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Experimental study of the flow structure in the near free-surface region

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Abstract

Results of an experimental study about the flow structure in the near free surface region of a tank agitated by jets located in the bottom are presented in the paper. Flow visualization and PIV techniques were used to compute instantaneous velocity fields, mean velocity profiles, turbulence intensities and turbulent kinetic energy distribution. Velocity spectra and autocorrelations were also calculated from the data collected.

A succession of events in the near air-water interface, forming a quasi-periodical pattern, was inferred from flow visualization and measurements. The most relevant event corresponds to a horizontal sweep, usually preceded by an upwelling of fluid. It is postulated that these events are associated to the renewal phenomenon, which is important in the gas transfer process across the interface.

Velocity spectra and autocorrelations showed some dominant frequencies associated to large scale motions in the tank. Isotropy loss and damping of the vertical velocity fluctuation was inferred from the velocity spectra. Ascending vortices deform when they approach to the free surface, increasing their horizontal size and diminishing the vertical one, or breaking down in smaller ones.

1 Introduction and objectives

Phenomena occurring at and near the free surface of turbulent flows play an important role in the mass and heat transfer mechanisms across the air-water interface. In particular, a better knowledge of the gas transfer mechanisms across the air-water interface is essential to predict concentration levels or distribution

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of many chemicals in diverse natural or industrial processes, like re-aeration in water bodies and waste water treatment. Mass transfer of highly soluble gases across the air-water interface is governed by the hydrodynamics of the liquid phase. Thus, it is important to have a better knowledge of the flow field close to the free surface.

Experiments in agitated tanks present some advantages when compared to traditional laboratory flumes. It is easier to generate different levels of turbulence and the flow has longer residence times in agitated tanks.

The objective of this paper is to present some experimental results regarding the flow structure close to the free surface in a tank with water agitated by jets emerging from the bottom. Characterization is based on flow visualization and PIV measurements in a 4.0 by 5.1 cm^2 vertical plane in the center of the tank.

2 Previous research

Although turbulent flows have been studied for more than a century, there is not a general description of them yet. The equations governing the phenomenon have been analyzed in detail, but for practical purposes, there is always a need for some empirical data.

Near the free surface there is an interaction between the surface and the vortices generated by the turbulence. During the last 30 years, there has been a special interest for understanding the mechanisms and parameters involved in this process. Most of the explanations for the flow behavior near the free surface in open channel flows consider eddies generated in the outer region that reach the free surface. Komori et al. [1] propose that large scale eddies intermittently reach the interface, renew it, and go back to the bulk of the fluid. According to Rashidi and Banerjee's model [2], the fluid ejected from the bottom reaches the free surface, interacting with the interface, where the large eddies break down in smaller ones, generating a large velocity gradient close to the free surface, and the fluid move downwards. Bernal and Kwon [3] visualized the evolution of vortical rings generated close to the free surface, with axis parallel to it, and found that the ring vortex lines opened during the interaction with the free surface. The resulting field is composed by vortices attached to the free surface, with their ends starting and finishing in the interface. Similarly, Dommermuth [4] explains the surface eddies observed in clean or contaminated free surfaces as the ends of U-shaped vortices.

Agitated tanks have been used at least since the middle 1950's to study turbulence phenomena [5]. Agitation of the water contained in the tank generates turbulence. Usually, agitation is achieved by oscillating grids [5-8], but agitation by a jet [9] and microjets [10] have also been reported.

Experiments in tanks in which water is injected and evacuated by nozzles located at the bottom [11] show that four flow regions can be identified in the bulk of the fluid (Fig. 1):

I) Lower region, where zones of high turbulence (injection jet zones) are surrounded by regions of lower turbulence (evacuating flow zones).
II) Middle region. Zone where there is a direct interaction of the jets.

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III) Zone of isotropic turbulence.
IV) Surface influenced layer.

