The circular wind/wave facilities at the University of Heidelberg

Dominik Schmundt[1]*, *Thomas Münsterer*[1], *Hermann Lauer*[2], *and Bernd Jähne*[1,2]

[1]Institute for Environmental Physics, University of Heidelberg
Im Neuenheimer Feld 366, D-69120 Heidelberg, Germany
email: Thomas.Muensterer@iwr.uni-heidelberg.de
[2]Interdisciplinary Center for Scientific Computing, University of Heidelberg
Im Neuenheimer Feld 368, 69120 Heidelberg, Germany
email: Hermann.Lauer@iwr.uni-heidelberg.de
email: bjaehne@giotto.iwr.uni-heidelberg.de

Abstract

At the University of Heidelberg circular wind/wave flumes are used to study small-scale air sea interaction processes under a wide range of conditions. The outer diameter of the large flume is 4 m and the channel width is 30 cm. Wind in the range of 0–12 m/s is generated by a rotating paddle wheel. The unique circular design yields to homogeneous quasi-infinite fetch conditions. Since the flume is gas tight and built from transparent PVC, it is suitable for experiments with various chemical species including acid gases and surface active materials. The flume accommodates a wide variety of techniques for noninvasive sensing of waves, water flow, air flow, and gas exchange. A brief summary of experiments performed within the last twenty years is given.

1 Introduction

In the early seventies, K. O. Münnich came up with the idea to built a small circular *wind/wave facility* for some basic studies in small-scale air sea interaction including isotope effects. Such a facility seemed to be more suitable for these such than conventional linear facilities:

- Homogeneous surface conditions in contrast to the *fetch*-dependent conditions in any linear facility. Homogeneous conditions are of special importance for studies of exchange processes since the transfer rates and other parameters based on mass balance methods can be measured only integrated over the whole facility.
- Compact, clean, and gas-tight facility. It is possible to work with corrosive gases, to use liquids other than fresh water, and to study the influence of surface active materials on air-water gas exchange and wind waves.

*Currently affiliated with Optoelectronics Research Centre, Southampton, GB

Figure 1: Detail view of the small circular facility at Heidelberg University. The cover with the wind paddle has been lifted to give view to the annular water channel with a cross section of $10 \times 10\ cm^2$. *(For color figure, see Plate 18.)*

- Independent control of wind speed and gas flush rate. In this way it is easy to control humidity and gas concentrations in the air space. In essence, the facility covers the conditions of closed-circulation and open-circulation linear facilities.
- It is still possible to study limited fetch conditions as in facilities by parting the annular water channel with a dam.

These significant advantages led to the construction of a small flume. Its annular water channel had a cross section of 10 cm × 10 cm and outer diameter of 60 cm (Figures 1 and 2). The instrument was given the nickname "Windmühle" (wind mill) because of the paddle wheel used to generate the wind.

The circular design also has disadvantages. Unlike in linear channels surfactants do not get pushed towards the end of the flume by wind sheer but stay on top of the water bulk. Therefore, it is much harder to remove surface active material; the water surface has to be thoroughly skimmed before each run. On the other side, it is much easier to experiment with surface active materials.

The most serious disadvantage is the influence of centrifugal forces which induce significant secondary currents. While these effects are quite significant in the bulk of the liquid and air, they tend to compensate each other at the interface in the viscous boundary layer. Therefore the study of air-water gas transfer and other processes close to the water surface is much less effected. The influence of secondary currents on the air-sea gas transfer rates could still be detected at low wind speeds in the small facility (up to 20%

Figure 2: The small circular wind-wave facility at Heidelberg University was contained in a thermostated box to run experiments between 4–35° C. The air space of the facility could be flushed with nitrogen at rates up to 60 l/min by evaporating liquid nitrogen from a tank with an electric heater (situated to the right of the thermostated box). (For color figure, see Plate 19.)

enhancement of the air-water gas transfer) [*Jähne*, 1980]. Therefore in 1977 work began to design and construct a larger circular facility. Unfortunately, the construction was delayed by a fire in the institute in 1981. The large circular facility was finally completed in 1985 and throughly renovated in 1994.

