1. INTRODUCTION
(Rao, Kobus)

1.1 Air-water mixtures

Mighty waterfalls, the sea waves breaking on beaches, the dancing cascade flows down mountain rivers and scores of other flow situations where air entrains into water causing a dazzling whiteness and presenting an intriguing spectacle have attracted the attention of research workers the world over in recent years. They are attempting to unfold the mechanics of aeration and provide for its effects such as bulking and energy dissipation characteristics. A knowledge of the laws governing the characteristics of self-aerated free surface flows is of great importance not only in understanding

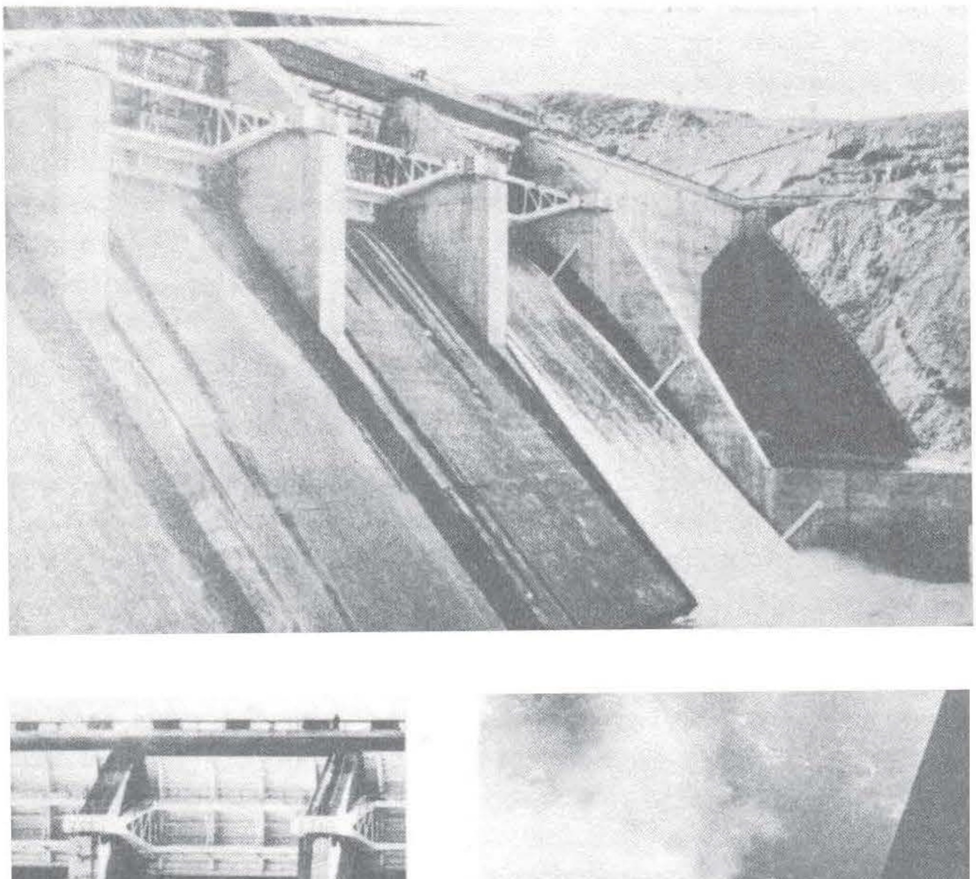

FIG. 1.1 AIR ENTRAINMENT IN FREE SURFACE FLOWS
(Aviemore Dam, New Zealand [86])

the phenomenon of air entrainment, but also in design problems of hydraulic structures such as overflow spillways, chutes and stilling basins. In the environmental field, the role of aeration at structures such as weirs for the oxygen balance of a river system and hence for water quality enhancement has been recognised for some time. Furthermore, the proper design of such devices as fire monitors, regulating valves in pipes, jet pumps, high-head gates or air-controlled siphons also require a thorough understanding of the phenomenon of aeration.

