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On the Dynamics of Turbulent Kinetic Energy in Bubble Columns

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The experimental evaluation of a cylindrical bubble column was performed in order to provide information on the influence of the passage of bubbles on the liquid movement. The kinetic energy fields were analyzed after the energy source of the flow had been removed, in order to visualize the Kolmogorov's energy cascade. The PIV technique was employed to acquire data on the turbulent kinetic energy of the liquid in different flow regimes (homogeneous, transition and heterogeneous). The results showed that the oscillation movement of the residual plume affects the kinetic energy dissipation during the cascade of energy from the largest to the smallest scales, which occurs faster in the heterogeneous flow regime.

1. Introduction

Multiphase flows are present in several industrial applications especially in oil and gas refining industries, as well as emergent technologies, and therefore it is important to understand their behavior. For gas/liquid multiphase flow specifically, turbulent structures present in the liquid phase and how they interact with the dispersed phase are considered among the most important issues to be addressed. These structures and their interactions alter the flow features, the volumetric fraction distribution and even the mechanisms of heat and mass transfer (Sathe et al., 2013; Hosokawa and Tomiyama, 2013; Soares et. al. 2013, Shi et al., 2019, Taborda et al., 2022).

Bubble columns are often employed in gas/liquid turbulent flows, due to their high transfer rates, lack of moving parts and simple operation. However, their dynamics is not fully understood due to their complex phase interaction. Turbulence is an important parameter in bubbly flows, being directly related to the transfer rates, mixing and, depending on the application, chemical reaction. Studies on turbulent bubbly flows have been widely reported in the literature (Liu and Bankoff, 1993; Mudde et al., 1997; Sheng et al., 2000; van den Berg et al., 2006; Fujiwara et al., 2004; Noriler et al, 2009; Sathe et al., 2013; Hoque et al., 2015, Mattiazzo et al., 2020). However, there are still many open questions concerning how bubbles affect the turbulence production, dissipation and distribution. It is well known that they induce fluctuations, which increases the global turbulence (Chahed et al., 2003), affecting the intensity and structure of turbulent motions, which feeds back to the dispersed phase flow characteristics such as the distribution, coalescence and breakup rates (Rzehak and Krepper, 2013).

Turbulence in a single-phase flow is characterized by fluctuations in the velocity and pressure due to the passage of vortices of different length scales. In bubble columns, turbulence is induced by the bubbles, which in small scale is generated from bubble wakes and fluctuating velocities and in large scale is due to the non-uniform gas holdup distribution and geometrical parameters such as sparger design and cross-sectional area (Sathe et al., 2013, Gong et al., 2022). In turbulent flows, vortices are produced in different length scales. The large vortices remove energy from the main flow and transfer it to the small vortices, which in turn transfer energy to even smaller vortices and so on, until their reduction to molecular movement. This continuous energy transfer process is known as the Kolmogorov's energy cascade. In bubbly flows the large-scale structures are promoted by bubble wakes, and when the bubbles detach, they interact with other bubbles and annul the vorticity.

In fact, turbulent flows are always dissipative, so they need a continuous energy feed to supply the viscous losses. Thus, if there is no energy source to support the flow, turbulence will quickly decay. In this context, this paper reports an experimental study where a laboratory bubble column was used to evaluate the dynamics of the turbulent kinetic energy when the energy source supplying the flow is removed, that is, the superficial gas velocity is zero. The information gained, in relation to Kolmogorov`s energy cascade due to the effect of the passage of bubbles on the liquid movement, provides a valuable source of experimental knowledge on the multiphase flow in bubble columns.

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2. Experimental Set Up

The laboratory bubble column used in this study is composed of acrylic, with an inner diameter of 144.2 mm and height of 870 mm. A stainless-steel mesh is used as the gas disperser, with 130 µm holes and 20% porosity, providing a total area of 24.75 cm². To avoid diffraction effects during the experiments, a square box with plane walls, filled with distilled water, was placed in the measurement region of the column, to avoid image distortion during the optical measurements.

To account for velocity fluctuations and turbulence intensities, the particle image velocimetry (PIV) technique was employed in this study. This is a non-intrusive optical measurement technique, which determines the flow velocity based on a tracer particle. Laser pulses illuminate these tracer particles. Their movement in the periods between the pulses is recorded as a pair of two single-exposure images. Thus, each pair is analyzed individually across the whole measurement interrogation window, scaled by the image magnification and then divided by the known pulse interval to obtain the flow velocity at each point of the velocity component (Raffel et al., 1998). A scheme of the experimental facility of the bubble column coupled with the PIV system is presented in Figure 1.

