INTERNATIONAL ASSOCIATION FOR HYDRAULIC RESEARCH
Hydraulic Works for Pollution Control (Subject C.b.)

ON THE USE OF AIR-BUBBLE SCREENS AS OIL BARRIERS

by

Helmut E. Kobus

Privatdozent, Institut für Hydromechanik und Sonderforschungsbereich 80
Universität Karlsruhe, Kaiserstr. 12, 75 Karlsruhe/Germany

Synopsis

From an analytical and experimental investigation of the flow field induced by an air-bubble screen, the resulting surface current can be predicted as a function of water depth and air discharge, both in a standing water body and in a cross current. This information about the flow field leads to a design procedure for pneumatic oil barriers. It is found that pneumatic installations designed properly for safe and economic performance offer functional and operational advantages over mechanical oil barriers.

Résumé

A la suite d'une étude analytique et expérimentale de l'écoulement produit par un ecran de bulles d'air, il est devenu possible de déterminer la vitesse supertielle de l'eau en fonction du débit d'air lâché à différentes profondeurs, tant dans l'eau calme que dans l'eau courante. Dès qu'on connait le champs des vitesses on peut trouver un procédé pour projeter des barrages d'air comprimé contre la propagation de l'huile, qui sont fonctionelment plus avantageux que les barrages mécaniques.

1. INTRODUCTION

The conservation of an acceptable water quality calls for ever increasing efforts in pollution control. In particular, the transport of mineral oil poses a continuous potential threat to the ecological balance of navigable waters. Therefore, efficient means for both combatting major oil spills at sea and containing spilled oil in harbours and waterways have to be developed. For the latter type of problem, air bubble screens can be used as a hydraulic method to close off endangered areas like oil harbours from the main water body in case of an accident. An air-bubble screen - generated by the release of compressed air at the bottom of a body of water - produces a surface current, which can be used to contain a surface layer of oil and prevent it from spreading any further. These so-called "pneumatic oil barriers" offer substantial advantages over conventional barrier types and have been used successfully in recent years.

2. THE FLOW FIELD OF AN AIR-BUBBLE SCREEN

The flow field induced by a rising swarm of air bubbles in a standing body of water is sketched in Fig. [1]. The resulting vertical flow of air-water mixture has been analysed by several investigators [1; 4 to 7; 10] and the author has conducted numerous laboratory experiments at various water depths (up to 2 meters) for the entire range of practically feasible air discharges [10]. The vertical flow of air and water can be analysed in analogy to a turbulent buoyant plume, taking proper account of the bubble slip velocity and of the compressibility of the air. Introducing similarity profiles, making an entrainment hypothesis and assuming the Boussinesq approximation (small density differences between air-water mixture and water) to be valid, the resulting system of equations can either be solved numerically [7], or an approximate closed solution can be derived [10]. In either case, the solutions contain empirical coefficients (entrainment coefficient, turbulent Schmidt number, bubble slip velocity) which are obtained from the authors laboratory data [6; 10]. For details, the reader is referred to the original papers.

At the free surface, the vertical plume is deflected 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 Fig. 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. EFFECT OF A CROSS FLOW

A crucial question for the application of air-bubble screens as an oil barrier (or for any type of oil barrier for that matter) is how well it performs under moderate cross flow conditions. Therefore, the effect of a cross flow upon the air-bubble flow field has been studied experimentally, with particular emphasis upon the "barrier

velocity" at the free surface.
In a cross flow, the bubble plume is deflected in the downstream direction (Fig. 3). 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 dissappears, so that no more barrier action is possible. From experiments over a wide range of depths, air discharges and cross current velocities (Fig. 4), an empirical relation of the form

$$\frac{v^*}{(gq_o)^{1/3}} = \frac{v_{m\,(U_H=o)}}{(gq_o)^{1/3}} - \frac{2}{3}\,\frac{U_H}{(gq_o)^{1/3}} \tag{1}$$

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

$$\frac{v_m}{(gq_o)^{1/3}} = \frac{v_{m\,(U_H=o)}}{(gq_o)^{1/3}} - \frac{5}{3}\,\frac{U_H}{(gq_o)^{1/3}} \tag{2}$$

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.

4. DESIGN OF A PNEUMATIC OIL BARRIER

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 Fig. 5 as

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

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

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

This relation is plotted in Fig. 5. 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 Fig. 6.

