INTERNATIONAL ASSOCIATION FOR HYDRAULIC RESEARCH

ON THE MODELING OF ARTIFICIAL REOXYGENATION

(Subject A.b.)

By Mark Markofsky and Helmut Kobus
Research Engineer and Professor, respectively
Institut für Hydromechanik, Universität Karlsruhe
Karlsruhe, Germany

SYNOPSIS

The results of laboratory studies on the efficiency of oxygen transfer from two dimensional bubble curtains produced by passing compressed air through a porous filter (mean diameter 180 μ) and a perforated diffusor pipe (1 mm diameter ports) are presented. Comparisons with other laboratory and field data as well as with an approximate theory for oxygen transfer are made. Surface effects are found to play an important role in the present experiments tending to increase the overall apparant oxygen transfer efficiency.

SOMMAIRE

Les resultats d'une étude experimentale sur l'efficacé de transfer d'oxygene par une colonne bi-dimensionelle des bulles d'air sont presentés. La colonne d'air est formée par l'injèction d'air à partir d'une filtre poreux (180 μ diametre) et d'une conduite perforée (1 mm diametre d'orifice). Les resultats obtenus sont comparés à ceux d'autres rechercheurs et à la théorie approximative du transfer d'oxygene. On peut constater que l'effect du surface libre est très important sous les conditions etudiés, causant une augmentation du transfer d'oxygene.

1. INTRODUCTION

The dissolved oxygen content of water is one of the indicators of water quality. Polluted rivers are typified by relatively low dissolved oxygen concentration or high oxygen deficits. In areas where large oxygen deficits occur it is sometimes desirable to oxygenate the water artificially using mechanical means. One such technique is the bubbling of air or pure oxygen through a diffuser pipe located at some depth in the river, thereby producing a bubble curtain from which oxygen transfer to the water occurs.

An approximate theory for oxygen transfer from bubbles indicates that the efficiency of oxygen transfer is directly proportional to the oxygen deficit and the water depth and inversely proportional to the bubble rise velocity, which in turn depends upon the air flow rate and crossflow velocity.

The results of laboratory experiments using diffusers over the entire width of a flume, perpendicular to the crossflow (i.e. two dimensional) are presented in terms of the efficiency of oxygen transfer per unit height versus air flow rate for different crossflow velocities. Comparisons are made with values presented in the literature both for the laboratory and field situations, and conclusions are drawn concerning the model-prototype relationships for reoxygenation installations.

2. THEORY

The oxygen transfer process from air bubbles rising in a fluid which is not saturated with oxygen, can be described using the first law of Fickian diffusion

$$\frac{dN}{dt} = -\rho_w D A \frac{dc}{dr} \tag{1}$$

where
- N = mass of oxygen in the bubble;
- t = time;
- ρ_w = water density;
- D = diffusion coefficient;
- A = bubble surface area;
- dc/dr = oxygen gradient at the bubble surface

With the assumption that the oxygen transfer at the bubble surface takes place through a boundary layer of thickness L over which the oxygen concentration linearly varies from the saturation value c_s to the value in the water column, c, Kobus [1] and Markofsky [4] have shown that the efficiency of the oxygen transfer process, $\bar{\eta}$, defined as the ratio of the absorbed to injected oxygen, can be approximated as

$$\bar{\eta} = K' \frac{(c_s - c)}{c_s} \frac{H}{\bar{u}_b} \tag{2}$$

where
- K' = average absorption coefficient;
- $\bar{u}_b$ = average bubble rise velocity;
- H = water depth.

Since for a given diffusor placed perpendicular to a channel in which water flows with velocity v, the bubble rise velocity increases with increasing air flow rate per unit width, q_a, and decreasing channel velocity [1] (Figure 1), the efficiency of gas transfer for a two dimensional bubble curtain is expected to increase with increasing oxygen deficit, water depth and cross-flow velocity and decreasing gas flow rate.