2 Experimental Conditions in the Large Flume

2.1 Wind Generation

The wind in the facility is generated by a paddle ring. This ring consists of a flexible 25 mm diameter PVC tube to which lightweight paddles are glued. The ring is hold by 8 sets of 3 rubber-coated wheels each of which is directly driven by a 24 V, 25 W Faulhaber DC miniature motor. The maximum speed of the paddle ring is 12 m/s. The wind speed lags only slightly behind the paddle ring speed, 20 % at high wind speeds and 33 % at low wind speeds (Figure 5). The wind speed is monitored with a sensitive miniature propeller-type anemometer. The wind shear sets the water body into motion. It is (slowly) accelerated until the momentum input at the water surface is balanced by momentum loss to the channel walls and bottom.

The relation between the wind speed and *friction velocity* in the water, u_{*w}, measured at a clean, wavy water surface is shown in Figure 6.

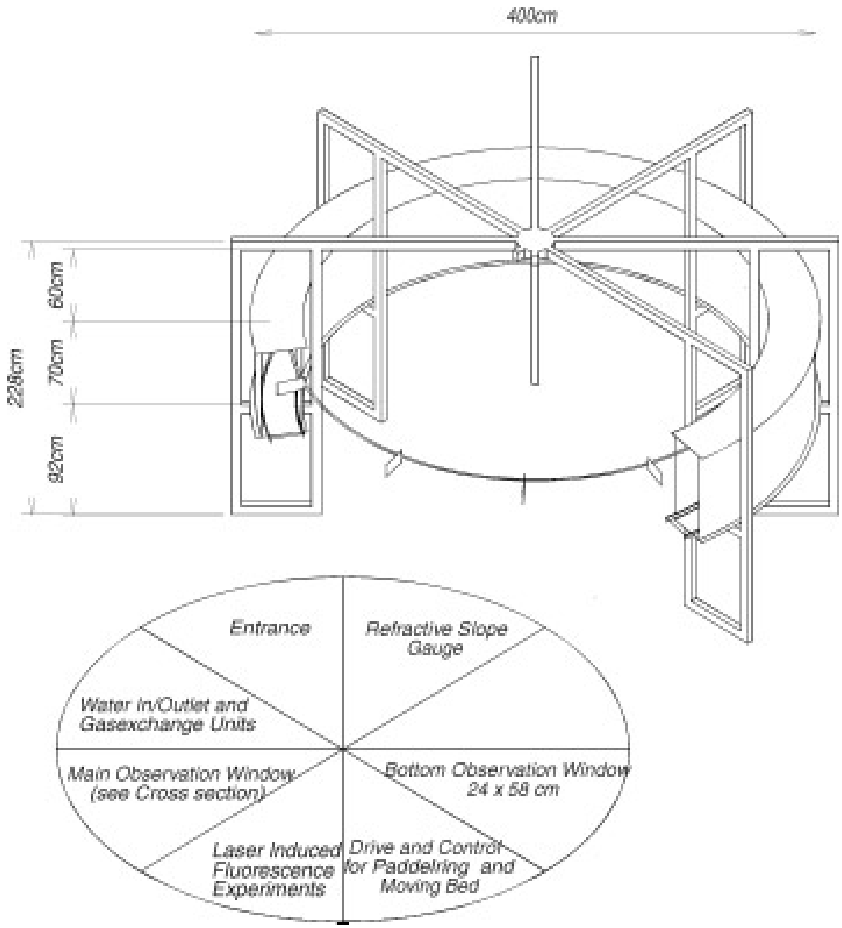

Figure 3: Schematic of the large circular wind/wave flume of the Institute for Environmental Physics at the University of Heidelberg. The outer diameter is 4 m, the channel width is 30 cm. The scheme in the lower part of the figure illustrates the position of the major instrumentation stations.

2.2 Air Circulation System

As already mentioned in *section 1*, the circular facility has the distinct advantage that the wind speed and air flush rate can be controlled independently. With a closed air circulation system, the channel is air tight for atmospheric pressure. In practice the leakages are low enough to achieve atmospheric residence times of more than an hour. In closed-circulation operation mode, experiments can be run with negligible heat exchange between air and water. The relative humidity is 100 % and the air temperature quickly adjusts to the water temperature.

The air-space of the facility can be flushed with a rate of up to 1.5 m^3/min.

