HYDRAULICS OF TWO-PHASE FLOW: AIR AND WATER

G. G. S. Pegram
Civil Engineering Department, University of Natal, Durban, South Africa

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Summary

Two-phase air-water flows occur when water plunges or jets into a body of water, when it cascades down steps, when it pours down a spillway, or when it jets into a hydraulic jump. These phenomena, together with their advantages and disadvantages, are described in this article, and supporting formulae describing their main features are presented.

1. Introduction

Two-phase flows are those where two different non-miscible fluids flow in a conduit. Examples are: flow of an oil-water mixture in a closed pipeline, and a mixture of air and water either in a pipe or with an interface at atmospheric pressure.

The phenomena considered in this article are confined to air and water with a free surface. This surface is the interface (often highly unsteady) between two zones: air bubbles in water and water droplets in air. The concentrations of each in each may vary from nearly zero to nearly one, depending on location.

In nature, two-phase air-water flows occur under steady conditions in river rapids (white water), in waterfalls (both in the falling and in the receiving water), and downstream of partial obstructions and sudden expansions. Unsteady two-phase air-water flows are encountered in breaking waves, bores and surges.

Engineered two-phase air-water flows are found in the following situations:

- jets impinging on solid or into water bodies;
- at weirs or other gravity structures;
- within the hydraulic jump at the base of a spillway or under-sluice gate; and
- in the flows on spillways, with air content sometimes increased by duct aerators.

The effect of air in water flows can be undesirable in life support systems involving hydraulic structures. Some situations that may arise are the following:

- vortex generation in outflows from reservoirs, reducing or blocking closed conduit flow of water;
- vortex generation in pump sump inlets, causing damage to pumps and other machinery;
- drop in density of the receiving water of a plunge-pool into which an overflow spillway discharges, exposing the pool's walls to increased erosion;
- aeration of spillway water, causing bulking and overflow of side walls and surrounds; and
- reduction of bed friction on steep spillways, leading to an increase in terminal velocity.

Desirable effects of aeration of water include the following:

- reoxygenation of polluted waters or sewage; and
- amelioration or prevention of cavitation damage in hydraulic structures.

This article will not consider air introduced actively into the flow by mechanical means. It will rather address those flow phenomena where air is introduced passively by the flow processes and by the geometry itself.

2. Phenomena Causing Air Entrainment in Free Surface Flows

When water flows past or through air, the air at the interface moves at the same speed as the water. Although difficult to visualize, there is a velocity gradient in the air away from the interface, as well as in the water. Thus, air can be carried into a water mass by the water velocity itself or can be sucked into the flow by being introduced into a zone of low pressure.

Zones of high shear induce violent turbulence, which in turn fragments large bubbles into smaller ones, reducing their terminal upward velocity, and hence increasing residence time in the flow. The means of introducing air into a water flow with a free surface include the following:

- a jet impinging on a water body;
- a hydraulic jump;
- flow down a smooth spillway,
- flow down a stepped spillway; and
- an aeration duct on a spillway.

These cases will be briefly discussed in the following sections.

2.3 A Jet Impinging on a Water Body

If smooth, laminar flow from a faucet over a sink falls into the water in the sink, there will be negligible air entrainment unless the stream is long enough to have broken up into droplets. As the flow is increased, the Reynolds Number (Re) increases and the flow in the jet becomes turbulent. A strongly nonuniform velocity distribution results across the jet where it leaves the nozzle.

The Reynolds Number is given by $Re = vd/\nu$, where v is the mean flow velocity, d is the diameter of the jet, ν is the kinematic viscosity of the fluid (see *Fluid Mechanics*).

This turbulent shearing flow has two effects, namely that the water in the interior of the jet moves faster than that at the edge, and that the jet has a rough surface, due to the highly turbulent nature of the flow in the high shear stress zone at the edge. This rough surface then carries the surrounding air along with it and the air concomitantly slows down the water at the outer edge. Soon the surface water layer breaks up into droplets. Because of their reduced velocity and the presence of air, the droplets cause the effective increase of the cross-section of the partially two-phase flow. This is due to the conservation of mass principle as applied to the partially two-phase steady-state flow.

What hits the receiving water body is an on-rush of water droplets and air moving at nearly the same velocity (possibly less than that of the issuing jet). This air-water mixture plunges to some depth into the water body before the kinetic energy is dissipated and the air bubbles begin to move sideways and upwards, eventually to escape into the atmosphere. The higher the flow rate and therefore the turbulence in the jet, the more opportunity there is for making small bubbles, which will take longer to dissipate in the water body. This increased retention time will aid the reaeration of the water. An important mechanism for air transport into the jet and consequently into the receiving water is the turbulence at the jet surface, which in the case of a jet is also the edge of the boundary layer. This principle is applied to aeration in water purification plants (see *Guidelines for Potable Water Purification*).

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Biographical Sketch

Geoffrey Pegram is Professor of Hydraulic Engineering in the Department of Civil Engineering at the University of Natal in Durban, South Africa. His Bachelors and Masters degrees in Engineering were obtained at the University of Natal and his doctorate was awarded by the University of Lancaster Mathematics Department for work on Probability Theory as applied to Storage. His expertise lies in hydraulic and hydrological modeling, stochastic hydrology and radar rainfall modeling. Apart from rain fields and rainfall modeling, his research interests include river flood hydraulics, flood protection and forecasting, as well as large reservoir system reliability. He has published in *Stochastic Hydrology, Water Resources and Hydraulics*, and has a current interest in the space-time modeling of rain fields measured by weather radar. He is the representative of the International Association of Hydrological Sciences (IAHS) on the International Commission on Remote Sensing and Data Transmission (ICRSDT). He is a member of the South African National Committee of the IAHS (SANCIAHS) for 2000 to 2003.