The basic characteristics of self-aerated free surface flows may best be explained by considering examples of water falls or flow over spillways and chutes (Fig. 1.1). Low velocity flow entering a spillway with negligible disturbances accelerates smoothly and presents a glass-like surface. If the water is clear, the surface of the dam may be seen distinctly as if the flow over it was not in motion at all. As the flow progresses down the spillway, the water surface shows increasing disturbances until it is no longer transparent. In the region of transparency, the flow is non-aerated, and the velocity distribution depends upon the surface roughness, the curvature of the spillway surface and the head and velocity distribution of the approaching flow. Beyond this point, the free surface consists of lots of disturbances in the form of projecting masses or boils. These flow protuberances disintegrate in the atmosphere into droplets, which reenter into the main flow, entraining air in the process and giving the appearance of "white water". The critical condition at which this phenomenon just begins may be termed as the "Inception Characteristic" of self-aerated free surface flows.

The degree of whiteness of the flow gradually increases downstream from the inception region and finally attains constancy. This is due to the increasing insufflation of atmospheric air into the flow. The flow swells downstream due to the entrainment process. Far enough downstream where constancy of whiteness prevails, equilibrium is reached between the amount of air escaping from the water and the amount of air entrained into it. The entrained air is mixed with the water and is distributed over the cross section in a particular fashion depending on the intensity of turbulence present in the flow.

The presence of air in water flows has several effects. The entrained air causes an increase in volume termed "bulking", which has to be provided for suitably in freeboard allowances in the design of hydraulic structures. As air entrains into the flow, energy is spent to distribute the air bubbles throughout the flow, and to keep them in suspension. This internal energy dissipation is of importance in flows over spillways and steep chutes, where floods have to be disposed off quickly and economically. Since the flow at the foot of such structures is invariably aerated, the formation of a hydraulic jump leads to so-called "pre-entrained jump" conditions, which need to be understood for a safe design of energy dissipation arrangements.

Air-water mixtures can be classified according to their type of generation. The various processes leading to the formation of air-water mixtures are listed in Fig. 1.2 together with a number of illustrative civil engineering applications. It is to be noted here that this monograph, rather than treating all types of flow configurations listed, presents only the most significant configurations of open-channel flows, hydraulic jumps and jets striking rigid or liquid surfaces. This emphasis has been placed in view of recent research results, and the authors did not attempt to give all aspects equal weight in the treatment.

