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STUDIES OF AIR ENTRAINMENT IN OPEN-CHANNEL FLOWS

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SYNOPSIS

The phenomenon of insufflation of air into water flowing at high velocities in open channels has long been of great interest to hydraulic engineers, but detailed experimental information regarding the occurrence and the investigation of the flow mechanism of air-water mixtures has been elusive because of an inadequacy of accurate observations made by means of customary instrumentation. New instruments for measuring velocities of mixed flows and the air concentration in such flows have been devised at the St. Anthony Falls Hydraulic Laboratory of the University of Minnesota, at Minneapolis, so that velocity traverses and air-entrainment traverses can now be made accurately for widely diverse flow conditions, both for velocities and percentages of air entrained.

This paper describes the results of experimental observations of self-aerated flows in an open channel for various slopes of from 15° to 45°. It is pointed out that customary open-channel flow relationships do not apply directly to air-entrained flows. For the range of conditions reported, actual velocities are shown to be greater than the velocities computed by hitherto proposed methods. The experiments reported are for the conditions of a smooth, painted-steel channel surface. The authors contemplate further studies with channels of differing roughness and greater slopes.

INTRODUCTION

The experimental investigation of self-aerated flows in flumes with steep gradients is a phase of the air-water mixture studies now in progress at the St. Anthony Falls (SAF) Hydraulic Laboratory of the University of Minnesota, at Minneapolis. These experiments are being conducted in a large laboratory facility (Fig. 1) especially designed and constructed to provide naturally

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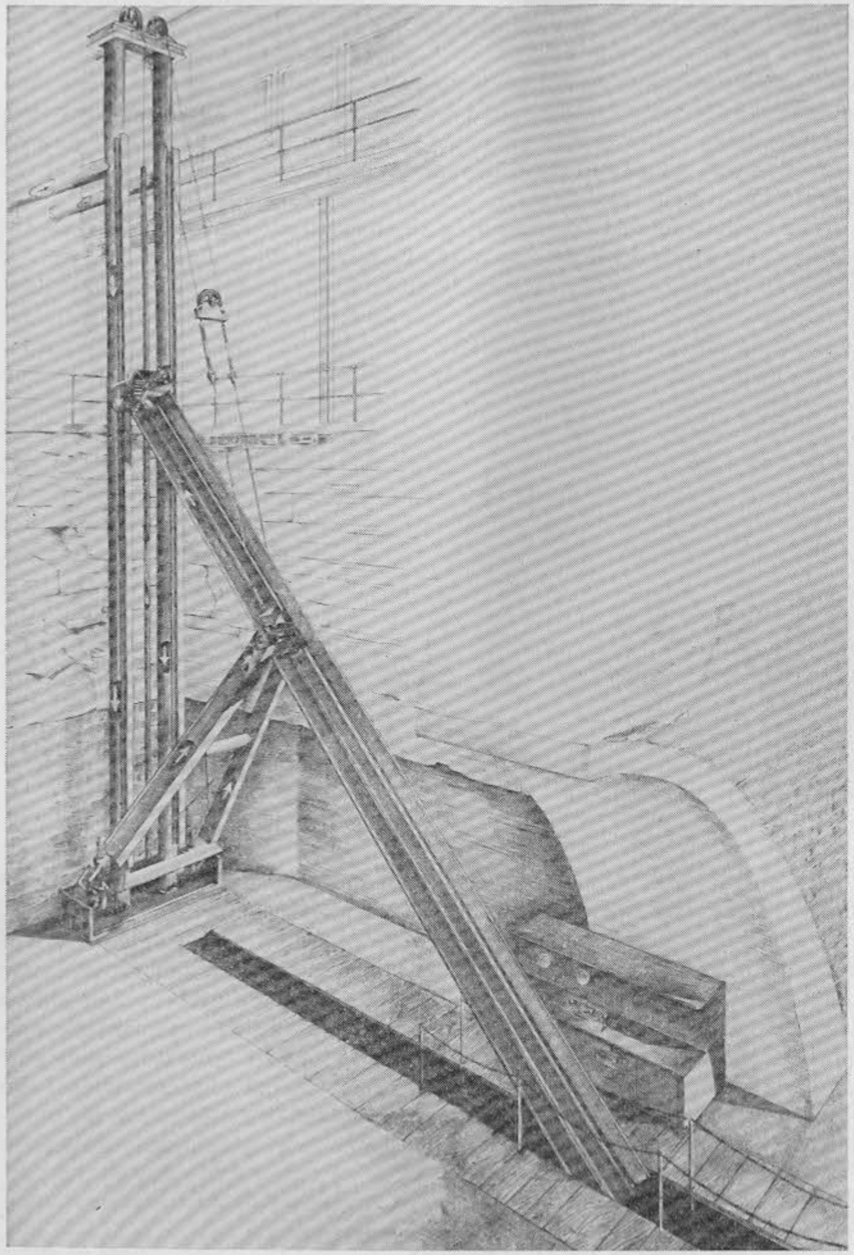