The various design steps are best illustrated by giving a numerical example (see Fig. 6). 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 meters and is supposed to retain a layer of gasoline ($\rho_m = 0.73$ t/m^3) of 8 cm thickness.

(1) By eq. (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 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 [10] .

5. COMPARISON WITH CONVENTIONAL OIL BARRIERS

Whenever an oil spill occurs, it is of primary importance to close off the spill area as fast as possible, since oil spreads very rapidly on water. The efficiency of an oil barrier is therefore strongly dependent upon the time required to get the barrier into operation. In this respect, a pneumatic barrier offers substantial advantages over a mechanical barrier: as a permanent installation, it is ready for "push button operation" and works within seconds. In contrast, mechanical barriers have to be towed in place, which requires both time, equipment and personell. A further advantage of pneumatic barriers is that - in contrast to mechanical barriers - they can be crossed by boats while they are in operation. Their performance is not endangered if the oil is set on fire, which may cause problems with floatable barriers containing combustible materials.

The main disadvantage of pneumatic barriers is their susceptibility to mechanical damage by anchors etc., which may cause high repair- and maintenance costs. Furthermore, since the efficiency of pneumatic barriers drops rapidly for very small water depths, embankment slopes may require supplemental efforts.

All in all, pneumatic oil barriers offer a sufficient number of advantages over conventional barriers which justify their preferential use for fixed installations in harbours, docks, canals or other zones susceptible to oil spills. Fixed or transportable installations may also be used to fence off such areas which must be kept free of oil pollution by all means, such as drinking water supply or recreation areas and the like.

6. CONCLUSIONS

1. The results of an analytical and experimental investigation of the flow field induced by an air-bubble screen yield a sound basis for designing pneumatic oil barriers and for predicting their performance and evaluating their economics of operation.

2. The effect of a cross flow upon the flow field has been studied experimentally. This yields a quantitative basis for assessing the susceptibility of the barrier to a cross flow.

3. Properly designed pneumatic oil barriers as permanent installations in oil harbours, docks etc. offer substantial functional and operational advantages over conventional type barriers.

SELECTED REFERENCES

[1] G.I. Taylor: "The Action of a Surface Current Used as a Breakwater." Proc., Royal Society of London, Series A, Vol. 231, 1955.

[2] E. Stehr: "Berechnungsgrundlagen für Preßluft-Ölsperren." Mitteilungen der Hannover´schen Versuchsanstalt für Grundbau und Wasserbau, Franzius-Institut der TH Hannover, Heft 16, S. 275 ff, 1959.

[3] P.S. Bulson: "Currents Produced by an Air Curtain in Deep Water." The Dock and Harbour Authority, May 1961.

[4] G. Abraham und P.v.d. Burgh: "Reduction of Salt Water Intrusion Through Locks by Pneumatic Barriers. "ASCE Journal of the Hydraulics Division, Hy 1, Jan. 1964.

[5] A. Sjöberg: " Strömningshastigheter kring luftbubbelridå i täthetshomogent ach stillåstående vatten." Meddelande nr. 39, Institutionen för vattenbyggnad, Chalmers Tekniska Högskola, Göteborg 1967.

[6] H. Kobus: "Analysis of the Flow Induced by Air-Bubble Systems." Proc., XIth International Conference on Coastal Engineering, London, Sept. 1968.

[7] K. Cederwall und J.D. Ditmars: "Analysis of Air-Bubble-Plumes." California Institute of Technology, W.M. Keck Laboratory of Hydraulics and Water Resources, Report No. KH-R-24, Sept. 1970.

[8] J. Grace und A. Sowyrda: "The Development and Evaluation of a Pneumatic Barrier for Restraining Surface Oils in a River." Journal Water Pollution Control Federation, Vol. 42, No. 12, pp. 2074-2093, December 1970.

[9] B. Verner: "Pneumatic Oil Barriers." Atlas Copco, tryckluft 1, 1972.

[10] H. Kobus: "Bemessungsgrundlagen und Anwendungen für Luftschleier im Wasserbau", Heft 7, Wasser und Abwasser in Forschung und Praxis, Erich Schmidt Verlag, Berlin, 1973.

