Air Bubble Screens as a Tool for Water Quality Control

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SYNOPSIS

The flow field induced by the release of compressed air in a water body has been studied analytically and experimentally. The quantitative knowledge of the flow pattern in standing water and in a cross flow serves as a basis for the design of air bubble installations, which can be used advantageously for a number of purposes in water quality control, such as pneumatic oil barriers, barriers against density currents due to differences in salinity, silt or sediment concentration or temperature, installations for combating the formation of ice, artificial destratification devices or installations for oxygenation purposes.

1. Introduction

The conservation and wise use of our natural water resources calls for an ever-increasing effort in water quality control. This contribution discusses an engineering device which holds considerable potential as a useful tool for a variety of water quality conservation tasks.

An air-bubble screen—generated by releasing compressed air in a body of water—produces a flow field in the receiving water body which can be used for engineering purposes. Unfortunately, its first application as a pneumatic breakwater more than 60 years ago, disputed for over 40 years, turned out to be a failure. The situation is quite different, however, with applications in water quality projects, where air-bubble screens have been used successfully in recent years (see Chapter 4).

A prerequisite for a successful and economic operation of air-bubble screens is a sound understanding of the quantitative relationships between the flow field generated by the bubbles and the parameters describing the air installation and the receiving water. In the following, the results of analytical and experimental research on this problem are presented and, wherever possible, compared to prototype observations. This leads to quantitative design information for air-bubble screens in natural waters.

2. Basic Analysis

The air is supplied to the water through narrow orifices from pressurized pipes or hoses. Under the action of inertia and gravity, the discharging air jets rapidly disintegrate into bubbles and are decelerated within decimetres to their buoyant free rising velocity. The main part of the flow field can hence be described as a freely rising bubble stream(1). For discharges in a sideways unlimited body of water otherwise at rest (Figure 1), integral equations for continuity of the air—and the waterflow and for vertical momentum flux (assuming similarity profiles and accounting for the change in bubble volume with pressure) can be formulated(4–7). These yield a description of the flow field with three empirical coefficients (entrainment coefficient, turbulent Schmidt number, bubble slip velocity). The same solution can be obtained by treating the bubble swarm as a modified turbulent plume, taking proper account of the bubble slip velocity and of the compressibility of the air.

The empirical coefficients were obtained from measurements of the velocity field and air concentration distribution in a laboratory flume of two metres in depth for the entire range of practically feasible air discharges(10). With these results, the flow field can now be predicted as a function of the air discharge and the water depth.