Limits of each zone depend on the jet velocities and water depth. Pujol [12] and Muñoz [13] have studied those limits and the characteristics of the different regions (some results are presented in [11]). The beginning (Z_0) of region III is given by:

$$\frac{Z_0}{S} = 0.634\left(\frac{V_{ch}L_C}{\nu}\right)^{0.154} \tag{1}$$

where S is the distance between jet nozzles, V_{ch} is the jet velocity, $L_C = \sqrt{\pi}D/2$ is a characteristic length, and ν is the kinematic viscosity. The turbulence intensity (U_0) at Z_0 is:

$$\frac{U_0}{V_{ch}} = 0.194\left(\frac{V_{ch}L_C}{\nu}\right)^{-0.318} \tag{2}$$

Most of the authors [5-8, 10, 11] report that the turbulent kinetic energy (k) decays like z^{-2} in the region of isotropic turbulence (z is the vertical axis). Measurements with an acoustic Doppler velocimeter and flow visualization in two tanks agitated by jets [11, 13], show a large scale secondary motion, having a donut-like shape, with an ascending motion in the center of the tank and descending close to the walls.

3 Experimental facility and flow conditions

The experimental facility is a perspex tank, 70 cm height and 95x95 cm^2 cross section. Water is injected and evacuated by 2.9 mm nozzles located in the bottom, spaced 5 cm each other. Water circulates in a closed circuit due to the action of a 1.5 kW pump. Thus, a zero net discharge is obtained in horizontal planes, parallel to the bottom.

The flow field close to the free surface was determined from PIV measurements. Aluminum flakes (10 μm size) and perspex particles below mesh 200 (0.065 mm) were used as tracers. A Spectra-Physics laser (model 171-270 Exciter, 20 W maximum power) supplied the illumination. The laser beam was carried by a fiber optic to a cylindrical lens (TSI 610082) that generated a light sheet. The laser light was pulsed by a TSI 620010 device and was synchronized with a video camera by a TSI 610030 synchronizer. The recording camera is a SONY, Digital 8 DCR-TRV210/TRV310.

Sequences of 300 pairs of video frames were processed in such a way to obtain 5-minute time series with a sampling rate of 1 Hz. In order to reach higher frequencies in the velocity spectra, 20-seconds time series at 15 Hz sampling rate were also generated. The recording plane is a 4 cm height and 5.1 cm wide plane located in the center of the tank, parallel to one of the walls (Fig. 2). Velocities

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were computed in the nodes of a 20x10 grid, with more nodes in the vertical direction.

The experimental flow conditions were defined by the water depth (H), and the jet velocity (V_{ch}). They are summarized in Table 1. In the Table, Q is the circulating discharge. A ninth experiment (C3, H = 22 cm, V_{ch} = 1.72 m/s) was carried out but not analyzed because of excessive deformation of the free surface.

Table 1: Experimental conditions.

Series	H (cm)	V_{ch} (m/s)	Q (lt/s)
A1	44	0.72	0.77
A2	44	1.17	1.25
A3	44	1.69	1.81
B1	33	0.71	0.76
B2	33	1.14	1.22
B3	33	1.72	1.81
C1	22	0.69	0.71
C2	22	1.16	1.24

Finally, video recordings with large time exposure were used to visualize the flow and to identify a diversity of structures developing close to the air-water interface.

4 Results

4.1 Flow visualization

The most recurrent structure visualized close to the free surface corresponds to vortices. These vortices have sizes sufficiently large to be easily identified in the visualization plane. Large scale motions convey these vortices, and they evolve when cross the plane. A complex flow pattern is inferred from flow visualization, having the following characteristics:

i) Irregularity: The flow pattern is irregular, with sudden fluctuations of velocity, and vortices appearing randomly in the visualization spot.

ii) Size: Vortices cover a large range of sizes, from very small (a few millimeters), up to sizes that only a portion of a vortex is seen in the visualization plane. Of course, the observed vortices correspond to a portion of the full range of sizes existing in the tank. The largest size corresponds to a toroidal motion scaling with the water depth [13], and the smallest ones are associated to the Kolmogorov scale.

iii) Free surface: The air-water interface behaves as a tense membrane, with negligible deformation, for the experimental conditions of Table 1. It did not present vertical deformations to be detected in the videos.

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iv) Vortex interaction with the free surface: Vortices that interact with the free surface increase their horizontal size and decrease the vertical one, or split in several smaller ones.
v) Tridimensionality: Observed as sudden changes of velocity magnitude and direction. In order to satisfy continuity, a third velocity component, normal to the visualization plane, must exist.
vi) Quasi-periodicity: The flow pattern presents some events that are quasi-periodic in time.
vii) Surface renewal: Upwelling motions followed by sweeping movements are evidence of substitution of fluid close to the free surface by fluid coming from lower regions from the tank.