FIG. 1.—CHANNEL FOR AIR-ENTRAINMENT STUDY AT THE ST. ANTHONY FALLS HYDRAULIC LABORATORY

aerated flows through a considerable range of discharges and at all flume slopes ranging from horizontal to vertical.

It was immediately evident that the customary instrumentation for fluid-flow observations would be inadequate; it would supply no more than superficial information which might be misinterpreted. Much attention was therefore given to devising instruments to measure the local values of air concentration and velocity in small increments of the cross-sectional areas of the flows in the experimental flume.

The method devised for measuring air concentration involves the determination of the electrical resistance of the filament of fluid mixture bounded by two small electrodes. The Maxwell equation for the resistance of a suspension of spheres in a conducting medium was utilized to initiate the design. An equivalent electric circuit was developed to adapt the expression to air-entrainment conditions in which the fluid mixture does not always occur as a homogeneous combination of the air phase and the water phase. The instrument, as it is now being used, is accurate, direct-reading, easily handled, and does not require calibration by volumetric means for its operation. The design and development of the apparatus are described in a separate publication.[3]

The method of measuring velocity in small filaments of the two-phase flows of air and water has been described in a previous publication.[4] Being a basic length/time determination over a very short distance (3 in. to 4 in.), the method required precise injection and timing components. Timing precision in the neighborhood of 1/100,000 sec and appropriate pickup and amplifying stages were incorporated into a unit electronic circuit; a diesel injection mechanism was used to achieve the necessary precise identification of the measured filament. The instrument is uniquely fitted for air-entrainment studies as it depends neither on a knowledge of the fluid density nor on a strict homogeneity of the fluid or mixture.

Description of the Flow

R. Ehrenberger, in his pioneering work on open-channel aerated flows,[5] loosely divided the flow into several zones: Water near the floor of the flume, individual air bubbles in water, a mixture of water and air, individual drops of water in air, and an overlying movement of air. Several writers subsequently adopted this arbitrary classification as a real delineation between flow phases and attributed special qualities to the intermediate phases to explain observations they had made. Earlier measurements at the SAF laboratory using flow sampling methods to obtain air concentrations[6] showed conclusively that the mean air concentration increased continuously with elevation above the flume bottom. The mean air concentration at the point of measurement closest to

[3] "An Electrical Method for Measuring Air Concentration in Flowing Air-Water Mixtures," by Owen P. Lamb and J. M. Killen, *Technical Paper No. 2*, Series B, St. Anthony Falls Hydr. Lab., Univ. of Minnesota, Minneapolis, Minn., March, 1950.

[4] "Velocity Measurements of Air-Water Mixtures," by Lorenz G. Straub, J. M. Killen, and Owen P. Lamb, *Proceedings-Separate No. 193*, ASCE, May, 1953.

