Spectral dynamics of Drag reduction by microbubbles

by

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ABSTRACT

An experiment on drag reduction by injection of microbubbles within the boundary was carried out in a turbulent water channel flow at a Reynolds Number, $Re = U_bH/\nu = 5128$ (considering half height of channel, H and the bulk velocity, U_b). Particle Image Velocimetry (PIV) measurement technique was used to obtain instantaneous velocity fields in the ~~x~~-y plane close to the upper wall. One dimensional spectra ($E_{uu}(k1)$) in the streamwise wavenumber was calculated. The information of the spectra with a dimensionless wavenumber (k_1H) lower than 2.3 was evaluated using the temporal information and assuming Taylor's frozen hypothesis while the information of higher wavenumbers values was obtained from the spatial information. Good agreement between the results obtained from both methods was observed in the overlapping region and it allows an increase of the wavenumber information. Moreover, the energy contain of spectra results for single phase flow within the buffer layer is larger than the energy contain of the flow when microbubbles are injected within the boundary layer over the whole wavenumber range. However, the opposite trend is observed outside the buffer layer. It suggests that the effect of the microbubbles within the buffer layer is different from the one occurring outside it.

1. INTRODUCTION

The presence of drag provokes a degradation of energy in several engineering and industrial applications such as pipeline transport of crude oil, hydraulic machines, hydraulic transport, marine applications, etc. Thus, it results clear that a reduction of the drag could have environmental and economical implications that can be materialized in energy and money savings.

Several techniques have been pursued for several decades to reduce the drag. However, the physical mechanism of this phenomenon is still not well understood. Significant results of drag reduction by addition of polymers have been reported by several authors. For instance a maximum 39 % of reduction was reported in a turbulent water channel (Wei and Willmarth, 1992), Warholic et al. (1999, 2001) reported values of rag reduction from 10 % to 69 % of drag reduction in a fully developed rectangular channel flow, Min et al. (2003) reported a direct numerical simulation and a maximum drag reduction of 44 %.

Riblets with several geometries have been tested in several experiments and in practical applications. Bechert et al. (1997) carried out several experiments in a oil channel with different riblet configuirations; they found about 5% drag reduction with semicircular and triangular groves and 8.7% drag reduction with and adjustable surface with closed longitudinal blade ribs and slits. Koeltzch et al. (2002) carried out some experiments over convergent and divergent riblets patterns and a drag reduction up to 10% was reported.

In the case of drag reduction by injection of microbubbles several studies have been performed. McCormick and Bhattacharyya (1973) reported one of the first experimental results in drag reduction by injection of microbubbles; they ran the experiments in an totally submersed axisymmetric body, an electrical current was driven through a wire that was wrapped to the body in order to produce the microubbbles beneath the boundary layer and a maximum total drag reduction of approximately 30 % was measured. Madavan et al. (1984) carried out some experiments that on zero pressure gradient turbulent boundary layer; they produced the microbubbles by injecting air through a porous media plate and the maximum drag reduction was greater than 80 %. Madavan et al. (1985) reported a basic numerical investigation where the viscosity and density vary locally; it showed that a reduction of the drag as much as 50 % can be realized. Deutsch and Castano (1986) performed some experiments in axisymetric body; they generated the microbubbles by injection of gas through a porous media and the maximum drag reduction was close to 80 %.

2. EXPERIMENTAL METHOD and PROCEDURES

2.1 Test facility

Experiments were conducted in a turbulent water channel, which is depicted in figure 1. The water was run at a low Reynolds Number, $Re = U_bH/\nu = 5128$ (considering half height of channel and the bulk velocity). The channel, built of cast acrylic due to the optical properties of this material, has a total length of 4.83 m, a width of 0.205 m and a height of 0.056 m. The measurement station is located at 3.15 m downstream the inlet of the channel. The microbubbles were produced by electrolysis 10 cm upstream the test station; two 76 μm platinum wires were used as electrodes. The water was pumped form the bottom tank to the upper tank, which is designed to have a constant pressure head that allows having a constant rate flow in the channel. Running the water through the channel by gravity avoid the flow oscillations that the pumps could produce if the were connected directly to the channel.The water flow was seeded with polystyrene neutrally buoyant particles with a diameter that goes from 6 to 9 μm and a density of 1.050 g/cm^3. When these particles are illuminated by a laser sheet they can reflect enough light to be detected by a CCD (Charge Couple Device) camera.