At the free surface, the vertical plume is deflected

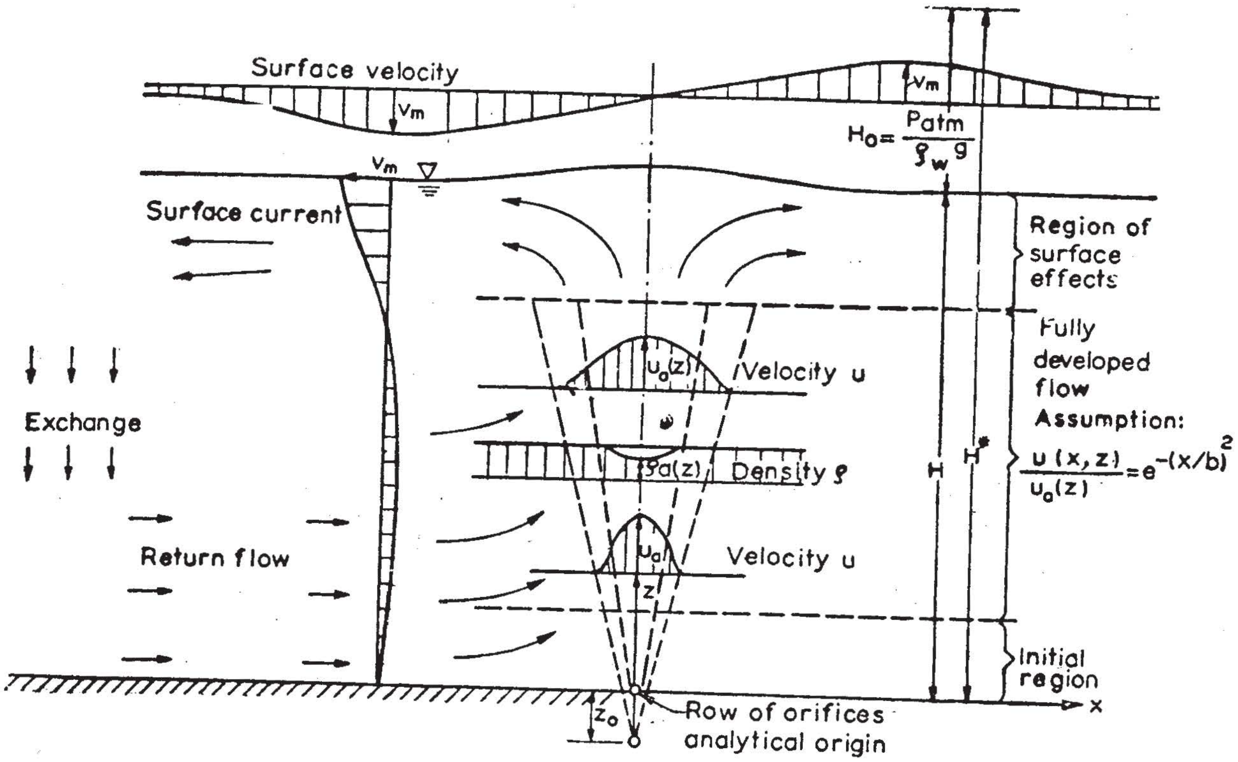

FIGURE 1 : Flow field of air bubble screen.

and produces a horizontal surface current. The maximum horizontal velocity at the free surface can—as proposed by G.I. Taylor[1] and checked experimentally—be taken as being approximately equal to the hypothetical velocity on the plume axis that would be attained at the elevation of the free surface if the latter were not present. With this assumption, the plume analysis data can be used to predict resulting surface velocities. A comparison of such predictions from various empirical formulas and the authors analysis with all available field data is given in Figure 2. The agreement between analysis and observed data is satisfactory over the entire range of conditions. Thus a tool is available for predicting surface velocities for given air discharges and water depths in standing bodies of water.

3. Ambient Flow Conditions

The ideal conditions assumed in the basic analysis are seldom met in nature : here one encounters frequently cross flow currents or density gradients, either of which may have a pronounced effect on the performance of the air-bubble screen.

3.1 *Effect of a Cross Flow*

A cross flow causes a deflection of the rising bubbles in the downstream direction and corresponding changes of the flow pattern (Figure 3). These effects have been studied experimentally, and analytically, so that the resulting surface currents in a cross flow can now be predicted.

In a cross flow, the flow towards the barrier in the lower layers is augmented, and the surface current in the downstream direction increases, whereas the region of return flow on the upstream side (which determines the barrier action) decreases both in size and intensity, until, for very strong cross currents, it finally disappears, so that no more barrier action is possible. From experiments over a wide range of depths, air discharges and cross current velocities (Figure 4), an empirical relation of the form

$$\frac{v^*}{(gq_o)^{1/3}}=\frac{v_m(U_H=0)}{(gq_o)^{1/3}}-\frac{2}{3}\,\frac{U_H}{(gq_o)^{1/3}} \qquad ...(1)$$

can be derived for the relative velocity v^*. The acting absolute "barrier" velocity v_m in the upstream direction follows as the difference between v^* and U_H to

$$\frac{v_m}{(gq_o)^{1/3}}=\frac{v_m(U_H=0)}{(gq_o)^{1/3}}-\frac{5}{3}\,\frac{U_H}{(gq_o)^{1/3}} \qquad ...(2)$$

This relation gives an estimate of the influence of a cross flow upon the surface velocity and can be used for design purposes until an analytical solution for this complicated flow configuration becomes available.