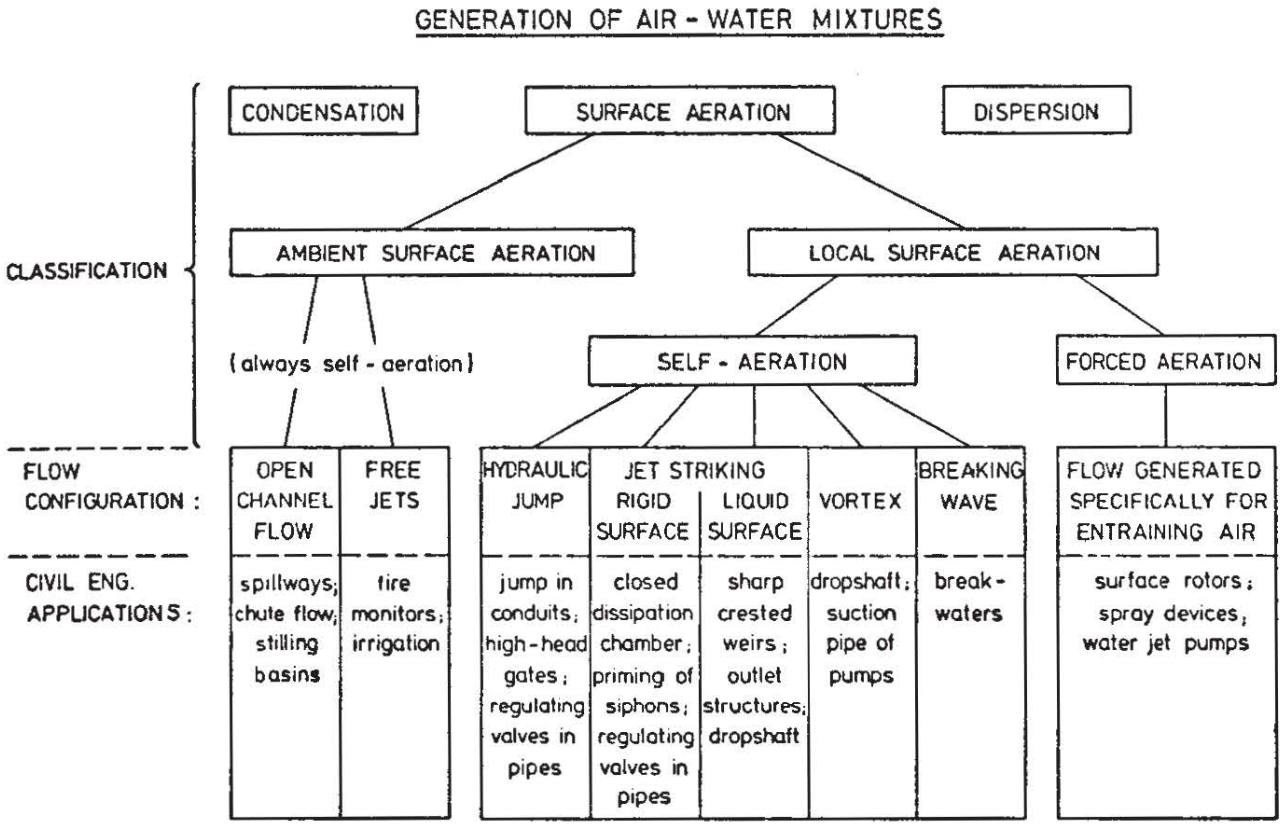

FIG. 1.2 CLASSIFICATION OF AIR-WATER MIXTURES ACCORDING TO THEIR TYPE OF GENERATION

A descriptive classification of turbulent free surface flows giving rise to self aeration has been given by Michels and Lovely [120] :

(1) "Rippled" flow: Generally a smooth surface undulation; no air entrainment.
   (a) Examples: Flow in a gently sloping uniform channel or in upper reaches of steep chute.
   (b) Common characteristics: Low or medium velocity, small turbulence and energy gradient.

(2) "Choppy" flow: Generally an agitated surface with only a small proportion occupied, at any instant, by individually breaking or mutually interfering waves which, sporadically and intermittently, envelop air and release it soon after subsiding; from a practical point of view, no sensible increase in flow depth occurs.
   (a) Examples: Flow in a gently sloping natural stream having an irregular bed; flow in a uniform channel of medium slope or near obstructions in an otherwise gently sloping invert.

(b) Common characteristics: Larger surface variations, greater local turbulences, and upward velocity components, with consequent local increases in energy gradient.

(3) "Scarified" flow: An air-water mixture formed generally as a relatively thin layer at the surface of a stream. The air is apparently trapped by water particles upon their leaving the surface and small or moderate increases in flow depths occur.

(a) Examples: Flow down rapids having an approximately uniform and gentle grade, but with moderately uneven bottom; flow down long, uniform chutes of narrow width and/or with wall surfaces having uneven shape, changes in direction, or frequent variations in their distance apart.

(b) Common characteristics: Large variations in water surface and considerable upward velocity components; generally greater velocities and energy gradients throughout the length of flow.

(4) "Emulsified" flow: A general, deep and continuous emulsification of air and water which presents a frothy uneven surface; flow depths may greatly exceed those computed without allowing for air entrainment.

(a) Examples: Flow down a steep, wide chute or spillway surface (air entrainment commences suddenly, at a relatively considerable distance from the upper or intake end and continues thereafter); flow over rapids with steep and uneven bed (air entrainment commences just below upper end and generally increases in downstream direction).

(b) Common characteristics: Air entrainment commences where stream velocity exceeds some minimum value; turbulence is general from this point downstream; velocity components normal to surface are large and energy gradient obviously considerable.

(5) "Ebullient" flow: A violent air-water mixture occuring as a "boil" on the surface, extending irregularly through a portion of the water in a pattern which depends on its boundaries and on the inflow and outflow conditions, is typical of these flows. The air is apparently enveloped or drawn in at the free surface of the turbulent impact zone existing between a rapidly moving stream and a slack or comparatively slowly moving body of water; air may also be entrapped at the upstream surface of the comparatively slowly moving body of water by the rise, dispersion, and fall of the water particles which possess large vertical velocity components. The air thus entrained may be recirculated in a vertical roller, but generally it escapes gradually in the direction of reduced turbulence. In this case, the depth of flow is locally increased but diminishes as turbulence is damped out and air escapes.