2.2 Experimental Techniques

Most of the flow information acquired in the vicinity of the wall has to be analyzed to clarify the drag reduction phenomenon. In this experiment, Particle Image Velocimetry (PIV) measurement technique was used to obtain x-y plane velocity fields close to the upper wall of the channel, two hundred images were recorded by a CCD camera (Kodak Megaplus ES 1.0/1.0) with a resolution of 1008 x 1018 pixels. The commercial frame rate of the CCD camera was increased from 30 to 60 frames per second by doing a precise synchronization between the laser light pulse and the double exposure capability of the CCD camera; this task was performed with an accurate pulse generator (Stanford Research System Inc. Model DG 535) which has four digital delay/pulse with an accuracy of picoseconds. The synchronization diagram is depicted in figure 2. Moreover, a dual oscillator Nd:YAG laser with a power of 300-350 mJ/pulse and a wavelength of 532 nm (green light) was used to illuminated the seeded flow. The laser beam was transformed into a sheet of light with a thickness of 1mm by an array of cylindrical lenses. Finally, one hundred velocity fields in an order grid of 50 x 50 and an area of 1.28 cm^2 are obtained.

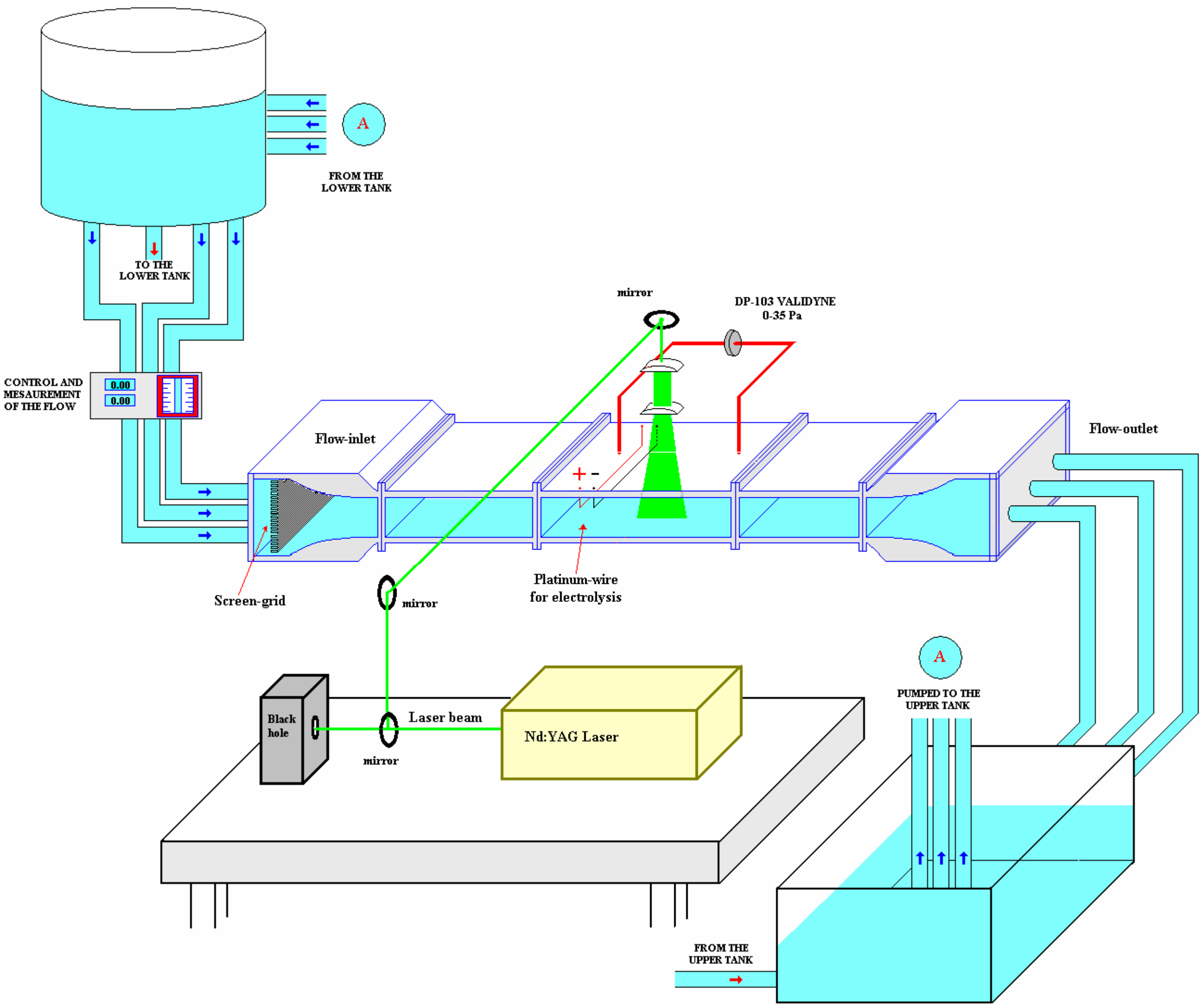

Fig. 1. Schematic diagram of the experimental set up

2.3 Procedure

Evaluation of spectra has been performed in several studies of drag reduction. However, most of the spectra measurements come from on-point measurement techniques such as hot wire velocimetry, which allow the evaluation of the spectra in the frequency domain. Moreover, a transformation of the spectra from the frequency domain to the wavenumber domain has to be performed by assuming Taylor's frozen hypothesis, which can be expressed as

$$E(k_1) = U_c E(f) \tag{1}$$

$$k_1 = f / U_c \tag{2}$$

where f is the frequency, k_1 is the wavenumber in the streamwise direction and U_c is the local convection velocity, which can be considered as the local mean velocity at that point in the flow.