Some pictures of the characteristics mentioned above are presented in Figs. 3 to 7. The quasi-periodic sequence of events can be described in terms of three stages, as follows:

1) An upward motion. A very strong vertical motion approaches the free surface.
2) The velocity changes direction, from vertical to horizontal motion, and small vortices are formed near the free surface.
3) A sweeping motion, where large-scale vortices literally "sweeps" the vortices close to the free surface. The dominant motion is horizontal.

The sequence is not always 1)-2)-3). Sometimes, before stage 3) is reached, another upward motion 1) comes, generating small vortices, close to the free surface. The frequency of event of type 1) is about three times higher than the frequency of event of type 4).

4.2 Characterization of the flow field and turbulence

The temporal mean velocity distribution is not zero for both horizontal (U_m) and vertical (W_m) velocities, due to the presence of the large scale motions of the flow [11-13]. The velocity distribution corresponding to Series B3 is presented in Fig. 8. Although the distributions are different for each flow condition, they have in common that the vertical velocity tends to vanish close to the free surface.

Turbulence intensities, characterized by the root mean square (rms) of the velocity fluctuations were also computed. It is observed that as the free surface is approached, U_{rms} increases, and W_{rms} decreases to zero, reflecting the damping of the vertical component. As an example, turbulence intensities for Series A1 are presented in Fig. 9. As in the case of the temporal mean velocity, the vertical distribution of turbulence intensities is different for each flow condition. Assuming that the turbulence intensity in the y-direction (V_{rms}) is equal to U_{rms}, the turbulent kinetic energy (K) close to the free surface was computed, and the distribution for Series A is given in Fig. 10. In the figure, K_0 corresponds to the turbulent kinetic energy at Z_0, computed as $K_0 = {}^3/_2 U_0^2$ (U_0 is computed from Eq. 2). The rest of the variables are defined in Fig. 1.

Assuming that the sweeping event corresponds mainly to horizontal motion, it is possible to determine the dominant frequencies associated to the large scale

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motions in the tank from the analysis of velocity spectra and autocorrelations of the horizontal velocity component (u'). Fig. 11 presents the spectrum and autocorrelation function of u' for experiment A3, at z/H = 0.97. Two peaks at 0.017 and 0.04 Hz are easily recognized in the spectrum, corresponding to delay times of 58 and 20 seconds, respectively, in the autocorrelation. The first peak of the spectrum has been associated to the frequency of the largest structure reaching the free surface. A summary with the frequency (f) of the first peak for series A and B is given in Table 2 and Fig. 12, where a dimensionless frequency was defined as $f_{ad} = fH'/U_0$, and the Reynolds number as $Re = U_0H'/\nu$ ($H' = H - Z_0$, with Z_0 computed from Eq. 1).

Table 2: Dominant frequency for Series A and B

Series	U_0 (m/s)	H' (m)	f (Hz)	f_{ad}	Re
A1	0.013	0.238	0.007	0.119	3094
A2	0.018	0.222	0.011	0.136	3996
A3	0.023	0.210	0.017	0.155	4830
B1	0.013	0.128	0.013	0.128	1664
B2	0.017	0.113	0.020	0.133	1921
B3	0.023	0.099	0.033	0.142	2277

Assuming that the energetic horizontal motions observed near the free surface are "portions" of large scale vortices reaching the vicinity of the interface, and following Komori et al. [1], it is possible to associate these events to the surface renewal process. Thus, the dependency between renewal rate and Reynolds number is corroborated.

When the spectra for the u' component is compared with those corresponding to w', the damping of the lower frequency vertical fluctuations is observed. Thus, in the vicinity of air-water interface, there is a transfer of turbulence intensity, from the vertical component to the horizontal one (Fig. 13).

The spectra above mentioned correspond to those obtained with 1 Hz sampling rate. In order to extend the frequency range, an image processing with sampling at 15 Hz was carried out, going one decade farther in the spectra. All of the spectra presented a well defined inertial subrange, starting at about 0.15 Hz. Fig. 14 presents one of these spectra, corresponding to w', at z/H = 0.97 from series A2.