3. EXPERIMENTAL APPARATUS AND PROCEDURE

Experiments were performed in a recirculating laboratory flume 21 m long and 0.6 m wide in water depths of 0.7 m (Figure 2). Compressed air was injected vertically across the entire width through a diffusor pipe located at the bottom of the flume. Perforated pipes with 8,24 and 72, 1mm ports (i.e. port spacings of 83,25 and 8ϕ) and a porous filter (Brandol 60,70/40-mm diam., mean pore size 180μ) were used as diffusors. Three mean water velocities, 2.5, 7.5 and 15 cm/s, and air flow rates between 3 and 50 $m^3/m.h$ were tested[+]. The dissolved oxygen content was measured at 20 and 80 % of the depth approximately 5 m upstream of the diffusor using two WTW Oxi 96 probes and recorded on a two-channel x-t plotter. Other probe locations had been tested, i.e. one probe upstream and one downstream at mid-depth. Due to the closed-loop circulating system the determination of the oxygen reaeration efficiency was found to be relatively insensitive (within 5 %) to probe location. Typical bubble curtains produced by the diffusors are shown in Figure 3.

The water was first deoxygenated using sodium sulfite (Na_2SO_3) with a cobalt catalyst ($CoCl_2 \cdot 6H_2O$). For each cross flow velocity a blank was run to determine the natural aeration rate, i.e. aeration without the diffusors in operation due to pumping and exchange at the water surface. In all cases the experimental results could be represented by the function

$$\frac{\Delta c}{\Delta c_o} = \frac{c_s - c}{c_s - c_o} = e^{-kt} \qquad (3)$$

where c_o = dissolved oxygen concentration at time $t = 0$;
k = reaeration constant.

The reaeration constant, k, was determined from the slope of the straight line on the semi log plot of Δc vs. t and converted to the corresponding values, k_{10} at 10 °C according to Pasveer and Sweeris [5] i.e. $k_{10} = k\sqrt{D_T/D_{10}}$

[+] The air flow rate / unit width, q_a, was determined in a calibration stand described in [2] from which a calibration curve relating the internal pressure on the diffusor to the air flow rate was developed.

where $\sqrt{D_T/D_{10}}$ is the ratio of the diffusion coefficient at temperatures T and at 10°C, respectively. The results are presented in Table 1.

Table 1: Reaeration Constant without Diffusor for Various Crossflow Velocities

crossflow velocity, v (cm/s)	reaeration constant, at 10 °C, k_{10} (min^{-1})
2.5	.044
7.5	.077
15	.151

For each experiment with the diffusor in operation the aeration constant, k_{d10} was determined in a similar manner. The oxygen transfer efficiency per unit height $\bar{\eta}/H$, was calculated from [4] by

$$\frac{\bar{\eta}}{H} = \frac{(k_{d10} - k_{10})\, V\, c_{s10}}{q_a\, (300)\, b\, H} \qquad (4)$$

where b = channel width;
V = total water volume;
c_{s10} = dissolved oxygen saturation value at 10 °C.

4. EXPERIMENTAL RESULTS

The experimental results along with published laboratory and field data [3] are presented in Figure 4 as a plot of transfer efficiency per unit height, $\bar{\eta}/H$ vs. air flow rate per unit width, q_a. The following conclusions can be drawn from Figure 4:

(1) Filter material is more efficient for oxygen transfer than perforated pipes. For example, at a crossflow velocity of 15 cm/s and air flow rates less than 15 $m^3/m \cdot h$, the porous filter resulted in efficiencies over double those of the perforated pipe. At lower crossflow velocities the efficiencies of the porous filter approach a factor of 3 times greater than those of the perforated pipe.

(2) For the porous filter, $\bar{\eta}/H$ decreases with increasing air flow rates and decreasing crossflow velocity. This was found both for the present experiments conducted at a water depth of 0.7m for the relatively low crossflow velocities between 2.5 and 15 cm/s and for the experiments of Pasveer [5] using the same filter material in 1 m of water with crossflow velocities between 15 and 52 cm/s. The agreement between the two independent sets of experiments (i.e. at 15 cm/s) is good (within 10 %). An upturn of the measured efficiencies $\bar{\eta}/H$ in the experiments with a water depth of 0.7 m for air flow rates above 15 $m^3/m \cdot h$ is noted indicating the influence of the free surface.