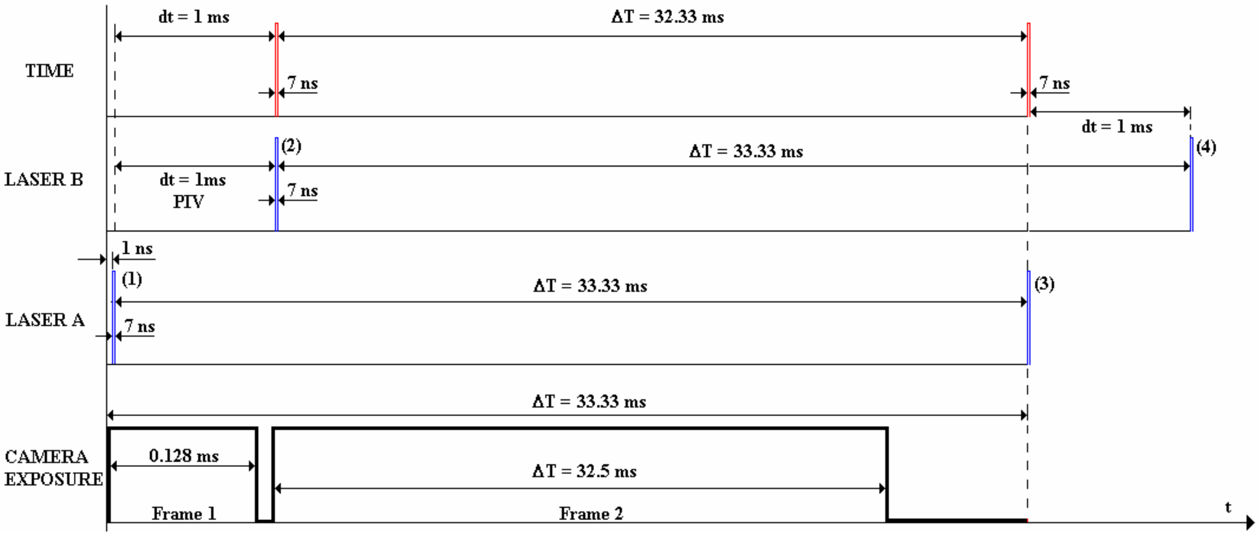

Fig. 2. Synchronization diagram

PIV is non intrusive measurement technique that offers both temporal and spatial instantaneous information. In this study the evaluation of the spectra in the streamwise wavenumber is summarized as follow.

1. Evaluate two-point correlation (spatial correlation) using equation (3) where “s” is a spatial increment

$$R_{uu}(s) = u(x)u(x+s) \tag{3}$$

2. Apply twice the Fourier transform to the two-point correlation

$$E_{uu}(k_1) = 2\int_{-\infty}^{\infty} R_{uu}(s)e^{-i2\pi k_1 s}ds = 4\int_{0}^{\infty} R_{uu}(s)e^{-i2\pi k_1 s}ds \tag{4}$$

3. Ensemble average the spectra results obtained from the one hundred velocity fields at each y/H

The physical length in the streamwise direction (L_x) of the PIV measurement area is directly related to the minimum dimensionless wavenumber that can be resolved as $(k_1H)_{min} = H/L_x = 2.3$, and the maximum dimensionless wavenumber is related to the size of the grid as $(k_1H)_{max} = H/(2L_x/N) = 58$. Then, the spectra evaluation presented above allows obtaining only information about wavenumber $2.3 \le k_1H \le 58$. However, from the temporal information is possible to calculate the spectra for dimensionless wavenumbers lower than 2.3. Both results should overlap at $k_1H = 2.3$ for this experiment.

1. Evaluate the temporal correlation (autocorrelation) using equation (5) where t’ is a time increment

$$R_{uu}(t') = u(t)u(t+t') \tag{5}$$

2. Apply twice the Fourier transform to the autocorrelation

$$E_{uu}(f) = 2\int_{-\infty}^{\infty} R_{uu}(t')e^{-i2\pi ft'}dt' = 4\int_{0}^{\infty} R_{uu}(t')e^{-i2\pi ft'}dt' \qquad (6)$$

3. Calculate $k_1 = f/U_c$ ($k_1[L^{-1}]$, f $[T^{-1}]$, $U_c[L/T]$)