Finally, integral and Taylor time scales were also determined for the horizontal velocity fluctuation. They were computed following Bouvard and Dumas' [6] procedure, in which the integral time scale (T) is associated to the first moment of the spectrum and Taylor time scale (Ta) is associated to the second moment. The results are summarized in Fig. 15. In the experimental range, both scales show a weak dependency on the Reynolds number. The data tend to follow a behavior that also depends on the water depth, but the efforts made to find a relation that makes the integral (or Taylor) time scales collapse into one curve were in vain, and the time in Fig. 15 was plotted with dimensions.

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5 Conclusion

Local characteristics of the flow pattern near the free surface of turbulent flow in a jet agitated tank were obtained by means of flow visualization and PIV measurements. Flow visualization allowed us to identify a succession of events forming a quasi-periodic temporal pattern. Upwelling and horizontal sweeping, indicating the replacement of fluid close to the free surface by fluid coming from lower regions characterize these events. This temporal flow pattern has been associated to the surface renewal phenomenon. The most frequent structures observed close to the free surface are vortices. When the vortices move closer to the free surface, they deform, decreasing their vertical dimensions, or breaking down in smaller ones, in a way similar to that proposed by Rashidi and Banerjee [2] for open channel flows.

The distribution of temporal mean velocities, turbulence intensities, and turbulent kinetic energy, close to the free surface were characterized from the data analysis. Velocity spectra and autocorrelation functions were also computed. A peak of the spectra of u' is associated to the frequency of the horizontal motion associated to the sweeping motion in the flow visualization. Turbulence intensities and spectra show the damping of the vertical component fluctuation and the enhancement of the horizontal one. Thus, turbulence isotropy is lost close to the free surface. Finally, the velocity spectra showed a well defined inertial subrange.

Acknowledgments

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References

[1] Komori, S., Murakami, Y., and Ueda, H., The relationship between surface-renewal and bursting motions in an open channel flow, *J. Fluid Mech.,* Vol. 203, pp. 103-123, 1989.
[2] Rashidi, M. and Banerjee S., Turbulence structure in free-surface channel flows, *Phys. Fluids*, Vol. 31, No. 9, pp. 2491-2503, 1988.
[3] Bernal, L.P. and Kwon, J.T., Vortex ring dynamics at a free surface, *Phys. Fluids A,* Vol. 1, No. 3, pp. 449-451, 1988.
[4] Dommermuth, D.C., The formation of U-shaped vortices on vortex tubes impinging on a wall with applications to free surfaces, *Phys. Fluids A*, Vol. 4, No. 4, pp. 757-769, 1991.
[5] Rouse, H. et Dodu, J., Diffusion turbulente à travers une discontinuité de densité. *La Houille Blanche*, No. 4, pp. 522-533, 1955.

Paper from: *Advances in Fluid Mechanics IV*, M Rahman, R Verhoeven and CA Brebbia (Editors).
ISBN 1-85312-910-0

[6] Bouvard, M. et Dumas, H., Aplication de la méthode du fil chaud a la mesure de la trubulence dans l'eau. Deuxieme Partie. *La Houille Blanche*, No. 3, pp. 723-734, 1967.
[7] Thompson, S.M. and Thurner, J.S., Mixing across an interface due to turbulence generated by an oscillating grid, *J. Fluid Mech.* Vol. 67, Part 2, pp. 349-368, 1975.
[8] Hoppfinger, E.J. and Toly, J.-A., Spatially decaying turbulence and its relation to mixing across density interfaces, *J. Fluid Mech.* Vol. 78, Part 1, pp. 155-175, 1976.
[9] Sonin, A.A., Shimko, M.A. and Chun, H.-H., Vapor condensation onto a turbulent liquid – I. The steady condensation rate as a function of liquid-side turbulence, *Int. J. Heat Mass Transfer*, Vol. 29, No. 9, pp. 1319-1332, 1986.
[10] Grisenti, M. and George, J., Hydrodynamics and mass transfer in a jet-agitated vessel, *Air-Water Mass Transfer*, eds. S.C. Wilhelms and J.S. Gulliver, ASCE, pp. 94-105, 1991.
[11] Tamburrino, A., Pujol, J., and Muñoz, Turbulence structure in a jet agitated tank, *XXIX I.A.H.R. Congress*, Vol. II, pp. 645-650, Beijing, China, 2001.
[12] Pujol, J., Turbulent structure of a flow generated by microjets, Civil Engineering Thesis, University of Chile, 1999. (In Spanish)
[13] Muñoz, A., Characteristics of the turbulent flow generated by microjets in tanks, Civil Engineering Thesis, University of Chile, 2001. (In Spanish)