(3) For the perforated pipe, $\bar{\eta}/H$ decreases with air flow rates up to approximately 15 $m^3/m \cdot h$. Thereafter, the efficiencies increase with increasing

air flow rate. The values of $\bar{\eta}/H$ determined from experiments performed with 8 ($q_a < 7$ m^3/m·h) and 24 ($q_a > 7$ m^3/m·h), 1 mm ports formed a continuous curve with trends consistent with those of the porous filter. The agreement with experiments performed at v=15 cm/s with 72 ports indicates that port spacing is not a primary variable. No significant differences in $\bar{\eta}/H$ were found between the experiments at 2.5 and 7.5 cm/s. Measured values of $\bar{\eta}/H$ with v=15 cm/s were approximately 1%/m higher than those with v=2.5 and 7.5 cm/s.

The observed increase in $\bar{\eta}/H$ (in a water depth of 0.7 m) for values of $q_a > 15$ m^3/m·h can be explained by considering surface effects. At higher air flow rates, the surface disturbances caused by the bubble curtain increase resulting in added air entrainment at the water surface and an increase in the "natural aeration" due to increased surface roughness. This seems to become significant at air flow rates above 15 m^3/m·h and is estimated to be on the order of 1-2%/m of the injected oxygen in 0.7 m of water at an air flow rate of 50 m^3/m·h. For the perforated pipe, the measured transfer efficiency is low (2-4%/m). Thus, the decrease in efficiency with increasing air flow rate is offset by the surface effects and an apparent increase in efficiency with increasing air flow rate occurs. For the porous filter the efficiencies are higher (4-12%/m). The ratio of the oxygen transfer due to surface effects to that produced by the bubble curtain is, therefore, lower than that of the perforated pipe. Thus, the decreases in efficiecy with increasing air flow rate are not as significantly influenced by surface effects. Nevertheless, above an air flow rate of 15 m^3/m·h surface effects for the porous filter are also recognizable.

The present results indicate that for diffusor aeration the primary factors affecting the transfer efficiency per unit height are the air flow rate, the type of diffusor used and the crossflow velocity. (Water quality has been shown by Pasveer [5] also to be a significant variable). In addition, the efficiency of the gas transfer process may be effectively increased in some situations by taking advantage of surface effects. This may help to explain the relatively high (1.78-2.95 %/m) oxygen transfer measured in 1 m of water at the Lippe at Heil for an air flow rate of 500 m^3/m·h (Figure 4) in relationship to an extrapolation of the laboratory results disregarding surface effects which would lead to values under 1 %/m.

5. SELECTED REFERENCES

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[2] Kobus, H., Honekamp, H., and Barczewski, B., "Experimentelle Ermittlung des von einem Luftschleier in einer Querströmung erzeugten Strömungsfeldes", Report SFB 80/ET/18, Sonderforschungsbereich 80, University of Karlsruhe, Dec., 1974.

[3] Londong, D., "Flußwasserbelüftung an der Lippe", Gewässerschutz-Wasser-Abwasser, Böhnke, B., Vol. 1, T.U. Aachen, 1968.

[4] Markofsky, M., "Laboruntersuchungen zur Frage der Sauerstoffanreicherung durch Luftschleieranlagen", Report No. 532, Institut für Hydromechanik, University of Karlsruhe, Sept., 1976.

[5] Pasveer, A. and Sweeris, S., "A New Development in Diffused Air Aeration", JWPCF (U.S.A.), Sept., 1965.