4. Ensemble average of the frequency spectra results obtained for the 50 points at each y/H
5. Evaluate $E_{uu}(k_1) = U_c E_{uu}(f)$

3. RESULTS AND DISCUSSION

The advantage of using both the temporal and spatial information of PIV allows increasing the wavenumber range that can be studied. The spectra were not made dimensionless in order to observe clearly what happen with the values of the energy at each wavenumber. Figure 3 illustrates the spectra of the streamwise velocity fluctuation ($E_{uu}(k_1)$) in the streamwsie wavenumber (k_1) for a single phase flow and for a maximum drag reduction of 38.4 %, which corresponds to a local void fraction of 4.8 %. The value of the distance from the wall in wall units, $y^+ = yu_\tau/\nu = 12$ was calculated using the friction velocity (u_τ) of single phase flow; this value correspond physically to a position y/H = 0.037. It is clearly observed in figure 3 that there is a redistribution of energy in the u-velocity fluctuations from high wavenumbers to low wavenumbers. Moreover, it is also shown that the energy contained in two phase flow is lower than the energy contained in single phase flow over the entire wavenumber range. A good agreement is also found in the overlapping region of the spectra ($k_1H = 2.3$) obtained from the spatial information and the one obtained from the spatial information. Figure 4 shows there is a shift of energy from low to high wavenumbers in the spectra at $y^+ = 39$ (single phase) or y/H = 0.121. Moreover, the energy contained in the spectra for single phase flow is lower than the one with a maximum drag reduction of 38.4%. Microbubbles seem to have a different effect in the viscous region (close to the wall) than in the outer region.