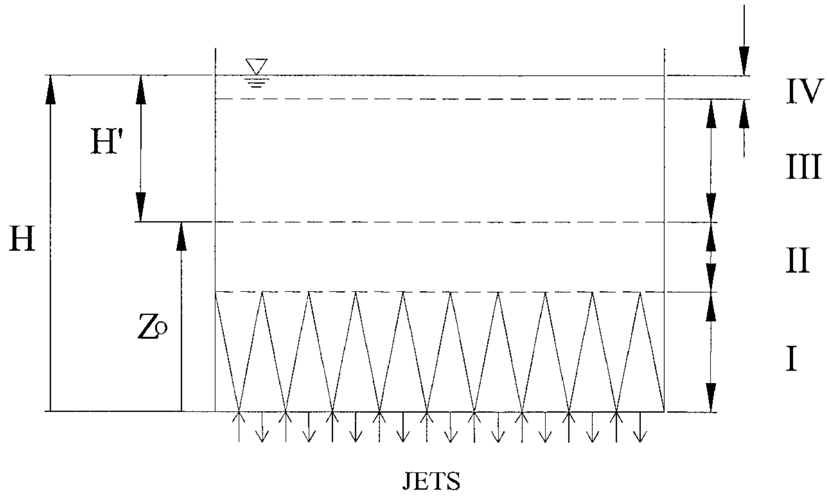

Figure 1: Flow regions in the jet agitated tank.

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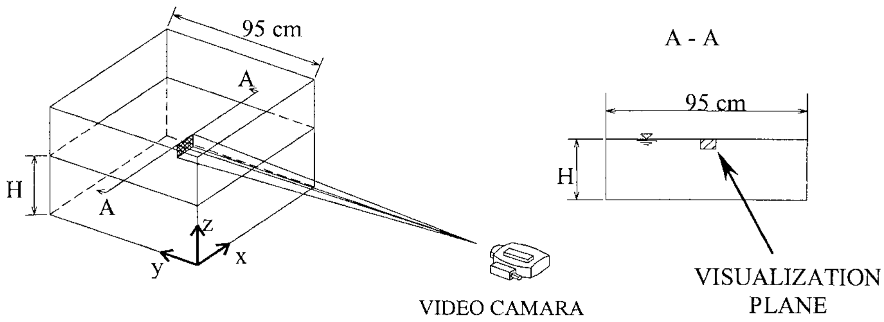

Figure 2: Location of visualization plane and coordinate system.

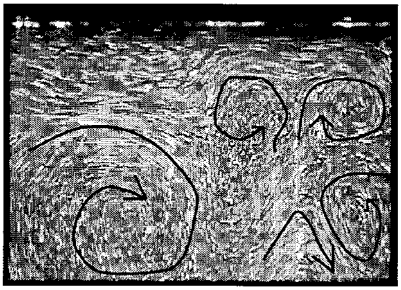

Figure 3: Presence of multiple vortices close to the free surface

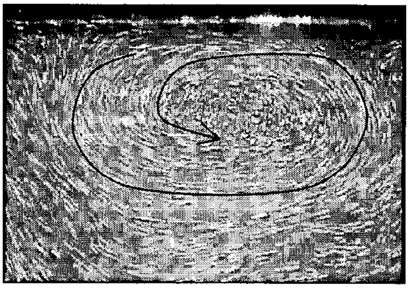

Figure 4: Deformation of vortices as they approach the free surface

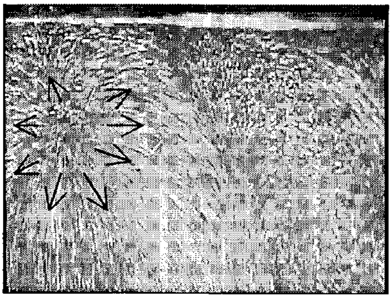

Figure 5: Flow is tridimensional. In this image, there is strong motion normal to the page