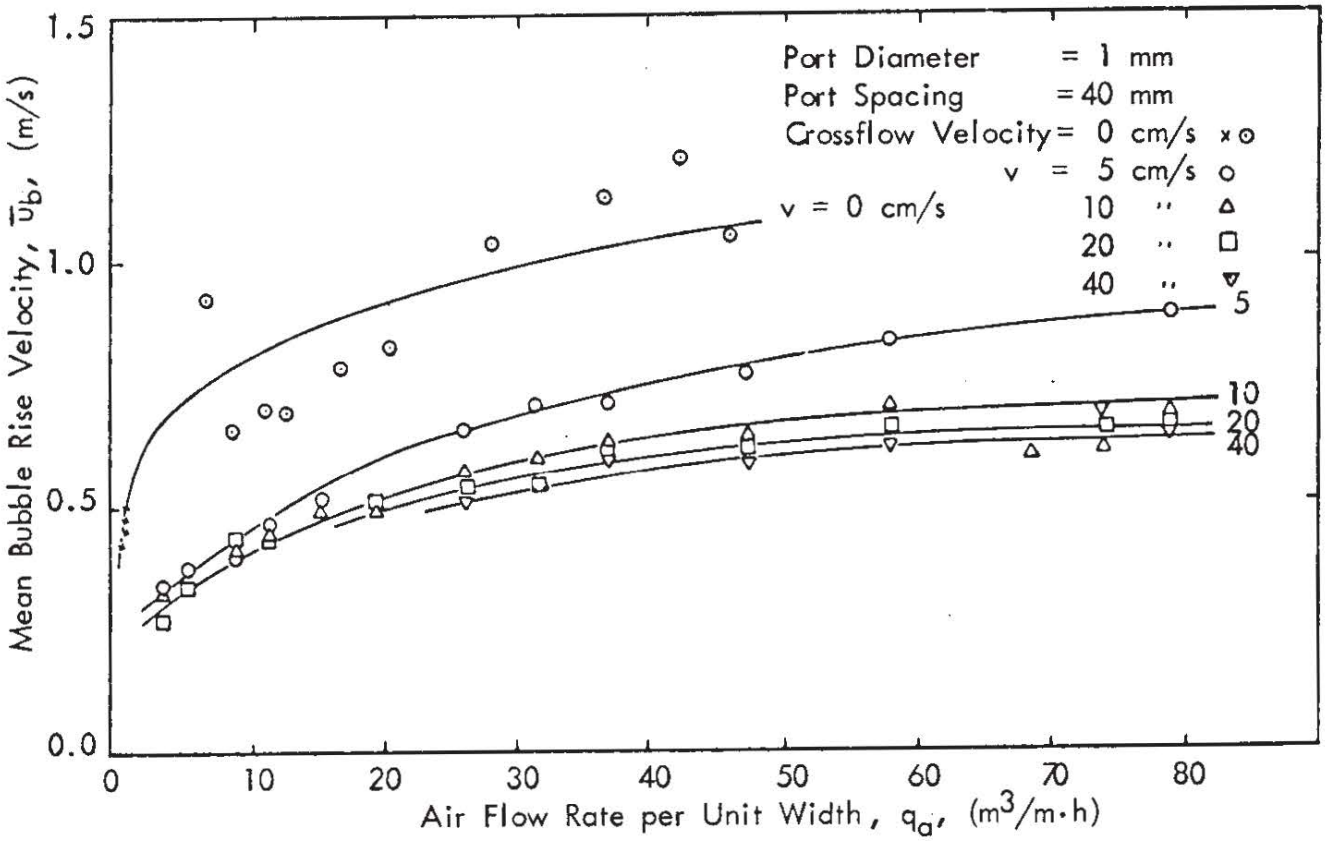

Figure 1: Mean Bubble Rise Velocity as a Function of Air Flow Rate and Cross Flow Velocity [1]
Vitesse Moyenne des Bulles d'air en Fonction de Débit d'air et de Vitesse d'écoulement [1]