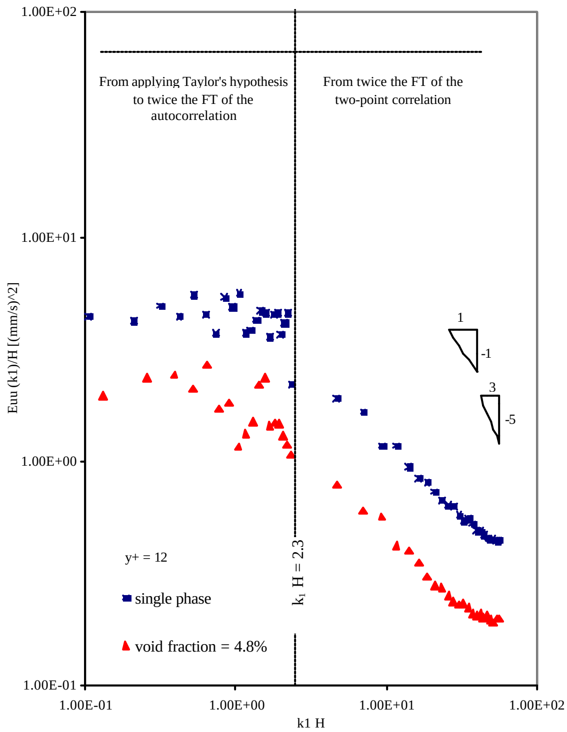

Fig. 3 dimensional spectra of the streamwise fluctuating velocity at y/H = 0.037

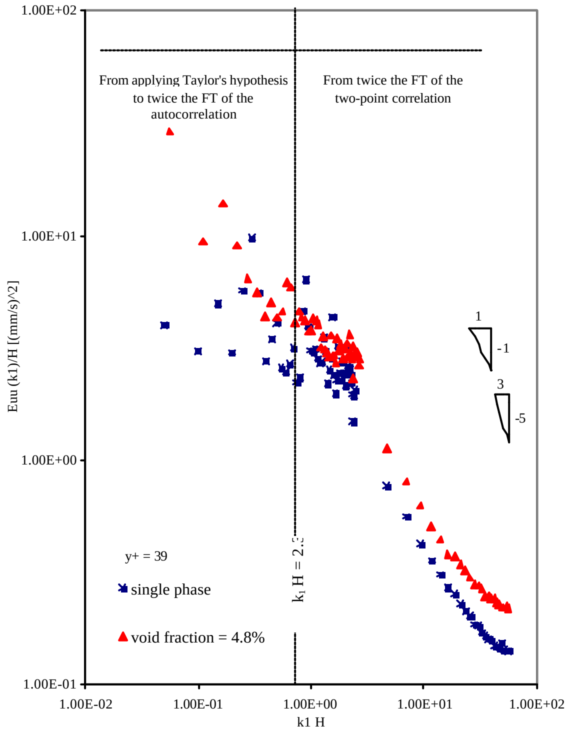

Fig.4 dimensional spectra of the streamwise fluctuating velocity at y/H = 0.121

4. SUMMARY

The conclusions that can be drawn from the evaluation of spectra ($E_{uu}(k_1)$) for single phase and for a drag reduction of 38.4 % (void fraction = 4.8 %) in the streamwise wavenumber are that injection of microbubbles in the boundary layer redistributes the energy from high to low wavenumbers in the buffer layer. However, the effect of the microbubbles in the outer region presents the opposite trend. It is likely that microbubbles interact differently in the region highly affected by the viscous forces (close to the wall) and a region poorly influenced by the viscosity of the fluid (outer region).

The approach of using both the spatial and temporal information of the velocity fields obtained from PIV to evaluate different regions of the spectra in the wavenumber domain have good agreement in the overlapping region of both results. This idea extends the capability of our PIV system.

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