Momentum induced gas exchange through a smooth water surface,

   models and experimental results from linear and circular

wind-water-tunnels

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1.   Introduction

When dealing with the influence of waves on gas exchange it is
useful to study the transfer through a smooth water surface without any
influence of waves first to see to what extent waves increase
gas exchange.

   While momentum transport from atmosphere to water is
controlled by the atmospheric boundary layer, the transport of
gases with low and moderate solubilities is controlled by the liquid
boundary layer because of the low diffusivities of gases in water.

   So the main resistance for gas exchange within the water is
shifted to the viscous sublayer, too. The transfer resistance
from the sublayer down to several meters is only a few percent
of that through the viscous sublayer.

   Therefore gases are very sensitive tracers for the low
turbulence intensity at the very surface which is not seen by heat
and momentum having a 100 respectively a 1000 larger diffusion
coefficient in water.

2.   Theories for the smooth water surface
2.1.   General

The only decisive parameters describing gas exchange in the smooth
case will be friction velocity in water u_{*_w}, kinematic viscosity
ν and the molecular diffusion coefficient D. So transfer velocity

w respectively transfer resistance R between the water surface
and the measuring level inside the water,

$$w = \frac{j}{C_m - C_s} \qquad\qquad R = \frac{C_m - C_s}{j} \qquad\qquad (1)$$

(j flux density; C_m, C_s gas concentrations at the measuring level
respectively surface) will be a function of D, ν and u_{*_w}.

Using the   dimensionless parameter Sc = ν/D (Schmidtnumber Sc,
ratio of molecular diffusivity and viscosity) and dimensionless
transfer resistance r (comparing momentum transfer with gas
exchange)

$$r = \frac{u_{*_w}}{w} = u_{*_w} \cdot R \qquad\qquad (2)$$

shows that for a smooth water surface the dimensionless transfer
resistance can only depend on the Schmidtnumber

$$r = f(Sc) \qquad\qquad (3)$$

Figure 1 shows the large variability of the Schmidtnumber
relative to temperature for different gases.

2.2. Different models

In the following the basic assumption and results for several models are summarized.

Models	Basic assumptions	Results
Film model Liss, (1973)	diffusion through a layer without any turbulence	$r = 11.7 \cdot Sc$
surface renewal model Danckwerts, (1970) Münnich & Flothmann (1975)	statistical renewal of the whole vicous sublayer	$r = 16 \cdot Sc^{\frac{1}{2}}$
"rigid wall assumption" Deacon, (1977)	Reichhardt's Ansatz (1951) for turbulent diffusivity at a smooth rigid wall $K_t = k\zeta_e(\zeta/\zeta_e - \tanh \zeta/\zeta_e)$ $k =$ von Kármán's constant $\zeta = u \cdot z/\nu \quad \zeta_e =$ constant	$r = 12.1 \cdot Sc^{2/3}$ $Sc > 100$ $r = 15.2 \cdot Sc^{0.61}$ $0.6 < Sc < 10$

All models use the universal velocity profile at a rigid smooth wall to determine the absolute values for the dimensionless transfer resistance. But at a rigid wall and for high Sc the surface renewal model should fail, because the water at the very surface cannot be swept away; additional transfer resistance must be added.

On the other hand the assumption for the film model is too rough. So the real values for a smooth free water surface should be in the region between rigid wall assumption and surface renewal model which means that the uncertainties of the absolute values should be limited to a factor of 2-3 and for the exponent of the Schmidt-number to the interval between 0.5 and 0.67 (see Fig. 2).

3. Experimental verification

Generally there are two ways of verification:
1. Determination of the dimensionless transfer resistance by measuring friction velocity and transfer velocity (absolute method).
2. Determination of the dependence of transfer velocity on Schmidt-number and evaluation of the exponent (relative method).

to 1.)

Unfortunately most authors presenting gas exchange data did not measure friction velocity or give sufficient data to calculate it. The available data are compared with theories in figs. 2 and 3.

