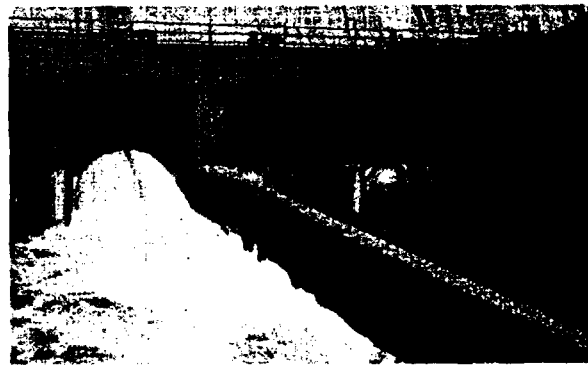
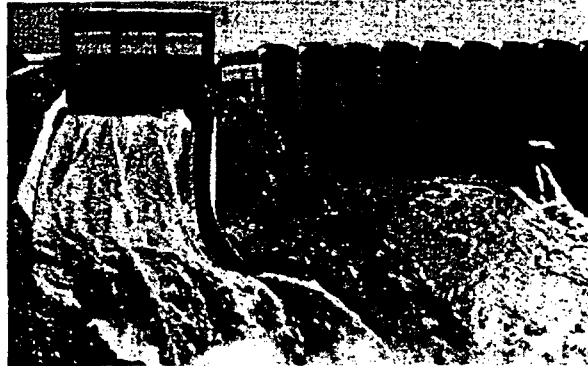


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# **AIR-WATER FLOW IN HYDRAULIC STRUCTURES**

**UNITED STATES DEPARTMENT  
OF THE INTERIOR  
WATER AND POWER RESOURCES SERVICE**

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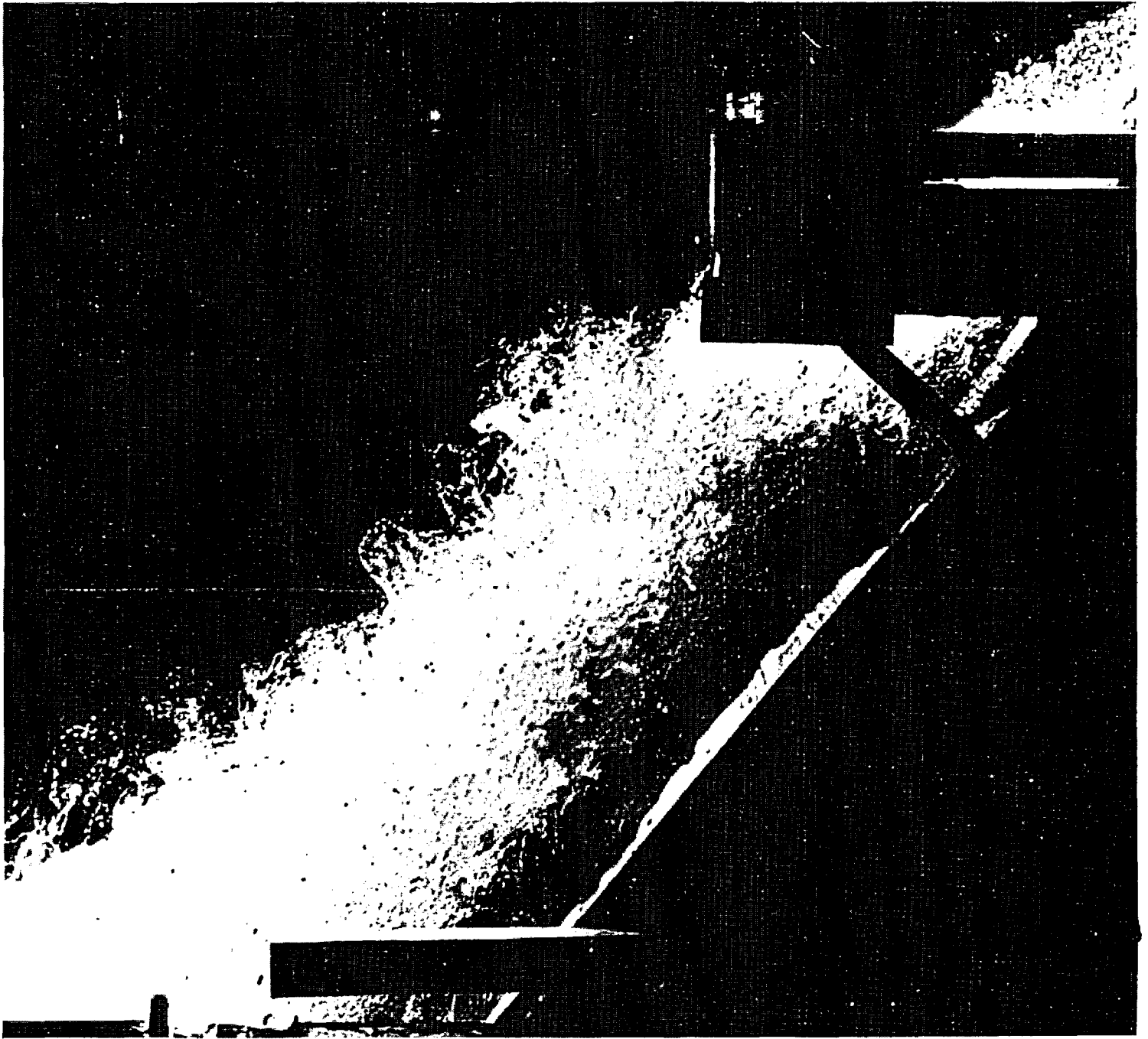
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# **AIR-WATER FLOW IN HYDRAULIC STRUCTURES**

By Henry T. Falvey  
Engineering and Research Center  
Denver, Colorado 80225

**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

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



# LETTER SYMBOLS and QUANTITIES—Continued

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

# LETTER SYMBOLS and QUANTITIES—Continued

Symbol	Quantity	Symbol	Quantity
$\alpha$ alpha	Angle chute invert makes with horizontal	E	Eötvös number = $\frac{\gamma D^2}{\sigma}$
$\beta$ beta	Ratio of volumetric airflow rate to waterflow rate	$E_u$	Euler number = $\frac{\Delta p}{\rho V^2}$
$\gamma$ gamma	Specific force of water	F	Froude number = $\frac{V}{(gD)^{1/2}}$
$\delta$ delta	Boundary layer thickness	P	Prandtl velocity ratio = $\frac{V}{(\tau_o/\rho)^{1/2}}$
$\epsilon$ epsilon	Mass transfer coefficient of bubbles	$P_o$	Poiseuille number = $\frac{h_a^2 (dp/dx)}{2\mu V}$
$\zeta$ zeta	Air concentration distribution constant	R	Reynolds number = $\frac{VD}{\nu}$
$\eta$ eta	Normalized wave height	$R_x$	Distance Reynolds number = $\frac{Vx}{\nu}$
$\theta$ theta	Void fraction	W	Weber number = $\frac{V}{(\sigma/\rho D)^{1/2}}$
$\kappa$ 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...		
$\rho$ rho	Density		
$\rho_a$	Air density		
$\rho_w$	Water density		
$\rho_g$	Gas density		
$\rho_l$	Liquid density		
$\rho_m$	Density of manometer fluid		
$\sigma$ sigma	Interfacial surface tension		
$\tau_o$ tau	Wall shear stress		
$\tau_j$	Shear stress at water jet		
$v_{atm}$ upsilon	Specific volume of air at atmospheric pressure		
$v_s$	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		

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# Introduction

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In many engineering projects a strong interaction develops 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)<sup>1</sup> 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*.

---

<sup>1</sup>"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.

# Open Channel Flow

---

## INTRODUCTION

In observing flow in a chute or on an overflow spillway, one normally observes a region of clear water where the water enters the chute or spillway. Then—at some distance downstream—the water suddenly takes on a milky appearance. Lane [46] suggested that the “white water” begins when the turbulent boundary layer from the floor intersects the water surface. The validity of this assumption has been verified by many researchers. The cases in which the boundary layer creates the air entrainment are referred normally to as *self-aerated* flows. However, this is not the only way in which air entrainment can begin on chutes and spillways. The American Society of Civil Engineers Task Committee on Air Entrainment in Open Channels [5]<sup>2</sup> has summarized tests in which air entrainment is generated by the boundary layer on the side walls of chutes. They also reported tests in which air entrainment was observed downstream of piers on overflow spillways. This latter case is the result of the flow rolling over on itself as it expands after passing through the opening between the

piers. Levi [49] reported on longitudinal vortices on spillway faces. These vortices can entrain air if they intersect the water surface. All of these forms of air entrainment are apparent in figure 1.

Air entrainment implies a process by which air enters into a body of water. Normally, the appearance of “white water” is considered to be synonymous with entrainment. This is not always true. For instance, if the water surface is rough enough and moving at a sufficiently high velocity, the surface will appear to be white even though the water volume contains no air. The whiteness of the water is caused by the large number of reflections coming from different angles off the rapidly moving highly irregular surface (refer to frontispiece). For high water velocities, one’s eye does not respond rapidly enough to observe each individual reflection. Instead, these individual reflections blur into a fuzzy mass which appears white. High speed photography of “white water” demonstrates this effect very well. This leads one to the obvious conclusion that a flow could conceivably appear frothy but actually does not entrain any air! With air in the water, reflections also come from the surface of the bubbles. These reflections produce the same impression

---

<sup>2</sup>Numbers in brackets refer to the bibliography.

# Closed Conduit Flow

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## CLASSIFICATION OF FLOW

The conventional term for the concurrent flow of air and water is *two-phase* flow. Here, *phase* refers to one of the states of matter (gas, liquid, or solid). Technically the term two-phase flow should be reserved to describe the motion of a substance which is present in two of its phases, such as a flow of ice and water. The word *multicomponent* is a better description of flows which do not consist of the same chemical substance, such as air and water. If both components move in the same direction, the flow is termed *concurrent flow*. If the components move in opposite directions, the flow is *counter-current*.

Closed conduit flow can be classified according to the type of pattern that develops. The flow patterns which develop depend upon the airflow rate relative to the waterflow rate and the slope of the conduit. For example, the flow

patterns in horizontal conduits have been defined by Baker [7], (fig. 20). The correlation can be applied to other gases and liquids by substituting appropriate quantities into the following parameters:

$G_g$  = mass velocity of gas,  $\text{kg}/(\text{m}^2 \cdot \text{s})$

$G_l$  = mass velocity of liquid,  $\text{kg}/(\text{m}^2 \cdot \text{s})$

$\lambda = [(G_g/\rho_g)(G_l/\rho_l)]^{1/2}$

$\mu$  = dynamic viscosity,  $\text{Pa} \cdot \text{s}$

$\rho_g$  = gas density,  $\text{kg}/\text{m}^3$

$\rho_a$  = air density (at 101.3 kPa and 20 °C) =  $1.20 \text{ kg}/\text{m}^3$

$\rho_l$  = liquid density,  $\text{kg}/\text{m}^3$

$\rho_w$  = water (at 101.3 kPa and 20 °C) =  $988 \text{ kg}/\text{m}^3$

$\sigma$  = interfacial surface tension,  $\text{N}/\text{m}$

$\sigma_{aw}$  = air-water surface tension (at 101.3 kPa and 20 °C) =  $0.0728 \text{ N}/\text{m}$

$\psi = (\rho_w/\rho_l)[\mu(\rho_w/\rho_l)^2]^{1/3}$ ,  $\text{Pa}^{1/3} \cdot \text{s}^{1/3}$

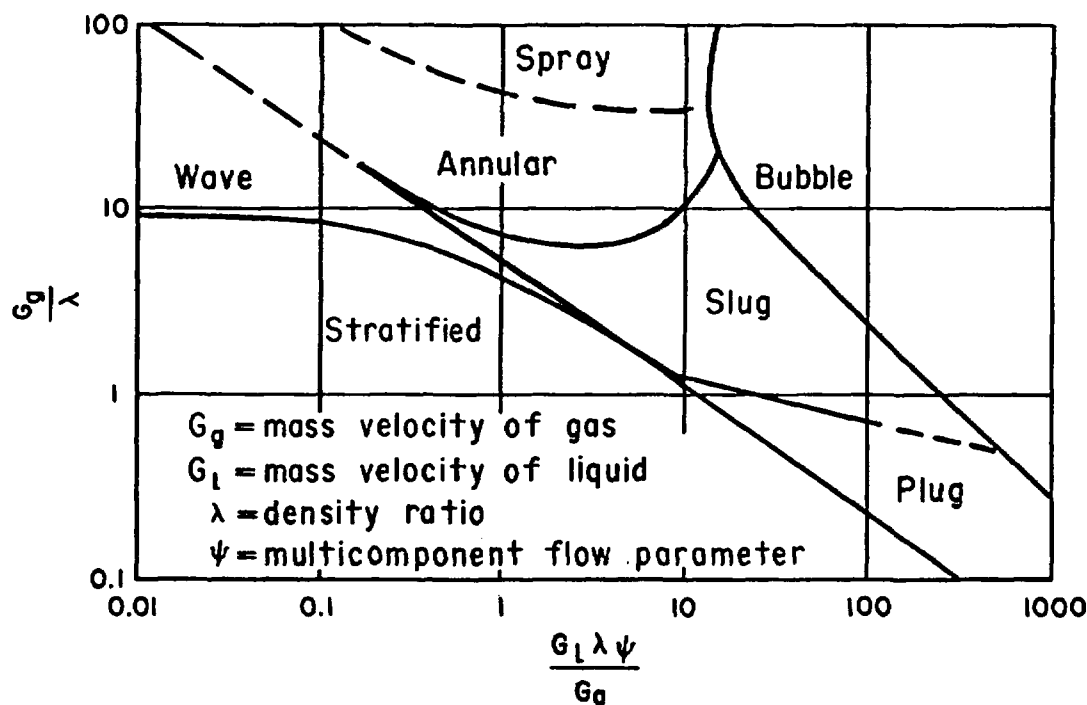


FIGURE 20.—Flow patterns in horizontal pipes, Baker [7].

These various flow patterns were described by Alves [1] according to the physical appearance of the flow as follows (fig. 21):

- **Bubble flow.**—The air forms in bubbles at the upper surface of the pipe. The bubble and water velocities are about equal. If the bubbles are dispersed through the water, the flow is called "froth flow."
- **Plug flow.**—For increased airflow rates the air bubbles coalesce with plugs of air and water alternately flowing along the top of the pipe.
- **Stratified flow.**—A distinct horizontal interface separates the air and waterflows.
- **Wave flow.**—As the airflow rate is increased, surface waves appear on the stratified flow interface.
- **Slug flow.**—Wave amplitudes are large enough to seal the conduit. The wave

forms a frothy slug where it touches the roof of the conduit. This slug travels with a higher velocity than the average liquid velocity.

- **Annular flow.**—For greater airflow rates the water flows as a film on the wall of the pipe, while the air flows in a high-speed core down the axis of the pipe.
- **Spray flow.**—For very great airflow rates the annular film is stripped from the pipe walls and is carried in the air as entrained droplets.

A similar set of flow pattern descriptions exist for vertical flows. They are:

- **Bubble flow.**—The air is distributed in the water as spherical or spherical cap bubbles which are small with respect to the conduit diameter.

- **Slug flow.**—As the air flow increases, alternate slugs<sup>5</sup> of air and water move up the pipe. The transition from bubble flow to slug flow is shown on figure 22. This transition occurs when the bubble diameter is about one-half the conduit diameter.

If the vertical conduit is rectangular instead of cylindrical, the appropriate relation for slug flow is given by Wallis [73] as

$$\frac{V_s}{V_t} = \left(0.325 + 0.184 \frac{D_s}{D_b}\right) \left(\frac{D_e}{D_s}\right)^{-1/2} \quad (65)$$

where

$D_s$  = larger dimension of a rectangular conduit

$D_b$  = smaller dimension of a rectangular conduit

$D_e$  = bubble diameter

$V_s$  = terminal velocity of air bubbles in slug flow

$V_t$  = terminal velocity of air bubbles in still water

With respect to the flow quantities, Martin [52] found that the transition from bubbly to slug flow occurs at a void fraction somewhere between 19 and 23 percent.

The void fraction  $\theta$  is the average volumetric concentration in a length of pipe (assuming uniform flow) and expressed as

$$\theta = \frac{\omega_w}{AL} \quad (66)$$

<sup>5</sup>It is not clear whether the term slug refers to a slug of air or a slug of water. The air bubble could be called a slug due to its bullet or slug shaped form. The water could be called a slug due to its similarity in form to the terrestrial gastropod in horizontal flows or due to its impact properties in vertical flow. The author prefers the reference to slugs of air.

where

$\omega_w$  = volume of water

$A$  = cross sectional area of conduit

$L$  = length of conduit over which the volume  $\omega_w$  is determined

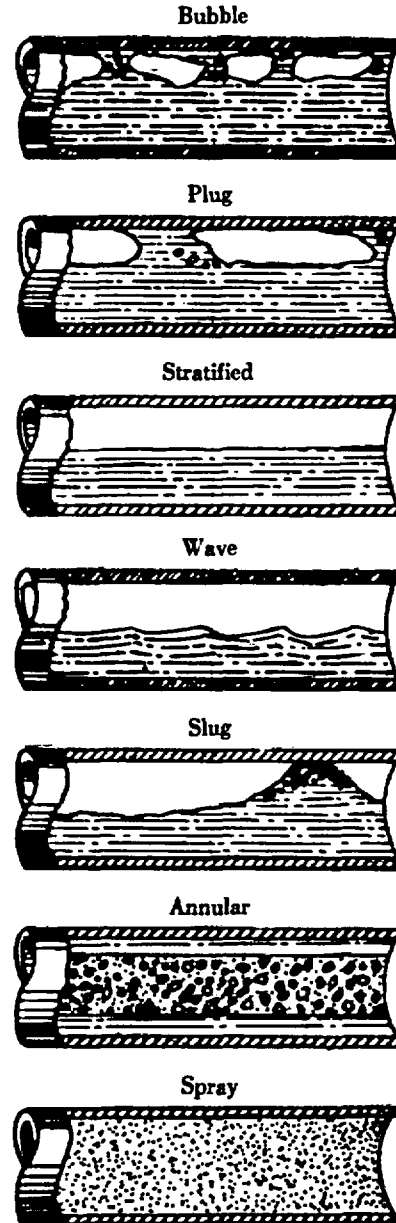


FIGURE 21.—Flow pattern sketches, Alves [1].

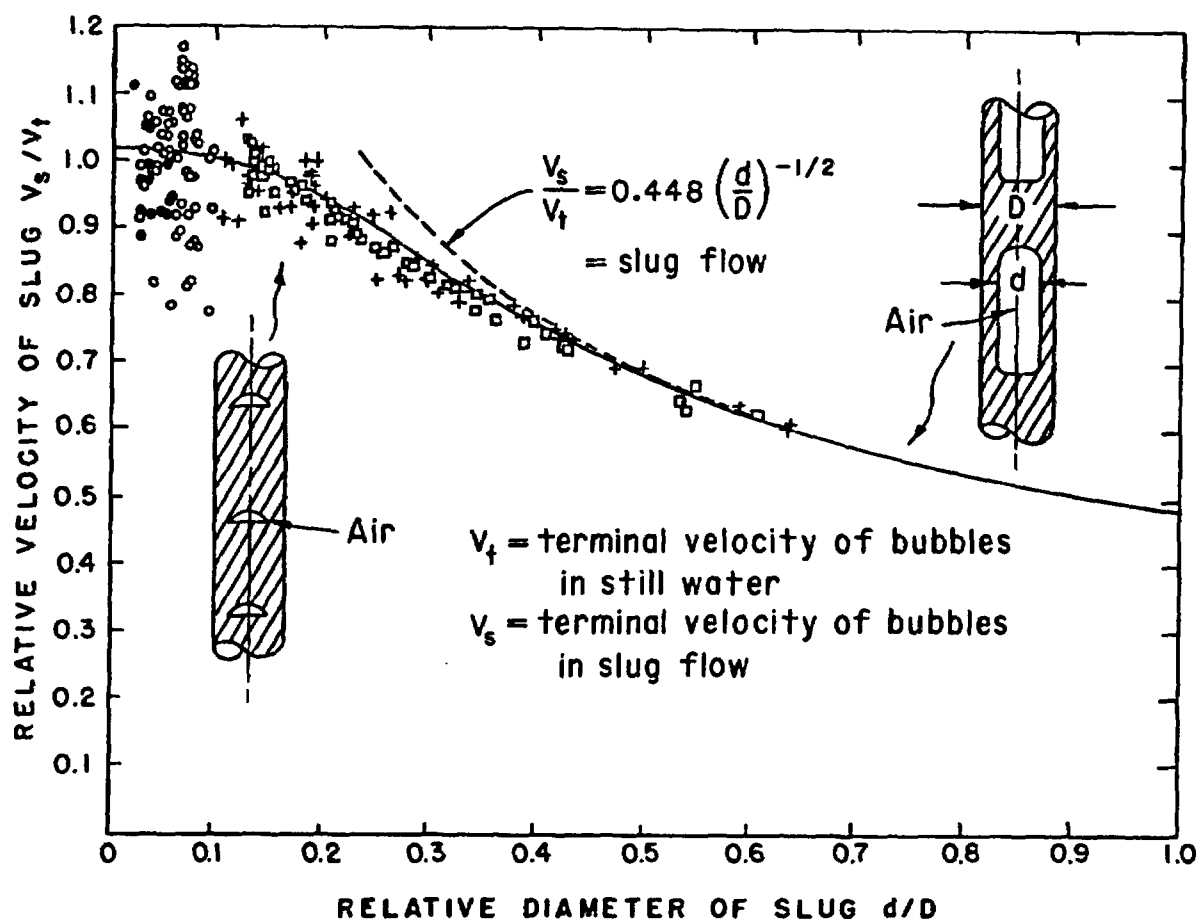


FIGURE 22.—Effect of conduit diameter on terminal velocity of a bubble, Collins [16].