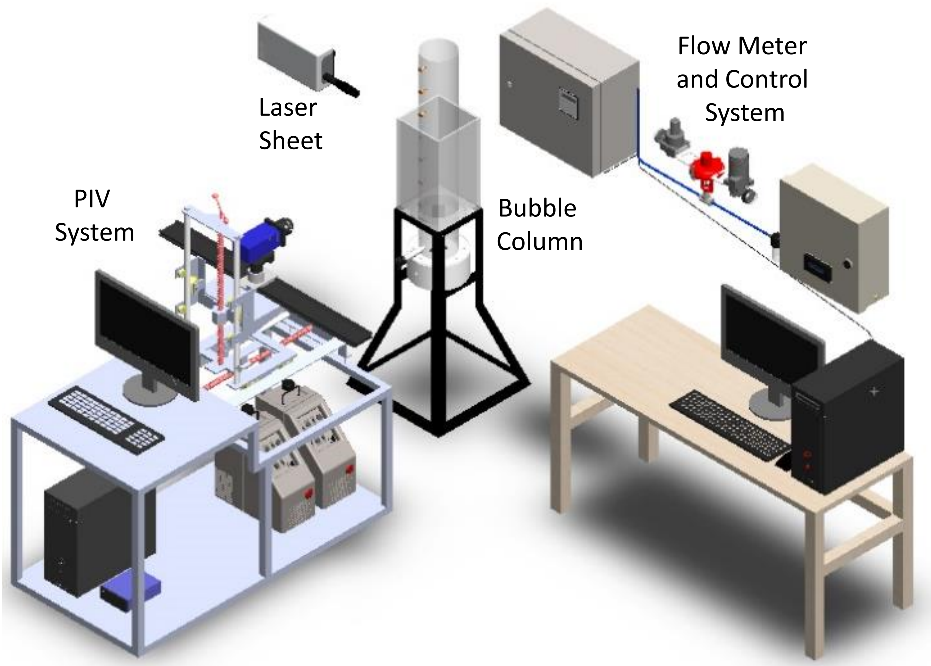


Figure 1: Experimental facility showing bubble column coupled with PIV system.

To illuminate the tracer particles, as required in the PIV technique, a Quantel Big Sky pulsed Nd:YAG laser (model Ultra PIV 50), with two cavities, was used. Each cavity generates a 50 ml pulse with a wavelength of 532 nm. The images were captured with a CCD camera (ImagerProPlus/ProX2M) with a resolution of 1600x1200 and pixel size of 10x10 µm and a LaVision Imager Intense cross-correlation model. This camera was fitted with a Nikon objective lens (model NIKKOR f/2.8D), with a focal distance of 60 mm, and a LaVision internal synchronizer (PTU-9) with a resolution time of 10 ns. This is responsible for synchronizing the emission of the cavity light from the laser and the initiation of the image capture by the CCD camera. A VZ07-01332 filter was coupled with the objective lens to allow the CCD sensor to capture only the tracer wavelength. In addition, LaVision software DaVis 8.1 was used to perform the data acquisition and image processing.

The tracer particle used was a modified carboxy-acrylate with a diameter of 15 µm, specific mass of 1100 kg/m3, maximum Stokes number of 2x10-5, refraction index of 1.56 and fluorescence due to the presence of tetraethyl rodamine C28H31N2O3CL, known as rodamine B. Firstly, the PIV system was calibrated, which involves associating the captured image with a real-scale object. Thus, a ruler was placed in the column and the CCD camera captured an image to establish the image/object scale using the DAVIS 8.1 software.

In all cases studied, the gas-liquid system was composed of air and distilled water at room temperature and pressure, and the liquid height was 560 mm from the column bottom.

Measurements were taken at a height of 500 mm from the column bottom for superficial gas velocities of 0.5, 2.0 and 3.5 cm/s, characterizing the homogeneous, transition and heterogeneous regimes, respectively. The experimental parameters and operational conditions are shown in Table 1.

Physical experiments were carried out to investigate the kinetic energy and velocity fluctuations. After flow stabilization, the gas flow was interrupted. PIV data acquisition started after 10 s, when the bubbles stopped rising up in the bubble column. Thus, only the residual movement left by the passage of bubbles was captured.

Table 1: Operational conditions and PIV parameters of the test cases.