3.2 *Effect of a Density Gradient*

In stably stratified water bodies (such as reservoirs

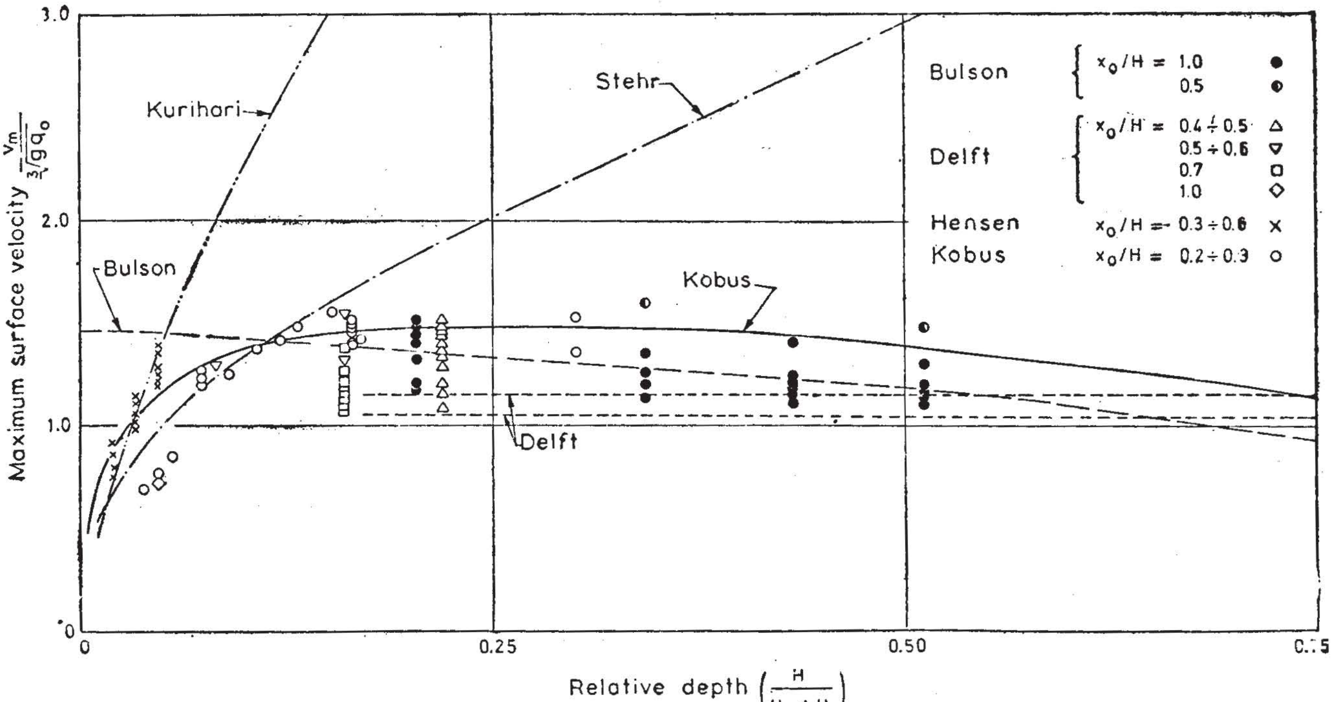

FIGURE 2 : Maximum surface velocity as a function of air discharge and depth.

with a summer temperature stratification, or ice-covered freshwater lakes in winter) the upward transport of water due to the bubble swarm is impeded by the negative buoyancy of the entrained water. At pronounced density interfaces (or when the total upward momentum of bubbles and entrained water becomes negative), some temporary decoupling between bubbles and entrained water may occur (Figure 5). However, after some time of operation the air bubbler will achieve local destratification.

4. Design Information for Applications in Water Quality Control

The results of the analysis and the experience collected with existing installations (both failures and successes) yield a sound basis for designing air-bubble screens and for predicting their performance and evaluating the economics of operation.

4.1 *Pneumatic Oil Barriers*

The operating principle of a pneumatic oil barrier is that the spreading tendency of the oil is counteracted by the surface current induced by the bubble stream. A simplified momentum equation (neglecting friction losses, etc., and thus being on the "safe" side) can be formulated for the configuration sketched in Figure 6 as

$$\frac{\rho_w}{2} v_s^2 (D-\delta) + \frac{\rho_w g}{2}(D-\delta)^2 = \frac{\rho_m g}{2} D^2 - (\sigma_{ML} + \sigma_{MW}) \quad \ldots(3)$$

From this, the barrier velocity v_s required to retain the oil film is given by

$$v_s = \sqrt{gD\left[1 - \frac{\rho_m}{\rho_w} - \frac{2(\sigma_{MW}+\sigma_{ML})}{\rho_m\, g D^2}\right]} \quad \ldots(4)$$

This relation is plotted in Figure 6. Since the influence of surface tension is secondary, the required barrier velocity is determined by the layer thickness and the density of the mineral oil.

With this all necessary information for the design of a pneumatic oil barrier is available. For a given mineral oil of a given layer thickness, Equation (4) yields the required barrier velocity at the surface, to which proper additions for safety have to be made. For a given water depth, the bubble plume analysis now yields the air discharge required to produce this barrier velocity. All these design components are combined in the nomogram given in Figure 7.

The various design steps are best illustrated by giving a numerical example (see Figure 7). Assume an oil harbour, which is to be protected against oil spills by a pneumatic barrier across the harbour entrance. The barrier is located at a depth of 8 m and is supposed to retain a layer of gasoline ($\rho_m = 0.73$ t/m³) of 8 cm thickness.

(1) By Equation (4), a surface velocity v_s of 45 cm/s would be required.

(2) This value has to be augmented (safety factor $\varepsilon = 1.5$ e.g.) in order to safeguard against possible