- Froth flow.—As the airflow increases, the slugs break up into a turbulent disordered pattern of air and water.

The annular and spray flow patterns are identical in both vertical and horizontal pipes.

In hydraulic structures, the conduits may also be placed on a slope. The additional complexities in the flow patterns caused by slope will be discussed later.

From a designer's viewpoint, air-water flows in closed conduits can be classified into four general categories. Each category may contain only one or a combination of the flow patterns enumerated previously. These categories are:

1. Flow in partially filled conduits,

2. Flow having a hydraulic jump that fills the conduit,
3. Flow from control devices, and
4. Falling water surface.

Each category listed above is considered in detail in the following subsections.

In addition to the four categories of flow, two others are considered separately. These are:

- Flow in pipelines and siphons
- Flow in vertical shafts

The pipelines and siphons require special consideration because of their length. Vertical shafts present special problems because of the various types of flow which can exist in the shaft.

## FLOW IN PARTIALLY FILLED CONDUITS

### Model Predictions

Flow in a partially filled conduit can be thought of as open-channel flow in a closed conduit. The air flows through the passage which is formed above the water surface.

The total volume flow of air, which enters at the upstream end of the air passage, equals the sum of the air that is insufflated into the flow and that which flows above the water surface as a result of the air-water shear forces. The quantity of air insufflated into the flow can be estimated from equation 59. The quantity of air that flows above the water surface is a function of the waterflow properties and the pressure drop in the air vent. This can be expressed as

$$Q_a = f(L, V, g, p, \gamma_e, Q_w) \quad (67)$$

where

$A$  = cross sectional area of water prism

$g$  = gravitational constant (acceleration)

$L$  = conduit length

$p$  = pressure intensity

$Q_a$  = total airflow rate

$T$  = top width of flow passage

$V$  = mean water velocity

$\gamma_e$  = effective depth =  $A/T$

$Q_w$  = water density

Applying dimensional analysis to equation 67 with  $\gamma_e$ ,  $V$ , and  $Q_w$  as the repeating variables gives

$$\frac{Q_a}{Q_w} = f\left(\frac{L}{\gamma_e}, \frac{1}{F^2}, \frac{p/\gamma}{V^2/2g}\right) \quad (68)$$

where

$F$  = Froude number

$Q_w$  = waterflow rate

$\gamma$  = specific force of water

The interrelation between these parameters can be found for a specific geometry through the use of model studies.

There are many literature references that indicate model predictions often underestimate in the quantity of air which actually flows in prototype structures. However, very careful model tests in which all air- and waterflow passages were modeled in their entirety have shown good agreement between model and prototype measurements.

For instance, Sikora [65] showed that the air-flow rates could be accurately predicted from model studies. His tests were with three geometrically similar models having scales of 1:1, 1:2, and 1:4 (fig. 23). The pressure values on the figure refer to the difference between atmospheric pressure and the air pressure at the upstream end of the waterflow passage.

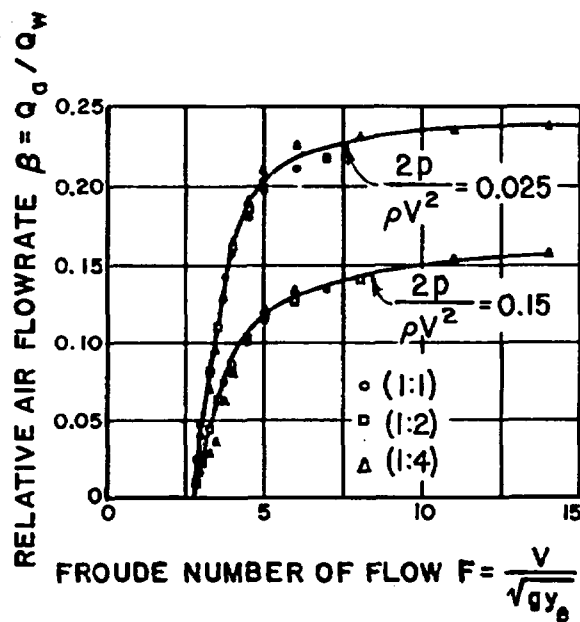


FIGURE 23.—Influence of air pressure in conduit in air-flow rate, Sikora [65].

Harshbarger, Vigander, and Hecker [32] conducted 1:20 scale model and prototype tests of a gated tunnel discharge. Free-surface flow

existed in the tunnel for all discharges. A scale effect was not detectable in their investigations.

These studies clearly indicate that for estimating airflow rates using models, it is necessary to accurately reproduce the entire airflow passage above the water surface. In those cases where air enters the water conduit through a vent, two options are available for measuring the airflow rates. The options depend upon whether or not the air vent has been designed.

*Air vent not designed.*—If the air vent design has not been determined, it is necessary to measure the airflow rate while controlling the air pressure at the upstream end of the water conduit. These tests must be performed for a series of flow depths and flow rates in the water conduit.

The upstream air pressures can be controlled by incorporating an air pump into the airflow measuring device. To be applicable for all possible designs, the pressure should be varied over the maximum possible range. The lowest end of the range corresponds with the condition of no airflow through the vent. The upper end of the range is achieved when the upstream air pressure is equal to the atmospheric pressure.

A good example of this procedure is the work by Sikora [65] who developed a set of curves for the airflow in the horizontal leg of morning-glory spillway (fig. 24).

Once the family of curves for the airflow rates has been experimentally determined it is possible to investigate the effect of adding various size air vents to the structure. This is done by first developing an expression for the air vent characteristics in terms of the dimensionless parameters on figure 24.

For air velocities less than 100 m/s and values of  $fL/4H \geq 4$ , the volume flowrate  $Q_a$  through a vent can be expressed as

$$Q_a = A_v \left\{ 2g \frac{(Q_w/Q_a)[(p_{atm}/\gamma) - (p_1/\gamma) + \Delta z(Q_a/Q_w)]}{\sum K_s + fL/4H} \right\}^{1/2} \quad (69)$$

where

$A_v$  = cross sectional area of vent

$f$  = Darcy-Weisbach friction factor

$g$  = gravitational constant (acceleration)

$H$  = hydraulic radius of prototype air vent

$K_e$  = entrance loss

$K_s$  = singular (form) loss in vent, the greatest of which is the entrance loss

$K_e = 0.5$

$L$  = vent length

$p_1$  = pressure at vent exit

$p_{atm}$  = atmospheric pressure

$\Delta z$  = difference between vent intake and vent exit elevations

$\gamma$  = specific force of water

$Q_a$  = air density

$Q_w$  = water density

Volume flowrate of water can be expressed as

$$Q_w = A \left[ 2g \left( \frac{V^2}{2g} \right) \right]^{1/2} \quad (70)$$

where

$A$  = cross sectional area of water prism

$V$  = mean waterflow velocity in conduit

Using these two expressions, the dimensionless airflow rate  $\beta$  can be expressed as

$$\beta = \frac{Q_a}{Q_w} = \frac{A_v}{A} \left\{ \frac{Q_w/Q_a}{\sum K_s + fL/4H} \left[ \frac{(p_{atm}/\gamma) - (p_1/\gamma)}{V^2/2g} \right] \right\}^{1/2} \quad (71)$$

when  $\Delta z \frac{Q_a}{Q_w}$  is negligible.

The first ratio inside the brackets is a function of the fluid properties, the singular losses, and the flow geometry. The second ratio is in the form of a pressure factor or Euler number. By using this equation, the characteristics of a given vent can be plotted on the dimensionless airflow curves (fig. 24). The intersection points



- $A$  = cross sectional area of water prism  
 $A_d$  = cross sectional area of conduit  
 $d_e$  = deflector height  
 $F$  = Froude number =  $\frac{V}{\sqrt{gy_e}}$   
 $\rho$  = air density  
 $g$  = gravitational constant  
 $p$  = pressure at end of air vent  
 $\Delta p$  = pressure drop across vent  
 $Q_a$  = volume flowrate of air  
 $Q_w$  = volume flowrate of water  
 $V$  = mean flow velocity  
 $y_e$  = effective depth

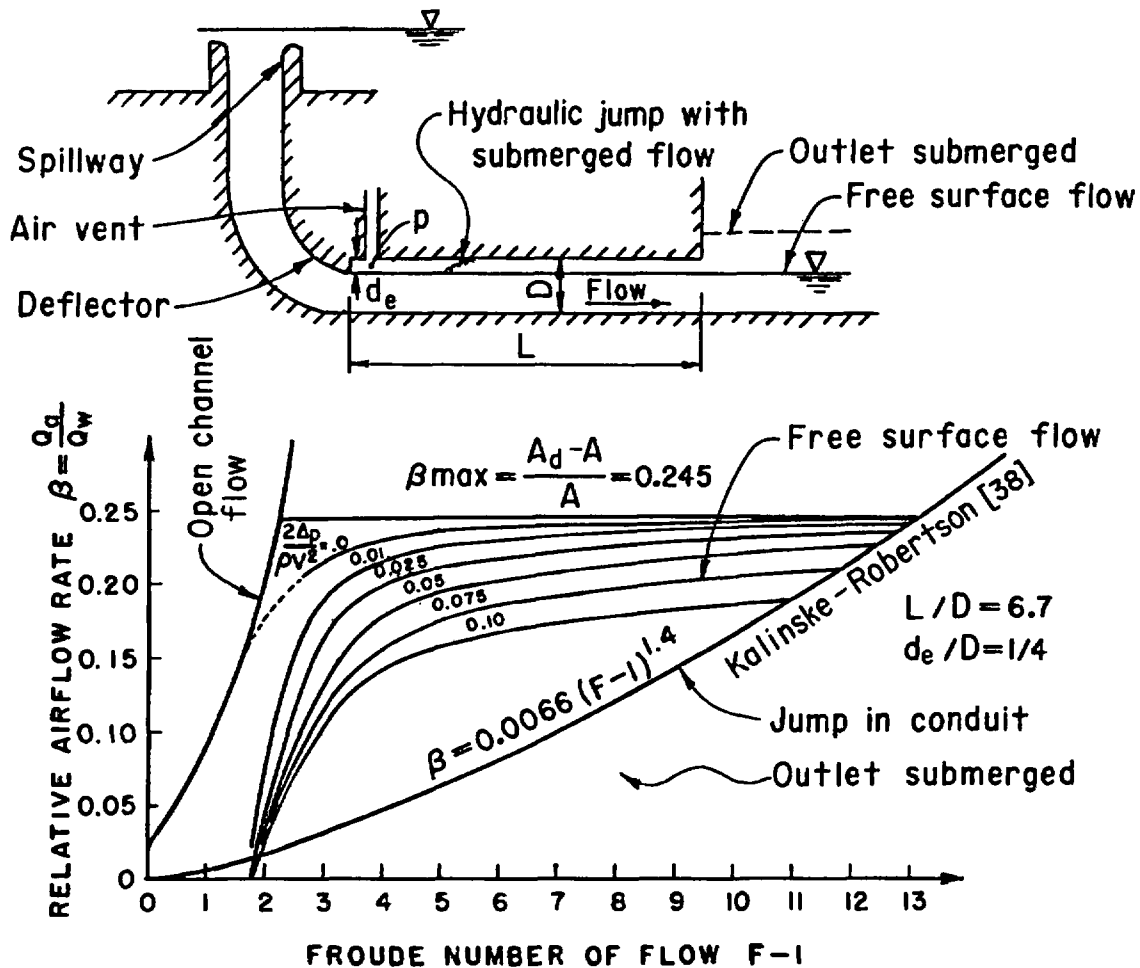


FIGURE 24.—Model tests on a spillway, Sikora [65].

of the two sets of curves gives the pressures and airflow rates for a given set of air vent parameters. If the resulting values are not satisfactory, another set of vent characteristics is chosen and the process repeated.

*Air vent designed.*—For some studies the design of the air vent is available. In these cases it is necessary to calculate the total loss for the vent and to simulate this loss in the model air vent. The loss for the prototype and the model must include both frictional and form losses. Normally, the air vent velocities are kept low enough so that incompressible loss coefficients are valid. The model air vent is simulated correctly when the loss coefficients in the model and prototype vents are made equal. If devices such as nozzles or orifices are installed into the model air vent for flow measurement purposes, the loss across them must be included in computing the total model air vent loss coefficient. In the case of an orifice, its loss coefficient often constitutes the entire loss for the model air vent. It is possible to express the required orifice size as

$$A_o = \frac{A_v}{C_o L_r^2 \left(1 + \sum K_s + fL/4H\right)^{1/2}} \quad (72)$$

where

$A_o$  = orifice area

$A_v$  = prototype air vent area

$C_o$  = orifice discharge coefficient

$f$  = Darcy-Weisbach factor for prototype air vent

$H$  = hydraulic radius of prototype air vent

$K_s$  = singular losses (including entrance, bends, and changes in area)

$L$  = length of prototype air vent

$L_r$  = prototype to model scale ratio

If the orifice is placed on the end of the model air vent pipe, its discharge coefficient is obtained from figure 25.

### Analytic Estimates

In many instances, model tests for predicting the airflow rates have not been performed. For these cases, the airflow rates often can be estimated closely enough by an approximate method. For this estimation three rather gross assumptions must be made, namely:

1. The amount of air flowing through the vent is a function of only the air insufflated into the flow and the air that is induced to flow by the moving water boundary,
2. The amount of air insufflated into the flow can be predicted by open channel flow equations, and
3. The air motion above the water surface is determined solely by the boundary layer  $\delta$  thickness at the most downstream conduit location.

These assumptions neglect the fact that air actually can enter from the downstream end of the conduit. Schlichting [63] showed that with Couette-Poiseuille<sup>6</sup> flow in the laminar region, a flow reversal occurs when

$$P_o = \frac{h_a^2}{2\mu V_o} \left( \frac{dp}{dx} \right) \leq -1 \quad (73)$$

<sup>6</sup>The dimensionless parameter  $P_o$  is known as the Poiseuille number. Its primary use is in the laminar fluid friction field. For example, in a round circular pipe, the Poiseuille number is equal to 32. In this case the pipe diameter is substituted for the height of the airflow passage in equation 73. Couette flow exists between two parallel walls when one wall is moving and the other is stationary. The motion is due solely to the shear field created by the relative movement of the two walls. Couette flow has no pressure gradient in the direction of flow. Couette-Poiseuille flow describes a Couette type flow having a longitudinal pressure gradient. Turbulent Couette-Poiseuille flow should describe the air motion above a moving water surface in a closed conduit.

$A_d$  = conduit area

$A_o$  = orifice area

$H_m$  = head across orifice

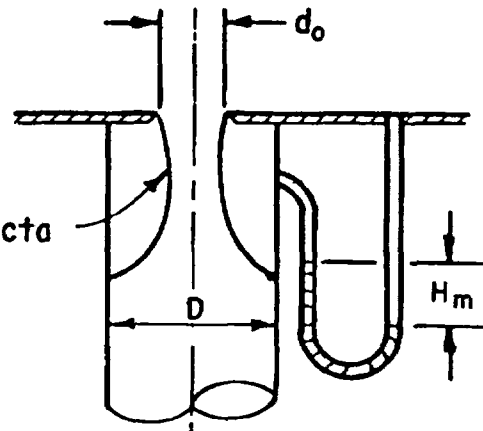
$$H_m = h_m (\rho_m / \rho_a)$$

$Q$  = volume flowrate of air

$\rho_a$  = density of air

$\rho_m$  = density of manometer fluid

Vena contracta



$$\frac{A_o}{A_d} = \frac{d_o^2}{D^2}$$

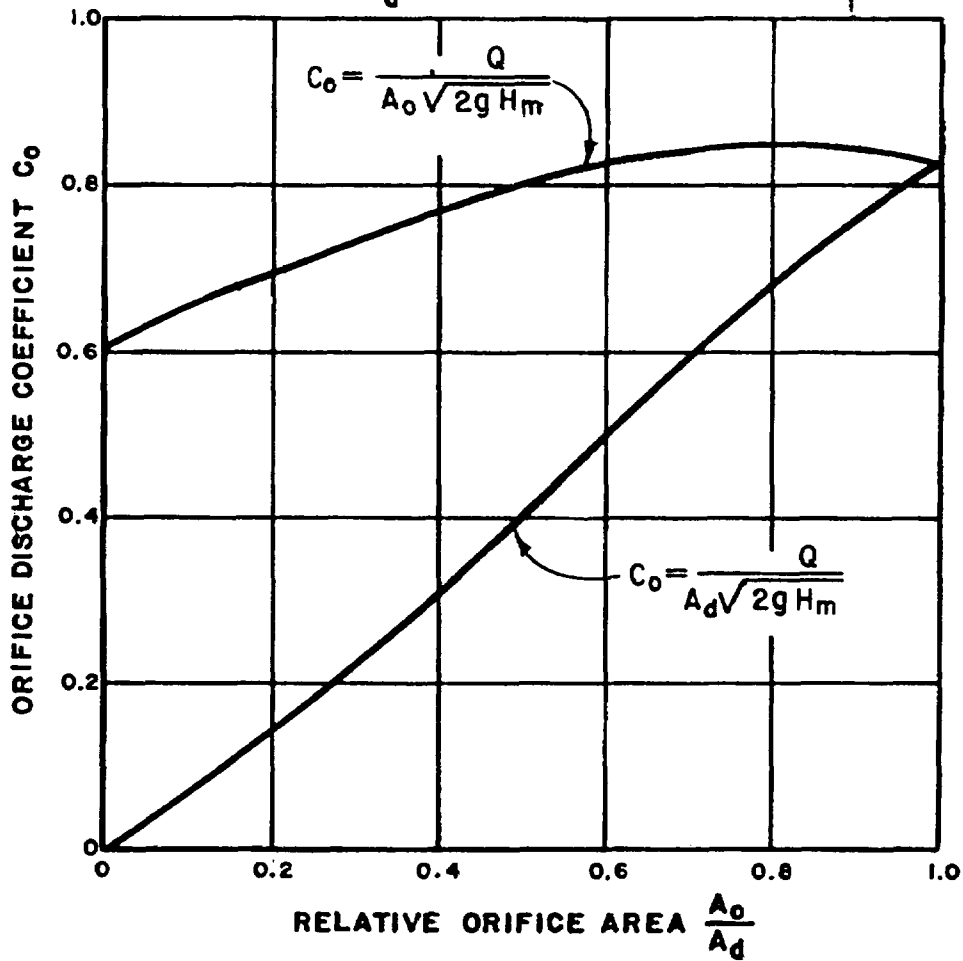


FIGURE 25.—Discharge coefficients for orifice at end of pipe.

where

$h_a$  = height of airflow passage  
 $dp/dx$  = pressure gradient in the air  
 $V_o$  = maximum water surface velocity  
 $\mu$  = dynamic viscosity of air

Leutheusser and Chu [48] have investigated Couette flow in the turbulent region. Insufficient tests have been made to determine the magnitude of the dimensionless parameter  $P_o$  for the turbulent Couette-Poiseuille flow. However, some laboratory tests indicate that with turbulence, reverse flow begins when

$$P_o \approx -1000 \quad (74)$$

The amount of air flowing above the water surface can be visualized by considering a boundary layer which increases in thickness from a value of zero at a gate, to a maximum value at the end of the conduit (fig. 26). The growth of a turbulent boundary layer that is induced by a moving rough boundary has not been studied. As a first approximation it is assumed that

$$\delta = 0.01x \quad (75)$$

where

$\delta$  = boundary layer thickness  
 $x$  = distance from gate

The velocity distribution within the boundary layer is assumed to obey a power law of the order:

$$u = V_o \left( \frac{y_a}{\delta} \right)^{1/n_v} \quad (76)$$

where

$n_v$  = velocity distribution power law coefficient

$u$  = local air velocity

$V_o$  = maximum water surface velocity

$y_a$  = distance from the water surface

$\delta$  = boundary layer thickness

The value of the coefficient  $n_v$  varies between 10 for flow over smooth surfaces to 5.4 for flow over rough surfaces when the Reynolds number is about  $10^6$ . Normally  $n_v$  is assumed to be equal to 7. This approach is similar to that used by Campbell and Guyton [12] except they assumed the boundary layer always coincided with the roof of the conduit.