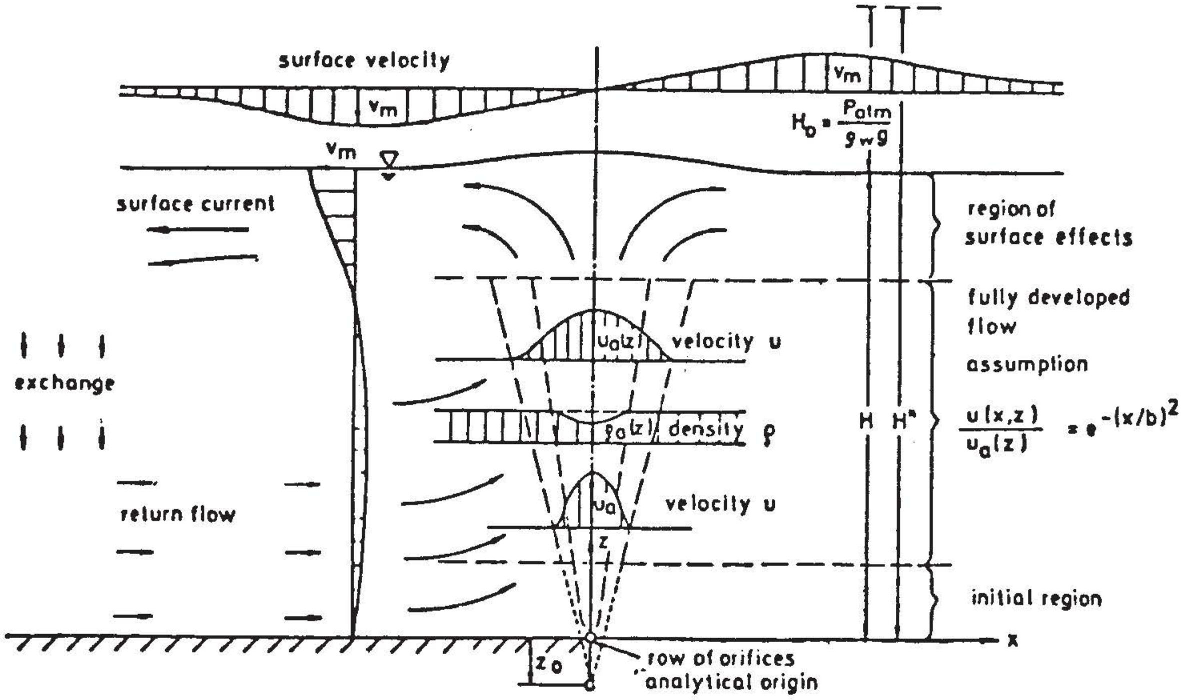


FIG 1 : FLOW FIELD OF AIR BUBBLE SCREEN

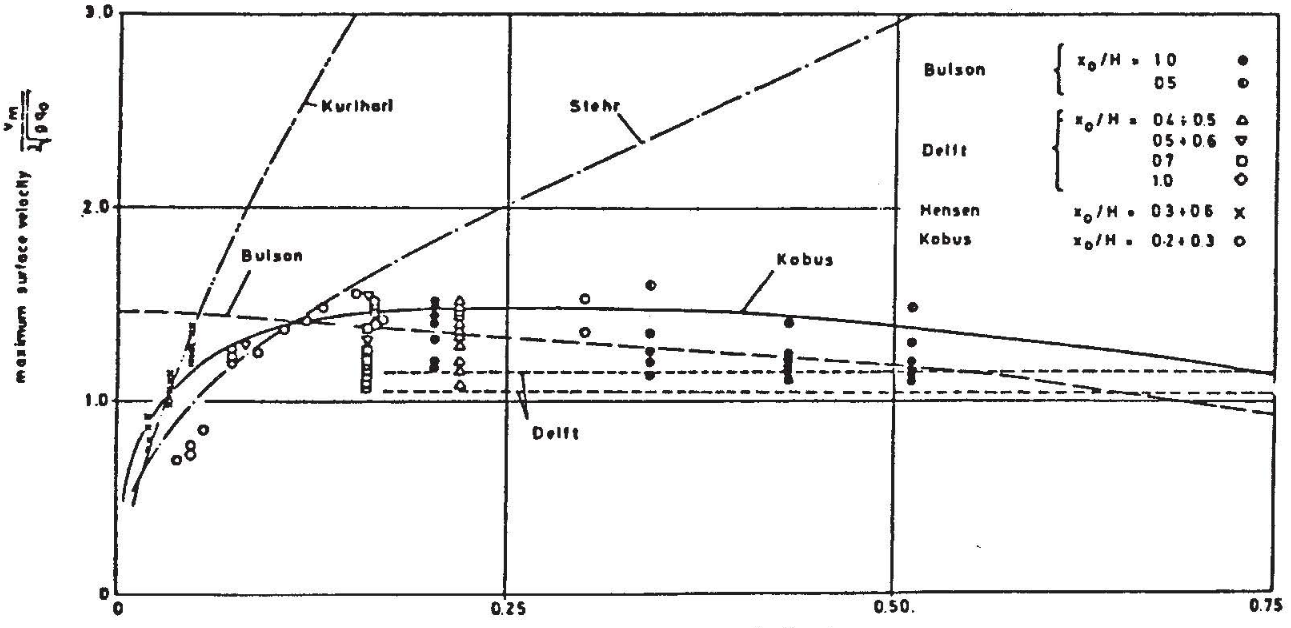