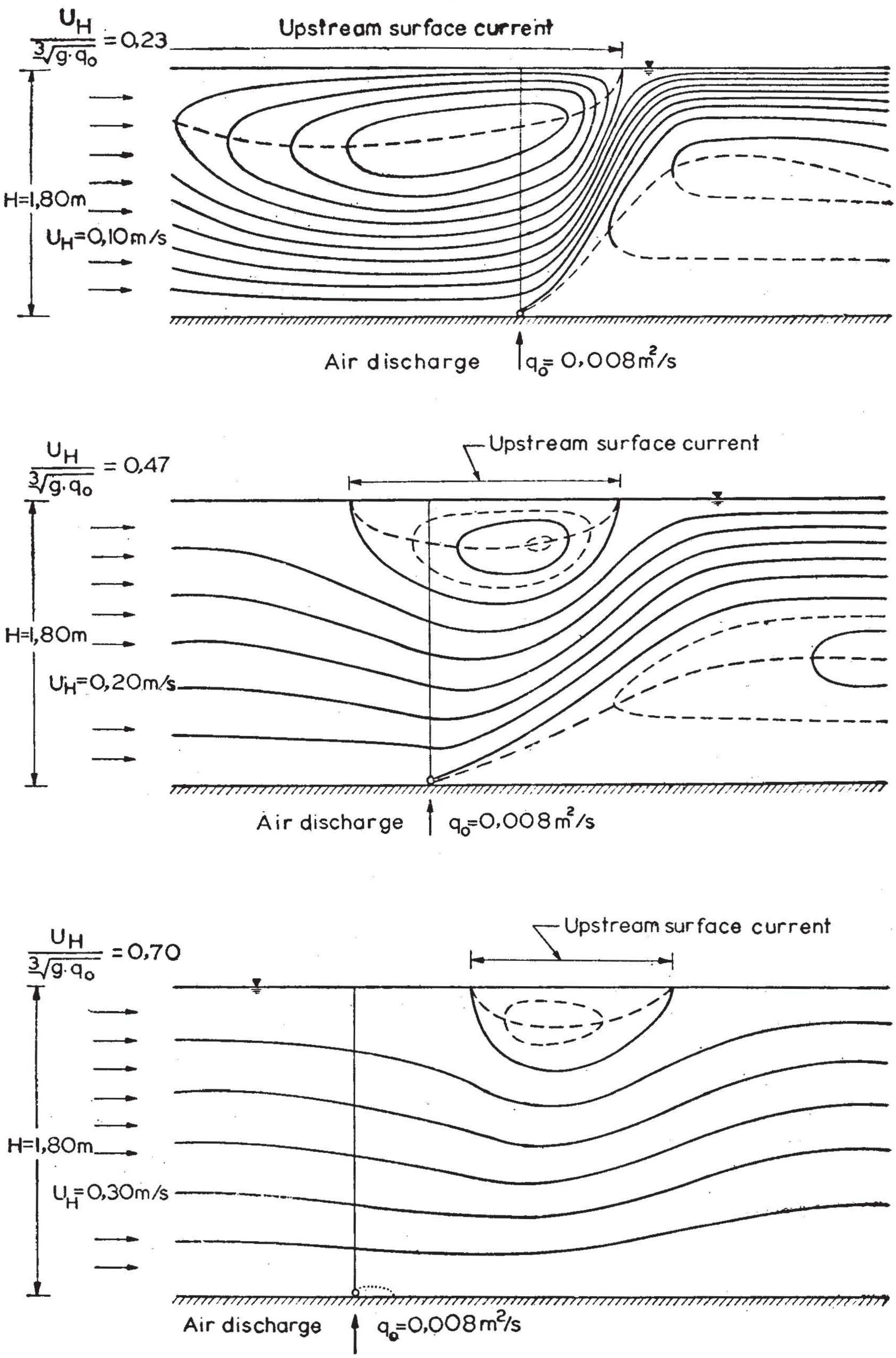

FIGURE 3 : Flow pattern of an air-bubble screen in a cross flow.