The boundary layer entrains the maximum amount of air at the extreme downstream location in the conduit. To maintain continuity, flow at upstream locations consists of boundary layer flow plus some mean flow (fig. 26). The air velocity at the water surface must be equal to the water velocity. Therefore, at the upstream locations, the air velocity above the water surface may have a larger magnitude than that at the water surface. Careful laboratory experiments by Ghetti [24] of the Vaiont Dam (Italy) gated outlets show that the maximum air velocity near the water surface at the vent can be as much as four times the water velocity.

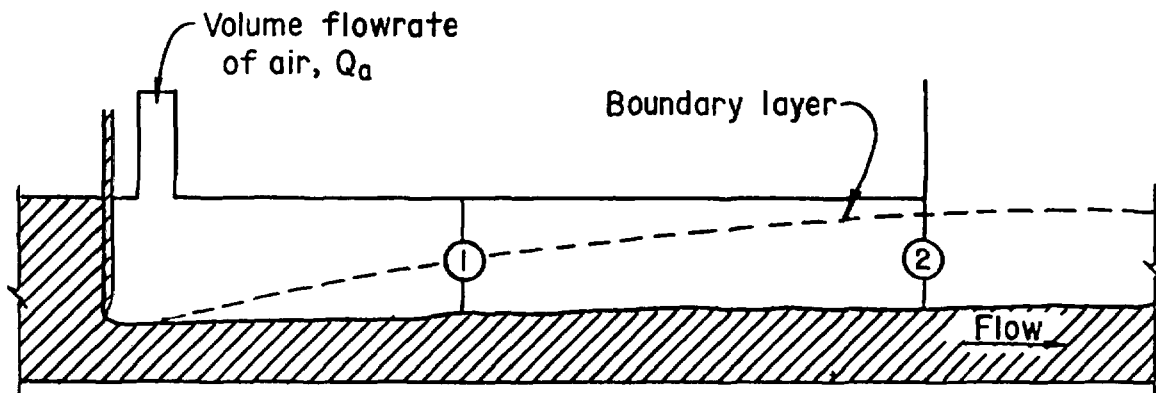
For some flow conditions the boundary layer will reach the roof of the conduit. When this happens the roof will begin to retard the flow. If the water surface and the roof of the conduit had equal roughness values, the maximum flow rate would be given by turbulent plane Couette flow. For this case the maximum airflow rate  $Q_m$  is

$$Q_m = \frac{A_a V_o}{2} \quad (77)$$

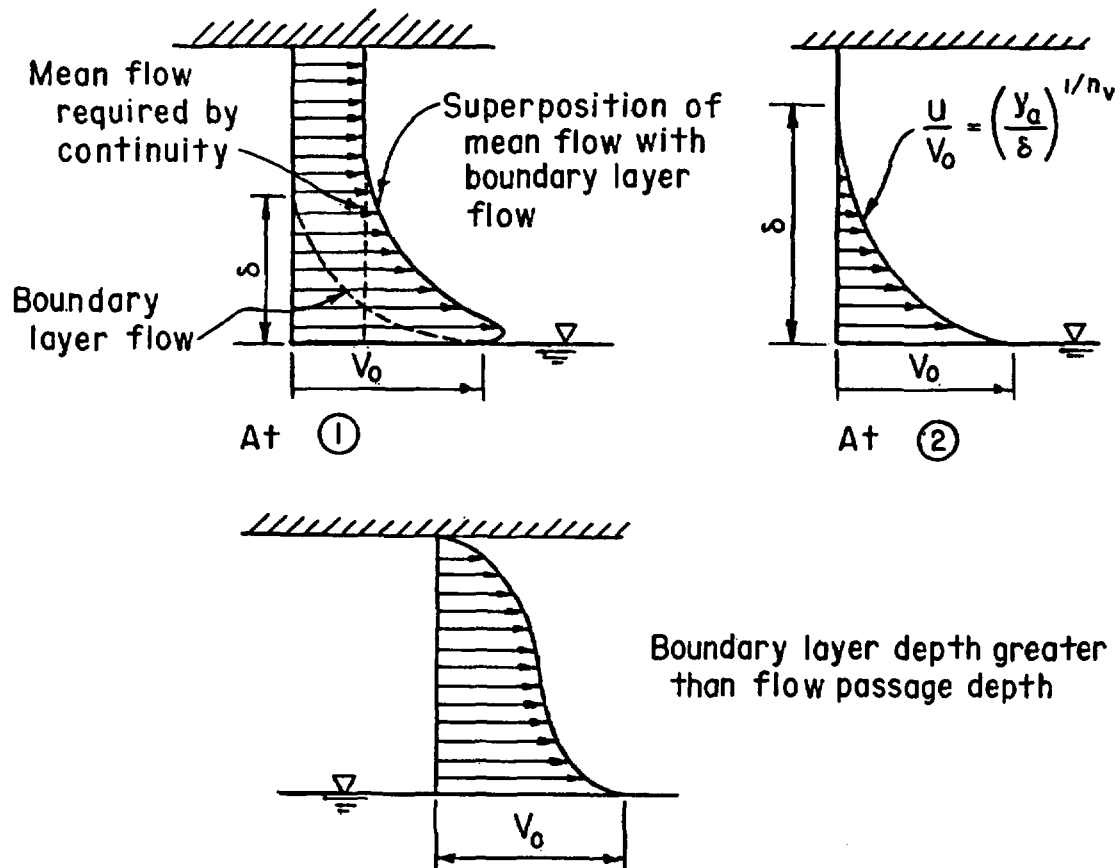
where

$A_a$  = cross sectional area of airflow passage (rectangular)

$V_o$  = maximum water surface velocity



A. Profile sketch



B. Velocity distribution

FIGURE 26.—Airflow above water surface.

Actually the roughness of the water surface is greater than that of the conduit roof. This increased roughness will produce higher air velocities near the water surface which result in airflow rates greater than those given by equation 77. Sikora [65] reasoned that the mean air velocity could not exceed the mean water velocity. This leads to the expression for the maximum possible airflow rate in a closed conduit, which is

$$\left(\frac{Q_a}{Q_w}\right)_{max} = \frac{A_d}{A} - 1 \quad (78)$$

where

$A_d$  = cross sectional area of conduit  
 $A$  = maximum cross sectional area of water prism

Application of equation 78 without regard to the boundary layer thickness will result in excessively large values of the airflow rates. However, for design purposes, this approach may be satisfactory since the resulting air vent will be oversized.

### FLOW HAVING A HYDRAULIC JUMP THAT FILLS THE CONDUIT

Kalinske and Robertson [38] studied the special case of two-layer flow in which a hydraulic jump fills the conduit. From dimensional analysis and model studies, they determined that the amount of air entrained by the jump is given by

$$\frac{Q_a}{Q_w} = 0.0066 (F - 1)^{1.4} \quad (79)$$

where  $F$  = Froude number upstream of the hydraulic jump.

In a circular pipe the Froude number can be calculated conveniently from the flow depth  $y$  using

$$F = \frac{V}{(gy_e)^{1/2}} \quad (80)$$

where

$A$  = cross sectional area of water prism  
 $D$  = conduit diameter  
 $T$  = top width of flow  
 $\text{passage} = 2[y(D - y)]^{1/2}$   
 $g$  = gravitational constant (acceleration)  
 $V$  = mean flow velocity  
 $y_e$  = effective depth =  $A/T$   
 $y$  = flow depth

Equation 79 is good only if all air entrained is passed downstream. Prototype tests—for which a hydraulic jump formed in the conduit and in which the conduit velocities were large enough to convey all the entrained air out of the conduit—confirm the experimentally derived curve (fig. 27).

If the conduit is horizontal or sloping upward in the direction of flow then all the entrained air will move with the flow. However, if the conduit slopes downward in the direction of flow air bubbles can either move upstream or downstream relative to the pipe wall.

The direction of movement taken by the bubbles can be examined by considering the relative magnitudes of the buoyant and drag forces upon a stationary bubble in the flow (fig. 28). For example, the bubble will move perpendicular to the pipe axis only when the upstream component of the buoyant force vector equals the drag force component. This can be written as

$$(q_w - q_g) \frac{\pi D_e^3}{6} (g S_o) = C_b \frac{\pi D_e^2}{4} \left( \frac{q_w V^2}{2} \right) \quad (81)$$

where

$C_b$  = drag coefficient on bubble  
 $D_e$  = equivalent bubble diameter  
 $S_o$  = pipe slope =  $\sin \alpha$

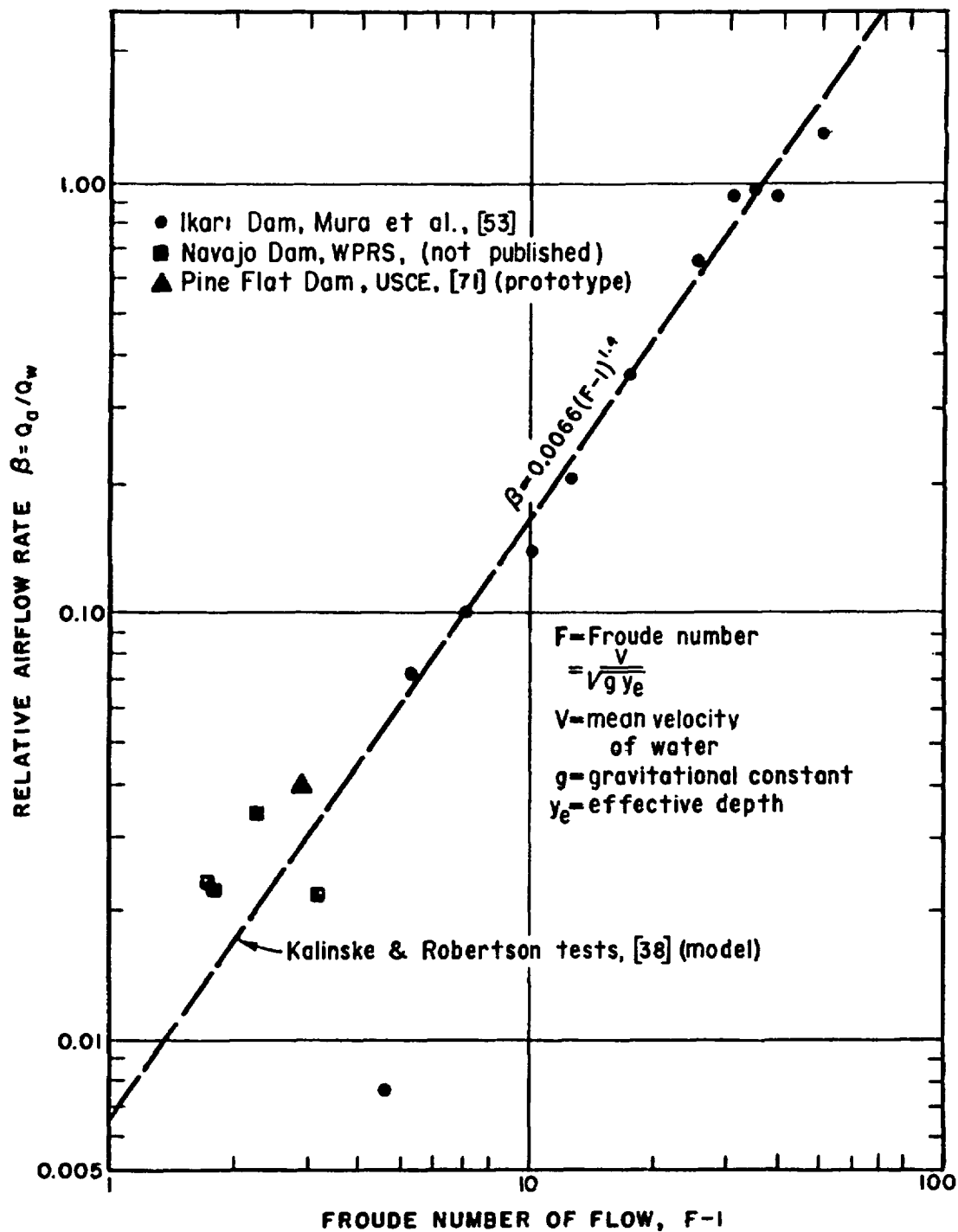


FIGURE 27.—Air entrainment with hydraulic jump closing conduit.

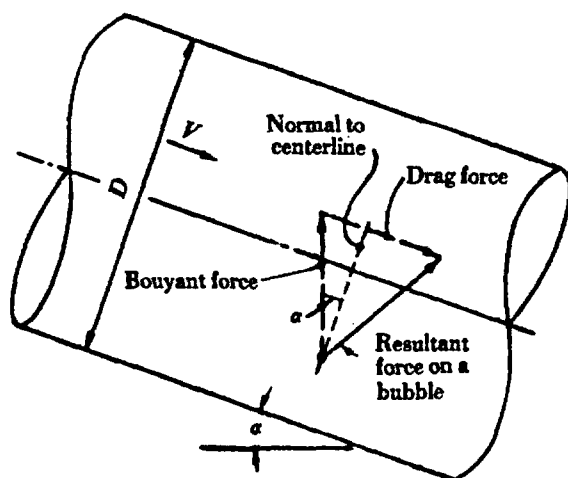


FIGURE 28.—Forces on a stationary bubble.

Rearranging terms and dividing by the conduit diameter gives

$$\frac{V^2}{gD} = \frac{4}{3} [1 - (\rho_g/\rho_w)] \frac{D_e(S_o)}{D(\bar{C}_b)} \quad (82)$$

or

$$\frac{Q_c^2}{gD^5} = \frac{\pi^2}{12} [1 - (\rho_g/\rho_w)] \frac{D_e(S_o)}{D(\bar{C}_b)} \quad (83)$$

where

$Q_c$  = critical discharge needed to carry bubbles with the flow

$D$  = conduit diameter

This relation shows that the critical discharge for bubble motion is a function of the effective bubble diameter  $D_e$ , the densities,  $\rho$ , the drag coefficient  $C_d$  of the bubble, and the pipe slope  $S_o$ . Unfortunately, the drag coefficient and effective bubble diameter can not be predicted for flow in a pipe. Therefore, the techniques of dimensional analysis must be used to determine the significant parameters for correlations.

As was shown under Design Parameters—Mean air concentration, the effective bubble

diameter is a function of the interfacial surface tension and the friction slope. In terms of dimensionless parameters, the critical discharge required to move the bubbles can be expressed as

$$\frac{Q_c^2}{gD^5} = f\left(\frac{\gamma D^2}{\sigma}, S_f, S_o, C_b\right) \quad (84)$$

The parameter  $\frac{\gamma D^2}{\sigma}$  is designated frequently as the Eötvös number  $E$ .

Kalinske and Bliss [37] found relatively good correlations for the initiation of bubble movement by using only the pipe slope  $S_o$  and the Eötvös number. Data by Colgate [15] also fits their curves relatively well (fig. 29).

Additional studies are required to define the bubble motion curve (fig. 29) for slopes greater than 45 degrees. Martin [52] showed that a stationary air pocket forms when the dimensionless discharge  $Q_w^2/gD^5$  is equal to 0.30 for vertically downward flow. Therefore, the increasing trend of the curve in figure 29 probably does not continue past the 45-degree slope.

As the bubbles travel downstream in sloping conduits, they tend to rise to the top of the conduit and form large pockets of air. Runge and Wallis [61] discovered that the rise velocity of these pockets is greater in sloping conduits than it is in vertical conduits (fig. 30). For a specific range of discharge, a flow condition can exist whereby bubbles will move downstream and form into pockets that move against the flow in an upstream direction.

Sailer [62] investigated prototype cases in which large air pockets moved against the flow with sufficient violence to completely destroy reinforced concrete platforms. The reverse flow region has been delineated on figure 29 using the data of Colgate [15] and the slug-flow curve of figure 30. The five structures pointed out by Sailer as having experienced blowbacks are indicated by crosses on figure 29. It is noted that



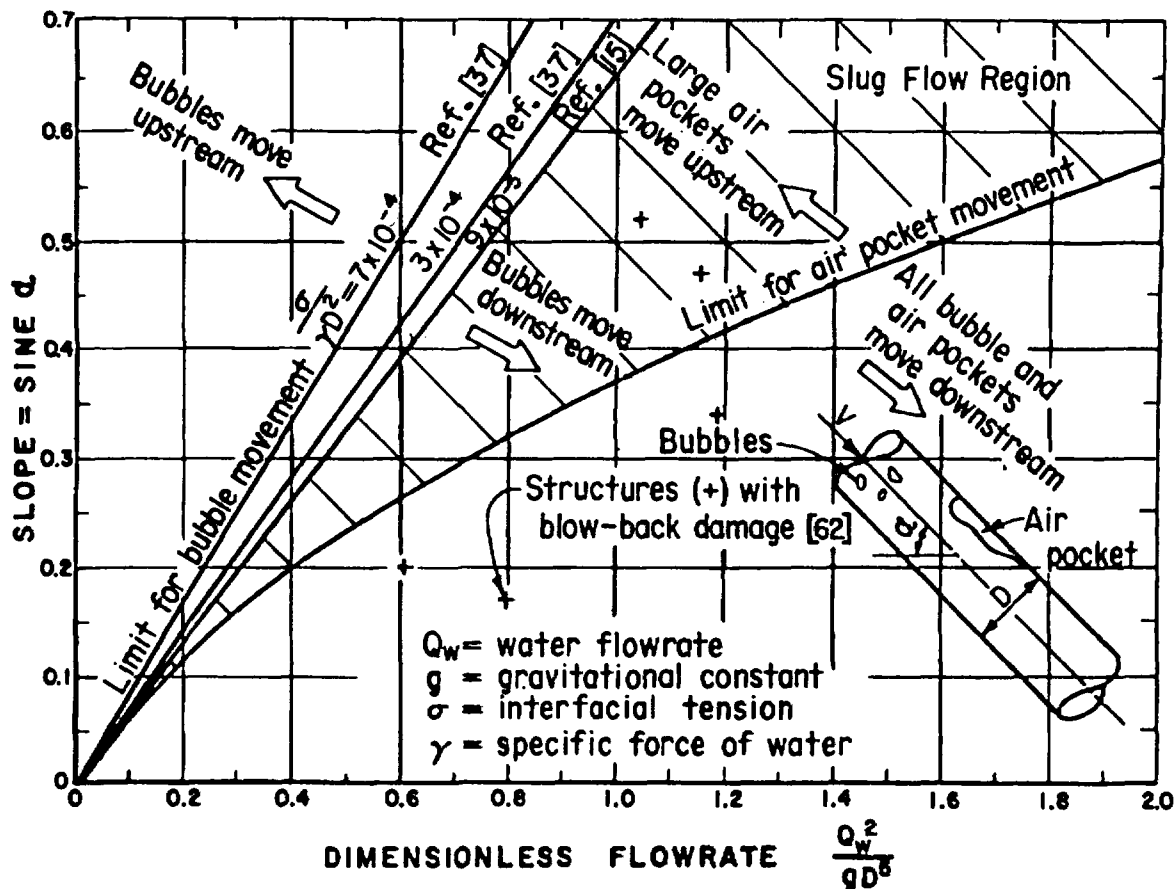


FIGURE 29.—Bubble motion in closed conduits flowing full.

two of these structures lie within the blowback zone at design discharge. The other three must pass through the blowback zone in coming up to the design discharge. For pipe slopes less than 0.1, the width of the blowback zone is so small that problems normally are not experienced.