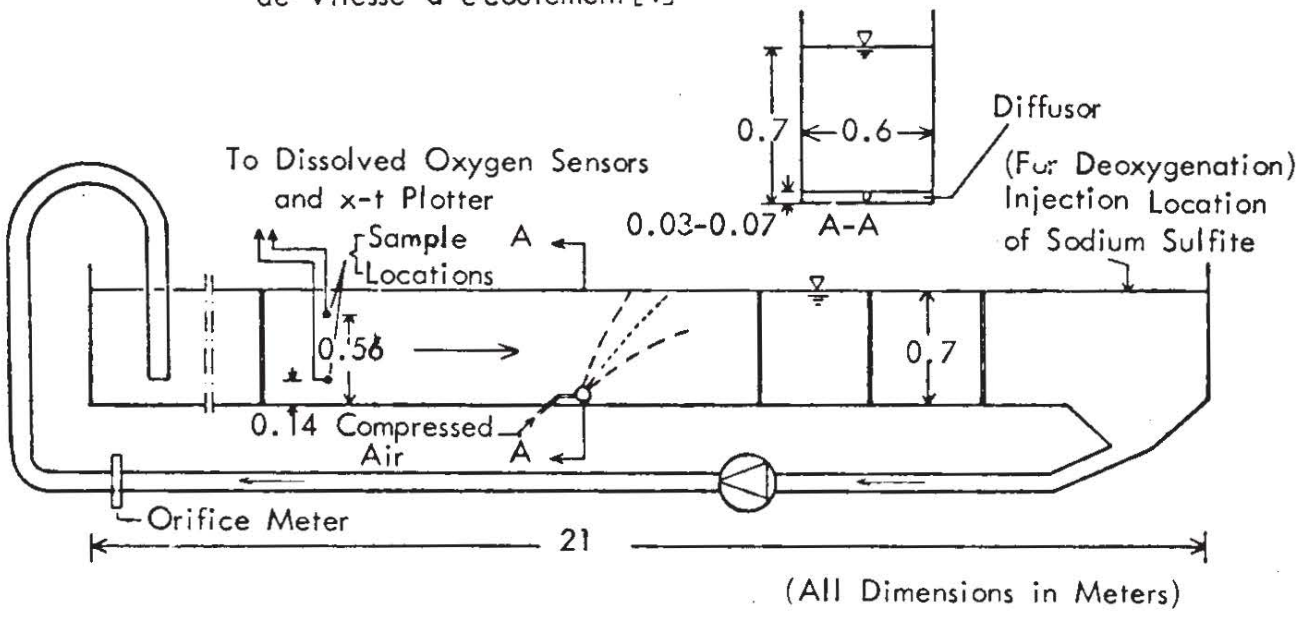

Figure 2: Schematic Representation of Experimental Apparatus
Esquisse de l'equipement Experimental