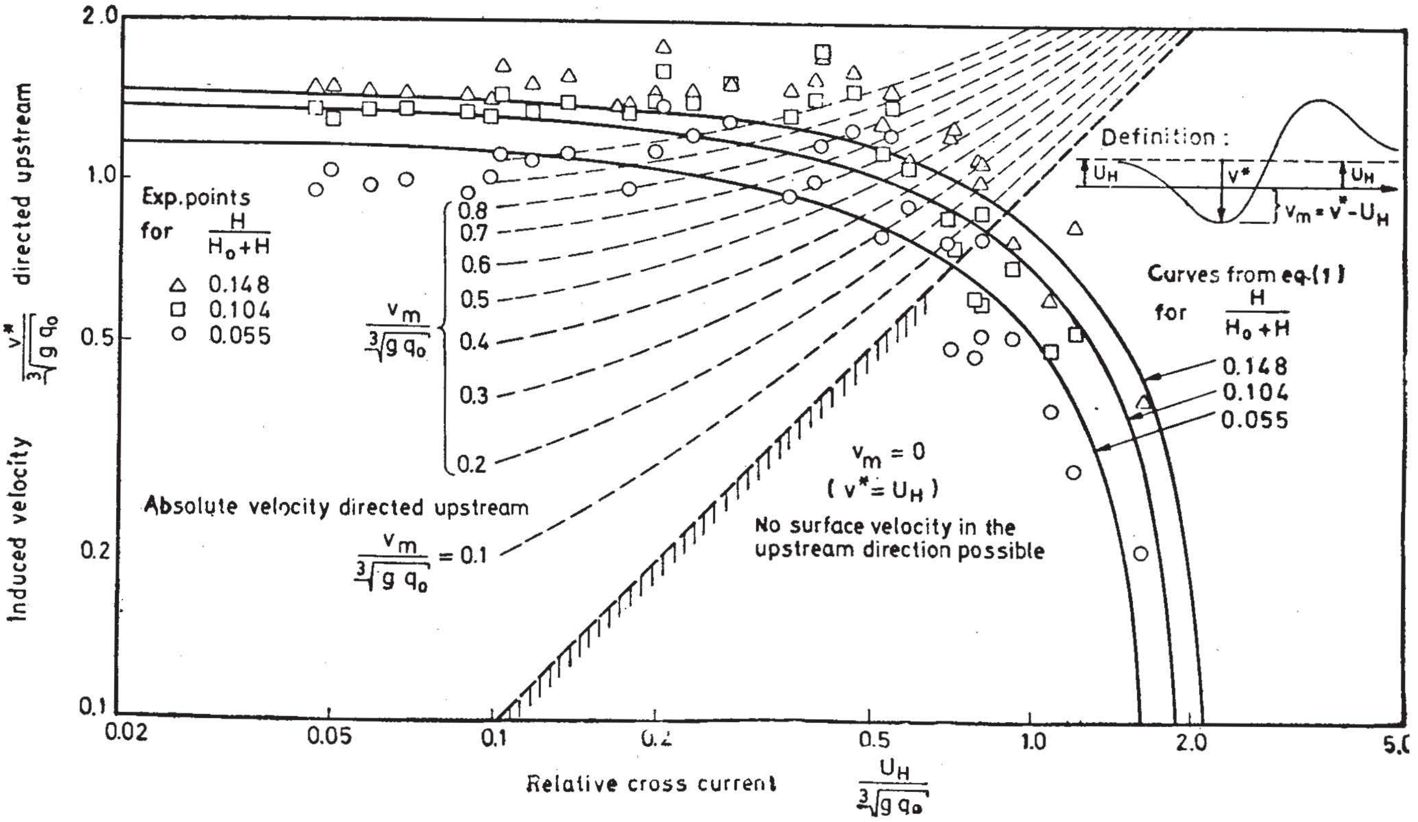

FIGURE 4 : Maximum surface velocity in the upstream direction.

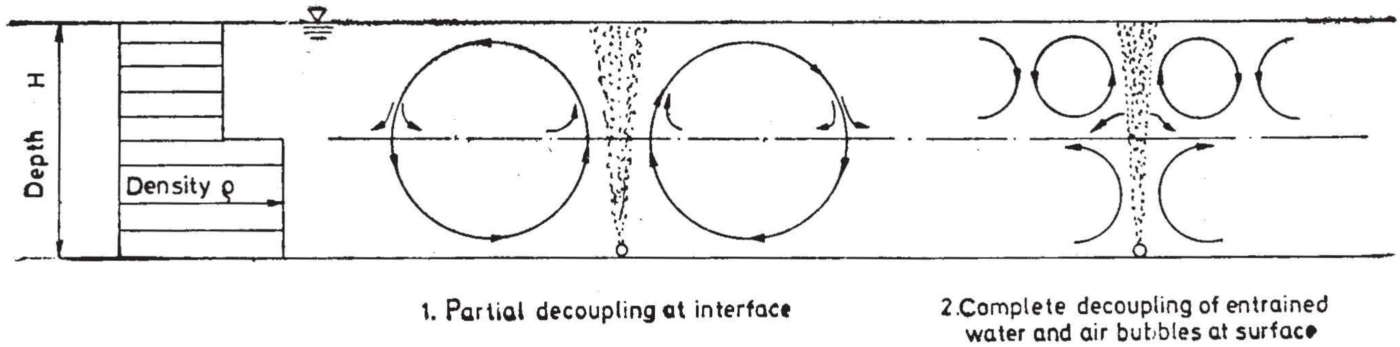

FIGURE 5 : Possible flow pattern at a density interface after Cederwall and Ditmars.

disturbances like plugged orifices, fluctuations of the barrier flow, etc., and provided with an addition for wind effects.

(3) Thus the air installation is to be designed for a maximum surface current of 80 cm/s, which requires, at a depth of 8 m, an atmospheric air discharge of 0.017 m^3/s.m or 1.05 m^3/min. m.

(4) For the compressor data and the orifice rating curves, given in the third diagram, there results a layout of the air installation of 2 mm orifices along the barrier spaced 20 cm apart, operating at a pipe pressure p_i of 5.1 kp/cm^2 absolute.

A more refined calculation would have to account for the pipe losses and variations along the barrier, of course, as is discussed in detail in Ref. ([10]).