### FLOWS FROM CONTROL DEVICES

Flows from control devices refer to cases in which the primary cause of the air demand is due to the waterflow conditions at a control device. Two types of flow control devices that will be considered are gates and valves. These

devices also induce air movement in open channel flows. However, in unconfined flows the water movement does not cause low pressures which must be relieved by air vents.

A distinction is made in the field of hydraulic machinery between valves and gates even though both serve as flow control in a closed conduit. A valve is a device in which the controlling element is located within the flow (fig. 31). A gate is a device in which the controlling element is out of the flow when it is not controlling and which moves transverse to the flow when controlling (fig. 31). The jets from gates are different than those from valves; therefore, the two cases are considered separately.

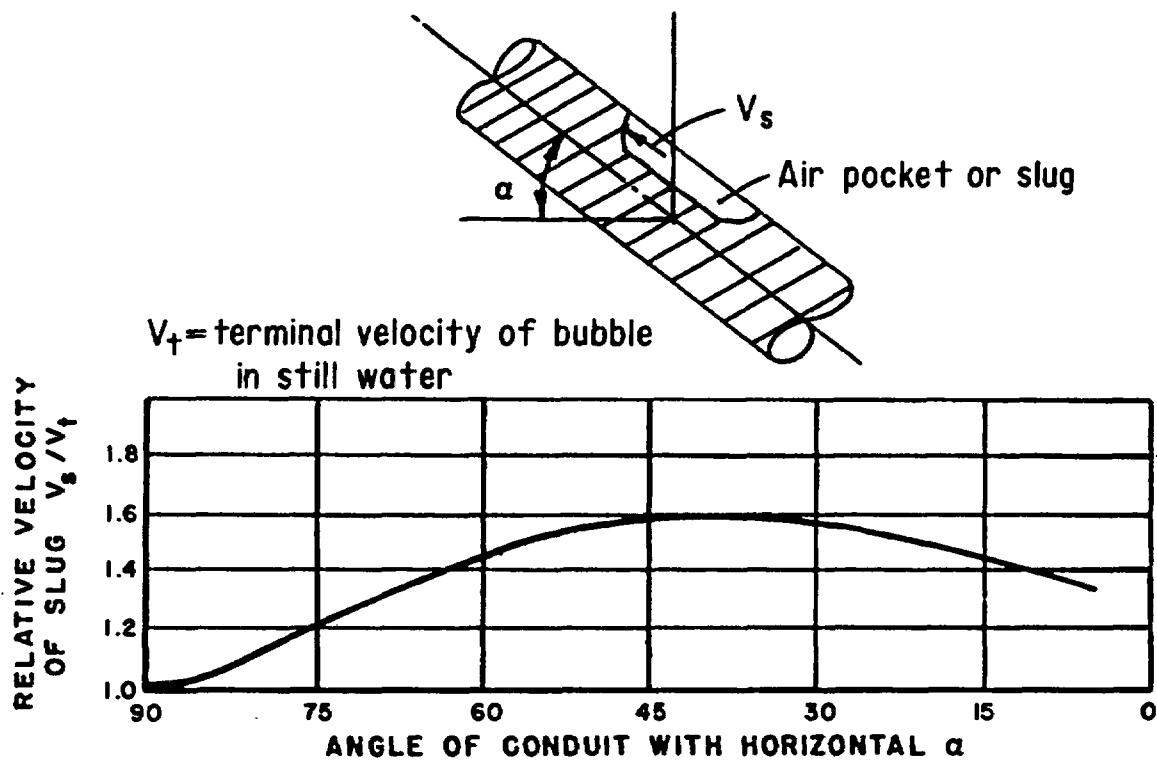


FIGURE 30.—Slug flow in inclined pipes, Runge and Wallis [61].

### Flows From Valves

Around the beginning of the 20th century, many outlet valves were placed on or near the upstream faces of the dams. Nearly all were severely damaged by cavitation erosion. Since a satisfactory method could not be found to reduce or eliminate the damage at all gate positions, the operating ranges of these valves were severely restricted. Because of this limitation, the location of the throttling valves was shifted to the downstream side of the dam. Present practice is to avoid placement of throttling valves within the conduit. Nevertheless, from time to time it is necessary to place the valves within the conduits. This is especially true when the downstream conduit is a tunnel—when spray could cause icing problems—and when a flow control station is placed in a pipeline.

If stratified or wave flow exists downstream of the valve, air is induced to move by a relatively low water velocity acting over a large surface area. However, if the flow from the valve impinges on the downstream conduit walls, the airflow is induced by high velocity waterjet acting over a relatively small surface area. In this case, the significant airflow parameters are the:

- Kinetic energy of the waterflow,
- Gate opening, and
- Air pressure at some characteristic location.

Parameters such as length of conduit downstream of the valve and the Froude numbers of the downstream flows are obviously of lesser importance.

## SERVICE CLASSIFICATION

## THROTTLING VALVES

SCHEMATIC DIAGRAM  FLOW DIRECTION →					
NAME	FIXED-CONE VALVE	HOLLOW-JET VALVE	NEEDLE VALVE	TUBE VALVE	SLEEVE VALVE
Maximum head (approximate)	300 m	300 m	300' m	90 m	75' m
Discharge coefficient (a)	0.85	0.70	0.45 To 0.60	0.50 To 0.55	0.80
Submerged operation	Yes (1)	No (1)	No	Yes	Yes (1)
Throttling limitations	None	Avoid very small discharge	None	None	None
Spray	Very heavy (2)	Moderate	Small	Moderate (1)	None
Leakage	None	None	None	None	None
Nominal size range, diameter (b)	200- to 2740-mm	760- to 2740-mm	250 to 2440-mm	910- to 2440-mm	310- to 610-mm*
Availability	Commercial standard (3)	Special design	Special design	Special design	Special design
Maintenance required	Paint	Paint	Paint (1)	Paint	Paint
COMMENTS AND NOTES:	(1) Air-venting required. (2) Spray rating will change to moderate if a down-stream hood is added. (3) Valves are not "stock" items but standard commercial designs are available.				
(a) Coefficients are approximate and may vary somewhat with specific designs.	(1) Submergence to centerline of valve is permissible.				
(b) Size ranges shown are representative, and are not limiting.	(1) If water operation is used, disassembly at 3 to 5 year intervals for removing scale deposits is usually unnecessary.				
	(1) Spray is heaviest at openings of less than 35%. At the larger openings the rating would be better than moderate.				
	(1) Valve is designed for use only in fully submerged conditions. (2) Larger sizes seem feasible and will probably be developed.				

## SERVICE CLASSIFICATION

## THROTTLING GATES

SCHEMATIC DIAGRAM  FLOW DIRECTION →					
NAME	UNBONNETED SLIDE GATE	BONNETED SLIDE GATES		JET-FLOW GATE	TOP-SEAL RADIAL GATE
		"HIGH PRESSURE" TYPE	STREAMLINED TYPE		
Maximum head (approximate)	25 m	60 m	150' m	150' m	60-75 m
Discharge coefficient (a)	0.6 To 0.8	0.95	0.97	0.80 To 0.84	0.95
Submerged operation	No	No	Yes (1)	Yes (1)	No
Throttling limitations	Avoid very small discharge	Avoid very small discharge	Avoid very small discharge	None	None
Spray	Minimum	Minimum	Minimum	Small	Minimum
Leakage	Small	Small	Small	None	Small to moderate
Nominal size range (b)	3660-wide & 3660-mm high	1830-wide & 2740-mm high	3050- to 6100-mm high	250- to 3050-mm dia.	4570-wide & 9140-mm high
Availability	Commercial standard (1)	Special design	Special design	Special design	Special design
Maintenance required	Paint	Paint	Paint (2)	Paint	Paint-seals (1)
COMMENTS AND NOTES:	(1) Gates are readily available from several commercial sources. They are not an "off-the-shelf" item, however.				
(a) Coefficients are approximate and may vary somewhat with specific designs.	(1) Air vents required (2) Use of stainless steel surfaced fluidways, will reduce painting requirements and cavitation damage hazard.				
(b) Size ranges shown are representative, and are not limiting	(1) Air vents required				
	(1) Seal replacement in 5-15 years is probable depending on design and use.				

FIGURE 31.—Valve and gate data, Kohler [44].

Colgate [14] made model studies of airflows in valves having a fixed-cone.<sup>7</sup> His results were given in terms of gate opening and discharge. Transforming these values into the appropriate dimensionless parameters results in good correlations for all conditions that were tested (fig. 32). In this case, the kinetic energy of the flow is proportional to the total upstream head. Thus

$$\frac{Q_a}{Q_w} = f \left( G, \frac{\Delta p/\gamma}{H_t} \right) \quad (85)$$

where

$G$  = gate opening in percent

$H_t$  = total potential and kinetic energy (upstream)

$\Delta p/\gamma$  = differential between atmospheric pressure and air pressure at end of vent

$\gamma$  = specific force of water

Once curves like those presented in figure 32 are developed, it is possible to determine the airflow rates through any air vent that is connected to the structure by using equation [71]. To perform the determination, equation 71 is plotted on figure 31. The intersections of the two sets of curves give the airflow rates for any particular vent.

### Flows From Gates

At small gate openings, a considerable amount of spray is produced by flow which impinges in gate slots. This spray induces considerably more air movement than that produced by stratified or wave flow. In a sense, the effect of spray in producing air movement is similar to that of flow from valves. However, with spray the jet does not impinge on the walls

of the downstream conduit; therefore, a seal does not form.

The significant parameters for flow with spray are the same as those for flow from valves; i.e.,

- Gate opening,
- A reference air pressure, and
- The total upstream energy.

Model studies can be used to obtain estimates of the airflow rates which can be expected when spray is present.

As the gate opening increases, the amount of spray decreases. Typically, spray is not significant for openings greater than 10 or 20 percent. The exact percentage depends upon the design of the gate. For the larger openings, the airflow rate is controlled by the two-layer flow relations. That is, the significant parameters are:

- Length of conduit,
- Froude number of the flow, and
- Air pressure at some reference location.

For jet-flow gates a point is reached—as the gate opening increases above some value—where the flow impinges on the downstream conduit. Typically this occurs at a 50- to 60-percent opening. With impinging flow, the airflow rate is correlated with the parameters used for flow from fixed-cone valves. For this type of flow, the length to diameter ratio of the conduit is significant only if the downstream conduit length is less than the distance to the impingement point or if the adverse pressure gradient is large.

### FALLING WATER SURFACE

A falling water surface in a closed conduit induces airflow in the conduit. This flow is analogous to that induced by a piston in a cylinder; the water corresponds to the piston. A typical example of this type of flow occurs during an emergency closure of the intake gate to a penstock (fig. 33). As the gate closes, water flowing into the penstock from the reservoir is

<sup>7</sup>The fixed-cone valve is also called a Howell-Bunger valve after its inventors.

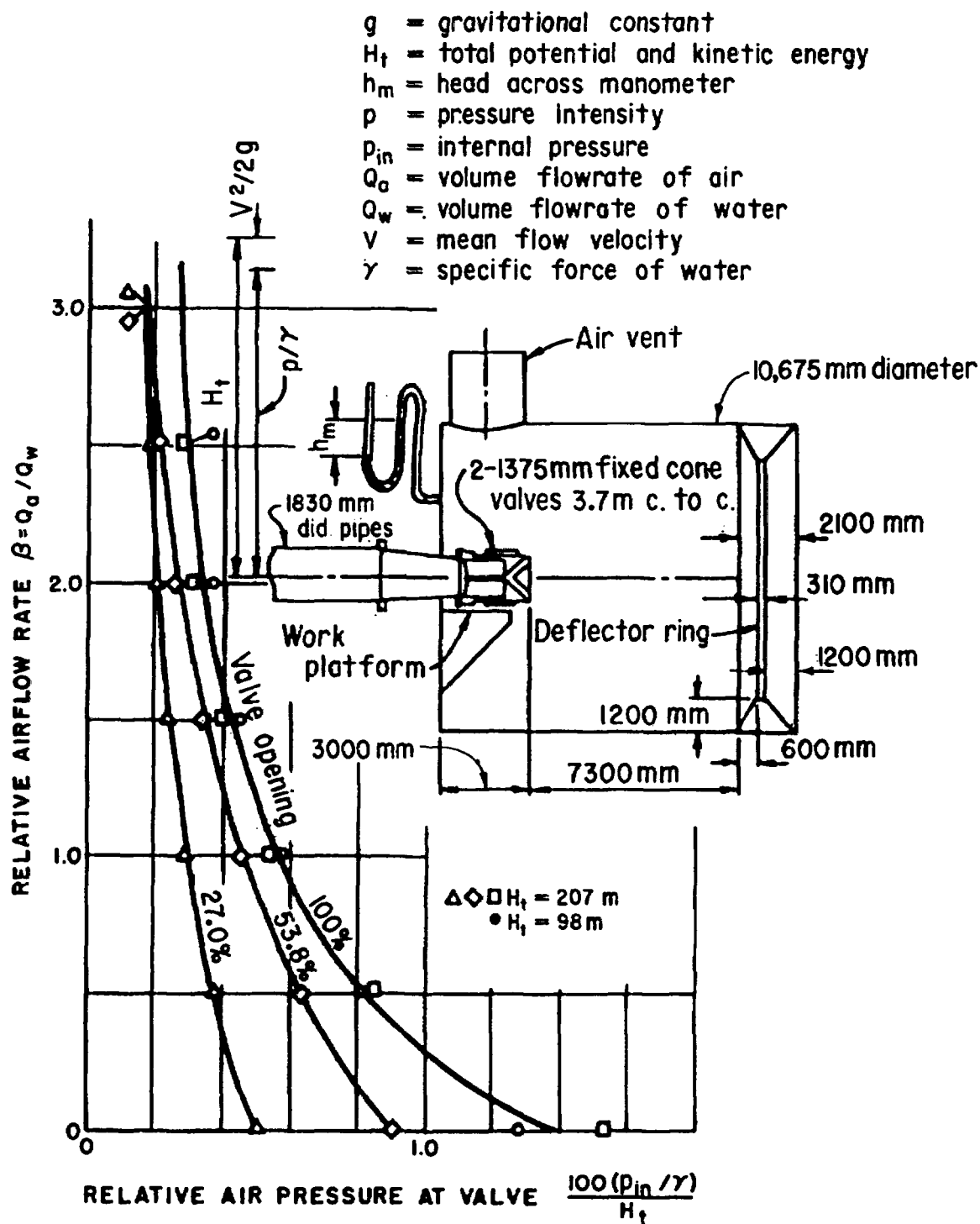
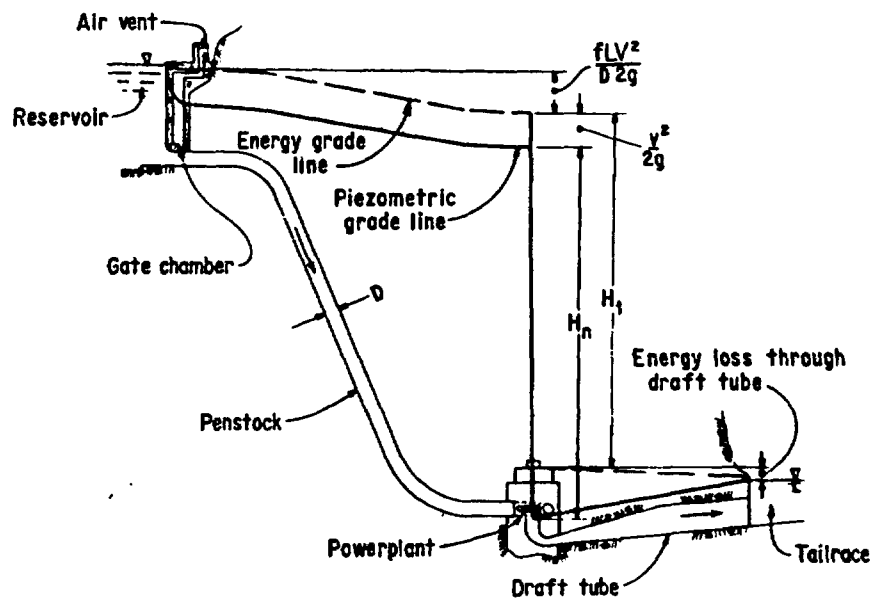
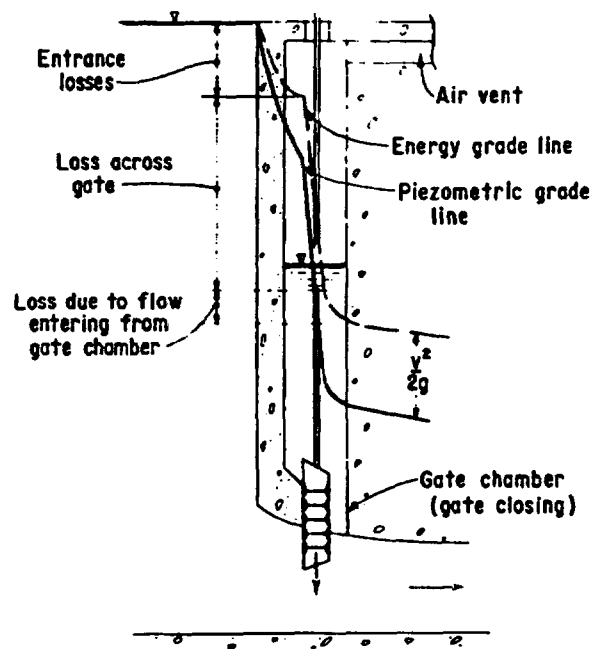


FIGURE 32.—Airflow rate for two 1375-mm fixed-cone (Howell-Bunger) valves.



a. ENERGY AND PIEZOMETRIC GRADE LINES  
IN PENSTOCK AND DRAFT TUBE



b. ENERGY AND PIEZOMETRIC GRADE LINES  
AT INTAKE STRUCTURE

FIGURE 33.—Falling water surface.

gradually stopped. However, water in the penstock continues to flow through the turbine in the powerplant. Eventually the gate becomes fully closed. For water to continue flowing from the penstock, air must be allowed to enter the system through a vent located just downstream from the intake gate.

The airflow and waterflow relations—through the penstock and gate chamber—can be simulated analytically by the appropriate mathematical model, Falvey [22]. This model, based upon momentum and continuity equations, yields the airflow rates, etc., as a function of time.

With relatively long penstocks; i.e., length to diameter ratios exceeding 30, the maximum airflow rate occurs slightly after the emergency gate closes completely. The magnitude of the airflow rate is equal approximately to the penstock discharge prior to the start of the gate closure. These observations provide “rules of thumb” which can be used for the design of the air vent structures on dams. The computer program presented in appendix III should be run if a time history of the air-water flow relation is required or if shorter penstocks are being analyzed. This program is a generalized version of the original program and includes typical turbine characteristics.

Good correlations have been found between the computer model calculations and prototype measurements (fig. 34).

## AIR VENT DESIGN CRITERIA FOR CLOSED CONDUITS

### Purpose

The design of air vents for closed conduits requires careful consideration. The preliminary step is to decide the purpose that the vent is to perform. For instance, air vents can permit air to enter a structure to prevent collapse or to prevent the formation of low pressures within the flowing water which could lead to cavitation

and its possible attendant damage. Conversely, air vents can permit air to escape from a structure. In this case the purpose is to bleed air from a conduit prior to operation.

### Location

The next step is to locate the vent properly. General rules cannot be delineated for all cases other than the vent usually is placed where the pressure in the conduit is the lowest. For instance, in gates the appropriate location is immediately downstream of the gate (fig. 31B). For valves the air vent is upstream from the point where the water jet impinges on the conduit walls (fig. 32). In some cases the location must be determined by intuition or carefully conducted model studies.

### Maximum Airflow Rate

After the vent is located, the maximum airflow rate through the vent must be estimated. This estimate should be based upon a consideration of the various types of flow which are possible in the water conduit. The previous sections have presented in detail some methods of estimating the maximum airflow rates for specific types of closed conduit flows.