FIG.2: MAXIMUM SURFACE VELOCITY AS A FUNCTION OF AIR DISCHARGE AND DEPTH

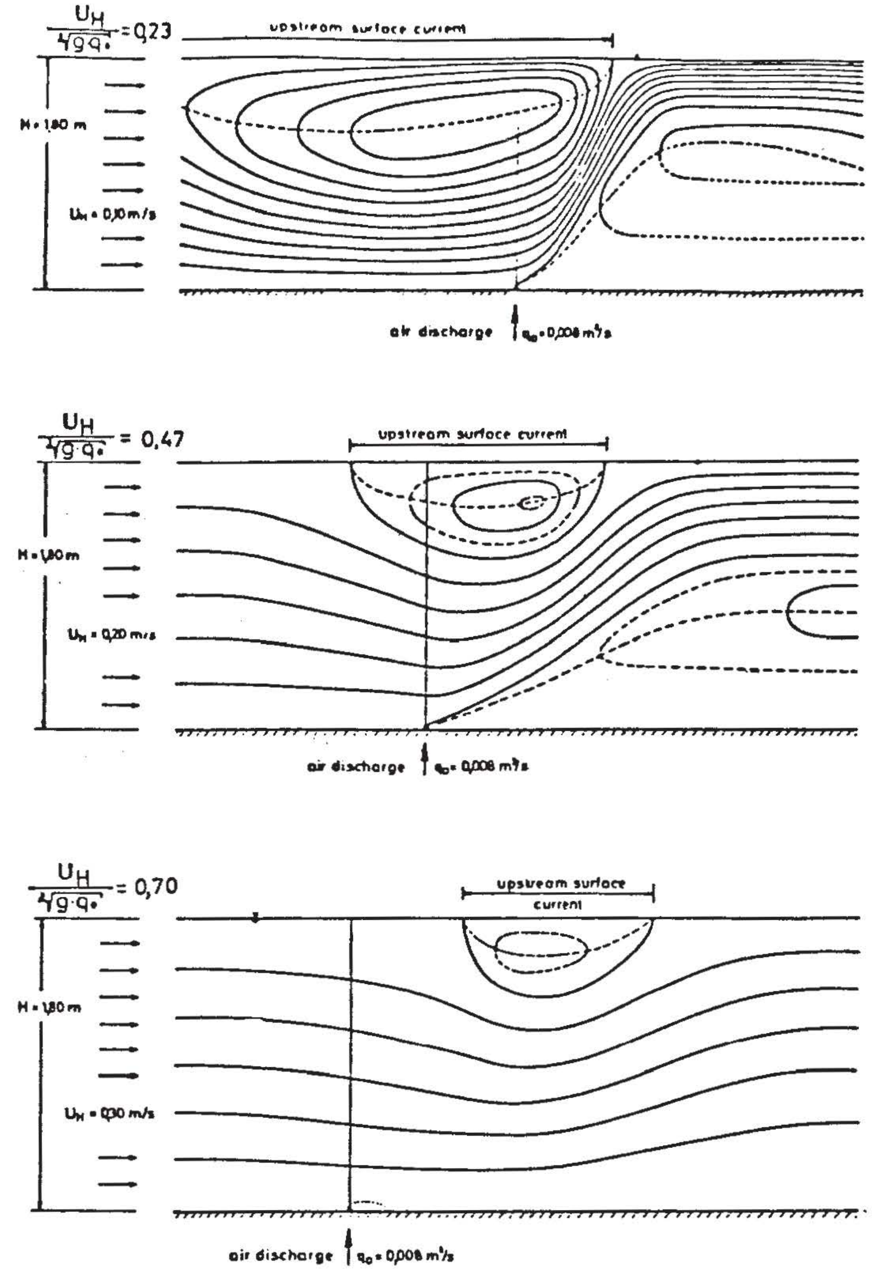