4.2 *Pneumatic Barriers against Silt or Salt Water Intrusion*

Since air bubble screens produce strong vertical mixing locally, they can be used for destratification

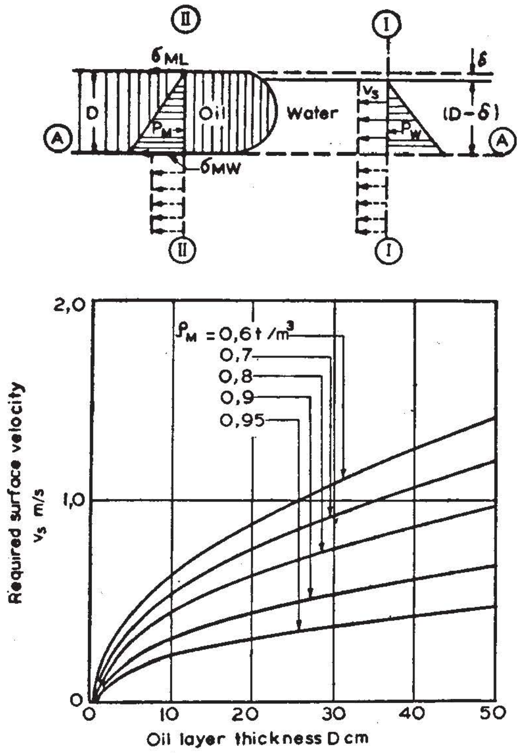

FIGURE 6 : Surface velocity requirements for pneumatic oil barriers.

purposes (see paras 4.3 and 4.4) and as barriers against density currents (Figure 8). Air bubble installations have been used successfully to reduce salt water intrusion into navigation locks joining freshwater canals and the sea[4]. They can also be installed in estuaries and canals or in harbours to prevent intrusion of silt or suspended sediments. Furthermore, they may be useful to prevent recirculation between cooling water outlet structure and intake of power plants.

If the air bubble stream is sufficiently strong, it produces a flowfield as sketched in Figure 8, and the density—induced exchange flow is greatly reduced by the barrier action. The minimum air flow rate required to establish this flow pattern depends upon the differential pressure acting upon the barrier (Figure 8). From an extensive study[10], design information for predicting the performance of an air bubble barrier against density currents is available.

4.3 *Pneumatic Installations for Preventing Ice Formation*

There are a number of hydraulic structures like sluices, weirs, gates or piers which must be kept free of ice in winter. Here also, air-bubble screens offer a simple but efficient means of achieving this purpose. In fresh water lakes and reservoirs, the warm water is transported from the deep layers to the surface by the action of the air bubbler, which thus makes use of the thermal reserve of the entire water body (Figure 9).