### Structural Considerations

The pressure drop across the air vent causes a reduced pressure in the penstock and gate structure. Each part of the structure which is subjected to reduced pressure should be analyzed to determine if it will withstand the imposed loads.

### Physiological Effects

The effects of noise produced by high air velocities as well as the structural integrity must

## AIR-WATER FLOW IN HYDRAULIC STRUCTURES

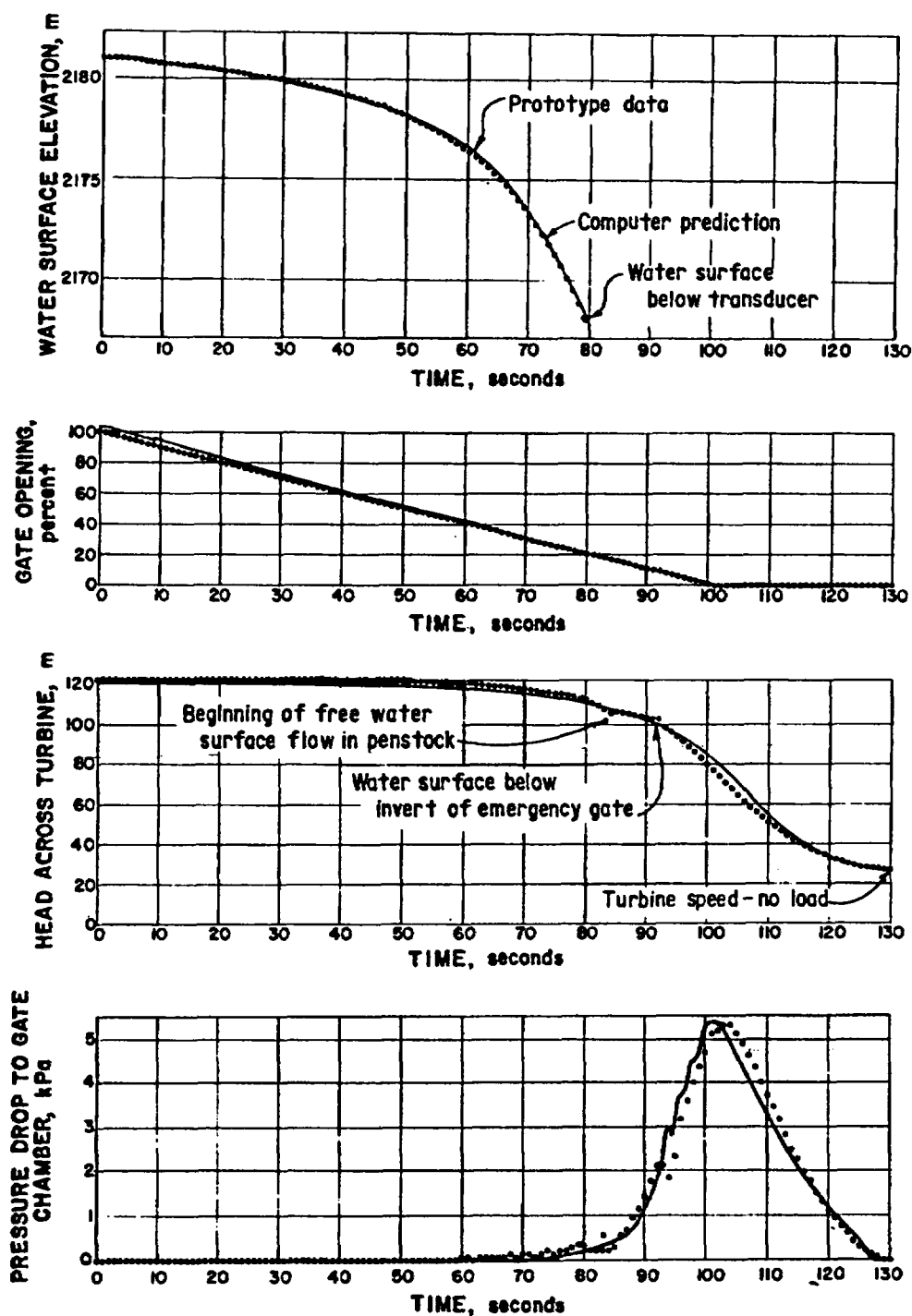


FIGURE 34.—Comparison of field data with computer prediction.



be considered in the design of air vents. The limiting air velocity—with respect to noise—in a vent has been established (by the Water and Power Resources Service) to be about 30 m/s. Above this velocity an objectionable whistling sound occurs. The intensity of the sound and not its mere presence is the governing factor. For instance, ear protection is required for exposure times greater than eight hours and pressure levels above 85 dB (decibels) Beranek and Miller [9].\* For pressure levels above 135 dB, ear protection is required for any exposure time.

Field measurements 5 meters from an air vent having an 80-m/s velocity produced sound level intensities of 105 dB. With this sound intensity, ear protection is required for exposure times exceeding 7 minutes. Since sound level intensities increase by the 6th to 8th power of velocity Davies and Williams [19], a 200-m/s air velocity would have produced a sound level intensity between 128 and 136 dB which is damaging to the ears for any exposure time. Based upon this limited result, a 90-m/s flow velocity appears to be a good value to use as a design criterion for air vents that operate for a short duration. If the air will flow through the vent for extended periods, the upper limit on the air velocity should be restricted to the 30-m/s value.

\**Construction Safety Standards, Water and Power Resources Services*, pp. 27-28, rev. 1979. The standard states \* \* \*. Protection against the effects of noise exposure shall be provided when the sound levels exceed those shown below when measured on the A-scale of a standard Type II sound level meter at a slow response.

Duration per day, hours	Sound level, dBA, slow response
8	90
6	92
4	95
3	97
2	100
1.5	102
1	105
0.5	110
0.25 or less	115

### Safety of Personnel

Another design consideration concerns the safety of personnel in the vicinity of the vent when it is operating. Generally, personnel barriers should be placed around vents at locations where the air velocities exceed 15 m/s. This will prevent personnel and loose objects from being swept either through the air vent or held on the air vent louvers.

### Freeze Protection

In areas where the vents operate in cold weather for prolonged periods, the vents should be protected from freezing. Icing occurs when supercooled air passes through the louvers and screens at the vent intake. In some cases ice buildup was sufficient to completely block the flow area (fig. 35). Icing protection includes using heating elements on the louvers, rerouting the vent to place the intake in a warm portion of the structure, or redesign of the intake to eliminate ice buildup areas.

### Cavitation Damage

The pressure downstream of gates discharging into conduits should be prevented from becoming too low. If the pressure does drop excessively, cavitation damage may result during prolonged periods of operation. Unfortunately, general guidelines concerning minimum acceptable pressures cannot be given. Each gate or valve design has its own particular characteristics. Some designs are more susceptible to cavitation damage than others. Research studies are needed to define minimum pressure values for the different classes of gates and valves.

### Water Column Separation

If the pressure in the water column reaches vapor pressure of the water a possibility exists



A.—View of the vent pipe installed to provide air for a square slide gate in an outlet works. Initial installation had a cap which required removal after frost plugged the screen. P801-D-79278



B.—Closeup view of the screen for a vent pipe after removal of the cap. P801-D-79277

FIGURE 35.—Air vent, Shadow Mountain Dam, Colorado-Big Thompson Project, Colorado.

that the column will separate. Depending upon the geometry of the conduit, the separation can occur at either one location or at several locations. If water column separation is indicated, special waterhammer computations should be performed to determine the overpressures when the water columns rejoin.

## AIR VENT DESIGN CRITERIA FOR PIPELINES

### Introduction

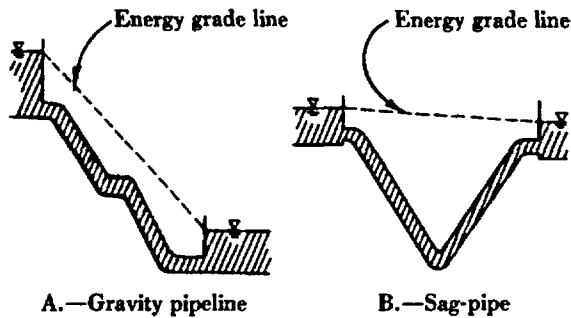
Flow in long pipelines presents a separate class of considerations from those already discussed. One of the reasons for the new set of considerations is the fact that the pipeline profile normally follows the ground surface topography very closely. This causes intermediate high locations which provide an opportunity for the collection of air pockets. To assure trouble-free pipeline operation, details of alignment, location, and sizing of vent structures must be considered.

There are essentially four main categories of pipelines. They are:

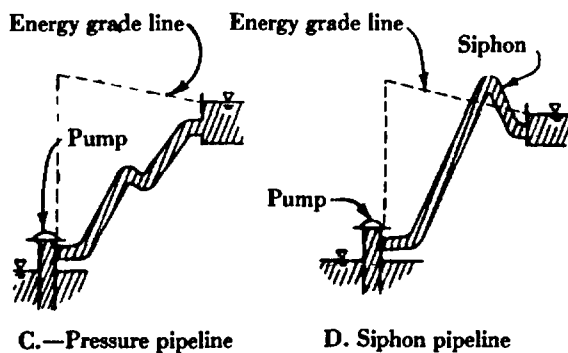
1. Gravity pipelines in which the water flows from a higher elevation to a lower one through the effect of gravity (fig. 36A).
2. Saggpipes (inverted siphons)<sup>9</sup> in which the flow from one canal to another is passed under a road or across a valley (fig. 36B).
3. Pump lifts in which the water flows from a low elevation to a higher one through pump action (fig. 36C).
4. Siphons in which some portion of the pipe is designed to operate at subatmospheric pressures (fig. 36D). This type of structure is used frequently to prevent water from the upper reservoir from passing back through the pump if a loss of electrical power occurs.

<sup>9</sup>See footnote 1.

Gravity systems, figures 36A and B, normally have different alinement problems than pumping systems (fig. 36C and D); therefore, the two are considered separately.



GRAVITY SYSTEMS



PUMPING SYSTEMS

FIGURE 36.—Pipeline configurations.

### Gravity Systems

A vertical section through a typical gravity system is shown on figure 37. The same type of layout also applies to sag pipes if the open vent structures are replaced by canal sections. Two types of summit configurations are depicted. In one case the intermediate summit is above the downstream vent structure. This forms a pool upstream of the summit at the no-flow condition. In the other case, the intermediate summit

is below the downstream vent structure. Therefore, it is submerged by the pool which forms at the no-flow condition.

To prevent difficulties during startup operations, certain criteria should be followed regarding both the vertical and horizontal alinement at the upstream vent structure and at intermediate summits whose elevations lie above the downstream open vent structure.

**Vertical alinement criteria.**—The pipe invert should be placed on a uniform slope between the vent or summit and the adjacent downstream pool. If this cannot be achieved then the pipe should be placed on continually steeper slopes so that during filling the flow continues to accelerate to the pool level. If the flow were allowed to decelerate, the water depth in a circular pipe could gradually increase until the pipe was about 82 percent full. At this depth the flow could become unstable, alternating between full conduit flow and the 82-percent depth.

At less than design discharge, the flow downstream of nonsubmerged summits passes from free-surface to closed-conduit flow. An air-entraining hydraulic jump always forms when the flow makes this transition. The entrained air can form large air pockets under certain circumstances which move against the direction of flow. This condition is commonly referred to as blowback (refer to previous section—Flow Having a Hydraulic Jump That Fills the Conduit).

If the alinement cannot be planned to avoid either operating in or passing through the blowback region delineated in figure 29, then the pipe diameter should be altered to avoid the region.

Some attempts have been made to collect the large air bubbles which form on the crown of the pipe and lead them away from the pipeline (fig. 38). In the example, the flow conditions never entered the blowback flow region. Therefore, the complicated air collection

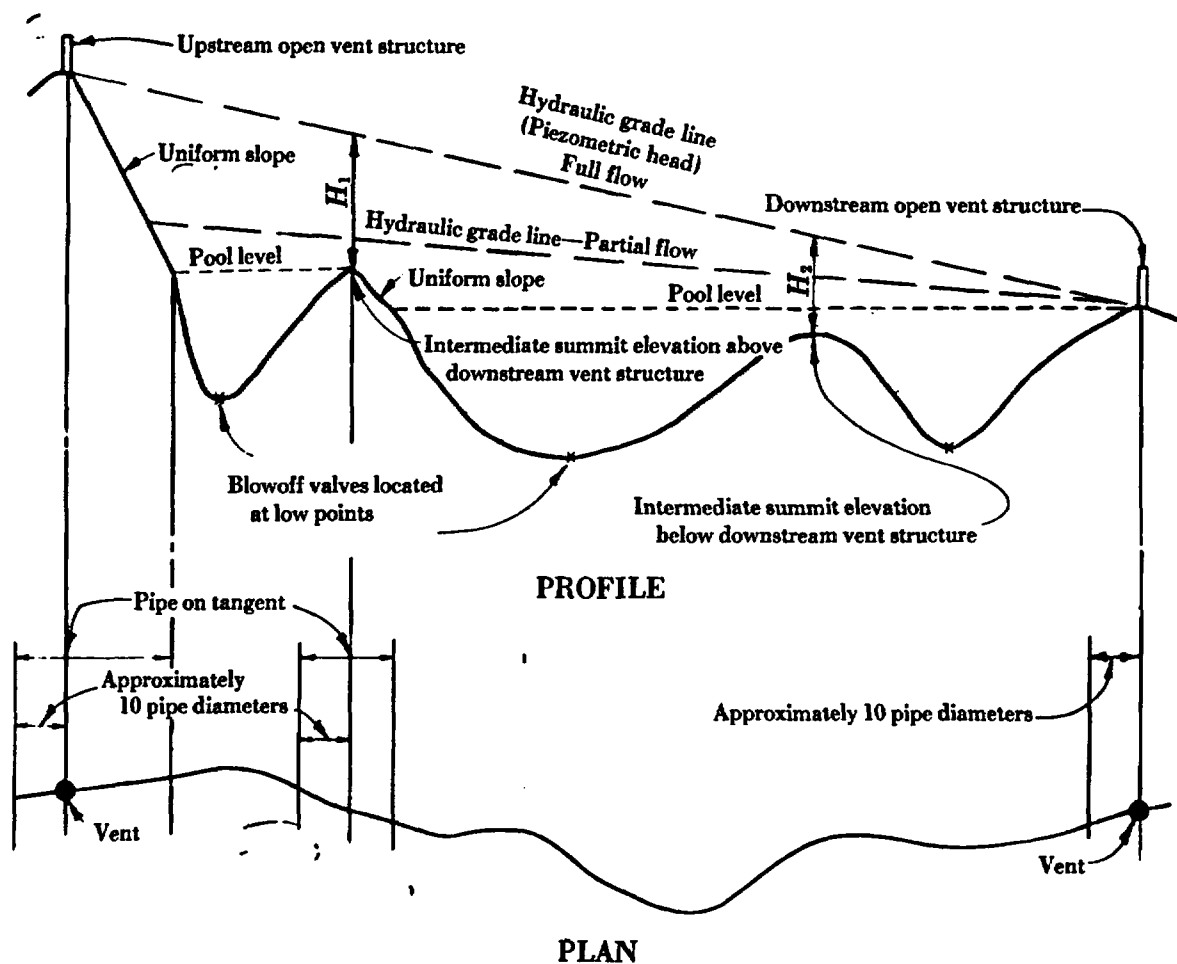


FIGURE 37.—Plan and profile of a gravity pipeline.

system was not needed. If flow had entered the blowback region, this structure probably would not have worked. Colgate [15] found that an unsteady flow condition develops when large air bubbles are bled from a pipeline with too small a vent. To minimize the unsteady flow it is necessary for the vent diameter to equal the pipeline diameter. The design of antiblowback structures like the type shown on figure 38 should not be attempted without hydraulic model studies.

**Horizontal alinement criteria.**—At the open vent structures and at the intermediate summits

higher than the downstream vent, the pipe should not contain bends for 10 pipe diameters upstream of the location. In addition bends should be avoided in the section between the vent on the summit and the adjacent downstream pool. These criteria prevent transverse waves from being formed on the free water surface which can exist downstream of the vent or summit at partial flows. These transverse waves could roll over with enough amplitude to intermittently seal the pipeline.

**Vent location.**—The type of air release structure to be used at a summit is determined by the

CLOSED CONDUIT FLOW

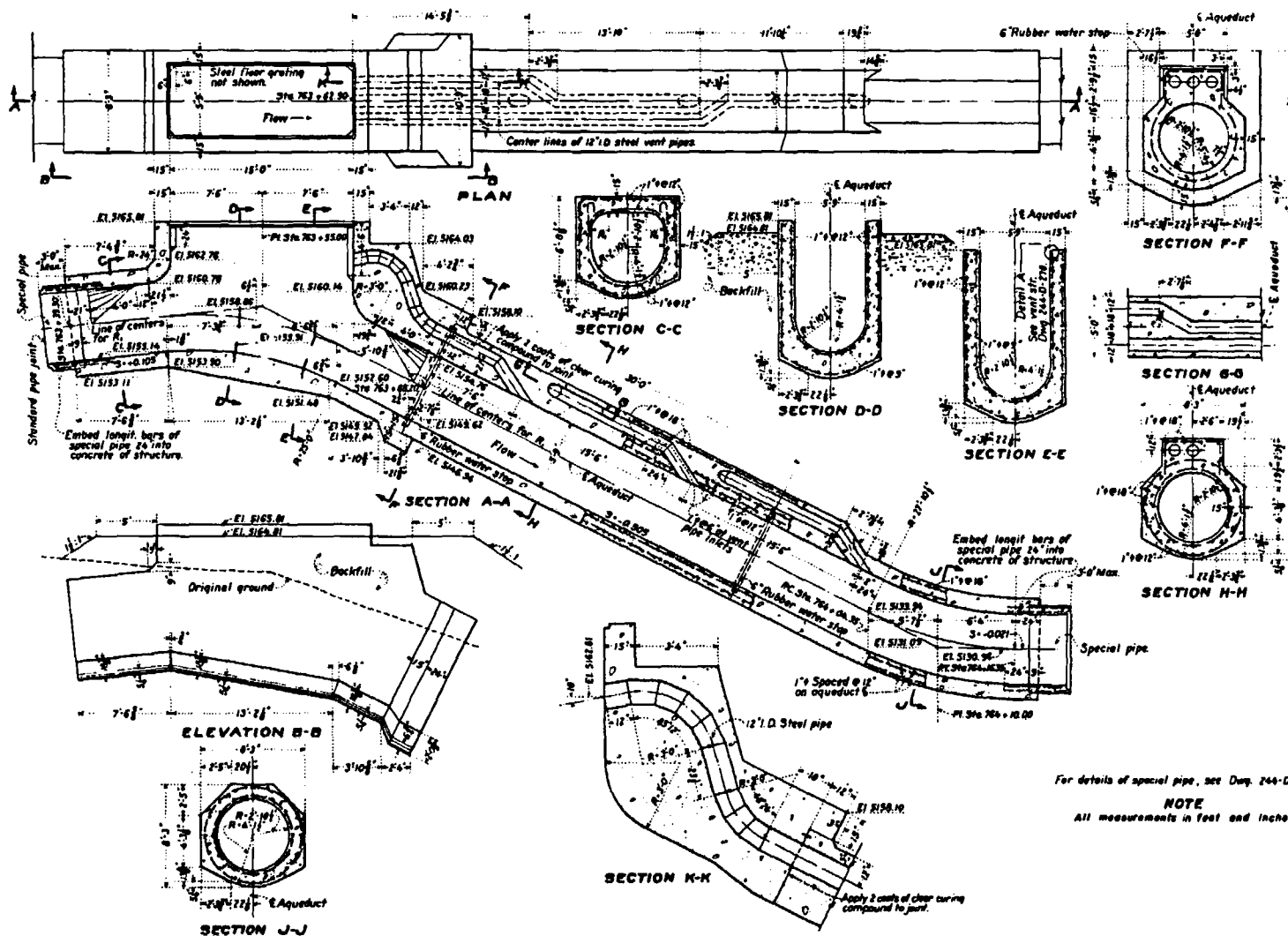


FIGURE 38.—Vent structure. 244-D-799

distance from the pipe invert to the hydraulic grade line at the summit. For summits higher than the downstream vent, an open vent is desirable. The maximum allowable vent height is determined from topographic, aesthetic, and economic considerations. Normally, open vents at intermediate summits are not feasible if the distance to the hydraulic grade line  $H_1$  exceeds 6 to 10 meters.