FIG.3: FLOW PATTERN OF AN AIRBUBBLE SCREEN IN A CROSS FLOW

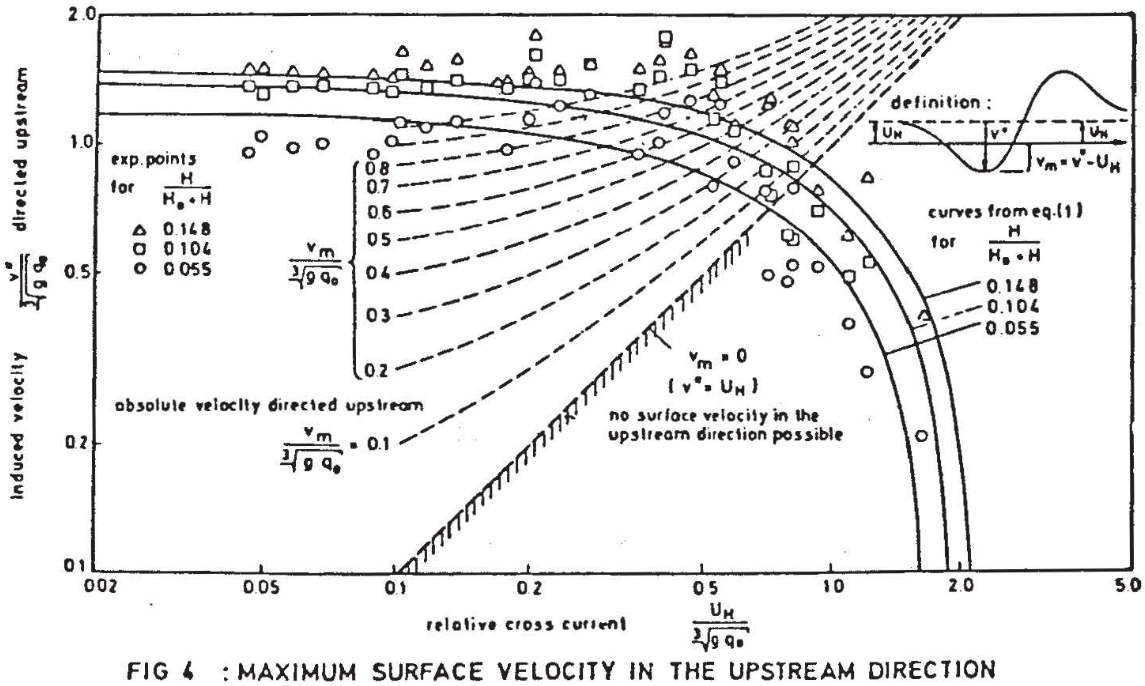
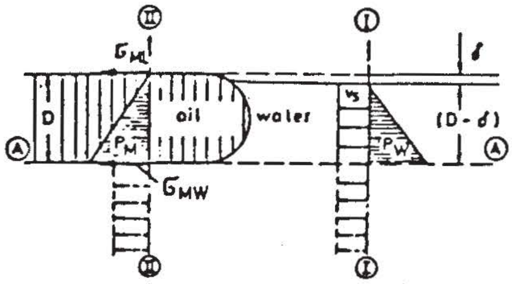