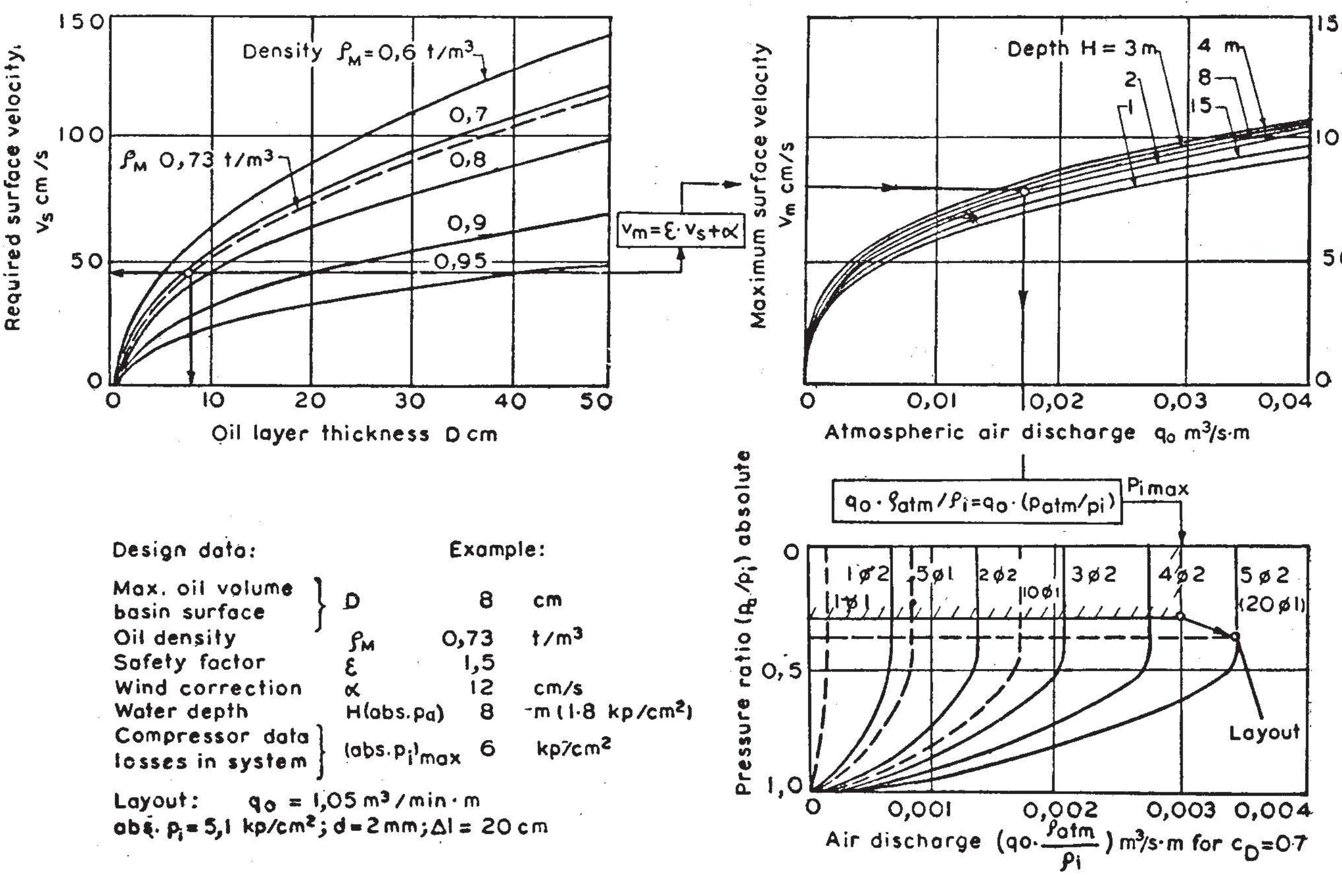

FIGURE 7 : Nomogram for the design of pneumatic oil barriers.

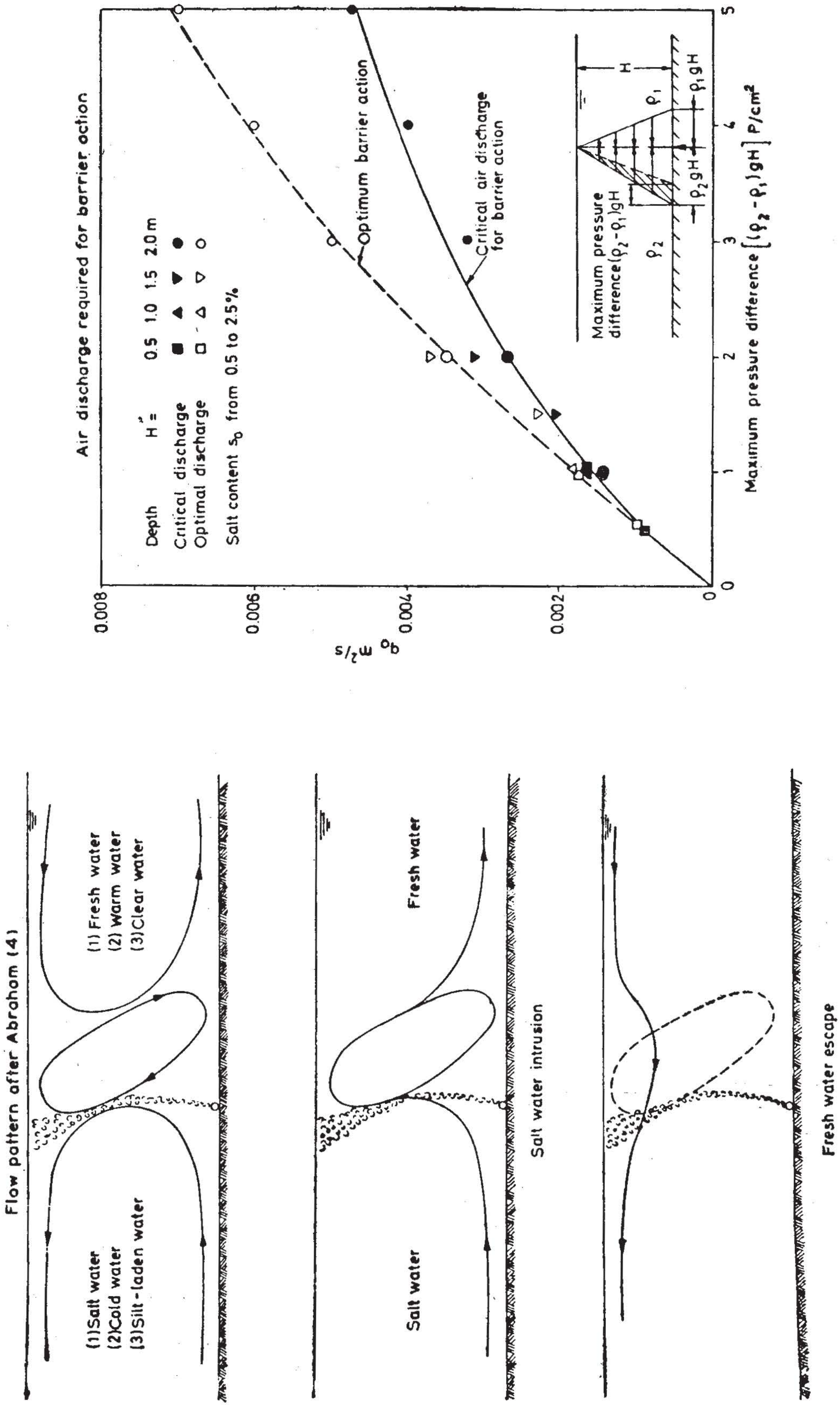

FIGURE 8 : Air bubble screen as a barrier against density currents.