For summits lower than the downstream vent, the type of air release structure is more difficult to determine. If the distance to the hydraulic grade line  $H_1$  is less than about 6 meters, an open vent should be used. However, if the distance exceeds 6 meters an air valve installation should be used (fig. 39). Since mechanical air valves tend to chatter and spit water if their operating pressures are too low, the top of the air valve should be set at least 3 meters below the pool level.

To provide desirable operating characteristics at all discharges, vents also are required at locations other than at the intermediate summits. If the water velocities are of sufficient magnitude to carry air bubbles with the flow, then vents are needed downstream of changes from negative to positive pipe slopes. Without the vents the air slugs, which collect on the crown of the pipe, will attain very high velocities in areas with large positive slopes. These slugs can damage the vent structures at intermediate locations, at downstream connecting canals, and can cause slamming of air valves. These vents should be located less than 30 meters downstream from the negative to positive pipe slope change. If the distance from the intersection of the pool with the negative slope and the proposed vent exceeds  $20D$ , where  $D$  is the conduit diameter, then the vent should be placed at the greater of the two distances (fig. 40). The criterion for the vent type is the same as for vents placed at intermediate summits below the downstream vent structure. If the distance between the upstream and downstream vent structures is very great,

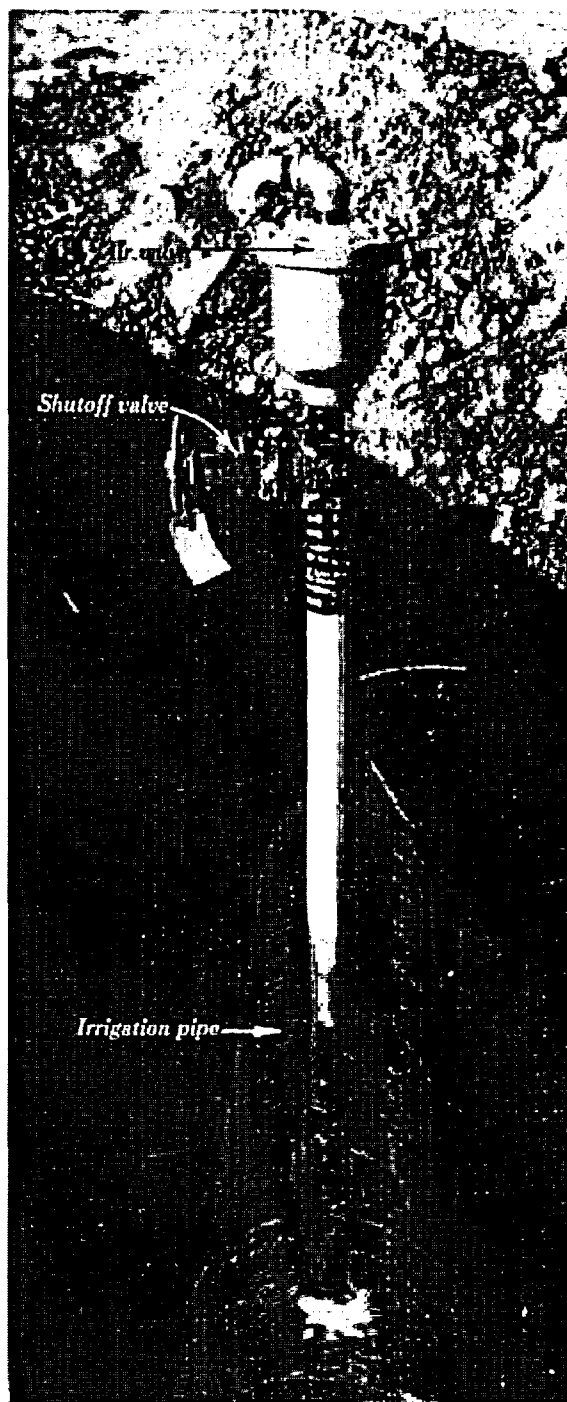


FIGURE 39.—Typical irrigation system air valve installation. P801-D-79279

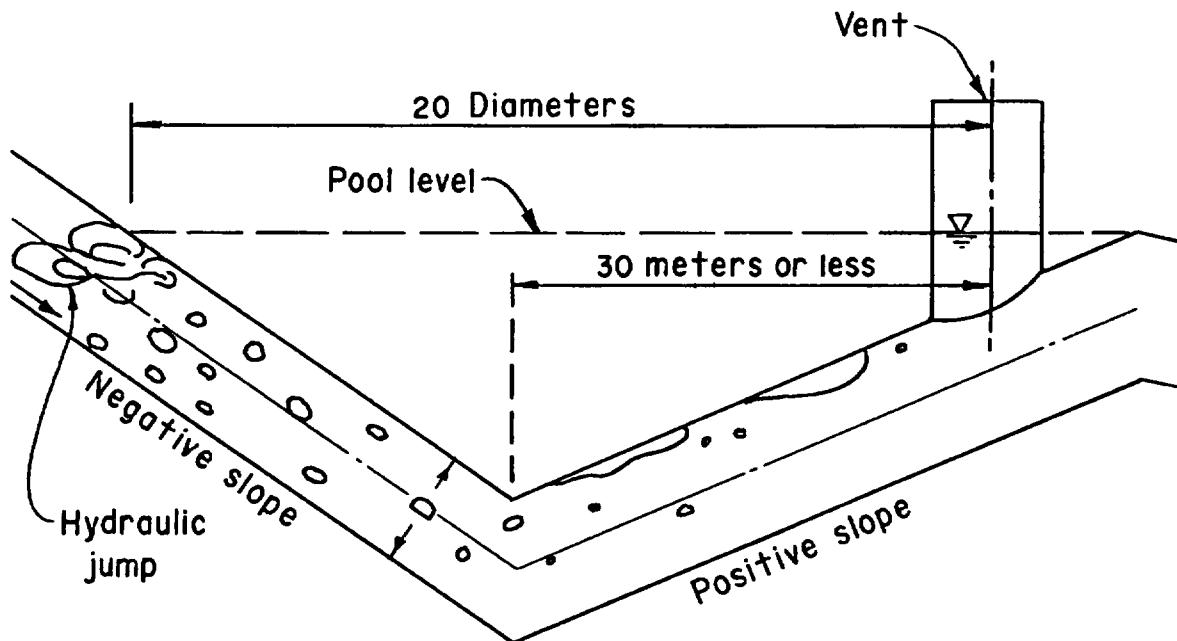


FIGURE 40.—Vent location at changes in pipe slope.

Lescovich [47] recommends that air valves be placed every 500 to 1000 meters along descending, horizontal, or ascending stretches that have no intermediate summits.

### Pumping Systems

All intermediate summits are potential locations for the collection of air pockets. If these pockets begin to develop, the hydraulic gradient downstream of the summit will equal approximately the pipe slope in the area where the air pocket has formed. For a pipe slope greater than the full-flow hydraulic gradient, the air pocket will require a greater head differential to produce a given discharge. Conversely, for a constant head differential, the presence of the air pocket will result in decreased discharges. The limiting condition is a complete blockage of flow. In pumping systems this blockage is known as *air binding* [58]. With air binding

the shutoff head of the pump will have been reached (fig. 41). One obvious solution to the problem of air collection at summits is to provide air release valves or vent structures at these locations. Another solution is to align the pipeline so that all intermediate summits are eliminated.

### Vent Structure Design Considerations

Vent structures have three primary purposes:

1. Evacuation of air during filling,
2. Removal of air during operation, and
3. Prevent pipe collapse during draining.

Each is considered in detail. The size of the vent and the piping connecting the vent to the pipeline is determined by the purpose for which the vent is installed.

*Evacuation of air during filling.*—The filling rate of pipelines usually is set at 5 to 15 percent

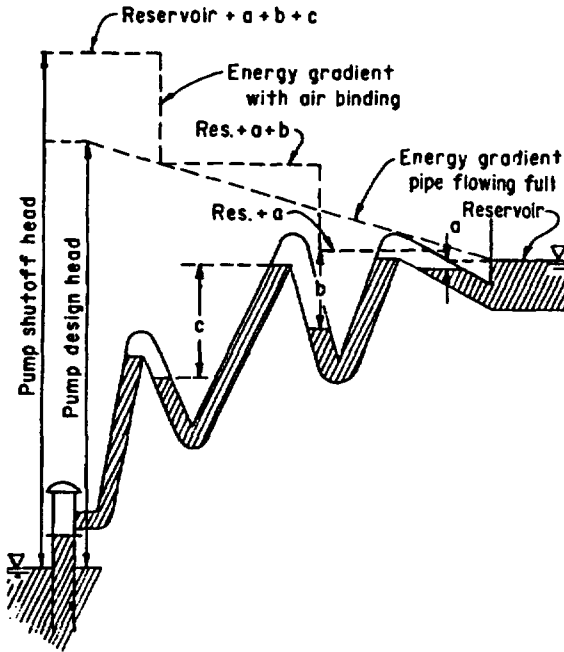


FIGURE 41.—Air binding in a pipeline.

of the design discharge. The actual rate is governed by the maximum waterhammer pressures that the pipeline and valves can withstand. These pressures are generated when the water column in the penstock reaches the air release valve. Based on waterhammer considerations the filling rate of pipelines can be computed from

$$Q_a = \frac{g A_p \Delta h_w}{c} \quad (86)$$

where

- $Q_a$  = penstock filling rate equals airflow rate through vent
- $A_p$  = cross sectional area of penstock
- $c$  = celerity of waterhammer wave in penstock
- $g$  = gravitational constant (acceleration)
- $\Delta h_w$  = allowable head rise in penstock due to waterhammer pressures

Lescovich [47] indicated that large orifice air valves should be used to permit air escape during filling (fig. 42). In this case a large orifice refers to diameters greater than 25 millimeters. This type of air valve is designed to remain closed after the pipeline is filled. Thus, they cannot be used to release small amounts of air that accumulate during operation. These valves will open immediately when the pipeline pressure drops below atmospheric. This allows air to reenter the pipeline and prevents a vacuum from forming.

Normally, air velocities discharging from an air valve should not exceed 30 m/s. The primary reason for limiting the velocity is to prevent the air valve from being blown shut. Some air valves are designed to eliminate this problem.

With the 30-m/s velocity limitation, the air can be considered to be incompressible. The equation for the airflow rate is

$$Q_a = A_o C_o \left( \frac{2 \Delta p}{\rho_a} \right)^{1/2} \quad (87)$$

where

- $A_o$  = orifice area,  $m^2$
- $C_o$  = orifice coefficient  $\approx 0.6$
- $\Delta p$  = pressure differential across the orifice, kPa
- $\rho_a$  = air density (at 20 °C and a pressure of 101.3 kPa,  $\rho_a = 1.204 \text{ kg/m}^3$ )

From this equation, performance curves for large-orifice air valves can be derived (fig. 43).

If the desired capacity cannot be achieved with a single air valve, the valves can be placed in clusters—up to four valves—on a single vent pipe from the pipeline.

**Removal of air during operation.**—Two types of structures are used to remove air during operation. These are an open-vent structure and small-orifice air valves. In either case the connection to the pipeline must be large enough



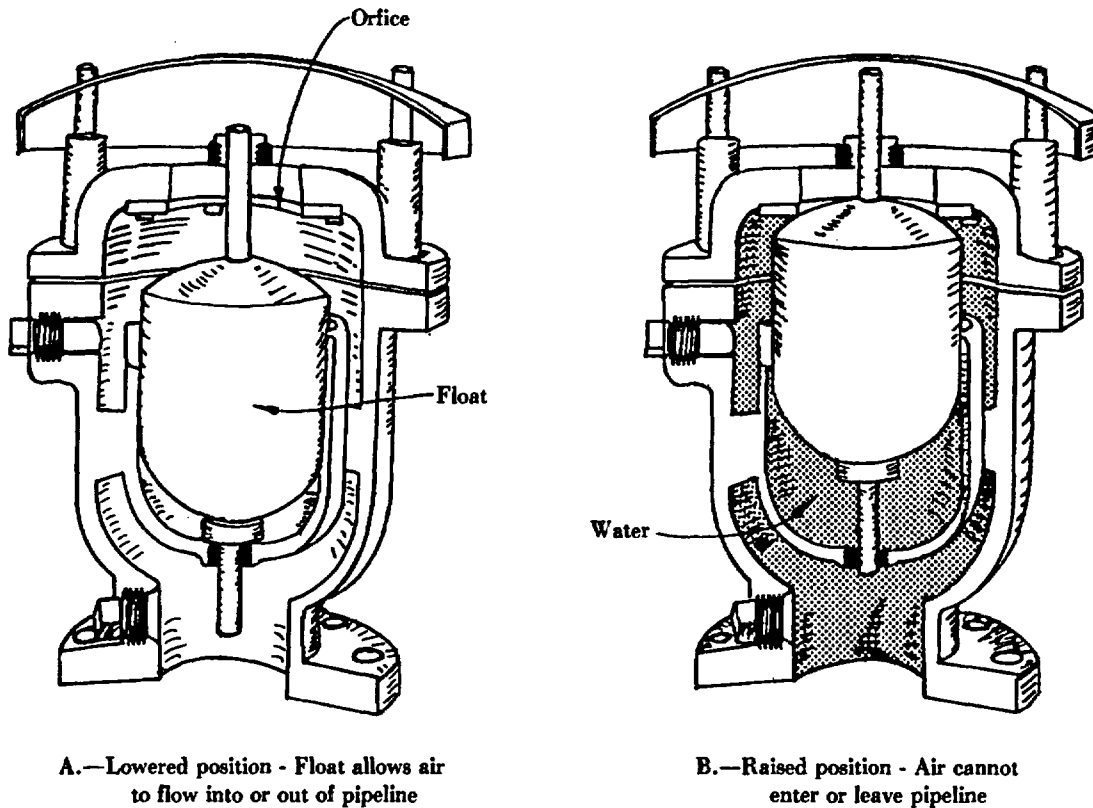


FIGURE 42.—Large-orifice air valve.

to collect the slugs and bubbles of air which are traveling on the crown of the pipeline.

Colgate [15] investigated the sizing criteria for open-vent structures. He found that if the collection port was too small, portions of large air slugs would pass by the vent. To trap all the air it was necessary for the diameter of the collection port to be equal to the pipe diameter. Additional tests were made to investigate the size of the vent structure itself. It was found that if the air vent diameter was less than the pipeline diameter, an unsteady flow was established in the vent as large air bubbles exited from the vent. This unsteady flow pumped air back into the pipeline. To minimize pumping it was necessary to make the vent diameter equal to the pipeline diameter.

Colgate [15] concluded that the collection and evacuation of air from a pipeline can be best accomplished by a vertical air vent which is connected directly to the pipeline. The diameter of the vent should be at least equal to the diameter of the pipeline. From access considerations, the minimum vent diameter usually is set at about 1 meter. Removal of air is promoted if the pipe slope immediately downstream of the vent is made steep enough to cause the air bubbles to return upstream. Figure 29 can be used to determine the required slope for a given discharge.

For the case in which the hydraulic grade line is too far above the pipeline to economically install an open vent, air valves are used to remove the air. Investigations concerning the design of

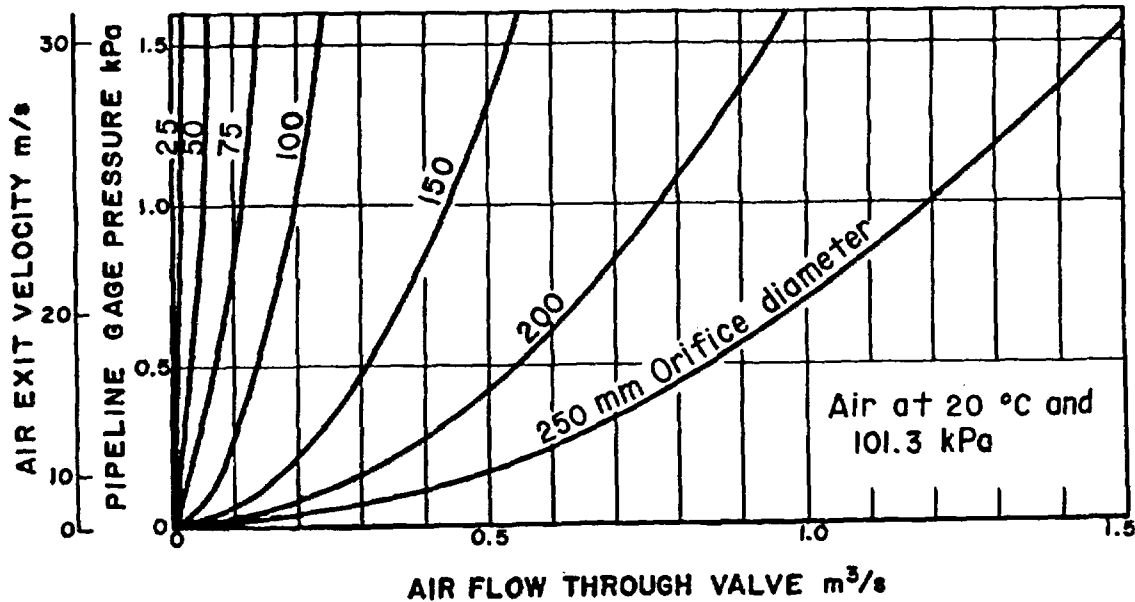


FIGURE 43.—Performance curves for large-orifice air release valves.

a collector have not been performed. Based upon the design of open vents it can be assumed that the diameter of the collector should be at least equal to that of the pipeline. The height of the collector also should be one pipeline diameter. In many cases, manholes in the pipeline can serve as collectors.

To release air from pipelines under high pressures, small-diameter orifice installations are used (fig. 44). The small orifice assures that the opening force of the float is not exceeded by the closing force whose magnitude is equal to the internal gage pipe pressures times the orifice area. The volume flow of air relation through an orifice with a back pressure is given by

$$Q_a = 460A_o[(p_{in}/p_{atm})^{0.2857} - 1]^{1/2} \quad (88)$$

for

$$\frac{p_{atm}}{p_{in}} > 0.53$$

and

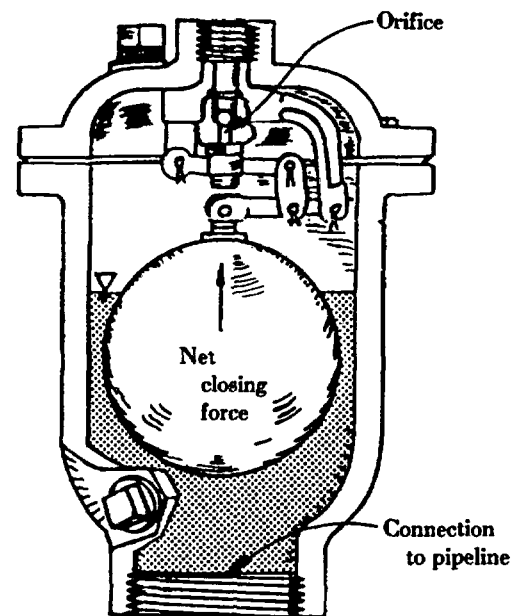
$$Q_a = 11.8A_o[p_{in}(p_{in}/p_{atm})^{0.7143}]^{1/2} \quad (89)$$

for

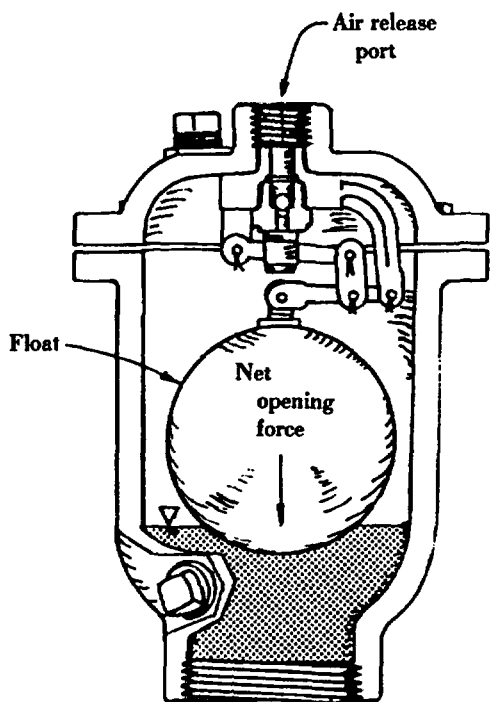
$$\frac{p_{atm}}{p_{in}} \leq 0.53$$

These equations are presented as performance curves (fig. 45).