(a) Examples: Flow of a high-velocity jet, laterally at the bed or surface level, or vertically upwards or downwards, into an energy dissipator or a natural pool.

(b) Common characteristics: Large vertical components of velocity and high local energy gradients; generally small lateral velocities beyond zone of impact.

(6) "Spraying" flow: A water jet discharging into the atmosphere (Because of the inherent lateral velocity components in turbulent flow, and as a result of contact with air) disperses and disintegrates into smaller masses and, provided sufficient travel distance is possible, expands considerably into a spraying flow which finally consists of fine droplets or mist containing enmeshed air.

(a) Examples: Flow from a needle outlet discharging into air, under a medium or high head.

(b) Characteristics: For considerable air entrainment to occur, the jet velocity must exceed a certain minimum value and the distance traveled must be sufficient; rate of energy dissipation is very large.

(7) "Separation" flow: High velocity flow in an open waterway and separation from a solid boundary causes reduction and instability of pressure. If the absolute value of the local pressure is sub-atmospheric, air and vapor volumes produced are considerable. Tremendous local boundary turbulence occurs, accompanied by entrainment from the atmosphere at any adjacent free surface with considerable local increase in depth of water.

(a) Examples: High-velocity flow around the chute blocks or baffle blocks on the floor of the energy dissipator; flow past a gate slot in the pier.

(b) Characteristics: High-velocity flow with violent additional turbulence caused by separation; considerable vertical velocity components, and large energy dissipation.

1.2 Historical Survey

A brief review of the research literature is made in order to give a perspective view of the problem and to list the outstanding contributions made in the advancement of this subject.

Ehrenberger [41] was the first to study the phenomenon of air entrainment in open channels in 1926. In his pioneering work he distinguished a layer of water near the bottom in which only small quantities of air bubbles are present, an intermediate layer in which water and air are present in almost equal quantities, and an uppper layer of air in which large water drops are in movement. He described a simple, but effective device for measuring air concentration in the flow of chutes: a tube pointing into the flow and communicating through an elbow with a vertical glass tube of a much larger diameter. The pitot-like tube was rated in a non-aerated flow with known velocity by measuring the time to fill a known volume of the vertical tube. The operation was repeated in aerated flow, and from the increased time to fill the tube the air concentration in the air-water mixture was calculated. The apparatus was crude compared to modern electronic methods, but the idea remains ingenious.

In 1939, Lane [106] advanced a theory, according to which the inception of air entrainment occurs when the boundary layer thickness equals the depth of flow. This concept led to experimental investigations by Hickox [70] , Halbronn [62] , Bauer [8] and Bormann [11] . Hickox [70] verified Lane's theory by conducting model experiments and prototype observations. Halbronn [62] computed the growth of the boundary layer and showed that the boundary layer thickness equals the depth of flow at the inception zone on spillways. These investigations led Bauer [8] to conduct more detailed experimental work on steep slopes with various discharge and roughness conditions. He eliminated the effect of slope by using a length parameter $x_B = U^2/2gs$, in which U is the potential flow velocity, g is the acceleration due to gravity, and s is the slope. Bormann [11] applied the equations for turbulent flow in pipes and along flat plates to the special case of flow in chutes in order to locate the "critical point" of air entrainment inception. Michels and Lovely [120] collected prototype data and defined various types of aerated flows. Campbell et.al [17] proposed an equation for the growth of the boundary layer on spillways: their equation, however, fails to consider the effect of discharge.

Hickox [70] observed that although the boundary layer reached the free surface, air entrainment was not noticed in models. This, according to him, was due to the kinetic energy of the surface eddy being insufficient to overcome the surface tension energy. This aspect of the inception condition was studied to some extent by Govinda Rao and Rajaratnam [56] , who presented an analysis based on the energy concept of a surface eddy, neglecting the effects of the wall shear stress. Hino [73] developed two criteria for "scarified flow" based on the momentum concept, - one for small and another for large eddies - and a third one for "emulsified flow". These criteria are difficult to apply since it is hard to define whether an eddy in the inception zone is "large" or "small" or whether the flow is "scarified" or "emulsified". Levi [110, 111] proposed another theory for the inception of air entrainment, using Benjamin's [9, 10] theory of the breakdown of vortices. All of these attempts leave a number of unanswered questions, and a more comprehensive approach is needed for a better understanding of inception, which must include the effects of wall shear stress, different eddy sizes and different flow conditions.