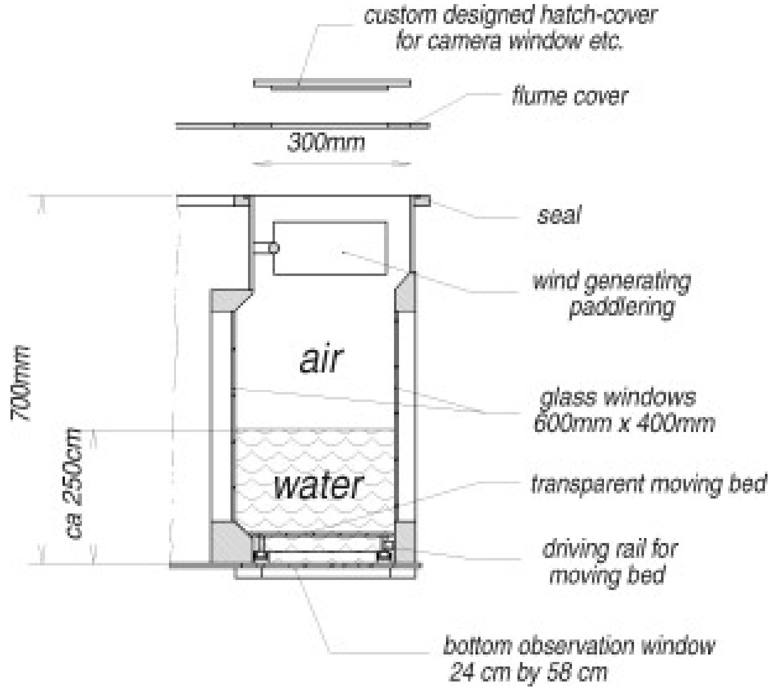

Figure 4: Cross-section of the flume at the position of the main observation windows. This section was specifically built for combined visualization studies of flow. It allows versatile imaging in the air and water from the inner and outer walls of the facility through (a) plane $0.6 \times 0.4\ m^2$ *large optical quality windows, (b) a* $0.24 \times 0.58\ m^2$ *large bottom window, and (c) through exchangeable hatch-covers.*

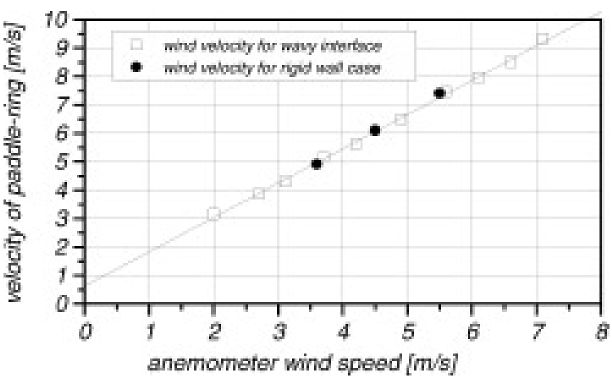

Figure 5: The wind velocity measured 23.5 cm above the mean water level with the standard water fill height of 0.25 m lags slightly behind the paddle ring speed.

Table 1: Dimensions of the large circular wind/wave flume at the Institute for Environmental Physics, Heidelberg University

Outer diameter of annular water channel	4 m ±0.002 m
Mean circumference	11.62 m
Cross section of the annular channel	0.30 m wide, 0.70 m high
Standard height of air space	0.45 m
Air volume	1.57 m^3
Maximum gas flushing rate	1.5 m^3/min
Minimum residence time of atmosphere	1 min
Water surface area	3.49 m^2
Maximum water depth	0.30 m
Volume of the water body	0.349 m^3 at $h_w = 0.10$ m
	0.872 m^3 at $h_w = 0.25$ m
	1.046 m^3 at $h_w = 0.30$ m
Extra volume in the two circulation systems including the degasing/loading columns	0.080 m^3

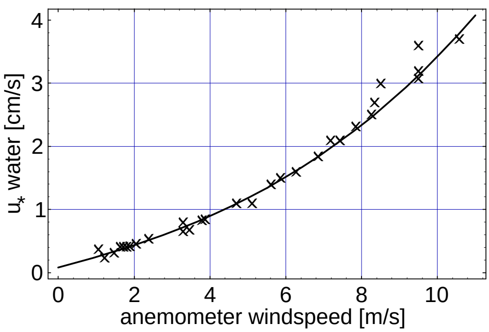

*Figure 6: Friction velocity in water, u_{*w}, as measured with the momentum balance method as a function of the wind speed [*Bösinger*, 1986;* Kandlbinder*, 1994].*

This leads to a minimum residence time of only a minute in the air space. In this way, gases can quickly be removed from the air space. The flush rate is also large enough to perform gas exchange experiments under evasion conditions, i. e., with negligible air concentrations even at high wind speeds. With the flushing-mode operation it is also possible to control and measure the evaporation rate. The total evaporative cooling can simply be computed from the humidities at the entrance and outlet of the air flush system and the flush rate.