To prevent the air valves from freezing, frequently they are placed in concrete structures located below the frost line (fig. 46). In this case it is necessary to provide adequate ventilation into or out of the structure. The required ventilation area is based upon a 2.5-m/s maximum air velocity through the gross area of a fixed louver vent. If wire mesh screen is used, the maximum air velocity is 6.6 m/s through the gross area of the screen.



A. High water level



B. Low water level

FIGURE 44.—Typical small-orifice air release valve.

**Prevent pipe collapse during draining.**—The venting criteria discussed thus far are based upon the need to remove air from the pipeline. In several instances above-ground steel pipelines have collapsed because vacuum formed during rapid draining operations or because of breaks in the pipeline. Parmakian [56] developed criteria for the size and location of air valves to be placed in steel pipelines to protect them against collapse.

On steel pipes, the collapse pressure can be estimated from (Parmakian [56])

$$p_c = 3.5 \times 10^8 \left( \frac{t}{D} \right)^3 \quad (90)$$

$$= p_{atm} - (p_{in})_{abs} = - (p_{in})_{gage}$$

where

$D$  = conduit diameter, mm  
 $p_{atm}$  = atmospheric pressure, kPa  
 $p_c$  = collapse pressure, kPa  
 $p_{in}$  = internal absolute or gage pressure, kPa  
 $t$  = pipewall thickness, mm

With stiffener rings, the appropriate equation is

$$p_c = \frac{5.1 \times 10^8 (t/D)^{2.5}}{(L_s/D)} \quad (91)$$

where  $L_s$  = distance between stiffener rings.

These two equations are presented graphically in figure 47.

Applying a safety factor  $N$  to the internal collapse pressure  $p_c$  gives the allowable internal pressure  $p_a$  as

$$p_a = p_{atm} - \frac{p_c}{N} \quad (92)$$

If the ratio of the internal to atmospheric pressure is greater than 0.53 then the volume

flow of air into the pipeline through an orifice is given by

$$Q_a = C_d A_o \left( \frac{p_{in}}{p_{atm}} \right)^{\frac{1}{\kappa}} \left\{ \frac{2 p_{in}}{2 Q_{atm}} \left( \frac{\kappa}{\kappa+1} \right) \left[ 1 - \left( \frac{p_{in}}{p_{atm}} \right)^{\frac{\kappa-1}{\kappa}} \right] \right\}^{\frac{1}{2}} \quad (93)$$

If the ratio is equal to or less than 0.53 then the airflow rate into the pipeline through an orifice is given by

$$Q_a = C_d A_o \left( \frac{2}{\kappa+1} \right)^{\frac{1}{\kappa-1}} \left[ \frac{2 p_{atm}}{Q_{atm}} \left( \frac{\kappa}{1+\kappa} \right) \right]^{1/2} \quad (94)$$

Using

$$C_d = 0.6$$

$$p_{atm} = 101.3 \text{ kPa}$$

$$\kappa = 1.4$$

$$Q_{atm} = 1.20 \text{ kg/m}^3$$

in equations 93 and 94 results in

$$Q_a = 460 A_o \left( \frac{p_{in}}{p_{atm}} \right)^{0.715} \left[ 1 - \left( \frac{p_{in}}{p_{atm}} \right)^{0.286} \right]^{1/2} \quad (95)$$

for

$$\frac{p_{in}}{p_{atm}} > 0.53$$

and

$$Q_a = 119 A_o \quad (96)$$

for

$$\frac{p_{in}}{p_{atm}} \leq 0.53$$

where

$$A_o = \text{orifice area, m}^2$$

$$Q_a = \text{airflow area, m}^3/\text{s}$$

These equations are presented as performance curves for various size vacuum relief valves (fig. 48).

Parmakian presented an alternate method of determining the required air vent size in terms of a dimensionless ratio. The ratio is in the form of an Euler number and is given by

$$\left( \frac{\Delta V^2}{C_o^2 p_{atm} v_{atm}} \right)^{1/4} = \frac{1}{C_o^{1/2} E_u^{1/4}} \quad (97)$$

where

$$C_o = \text{orifice discharge coefficient}$$

$$E_u = \text{Euler number} = p_{atm} / Q_a V^2$$

$$p_{atm} = \text{atmospheric pressure}$$

$$\Delta V = \text{change in water velocity approaching and leaving air vent}$$

$$Q_a = \text{density of air at standard atmospheric pressure}$$

$$v_{atm} = \text{specific volume of air at atmospheric pressure}$$

The pressure and specific volume of the atmosphere are both functions of elevation (fig. 49). This alternate method results in the required air vent orifice diameter as a function of the pipeline diameter (fig. 50).

Normally, air valves are placed at the crests in the pipeline profile and at locations where the pipeline begins a steep downward slope.

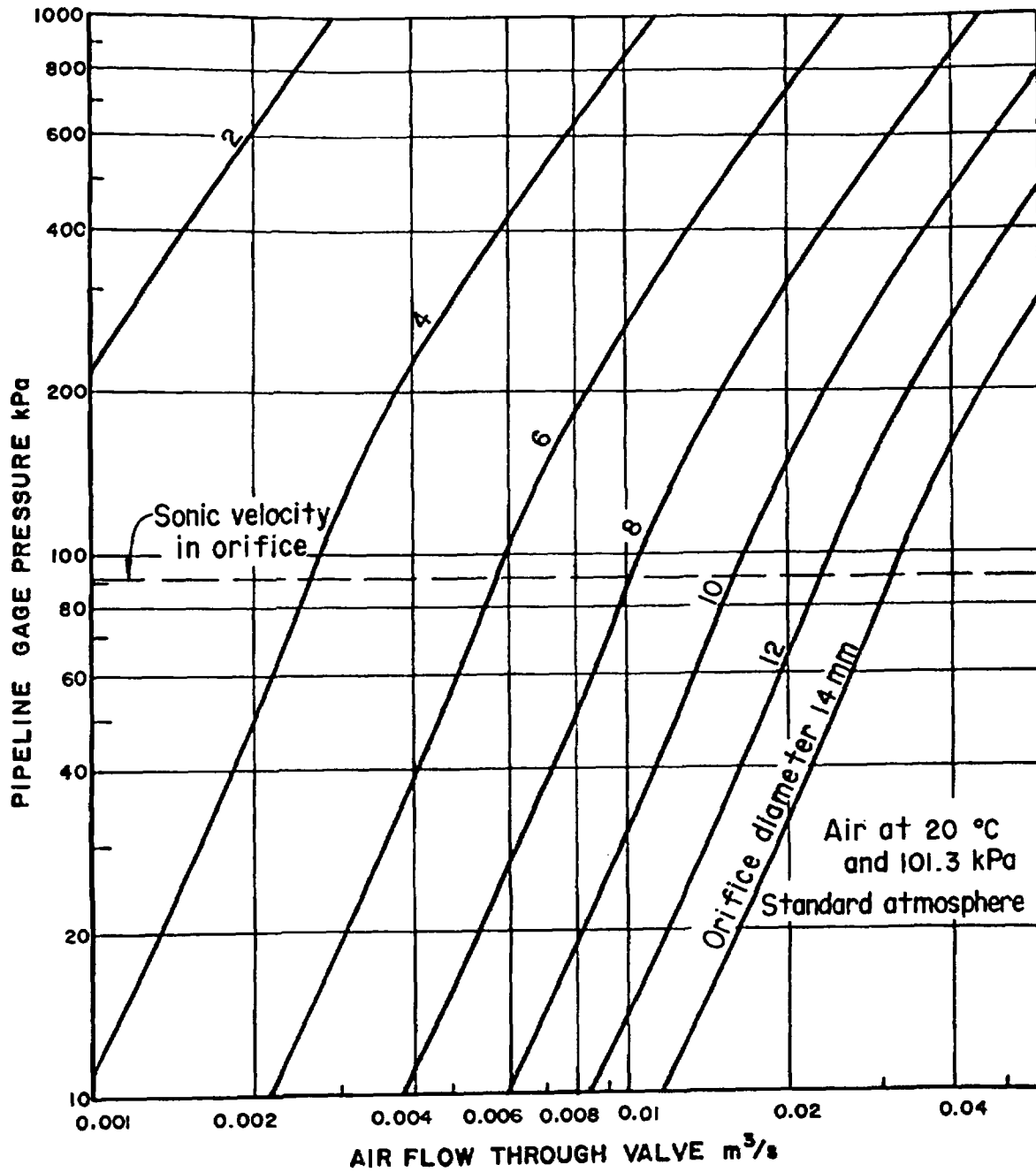


FIGURE 45.—Performance curves for small-orifice air release valves.

## AIR-WATER FLOW IN HYDRAULIC STRUCTURES

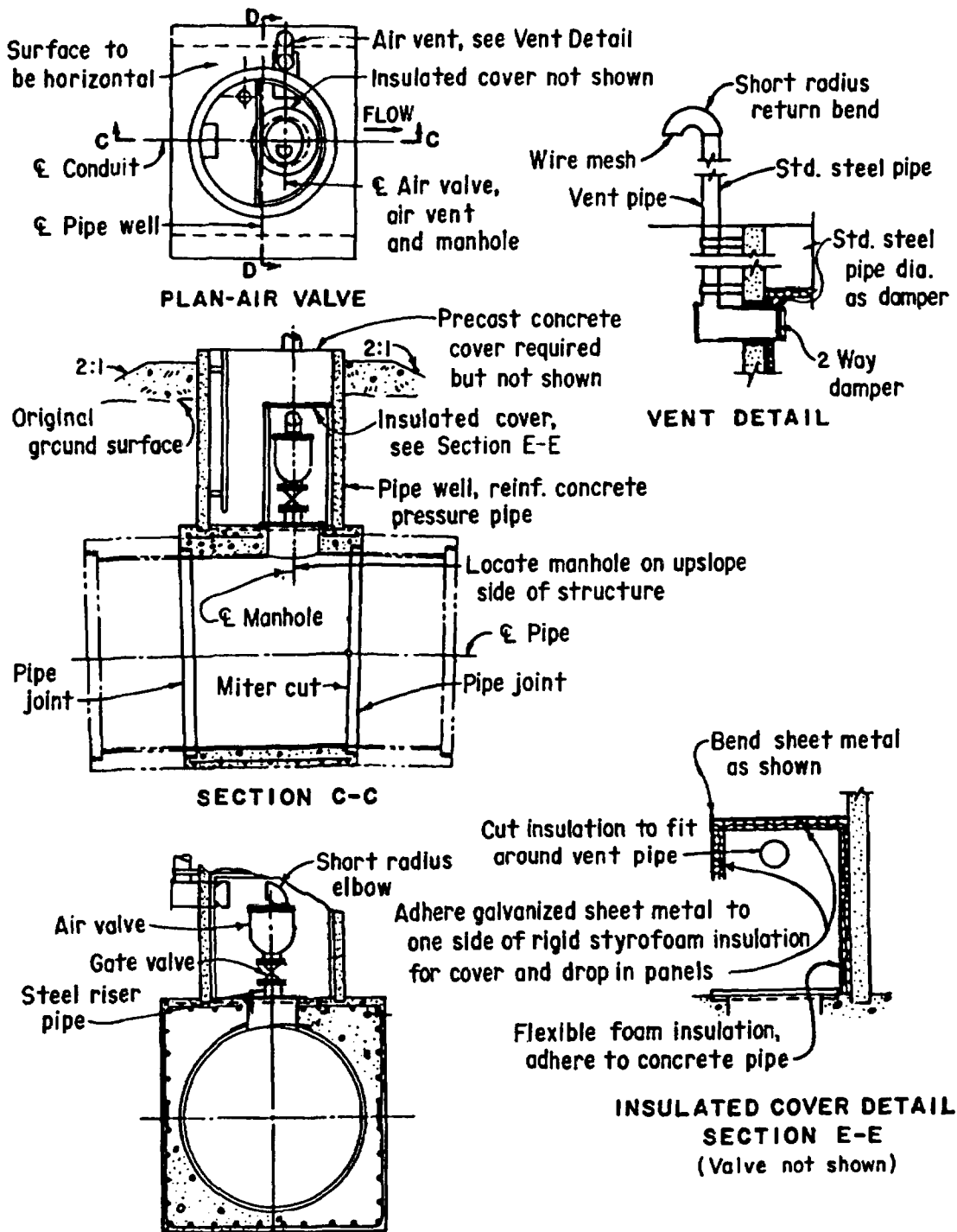


FIGURE 46.—Typical frost protection installation.

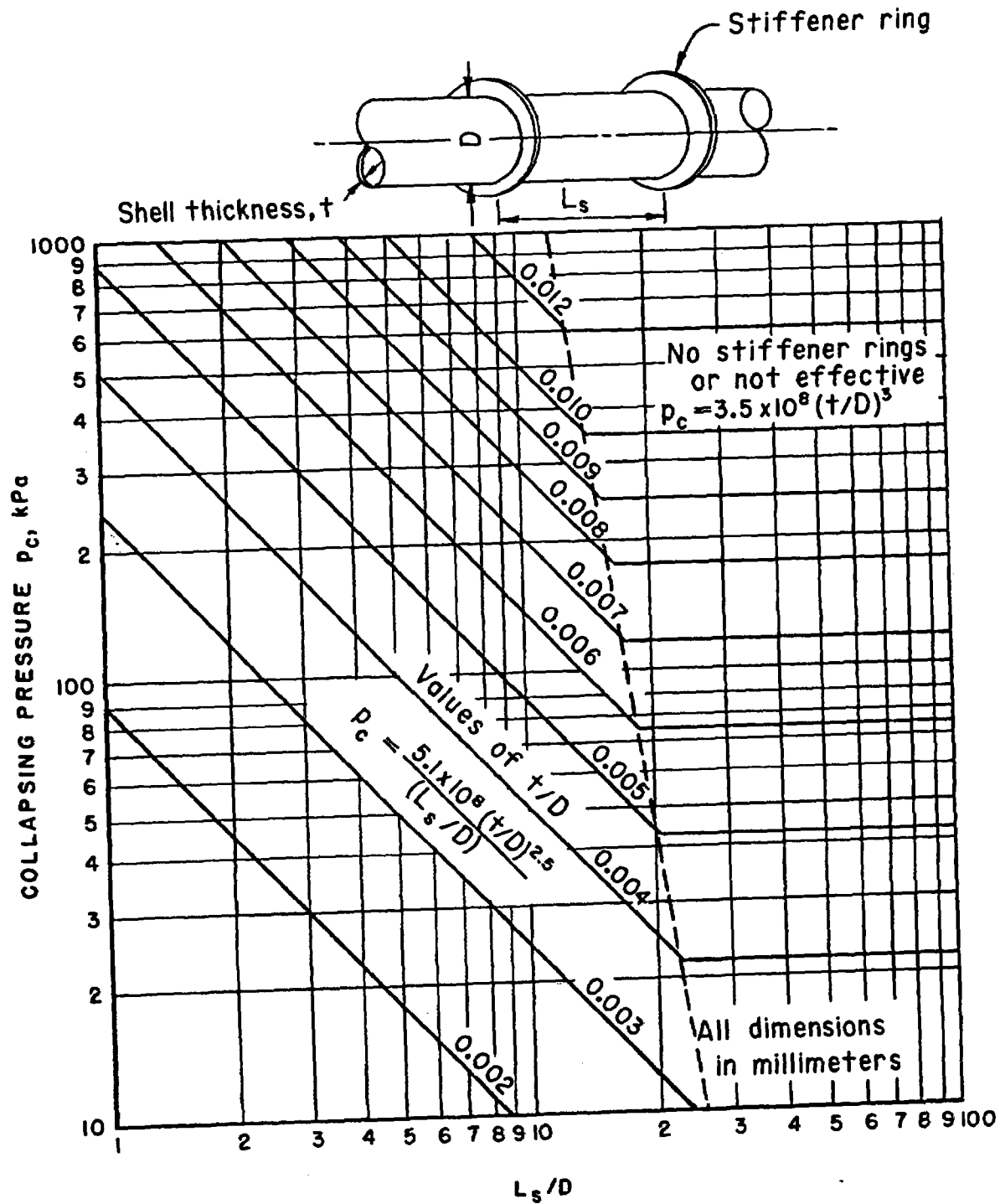


FIGURE 47.—Collapsing pressure of a steel pipe with stiffener rings.

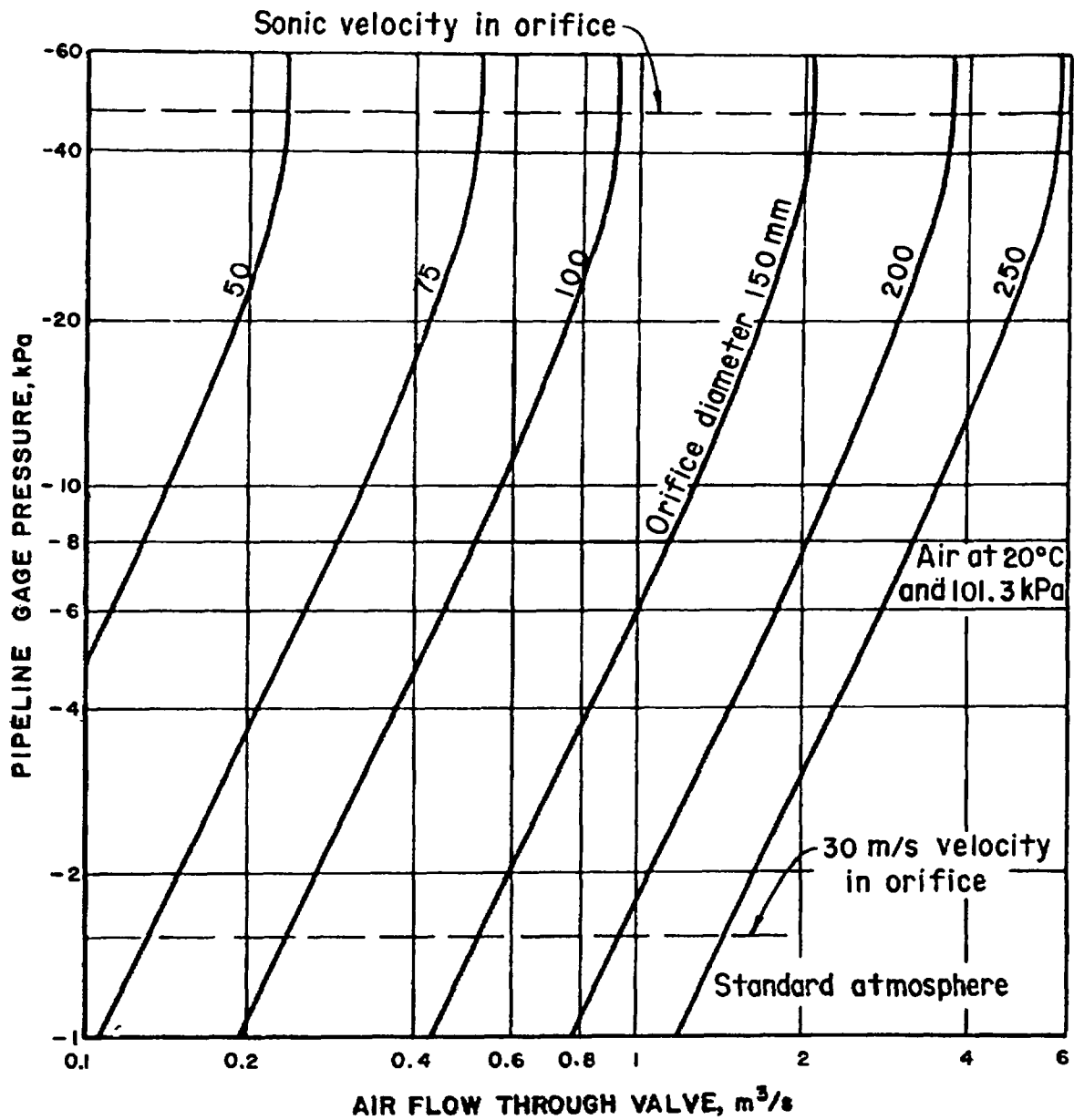


FIGURE 48.—Performance curves for large-orifice vacuum relief valves.