A significant contribution to aerated flow research was made by Straub and Anderson [168] , who investigated in detail the distribution characteristics of the air-water mixture in fully developed free surface flows. They divided the flow into two broad zones, viz., one in which air bubbles are present in water, and another in which water drops are present in air. Their analysis of air concentration in the lower zone (air bubbles in water) is similar to the laws of flows with suspended sediment - with the difference that the air bubbles tend to rise whereas the sediment particles tend to sink. The agreement of their analysis with experimental results conducted for various flume slopes and discharges is remarkable. It should be noted, however, that their analysis does not take into consideration any interaction with the atmosphere, and that it contains an eddy-viscosity assumption which is not in agreement with the experimental results of Straub et. al [167] . Barring these shortcomings, their contribution to the analysis of air concentration distribution is a milestone in aerated flow research.

Extensive prototype data on the relation between mean air concentration and Froude number were presented by Hall [64] in 1943. Douma [39] reanalysed Hall's data and developed a relation between Manning's "n" and the mean air concentration. CWPRS (The Central Water and Power Research Station) Poona [20, 21] also conducted experiments on different types of roughnesses and discharges and related the Froude number with the mean air concentration. The ASCE Task Committee on aerated flow [171] analysed the data of Hall [64], Straub and Anderson [168] and Anderson [2] and proposed an expression for the mean air concentration in terms of the discharge per unit width, and the angle between the bed and the horizontal.

All analytical attempts (except reference [171]) are performed using the data of the aerated flow, such as mean air-water velocity and air-water hydraulic radius, which are controversial [28, 35, 39, 94, 117, 165]. It therefore seems necessary to investigate whether the data of the non-aerated flow can be used to estimate the velocity and depth of the air-water flow. It may also be useful to relate the non-aerated Froude number with the roughness factor and the shape factor of the channel to estimate the probable mean air concentration.

Air entrainment in a hydraulic jump was first investigated by Kalinske and Robertson [85], who studied air entrainment in pipes with particular reference to the removal of air pockets from water supply lines. A very thorough study of air entrainment in hydraulic jumps (including the pre-entrained case) has been presented by Rajaratnam [138]. As a result of his detailed experimental investigations, the effect of air entrainment can now be properly accounted for in stilling basin design.

As air is entrained into the flow, energy is spent to distribute the air and to keep it in suspension. Thus air entrainment acts as an indirect energy dissipating device. Papers of Jevdjevich and Levin [82], Franckovich [46] and Chanishvili [25] are devoted to this and some other technical aspects connected with aerated flows.

An essential prerequisite for aerated flow research is the availability of precise instruments to measure air concentration and air-water velocity. A pioneering contribution in this area was made by Lamb and Killen [105], who devised an electrical probe which measures air concentration in terms of resistance. Many investigators have adopted this principle and extended its applicability, such as Halbronn [62, 63] and Rajaratnam [138]. Beyond these classical devices, the measurement techniques in air-water flows have experienced a rapid development in recent years. Delhaye [37], Resch [143] and Leutheusser et.al [109] have applied hot-film anemometer techniques to measurements in two phase flows. Keller [86, 87] has designed an air concentration probe and a velocity meter suitable for use under field conditions, and most recently Barczewski has developed an optical technique for the measurement of concentration of air bubbles in stagnant and flowing water.

For a more detailed and complete summary and bibliography on aerated flow research, the reader is referred to references [21] and [171] .

1.3 Definition of Terms

The first task in aerated flow research is to define some of the basic terms. Straub and Anderson [168] have defined the essential terms like "concentrations" and "depths". Additional definitions such as "air-water velocity" and "air-water density" have been proposed by Lakshmana Rao et. al [103] .

The air concentration C is defined as the ratio of volume of air per unit volume of mixture.

The upper limit of flow d_u is an upper boundary of air-entrained flow and may be defined as the depth at which the value of air concentration C reaches 99 percent.