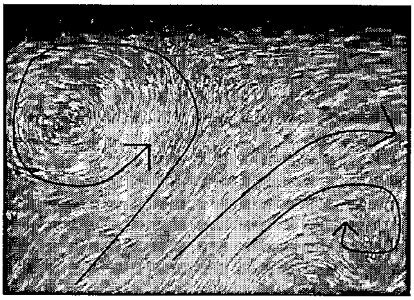

Figure 6: Upwelling motion

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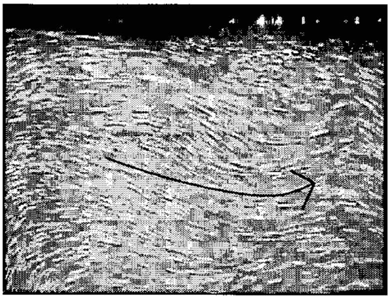

Figure 7: Sweeping motions

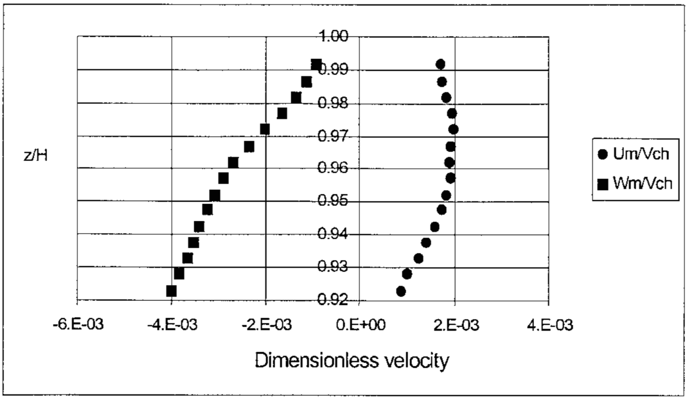

Figure 8: Velocity distribution. Series B3.

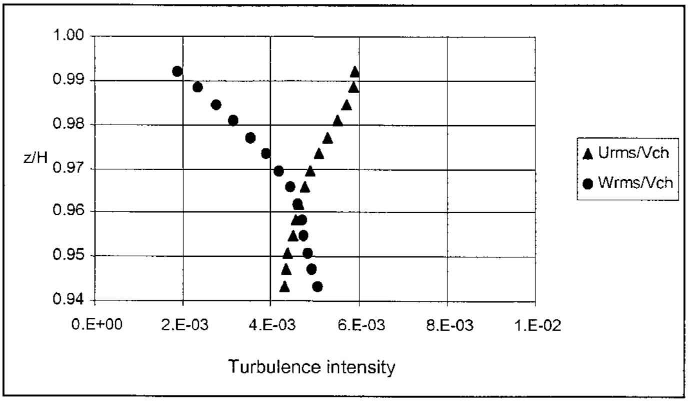

Figure 9: Turbulence intensity distribution. Series A1.

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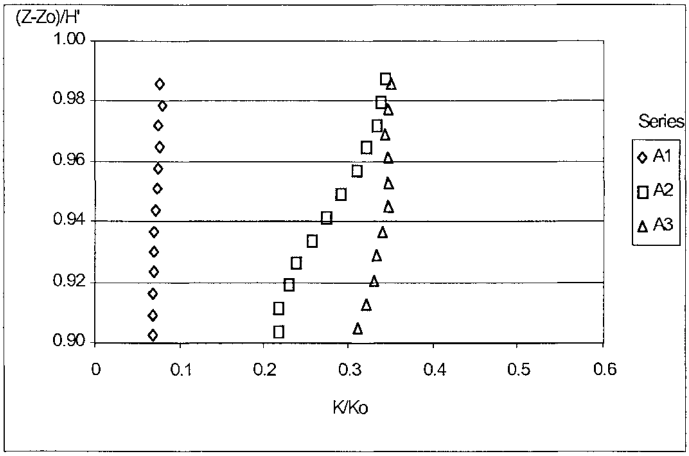

Figure 10: Turbulent kinetic energy distribution. Series A.

