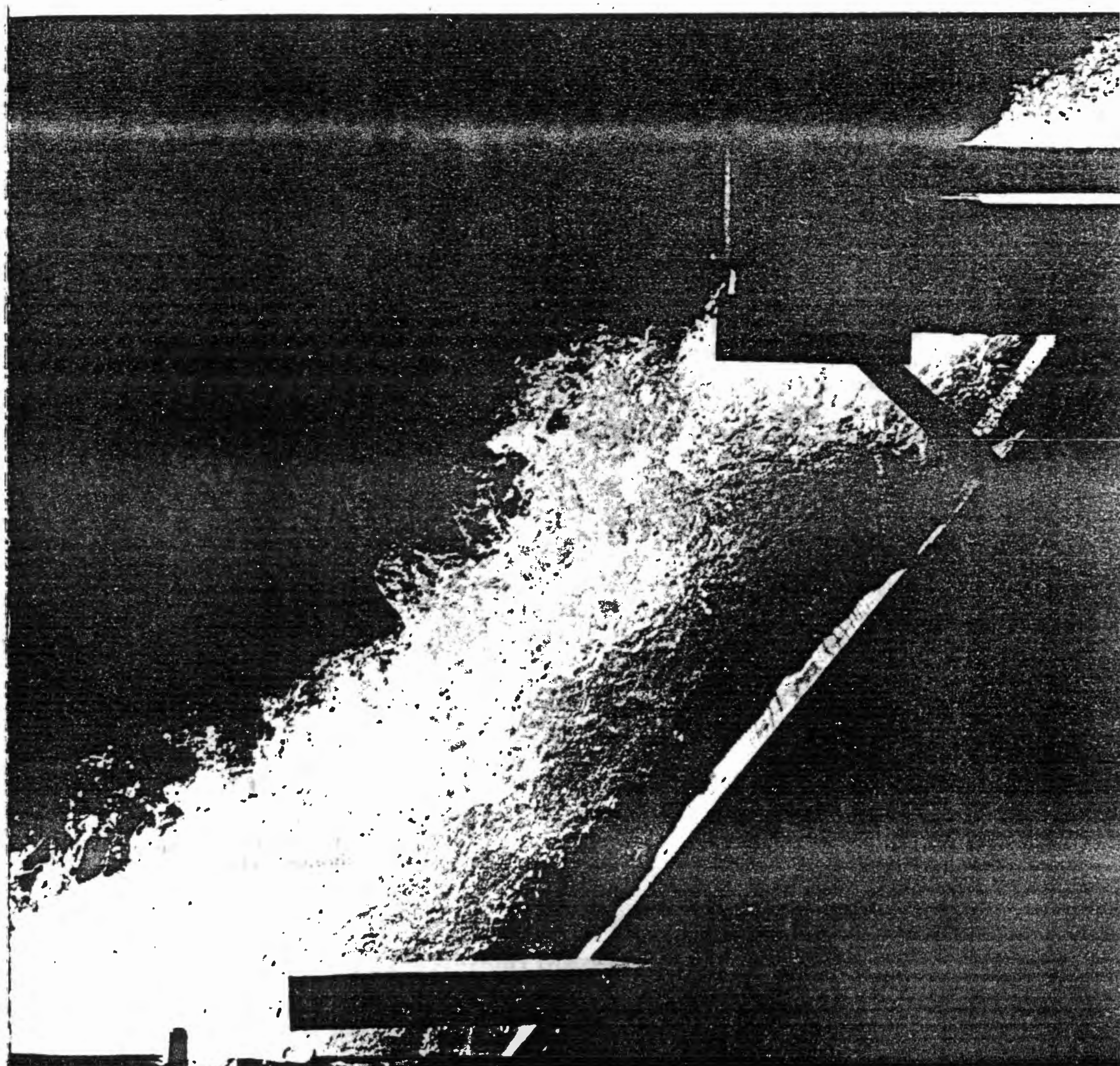
EXCERPT FROM

AIR-WATER FLOW IN HYDRAULIC STRUCTURES

UNITED STATES DEPARTMENT
OF THE INTERIOR
WATER AND POWER RESOURCES SERVICE



FRONTISPIECE.–*High velocity jet from a slide gate. P801-D-79275*

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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.

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
α	alpha	Angle chute invert makes with horizontal
β	beta	Ratio of volumetric airflow rate to waterflow rate
γ	gamma	Specific force of water
δ	delta	Boundary layer thickness
ε	epsilon	Mass transfer coefficient of bubbles
ζ	zeta	Air concentration distribution constant
η	eta	Normalized wave height
θ	theta	Void fraction
$\varkappa$	kappa	Gas constant
λ	lambda	Density ratio
μ	mu	Dynamic viscosity
μ_a		Dynamic viscosity of air
μ_w		Dynamic viscosity of water
ν	nu	Kinematic viscosity
ν_f		Water viscosity
π	pi	Ratio of the circumference of any circle to its radius, 3.14159...
ϱ	rho	Density
ϱ_a		Air density
ϱ_w		Water density
ϱ_g		Gas density
ϱ_l		Liquid density
ϱ_m		Density of manometer fluid
σ	sigma	Interfacial surface tension
τ_o	tau	Wall shear stress
τ_j		Shear stress at water jet
υ_{atm}	upsilon	Specific volume of air at atmospheric pressure
υ_*		Shear velocity
ψ	psi	Multicomponent flow parameter
ω	omega	Volume of gas bubble
ω_a		Volume of air
ω_w		Volume of water
∞		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	$= \frac{V}{(\sigma/\varrho D)^{1/2}}$

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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.