The mean depth of flow $\bar{d}$ represents a flow depth that would exist if all the entrained air were completely removed. It corresponds to the depth of a non-aerated flow of a given discharge with a velocity equal to that of the air-water mixture and may be defined as

$$\bar{d} = \int_0^{\infty} (1-C)\, dy \tag{1.1}$$

where y is the normal distance measured from the bed, and C is the concentration of air as a function of y.

The bulkage depth factor B is defined as the ratio of the excess depth due to air entrainment over the calculated mean depth of waterflow and may be written as

$$B = \frac{d_u - \bar{d}}{\bar{d}} \tag{1.2}$$

The transitional depth d_T is a parameter based on the air concentration distribution. It is defined as the distance y from the bed at which the gradient of the air concentration dC/dy is a maximum and has an inflection point.

The mean air concentration $\bar{C}$ is defined as

$$\bar{C} = \frac{1}{d_u} \int_0^{d_u} C\, dy \tag{1.3}$$

The mean air concentration below transitional depth $\overline{C_T}$ is defined accordingly for the lower region of flow only as

$$\overline{C_T} = \frac{1}{d_T} \int_0^{d_T} C \, dy \tag{1.4}$$

Velocity of air-water mixture [103]. The volume of air-water mixture V is given by the sum of the water volume V_w and the air volume V_a

$$V = V_w + V_a \tag{1.5}$$

It follows from the definitions that

$$\frac{V_a}{V} = C \; ; \; \frac{V_w}{V} = 1 - C \tag{1.6}$$

For an elemental length of flow, dx, in which concentrations may be assumed to remain constant, the volumes can be expressed as

$$V = A\,dx \; ; \; V_w = A_w\,dx \; ; \; V_a = A_a\,d_x \tag{1.7}$$

in which A, A_a, A_w are cross-sections of air-water mixture, air and water respectively, with

$$A = A_w + A_a \tag{1.8}$$

With this, it follows that

$$\frac{A_a}{A} = C \; ; \qquad \frac{A_w}{A} = 1 - C \tag{1.9}$$

The total discharge of air-water mixture, Q, can be written as

$$Q = Q_w + Q_a \tag{1.10}$$

Assuming u, u_a and u_w to be the velocities of the air-water mixture, air and water respectively, and using equation 1.9, equation 1.10 may be written as

$$u = (1 - C)\, u_w + C u_a \tag{1.11}$$

Density of air-water mixture. The mass flow of the air-water mixture can be written as the sum of the individual mass flows of water and air as

$$M = M_w + M_a \tag{1.12}$$

Denoting the densities of air-water mixture, air and water respectively as, ρ, ρ_a and ρ_w and substituting equations 1.10 and 1.11 into equation 1.12, it may be shown that

$$\rho = \frac{\rho_w (1-C)\, u_w + \rho_a C u_a}{(1-C)\, u_w + C u_a} \qquad (1.13)$$

From eqs. 1.11 and 1.13, the air-water velocity may be written in terms of water velocity as

$$u = \left[\frac{\rho_w - \rho_a}{\rho - \rho_a}\right] (1-C)\, u_w \qquad (1.14)$$

Eqs. 1.11 and 1.13 may be combined and rewritten in the form

$$\frac{\rho}{\rho_w} = (1-C)\frac{u_w}{u} + C\,\frac{u_a}{u}\,\frac{\rho_a}{\rho_w} \qquad (1.15)$$