FIG 4 : MAXIMUM SURFACE VELOCITY IN THE UPSTREAM DIRECTION



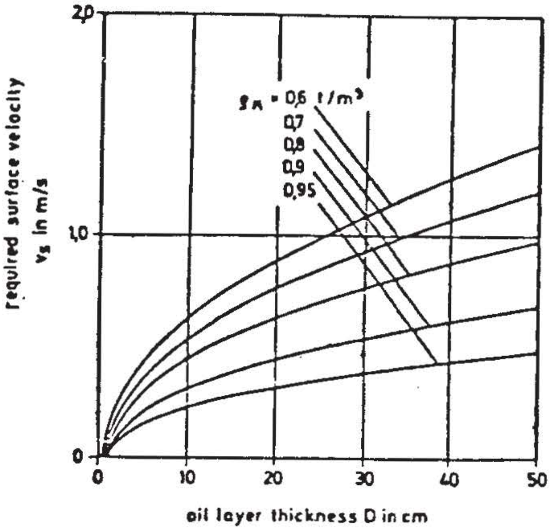
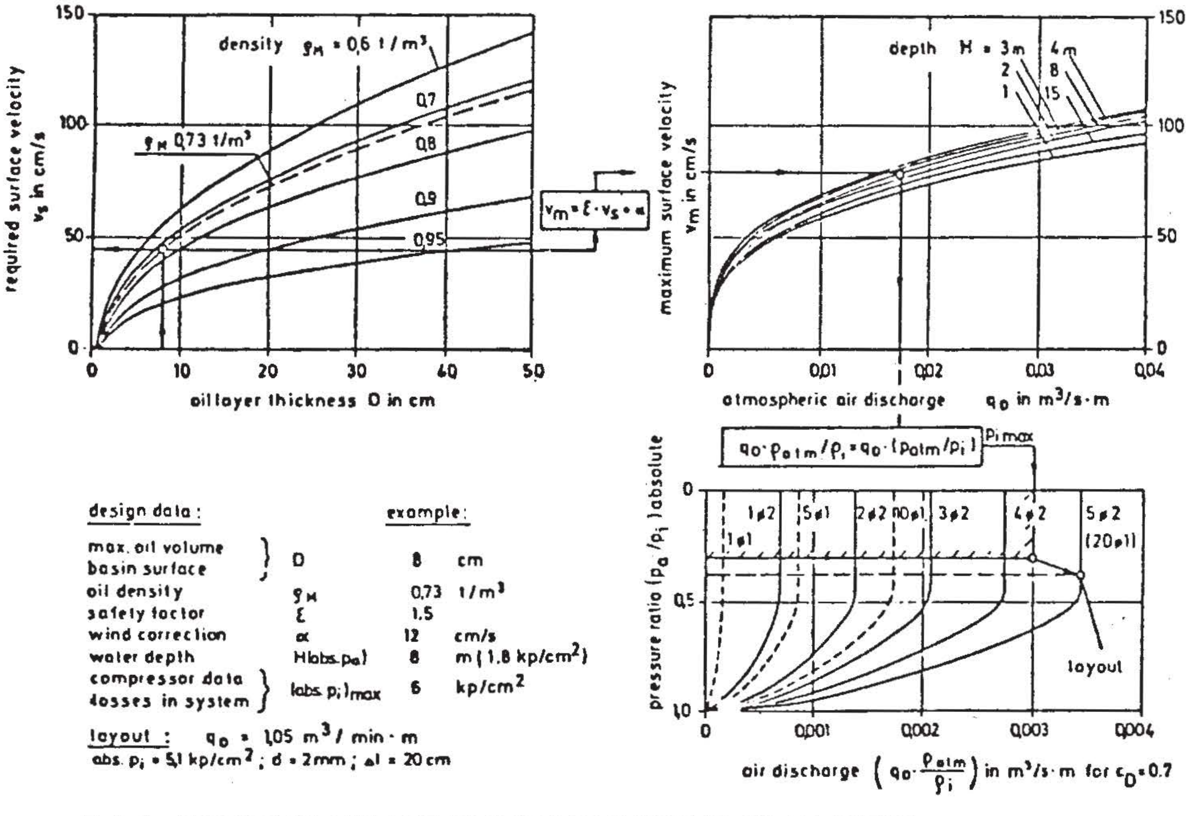


FIG 5 : SURFACE VELOCITY REQUIREMENTS FOR PNEUMATIC OIL BARRIERS



design data:		example:	
max. oil volume basin surface	D	8	cm
oil density	ρ_M	0,73	t/m³
safety factor	ε	1,5	
wind correction	α	12	cm/s
water depth	H(abs. p_a)	8	m (1.8 kp/cm²)
compressor data losses in system	(abs. p_i)$_{max}$	6	kp/cm²

layout : q_0 = 1,05 m³/min · m
abs. p_i = 5,1 kp/cm² ; d = 2mm ; Δl = 20 cm

FIG 6 : NOMOGRAM FOR THE DESIGN OF PNEUMATIC OIL BARRIERS