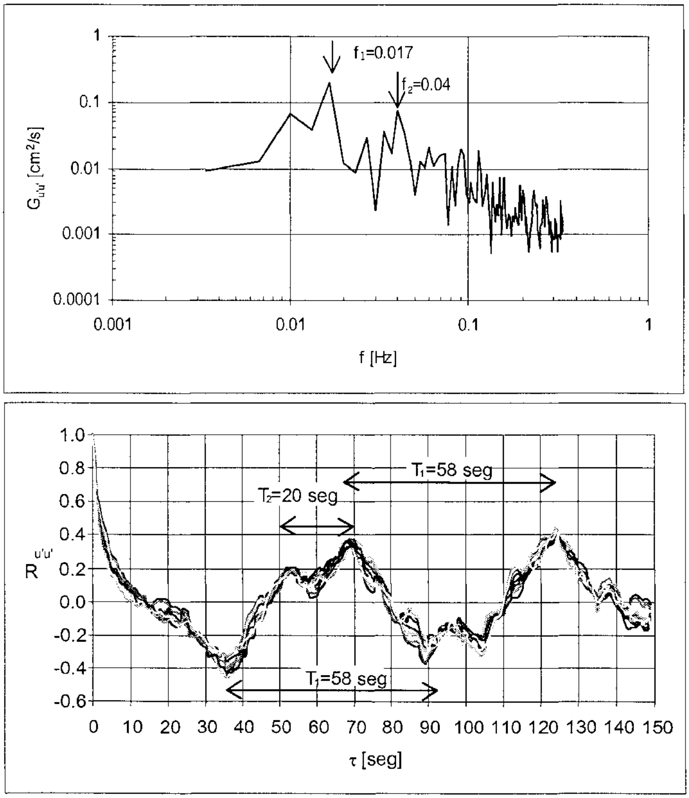

Figure 11: Series A3. Location z/H = 0.97. u' component.
Upper figure: Velocity spectrum
Lower figure: Autocorrelation

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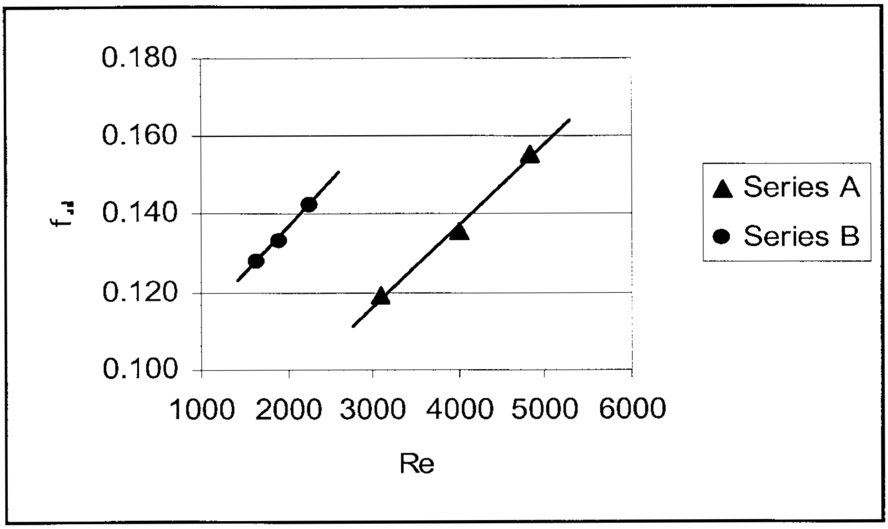

Figure 12: Dimensionless dominant frequency as a function of Reynolds number.