2.3 Wind Wave Conditions

As the flume has an annular geometry, it features a quasi unlimited fetch. The principle advantage of this geometry has already been discussed in *section 1*. Wave growth is, of course, still limited by the shallow water depth (standard 0.25 m) and interference effects. Constructive interference occurs for wavelengths that are an integer fraction of the circumference and destructive interference otherwise. But with a circumference of only 12 m, wind waves still grow to significant larger wavelengths than in the largest linear wind/wave facility with 100 m fetch at Delft Hydraulics, the Netherlands [*van Vliet et al.*, 1995].

The wave field in the circular facility appears much more random than in a linear facility. In this respect it is much more like the wave spectra in the ocean. A strong dominant peak in the gravity range is missing. The wave number spectra of waves in the capillary/gravity range look very similar to those in linear facilities at large fetches. A selection of 2-D wave number spectrum is shown in Figure 7.

Figure 8 shows the dependency between the *mean square slope* and the water-sided friction velocity u_* for clean water conditions as measured with two different optical techniques. Measurements of the two-dimensional wave slope distribution will become routine in all future experiments. The mean square slope can be measured with a temporal resolution of better than 5 min and is a very sensitive indicator for contamination by surface active material that tends to damp the short waves and thus the mean square slope in the course of an experiment.

2.4 Moving Bed

Tamburrino and Gulliver [1992] designed a *moving bed* facility in which the mean flow can be set to zero. This idea has been adapted for the annular channel by inserting a false bottom that can rotate with speeds of up to 0.6 m/s against or with the wind direction. Figure 9 shows a plot of the surface drift velocity vs. moving bed speed for no-wind conditions and a plot of the depth dependent induced drift.

2.5 Gas Loading and Degasing Facilities

The flume can be degased to 1/10 of the equilibrium concentration in approximately two hours (Figure 10) by means of a bubbleless hollow fiber membrane unit [*Weiss and Gulliver*, 1995]. With a second hollow fiber membrane unit, the water of the channel can be loaded with gases without losses in even shorter times. Dissolved oxygen concentration are measured with a temperature-compensated oxygen meter in a bypass of the water circulation system.