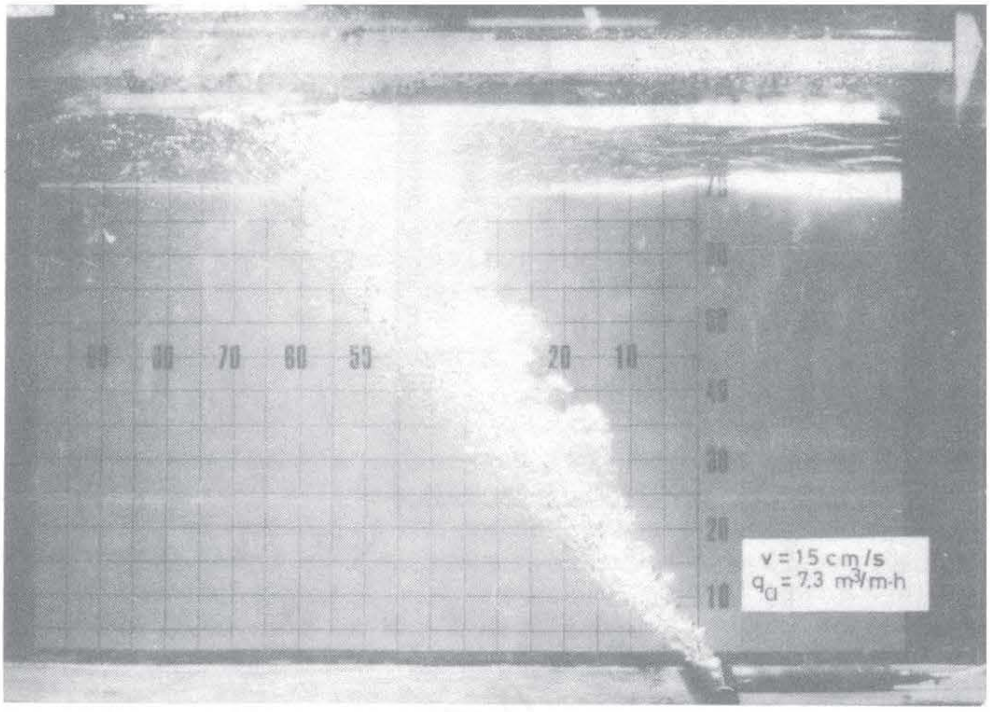

Figure 3a: Typical Bubble Curtain Produced by a Perforated Pipe
Colonne Typique des Bulles d'air Resultant d'une Conduite Perforée

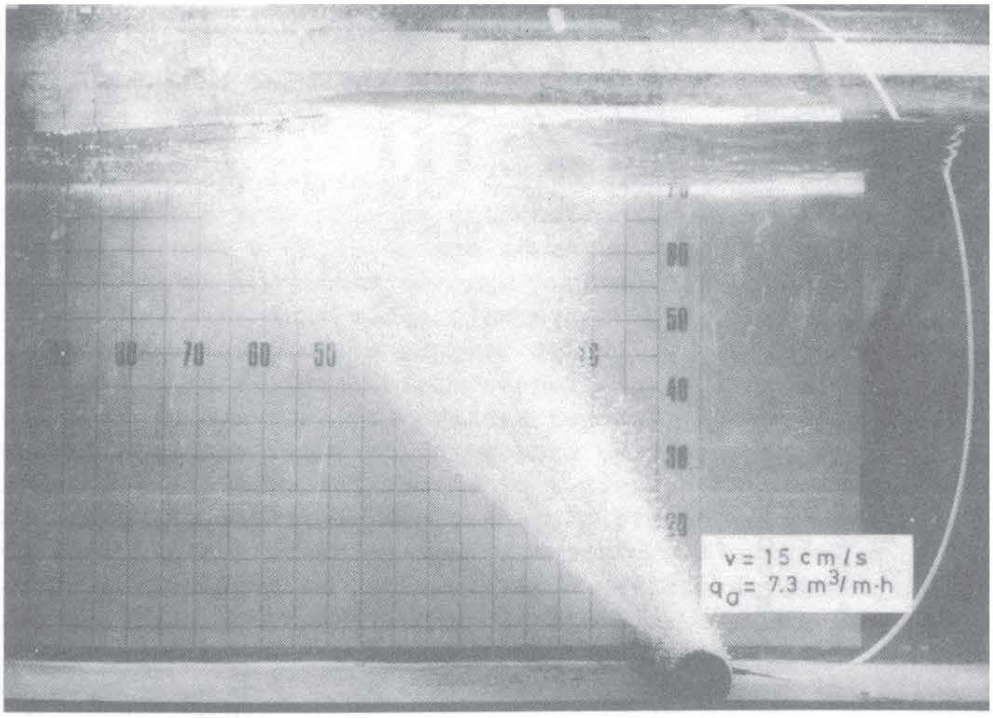

Figure 3b: Typical Bubble Curtain Produced by a Porous Filter
Colonne Typique des Bulles d'air Resultant d'une Filtre Poreux