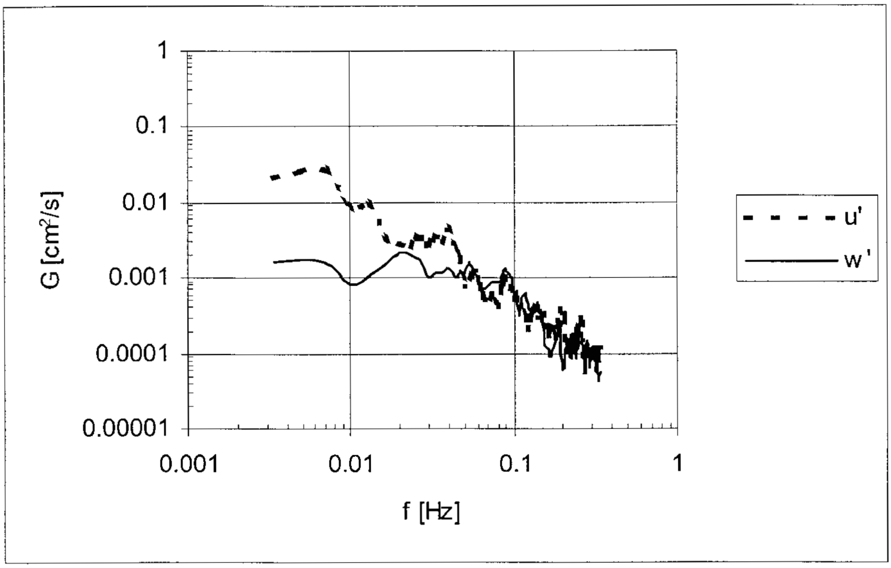

Figure 13: Velocity spectrum. u' and w' components.
Series B1. Location z/H = 0.95.

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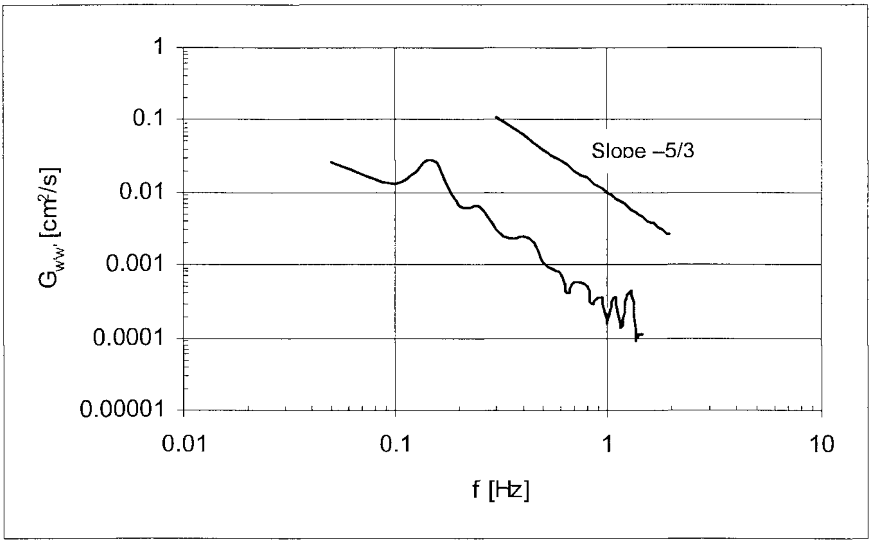

Figure 14: Spectrum of the vertical component of velocity.
Series A2. Location z/H = 0.95.

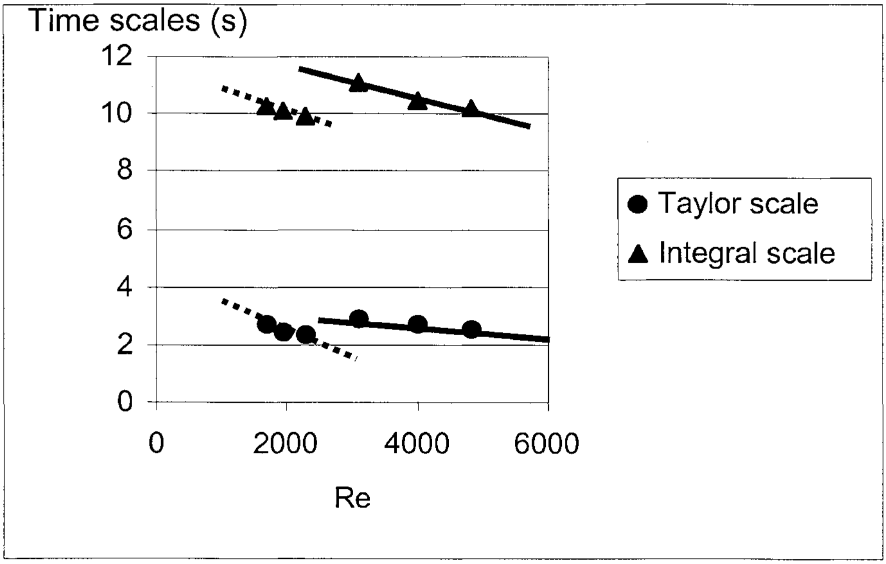

Figure 15: Integral and Taylor time scales