[5] "Wasserbewegung in steilen Rinnen (Schusstennen) mit besonder Berucksichtigung der Selbstbelüftung," by R. Ehrenberger, *Österreichischer Ingenieur und Architektverein*, Nos. 15/16 and 17/18, 1926.

[6] "The High Velocity Flow of Water in a Small Rectangular Channel," by W. W. DeLapp, thesis presented in 1947 to the University of Minnesota, at Minneapolis, in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

the flume floor varied considerably between flows, depending on roughness of the bottom, flow depth, mean flow velocity, and the distance from the initiation of aeration. Whatever the value of this lowest measured point, there was established a definite gradient of air concentration with no indication of layer flows or sharply separated flow phases.

The hypothesis that aeration becomes incipient in a flume or on a spillway when the turbulent boundary layer from the channel bottom intersects the water surface was forwarded by Emory W. Lane,[7] M. ASCE. Later and more elaborate discussions[8,9] substantiated his hypothesis, showing close agreement between computations and observations in several cases.

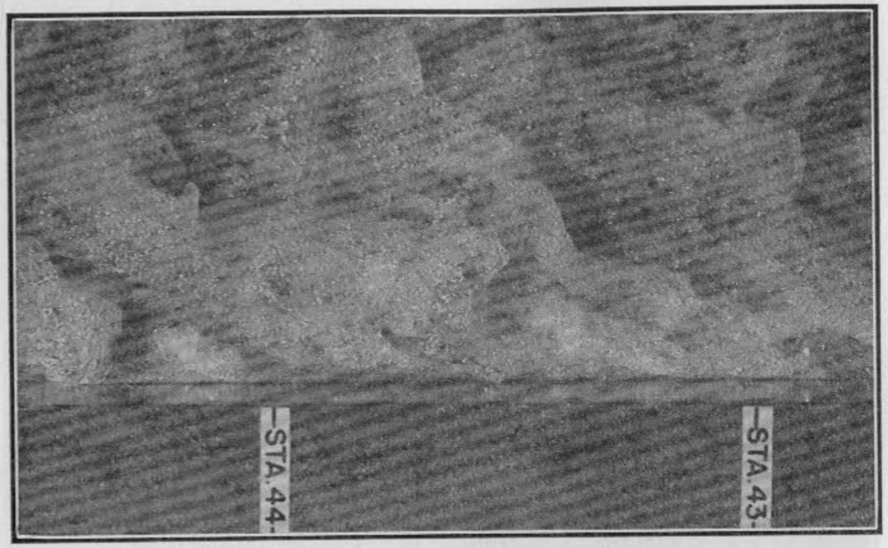

FIG. 2.—SURFACE OF FULLY AERATED FLOW (EXPOSURE: 1/100,000 SEC)

A characteristic roughening of the water surface immediately before the appearance of "white water" can readily be seen in most free-surface installations where self-aeration occurs. Further observations with high-speed photographs such as Fig. 2 illustrate the persistence and magnification of this roughening of the interface into and during the highly aerated condition so that at any instant the aerated flow has the appearance of exceedingly rough and irregular topography. The depressions or open pockets of air at the interface above the dense underlying fluid and the spikes of water mixture projecting into the air are of varying dimensions and are spaced in seemingly random occurrence. This violent agitation of the interface between the mixture and the air causes quantities of air to be entrapped and broken into bubbles of a size that presents a balance between the work of agitation of the liquid and the

[7] "Entrainment of Air in Swiftly Flowing Water," by Emory W. Lane, *Civil Engineering*, February, 1939, pp. 89–91.

[8] "Air Entrainment on Spillway Faces," by G. H. Hickox, *ibid.*, December, 1945, pp. 562–563.

[9] "Study of Entrainment of Air by Flowing Water," by G. Halbronn, thesis presented in 1951 to the University of Grenoble, France, in partial fulfilment of the requirements for the degree of Doctor of Philosophy.