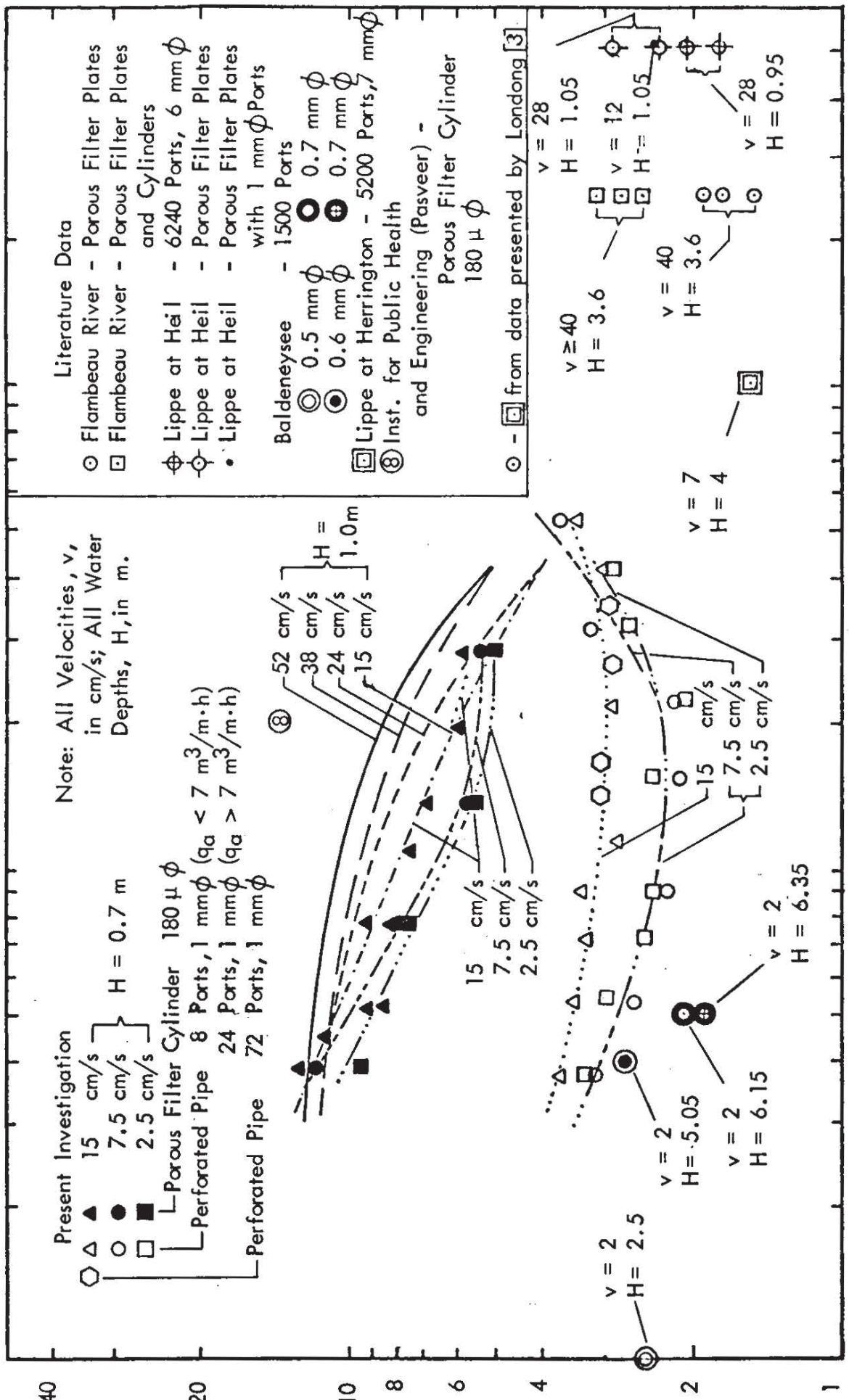

Figure 4: Oxygen Transfer Efficiency for Diffusors in a Cross Flow
L'efficace du Transfer d'oxygene des Diffuseurs dans l'écoulement