Flow Rate (L/min)	Superficial Gas Velocity (cm/s)	Δt (µs)	Laser A Intensity (%)	Laser B Intensity (%)
5.0	0.5	6,000	31	29
20.0	2.0	6,000	33	31
35.0	3.5	6,000	33	31

3. Results and Discussions

In this study, the axial liquid velocity and its fluctuations were determined using the PIV technique in order to evaluate the turbulent kinetic energy, when the energy source is cut off. The cases studied relate to homogeneous, transition or heterogeneous flow regimes, as in previously reported test cases (Soccol et al., 2015).

Based on the Kolmogorov's energy cascade, the larger vortices remove energy from the main flow and transfer it to the smaller vortices until molecular movement is reached. Therefore, it is well known that turbulent flows are always dissipative, and they need a continuous energy source to supply the viscous losses. Thus, if the energy source is removed, turbulence will quickly decay (Tennekes and Lumley, 1972).

In order to evaluate the influence of the movement induced by the bubbles on the liquid behavior, the gas injection was interrupted and only the residual movement due to the passage of the bubbles remained during the measurements. In all cases, the superficial gas velocity was set to a predetermined value, the flow was stabilized, the superficial gas velocity was dropped to zero, and after approximately 10 s PIV measurements were taken.

Figures 2 and 3 show maps of the turbulent kinetic energy, for a superficial gas velocity of 0.5cm/s, typically providing a homogeneous regime, in the first 36 s and up to 66 s, respectively, after interrupting the gas injection.

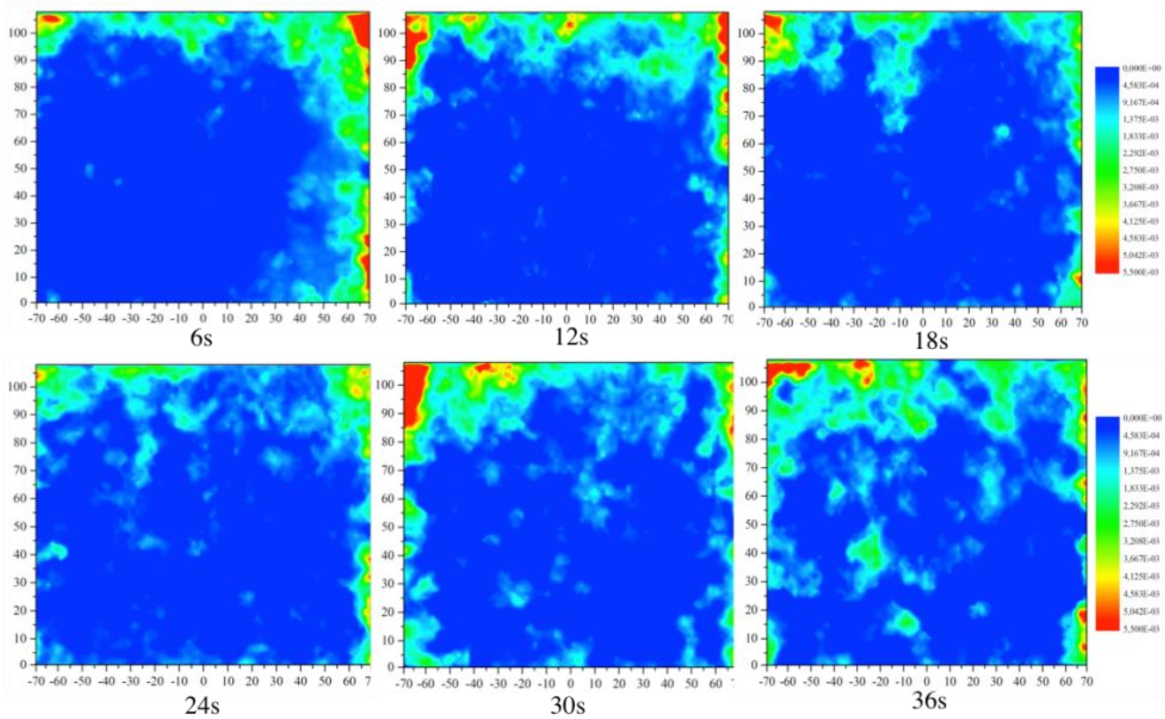


Figure 2: Fields of turbulent kinetic energy for homogeneous regime (up to 36 s for a superficial gas velocity of 0.5 cm/s).