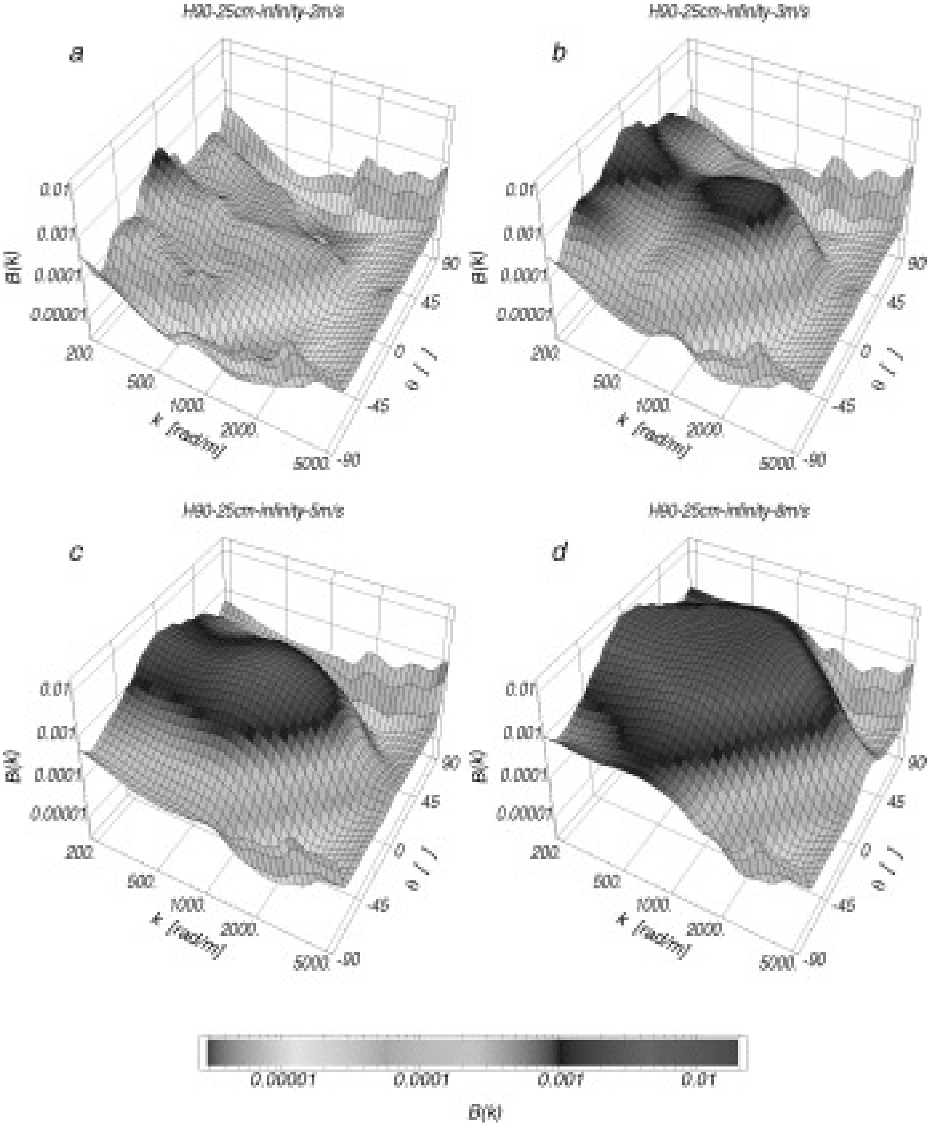

*Figure 7: Selected 2-D wave number spectra from the Heidelberg facility at infinite fetch for wind speeds **a** 2.0 m/s, **b** 3.0 m/s, **c** 5.0 m/s, and **d** 8.0 m/s. (For color figure, see Plate 20.)*

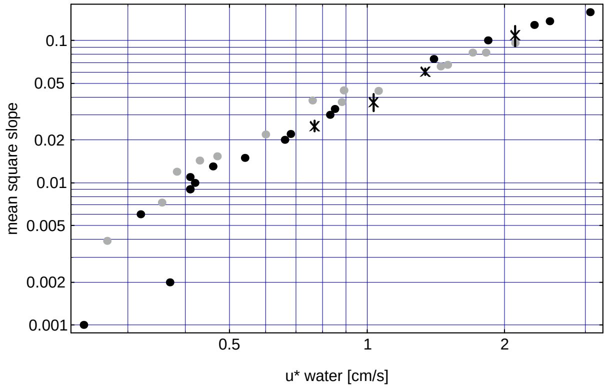

Figure 8: Mean square slope versus the friction velocity in water, $u_{*\mathrm{water}}$, measured with a reflective slope gauge from slope distributions (crosses with error bars) and a laser slope gauge by integrating slope frequency spectra (black dots, large circular flume; grey dots: small circular facility).

2.6 Water Chemistry

Built entirely with non-corrosive and inert materials (PVC, stainless steel, and brass), the facility is idealy suited to perform delicate chemical experiments. It is filled with deionized water and the conductivity in the water can be maintained even for long experimental runs lower than $1\mu S$. Only because of these low residual water ionic water contaminations, the sensitive visualization techniques using low (in the 10^{-5} molar) pH indicator buffer solutions and acid gases reported by *Münsterer et al.* [1995] became feasible.

Experiments with *surfactants* are also possible. It requires, however, several water fill cycles because of slight surfactant bleeding from the plastic materials used in the flume, before sufficient clean water conditions can be achieved [*Frew et al.*, 1995].

Standard instrumentation of the facility includes high-precision conductivity measurements and a pH electrode suitable for low ionic strength solutions (i.e. deionized water) to monitor the pH-value.

3 Key Experiments

In this section, some key experiments that have been performed in the two circular facilities in last twenty years are briefly summarized:

3.1 Small Circular Facility

1975 Measurement of the *kinetic isotope separation* during evaporation [*Münnich and Flothmann*, 1977].

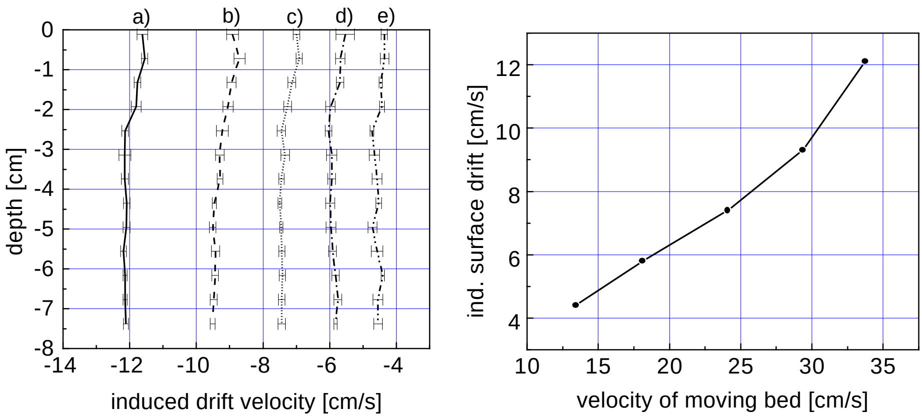

Figure 9: Left: *Depth dependent drift velocity induced by different moving bed velocities: a)* 33.8 *cm/s, b) 29.4 cm/s, c) 24.1 cm/s, d) 18.1 cm/s and e) 13.5 cm/s.* Right: *induced surface drift vs. velocity of the moving bed [Hering, personal communication].*

1979 Direct proof of the enhancement of the air-water gas transfer rate by wind waves. At the same friction velocity, data could be taken with and without waves [*Jähne, Siegenthaler and Münnich*, 1979].

1982 Development of an optical technique to measure the slope of capillary waves by refraction of a laser beam [*Lange et al.*, 1982].

1984 Measurements of the decrease of the *Schmidt number* dependency of the air-water gas transfer rate with a multi-tracer study including measurements of the transfer rates for heat, He, CH_4, Kr, Xe, and CO_2 With the transition from a smooth to a wavy surface the Schmidt number exponent decreases from 2/3 to 1/2 [*Jähne et al.*, 1984].

3.2 Large Circular Facility

1985 Development of a new optical technique to take images of the slope of wind waves and first attempt to visualize the penetration of a gas into the aqueous viscous boundary layer [*Jähne*, 1985, *Jähne*, 1986]

1989 Development of the "controlled flux" technique using heat as a proxy tracer for fast and local measurements of the gas transfer rate [*Jähne et al.*, 1989]

1990 Systematic study of two-dimensional wave number spectra of wind waves [*Jähne and Riemer*, 1990]

1991 Experimental studies of the turbulent flow beneath wind waves using particle tracking techniques [*Wierzimok and Jähne*, 1991]

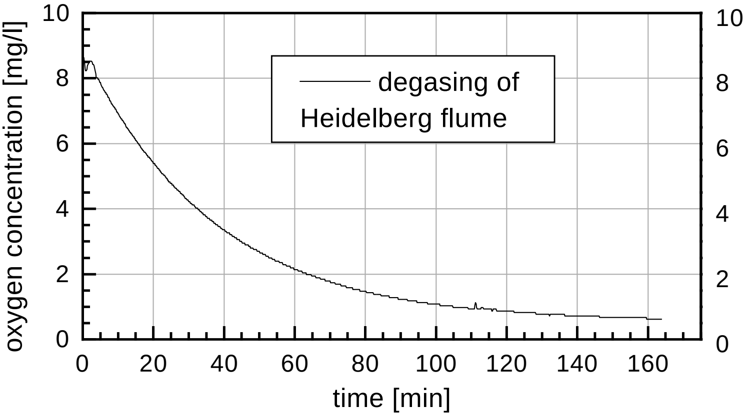

Figure 10: Degasing from equilibrium concentration to 10 % of equilibrium concentration takes approximately 2 hours using a hollow fiber membrane unit.

1992 First measurements of high-resolution vertical profiles of the concentration of dissolved gases in the aqueous mass boundary layer using laser-induced fluorescence and a fluorescent indicator [*Jähne*, 1993; *Münsterer and Jähne*, 1993]

1994 Joint experiments with E. Bock, N. Frew, T. Hara and W. McGillis from WHOI on the influence of surfactants on gas exchange and wave fields. Combined experiments measuring gas exchange with SF_6, O_2 and the controlled flux technique and wave field measurements with the scanning laser slope gauge (WHOI), the RSG and the color imaging slope gauge.

Acknowledgments

The construction and instrumentation of the large wind/wave flume has been partly supported through grants from the German Science Foundation (DFG).