The data for smooth surface (Liss, 1973; Jähne, Münnich and Siegenthaler, 1979) verify the rigid wall assumption. When capillary waves commence dependent on the geometry of the channel, gas exchange is enhanced. The maximum enhancement is up to a factor of 2 to 3 in the smaller channels with low water depth (Liss, 1973; Jähne et al., 1979, maximal 10 cm depth) and up to 10 times in the larger ones (water depth $\sim$ 50 cm).

to 2.) When measuring the dependence of gas exchange on the Schmidt-number there are two possibilities. One is to measure the transfer velocities of the different gases simultaneously, and the other is to measure the temperature dependence of the exchange rate of one gas at constant friction velocity.

As far as we know, none of these methods has been successful.[*] The first method is problematic because of the high uncertainties in diffusion coefficients, so that a distinction between the different theories is hardly possible. It is necessary to get more exact values of the diffusivities of dissolved gases in water. We measured the temperature dependence of gas exchange in our channel, but the determined exponent of n = 0.41 ± 0.09 is obviously too low according to the larger enhancement of gas exchange by centrifugal forces at lower temperatures. We hope to be able to quantify this influence and also to by-pass it in our larger circular wind-water tunnel.

Thus for a smooth free water surface the rigid wall assumption seems to be correct even though the exponent of 2/3 has not yet been verified.

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[*] (see also W. Broecker et al. (1979) who did gas exchange measurement at ELA Lake 226 with ^{3}He and ^{222}Rn. He obtained an exponent of n = 0.74±0.26. The large error is mainly caused by uncertainties in the diffusivity of ^{3}He).

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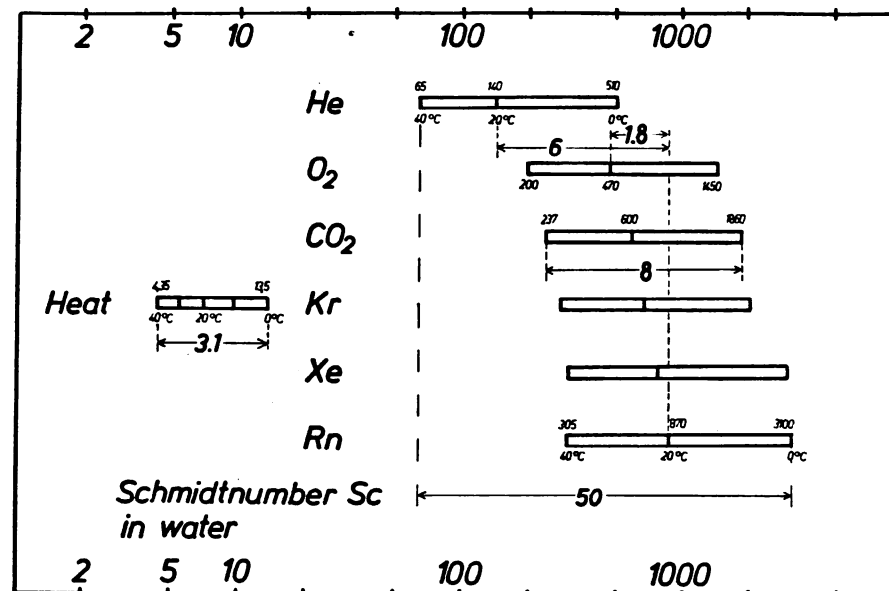   Board Natl. Res. Council, Wash. D.C. 1977)

Fig. 1.   Schmidtnumber Sc $= \frac{v}{D}$ for several gases dissolved
        in water and heat transfer in water in the temperature
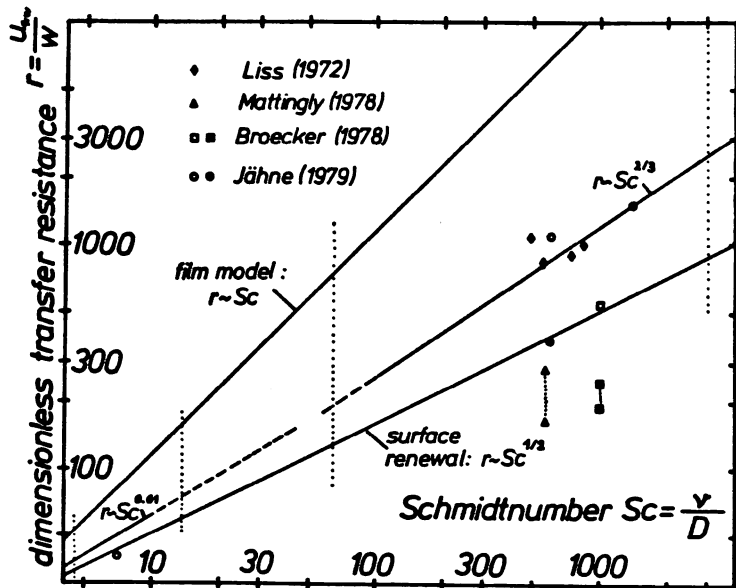   range from 0 to 40°C.