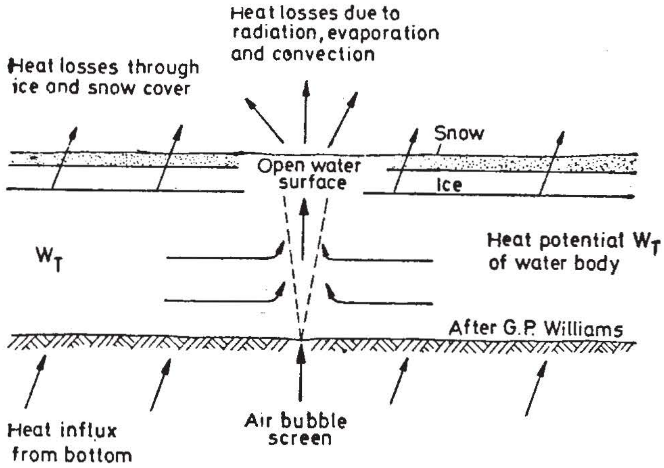

FIGURE 9 : Air-bubble screen for ice protection.

4.4 *Air-bubble Installations for Destratification and Oxygenation*

Freshwater lakes and reservoirs develop a thermal stratification during summer, in which the warm, oxygen-rich surface waters (epilimnion) are separated by a sharp thermocline from the cold, lower layers (hypolimnion), which can deteriorate to a very poor water quality and be depleted of oxygen. At the thermocline, no natural exchange processes occur any more between the two layers.

There are basically two approaches to the problem of improving the water quality in the hypolimnion (Figure 10). One can cause an artificial destratification, so that natural exchange processes in the vertical can take place again. It seems, however, that the vertical mixing necessary in this procedure may also have detrimental effects upon the water quality. Therefore, the use of various devices for oxygenation of the hypolimnion without disturbing the natural temperature stratification (Figure 10) seems to be more promising for water quality improvement.

5. Conclusion

The flow field induced by an air-bubble screen in a sideways unlimited body of water has been investigated analytically and experimentally, and the effects of a cross flow and of a density stratification have been studied. The description of the flow field serves as a basis for a quantitative analysis of air-bubble installations for various applications in water quality control : pneumatic oil barriers, installations for combating density currents due to temperature, salinity or sediment concentration gradients, for preventing ice-formation, for density-destratification of lakes and reservoirs, or for in-stream aeration. These applications are briefly discussed ; for a detailed account, the reader is referred to Ref. ([10]), where a quantitative basis is given for assessing the feasibility of air-bubble installations both technically and economically.

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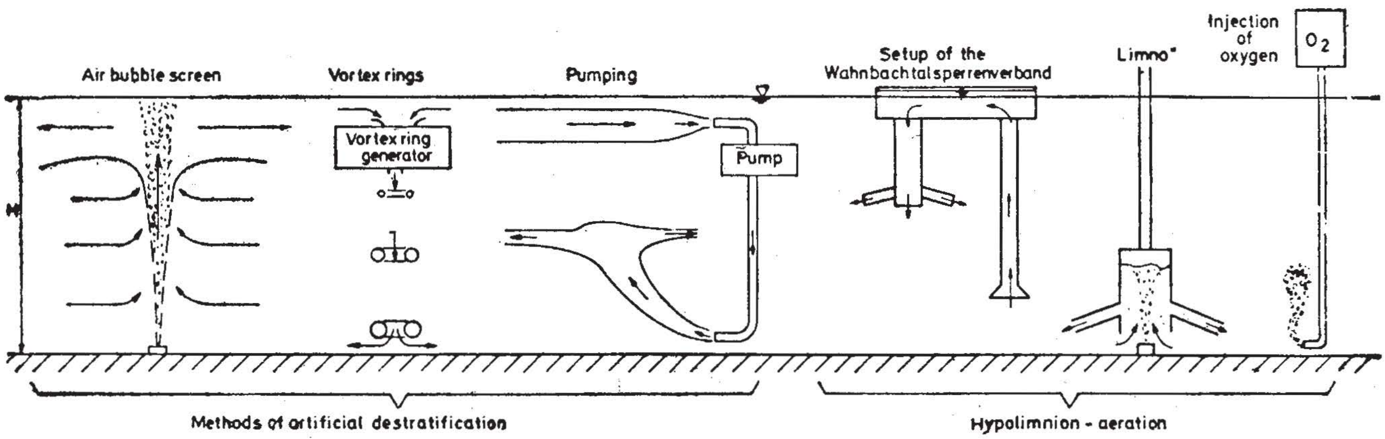

FIGURE 10 : Various methods of aerating lakes and reservoirs.

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