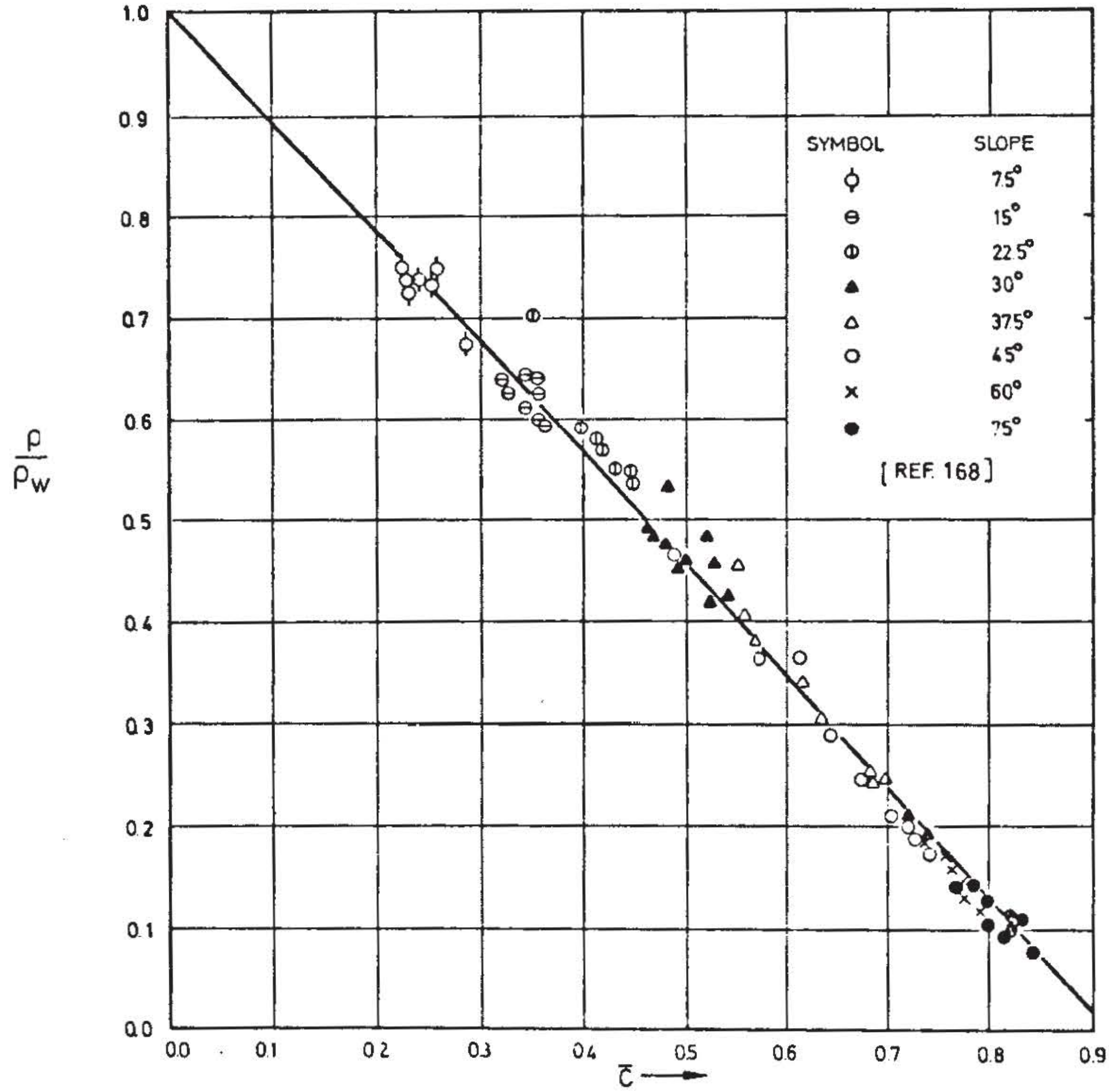

FIG. 1.3 RELATIONSHIP BETWEEN AIR-WATER DENSITY AND MEAN AIR CONCENTRATION IN OPEN-CHANNEL FLOW

Considering that C is either less than unity or tends to unity, that u_a/u is of the order of unity, and that ρ_a / ρ_w is very small ($\sim 10^{-3}$), it becomes clear that the second term on the right-hand side of eq. 1.15 is negligibly small compared to the first term. Therefore, eq. 1.15 can be rewritten as

$$\rho = (1-C) \frac{u_w}{u} \rho_w \tag{1.16}$$

Using the results computed by Straub and Anderson [168], a plot of ρ / ρ_w versus mean air concentration is shown in Fig. 1.3. A simple empirical equation for ρ can be derived from a fit to the data in Fig. 1.3 as

$$\frac{\rho}{\rho_w} = 1 - \theta \overline{C} \quad \text{with} \quad \theta = 1.1 \tag{1.17}$$

The mean air-water density can be computed from this relationship up to values of $\overline{C} \approx 0.85$, beyond which it fails to give correct values.