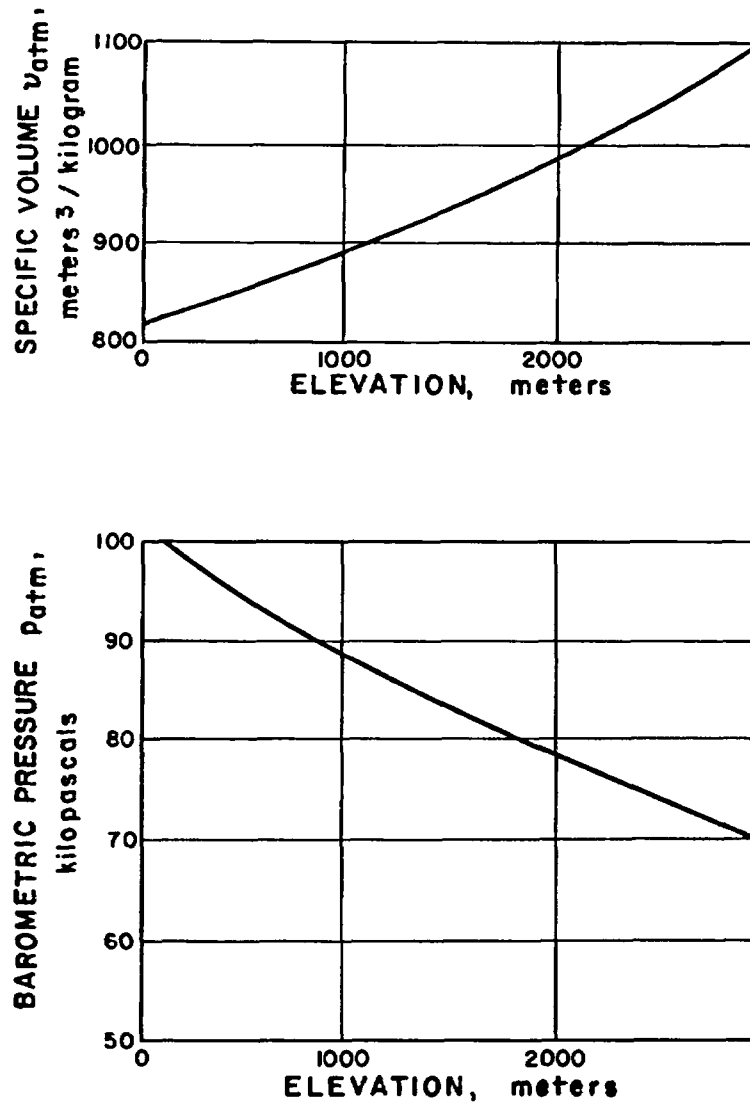


FIGURE 49.—Specific volume and barometric pressure of air as a function of elevation.

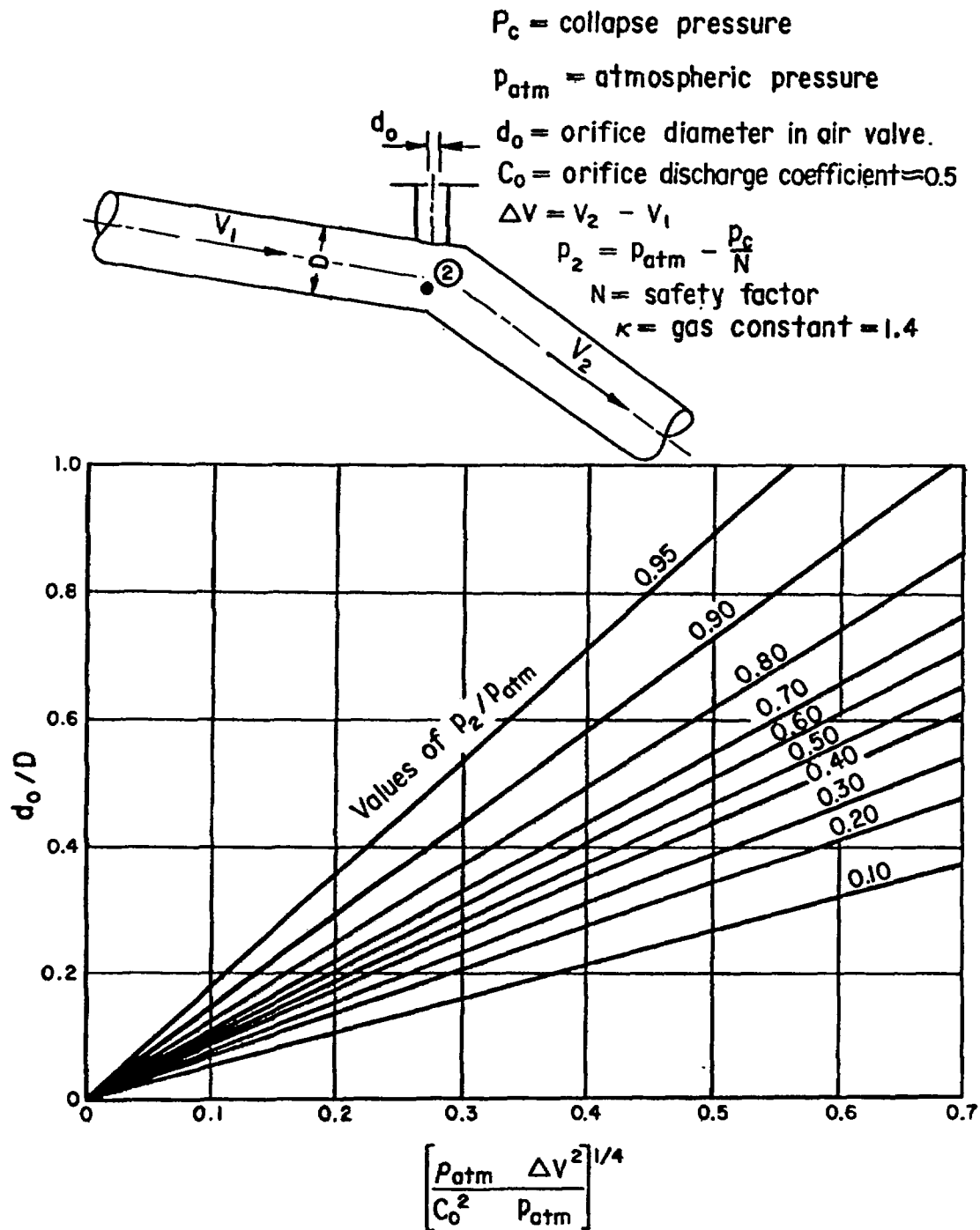


FIGURE 50.—Required air relief orifice diameter to prevent collapse of steel pipelines.

## FLOWS IN VERTICAL SHAFTS

### Classification of Airflows

Three types of hydraulic structures that use a vertical shaft to convey water from one elevation to another are:

- Spillways
- Intakes
- Drop shafts

The air entrainment properties of these structures are important since at certain flowrates explosive air blowbacks are possible (fig. 51). Often extensive studies are necessary to design vent structures to remove the air which is entrained in the vertical shaft Anderson [3] and Babb [6].

The amount of air entrained in the shaft is strongly dependent upon the type of flow into the shaft and upon the water level in the shaft. The inlet flow can vary from radial to tangential with flow entering around the circumference of the shaft. Typical types of inlet structures (fig. 52) are:

- Circular weirs
- Vortex inlets
- Radius elbows

The effect of water surface (reservoir) elevation at the entrance to a shaft can be examined by considering the discharge characteristics of a vertical shaft spillway (fig. 53). For low water surface levels the discharge is proportional to the three-halves power of the total head on the crest. The flow in the shaft clings to the walls in

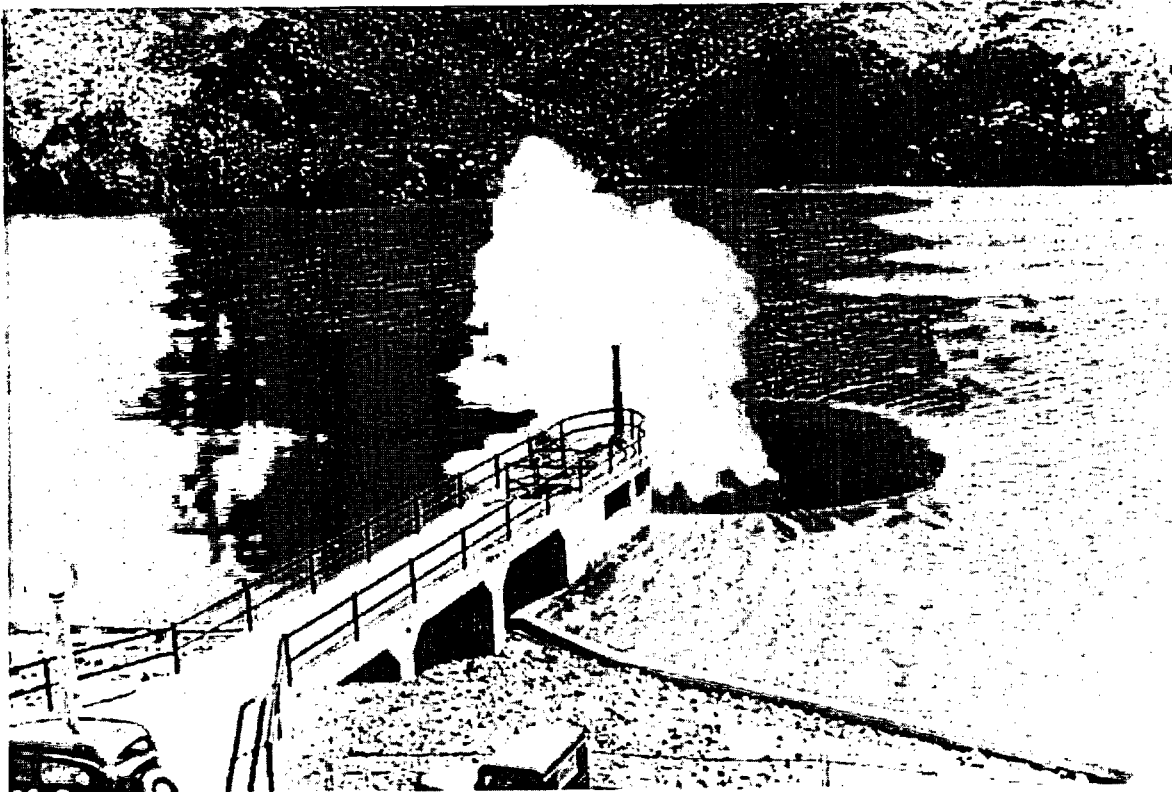


FIGURE 51.—Observed air blowback in morning glory spillway at Owyhee Dam, Oregon. P801-D-79280

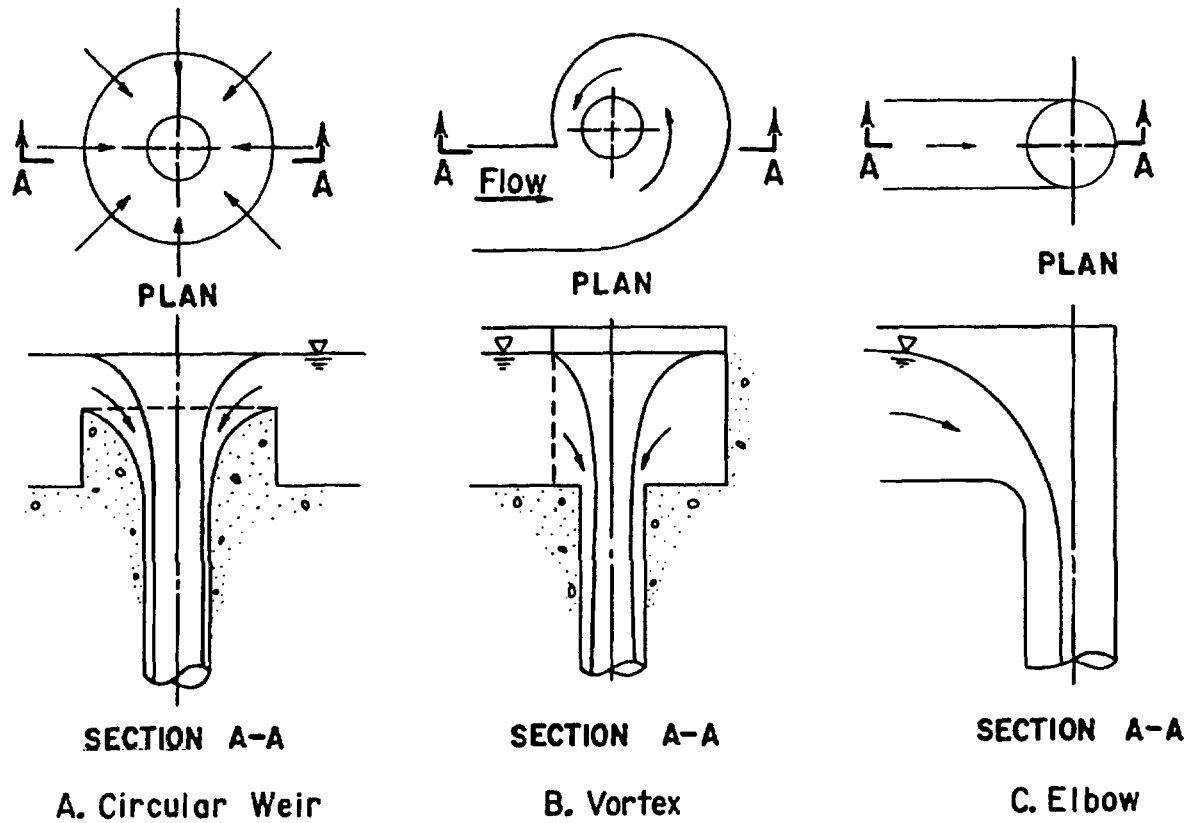


FIGURE 52.—Typical types of vertical shaft inlet structures.

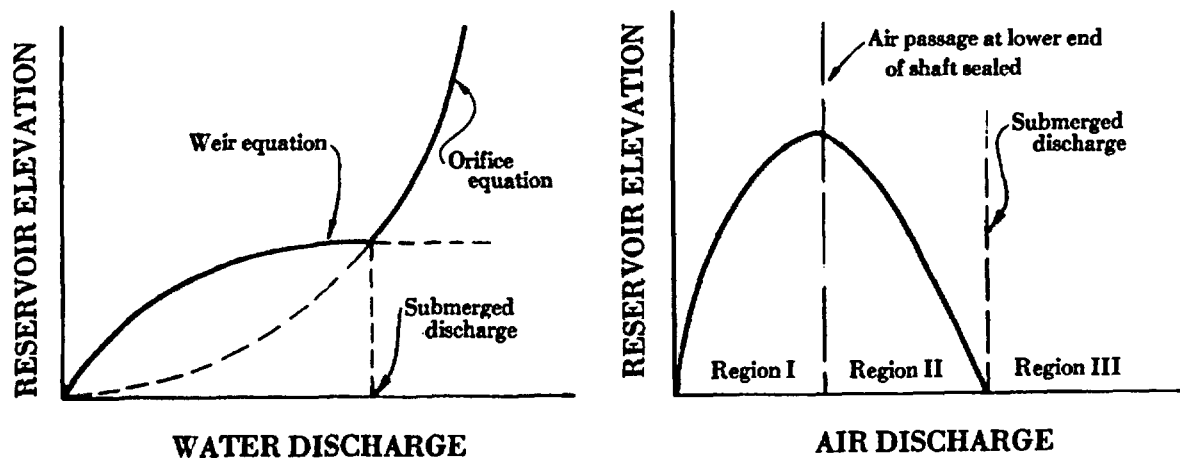


FIGURE 53.—Vertical shaft spillway discharge characteristics.

a relatively thin sheet. The volume flow rate of air is determined primarily by the shear action of the air-water interface and by entrainment into the mass of the water. This type of flow has been designated as region I on figure 53. As the water discharge increases with increasing reservoir elevation, a point is reached when the sheet of water is sufficiently thick to completely fill the upper end of the conduit. This water discharge separates region I from region II type flows.

Region II type flows are characterized by an annular hydraulic jump. Further increases in reservoir elevation merely cause the location of the jump to move upward in the vertical shaft. When the jump reaches a point near the top of the shaft, the flow is said to become submerged.

For reservoir elevations in excess of that required to produce the submerged water flow, all inflow of air to the shaft ceases. The discharge for this flow range is proportional to the one-half power of total energy over the crest.

If the bottom of the shaft is always submerged, then a region I type flow will not develop. Instead, the air motion will be described by a region II type flow up to the point when the vertical shaft is submerged.

The airflow rates discussed above should not be confused with those that are present in the portions of the structure downstream of the vertical shaft. The methods discussed in this chapter—Flow in Partially Filled Conduits—should be used to analyze the flow of air in the horizontal sections of vertical shaft spillways and similar structures. Mussalli and Carstens [55] studied surging problems that develop as the horizontal conduit seals [fig. 21 (5)]. However, they did not develop any air entrainment criteria for the vertical shaft.

### Region I Airflow Rates

The airflow rate down the vertical shaft can be calculated by assuming:

- a. The water flow on the shaft walls is similar to open channel flow, and
- b. The lower end of the shaft is open to the atmosphere.

If the inlet is not designed to keep the water flow attached to the wall, the airflow rate cannot be calculated.

Several methods are available to estimate the airflow rate when the water forms in a sheet on the walls. For instance, the air insufflated into the flow can be estimated from equation 59 using open channel flow relations. The amount of air flowing on the core of the pipe can be determined from

$$Q_a = V_o A_c \quad (98)$$

where

$A_c$  = cross sectional of air in core

$V_o$  = maximum water velocity in vertical shaft

Hack [27] recommends that the total airflow be determined from

$$Q_a = 0.35 + 16.1 \bar{C}^{2.88} \quad (99)$$

where  $\bar{C}$  = mean air concentration

The mean air concentration is estimated from

$$\bar{C} = \{1 + [4(1 - e^{k_r(F_o^{4/3} - F^{4/3}))}]^{-1}\}^{-1} \quad (100)$$

where

$D$  = conduit diameter

$F$  = Froude number at end of shaft

$F_o$  = Froude number at point where boundary layer intersects water surface

$k_r = 1.8 r_s + 0.0108$

$k_s$  = equivalent sand grain roughness

$r_s$  = relative roughness =  $k_s/D$

The point where the boundary layer intersects the water surface is found through the application of equations 27 through 30.

**Region II Airflow Rates**

Various investigators have studied the entrainment of air by an annular jet.

Haindl [29] found that the air entrainment obeys a law very similar to that found by Kalinske and Robertson [38] for a hydraulic jump in a conduit. The relation is

$$\beta = \frac{Q_a}{Q_w} = 0.02 (F - 1)^{0.86} \quad (101)$$

where  $F$  = Froude number

$$F = \frac{Q_w}{R_j D [1 - (R_j/D)] (g R_j)^{1/2}} \quad (102)$$

$D$  = outside jet diameter (conduit diameter)

$g$  = gravitational constant (acceleration)

$Q_a$  = volume flowrate of air

$Q_w$  = volume flowrate of water

$R_j$  = thickness of annular jet

Kleinschroth [43] found a correlation for flows in vertical shafts having a vortex inlet. The relation is

$$\beta = 0.022 \frac{h_f}{D}^{2/5} \quad (103)$$

where

$h_f$  = distance from the inlet to the water level in the vertical shaft

$D$  = shaft diameter

**Reverse Airflow in a Vertical Shaft**

All the preceeding relations assume that the waterflow rates are sufficient to remove all the entrained air from the system. Martin [51] showed that slug flow begins when the dimensionless airflow  $\beta$  exceeds 0.223. It was shown earlier that these slugs move up the shaft for

$$\frac{Q^2}{g D^5} < 0.3 \quad (104)$$

Therefore, for dimensionless water flow ratios less than 0.3, the airflow quantities given by equations 101 and 103 are too large. In addition, it is possible that blowback will occur in the shaft.

**Submergence**

The water depth which causes a vertical shaft to flow submerged has been determined only for the case of radial inflow. Jain, Raju, and Garde [36] determined that the submergence at which airflow down the shaft ceases is given by

$$\frac{S}{D} = 0.47 F^{1/2} \quad (105)$$

where

$D$  = shaft diameter

$F = V/(gD)^{1/2}$

$g$  = gravitational constant (acceleration)

$S$  = submergence depth

$V$  = mean water velocity in shaft flowing full

For a vortex inlet or for approach flow having some circulation, the required submergence would be greater than that given by equation 105.

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