Fig. 2. Dimensionless transfer velocity r = u_{*w}/w versus
Schmidtnumber Sc in a double logarithmic plot. Comparison
of theories for a smooth water surface with experimental
results. Filled points indicate a rough surface with
capillary waves. H. Broecker's data □ are obtained
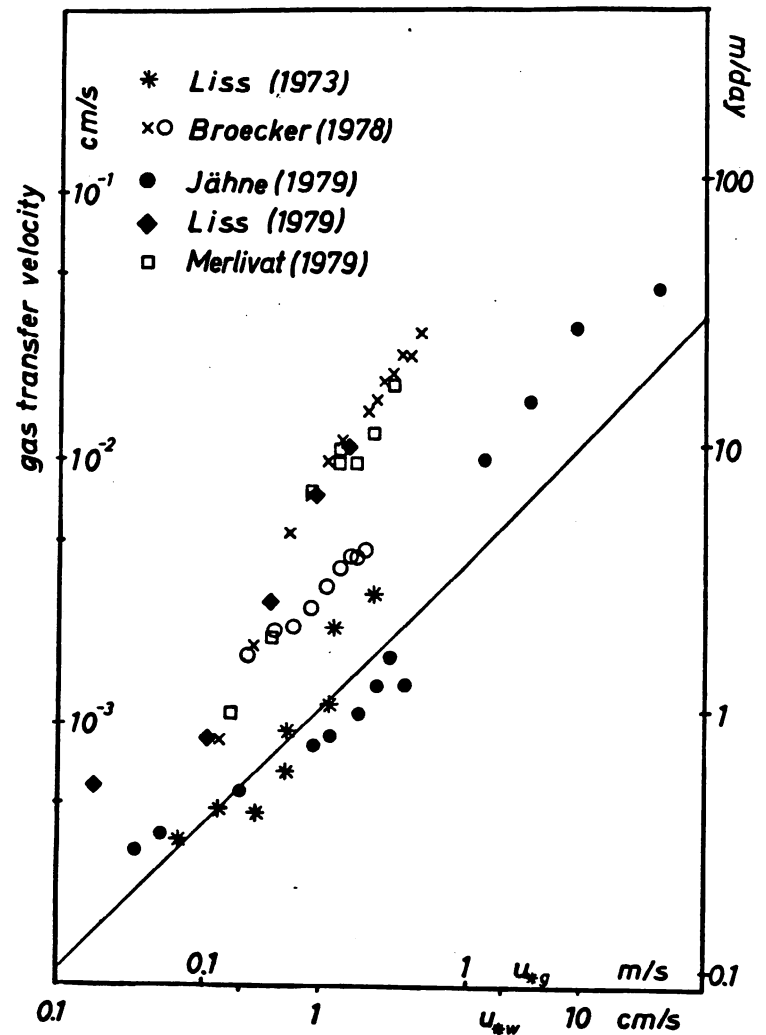when damping waves with a monomolecular surface film.

Fig. 3. Double logarithmic plot of the transfer velocity w
against friction velocity in water u_{*w}. Experimental
data are corrected for a Sc-number of 600 (CO_2 at 20°C)
assuming $w \sim Sc^{2/3}$ (10% error at maximum if $w \sim Sc^{1/2}$
should be true). Straight lines are theoretical values
for a __smooth__ water surface according to the "rigid wall
assumption" (Deacon, 1977).