References

Bösinger, R., Messungen zur Schmidtzahlabhänigkeit des Gasaustausches, Diploma Thesis, Institute for Environmental Physics, University of Heidelberg, 1986

Frew, N. M., E. J. Bock, W. R. McGillis, A. V. Karachintsev, T. Hara, T. Münsterer and B. Jähne, Parameterization of Air-Water Gas Transfer using Wind Stress and Viscoelasticity, *this volume*

Hering, F., personal communication.

Jähne, B., K. O. Münnich, and U. Siegenthaler, Measurements of gas exchange and momentum transfer in a circular wind-water tunnel, *Tellus, 31*, 321–329, 1979

Jähne, B., *Zur Parameterisierung des Gasaustausches mit Hilfe von Laborexperimenten*, Dissertation thesis, Fakulty for Physics and Astronomy, Univ. Heidelberg, 1980

Jähne, B., W. Huber, A. Dutzi, T. Wais, and J. Ilmberger, Wind/wave-tunnel experiments on the Schmidt number and wave field dependence of air-water gas exchange, in *Gas transfer at water surfaces*, edited by W. Brutsaert and G. H. Jirka, pp. 303–309, D. Reidel, Hingham, Mass., 1984

Jähne, B., *On the transfer processes at a free air-water interface*, Habilitation thesis, Faculty of Physics and Astronomy, Univ. Heidelberg, 1985

Jähne, B., Bildfolgenanalyse in der Umweltphysik: Wasseroberflächenwellen und Gasaustausch zwischen Atmosphäre und Gewässern, in *Mustererkennung 1986*, Proceedings, 8th DAGM-Symposium, Paderborn, 30. Sep. – 2. Okt., 1986, Informatik-Fachberichte 125, pp. 201–205, Springer, Berlin, 1986

Jähne, B., P. Libner, R. Fischer, T. Billen, and E. J. Plate, Investigating the transfer processes across the free aqueous viscous boundary layer by the controlled flux method, *Tellus, 41B*, 177–195, 1989

Jähne, B., and K. Riemer, Two-dimensional wave number spectra of small scale water surface waves, *J. Geophys. Res.*, 95, 11,531–11,546, 1990

Jähne, B., Imaging of gas transfer across gas/liquid interfaces, *Imaging in Transport Processes*, edited by S. Sideman and K. Hijikata, Begell House Publishers, New York, pp. 247–256, 1993

Kandlbinder, T., Gasaustauschmessungen mit Sauerstoff, Diploma Thesis, Institute for Environmental Physics, University of Heidelberg, 1986

Lange, P. A., B. Jähne, J. Tschiersch, and J. Ilmberger, Comparison between an amplitude-measuring wire and a slope-measuring laser wave gauge, *Rev. Sci. Instrum., 53*, 651–655, 1982

Lauer, H., Messung der Neigungsverteilung von Wasseroberflächenwellen mittels digitaler Bildverarbeitung, Diploma Thesis, Institute for Environmental Physics, University of Heidelberg, 1994

Münnich, K. O., and D. Flothmann, Gas exchange and evaporation studies in a circular wind tunnel, continuous radon-222 measurements at sea and tritium/helium-3 measurements in a lake, NATO Symposium *Turbulent Fluxes through the Sea Surface, Wave Dynamics and Prediction*, Marseille, 12.–16. Sep. 1977, A. Favre and K. Hasselmann, eds., Plenum Press, New York, 1977

Münsterer, T., and B. Jähne, A fluorescence technique to measure concentration profiles in the aqueous mass boundary layer, Proceedings, *Air-Sea Interface Symposium*, Marseille, 24.–30. June 1993, in press.

Riemer, K., Scholz, T., und Jähne, B., Bildfolgenanalyse im Orts-Wellenzahl-Raum, *Mustererkennung 1991*, Proc. 13. DAGM-Symposium, 9.-11. Oktober 1991, ed. B. Radig, pp. 223-230, 1991

Tamburrino, A., and J.S. Gulliver, Comparative flow characteristics of a moving bed flume, *Exp. in Fluids*, vol. 13, no. 5, 289–298, 1992

Wierzimok, D., and B. Jähne, Measurement of wave-induced turbulent flow structures using digital image sequence analysis, *Air-Water Mass Transfer*, selected papers from the 2nd International Symposium on Gas Transfer at Water Surfaces, September 11–14, 1990, Minneapolis, Minnesota, S. C. Wilhelms and J. S. Gulliver, eds, pp. 200–209, ASCE, New York, 1991