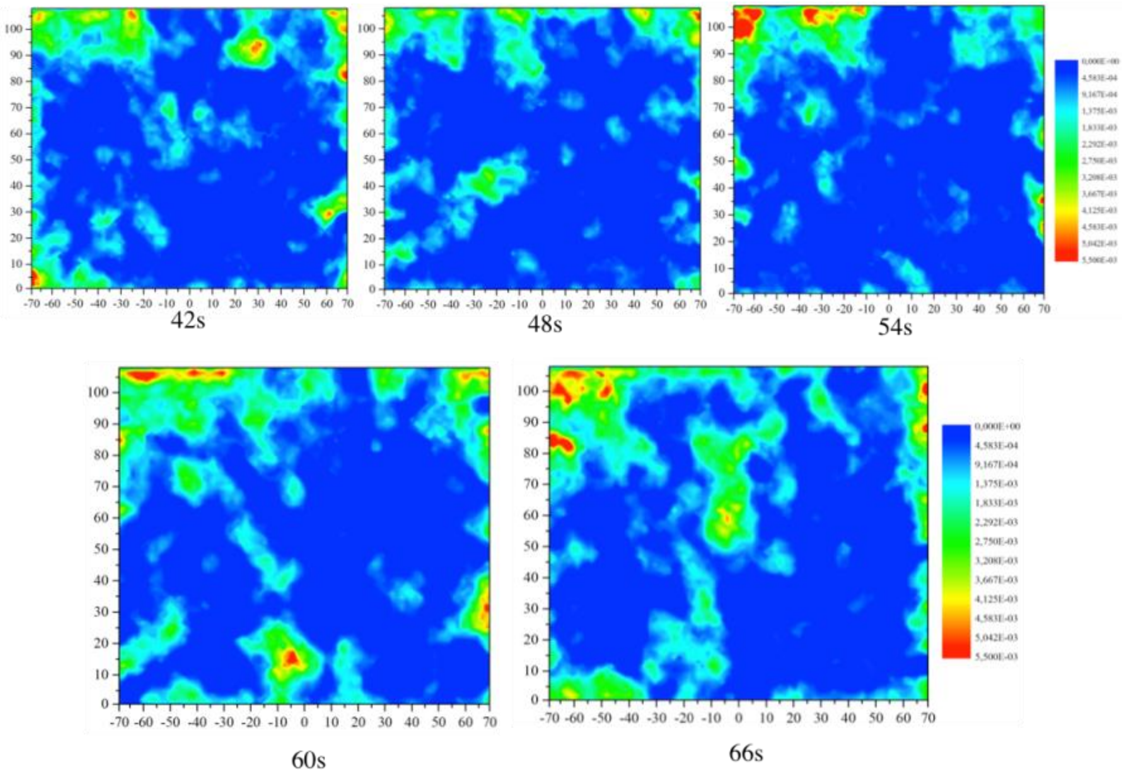


Figure 3: Fields of turbulent kinetic energy for homogeneous regime (from 42 to 66 s for a superficial gas velocity of 0.5 cm/s).

Figures 2 and 3 show that the turbulent kinetic energy is concentrated near one side of the column in the first 6 s. It then starts to be distributed along the column. During the first 6 s fluctuations are more intense close to the column wall. Also, the flow tends to migrate toward the wall, indicating a plume oscillation movement. According to Soccol et al., 2015, the plume oscillation period (POP) lasts approximately 10-11 s close to the wall and around 5 s in the center of the column. This tendency can be seen in Figure 2 where, as seen in the first image, after 12 s the residual movement tends toward the column center, where its distribution is faster.

After 66 seconds, the fluctuations were more accentuated in the center of the column, indicating higher kinetic energy. For a superficial gas velocity of 0.5 cm/s, residual movement is observed in all measurement windows, where the energy is distributed throughout the window. It is known that the turbulent kinetic energy distribution can be divided into production, diffusion and dissipation process; however, after the energy source ceases, it is only redistributed and lost due to the viscous forces.

Figure 4 shows color maps of the turbulent kinetic energy during the first 36 s after interrupting a superficial gas velocity of 2.0 cm/s. At this flow rate, the operational regime changes to transition, in which bigger bubbles concentrate in the center of the column, generating greater fluctuations in this area. However, with the progression of time the higher values for the turbulent kinetic energy become concentrated near the column wall, which may be due to the plume oscillation, which makes the residual movement migrates toward the wall (Figure 4 – 24s). After 30 s, there is not much of energy left. After 36s, the maximum value is located at the right wall, which could reflect the influence of the foam formed with the bed expansion due to the gas injection. During the last 30 s the behavior of the turbulent kinetic energy did not change significantly and remained practically constant throughout the column.

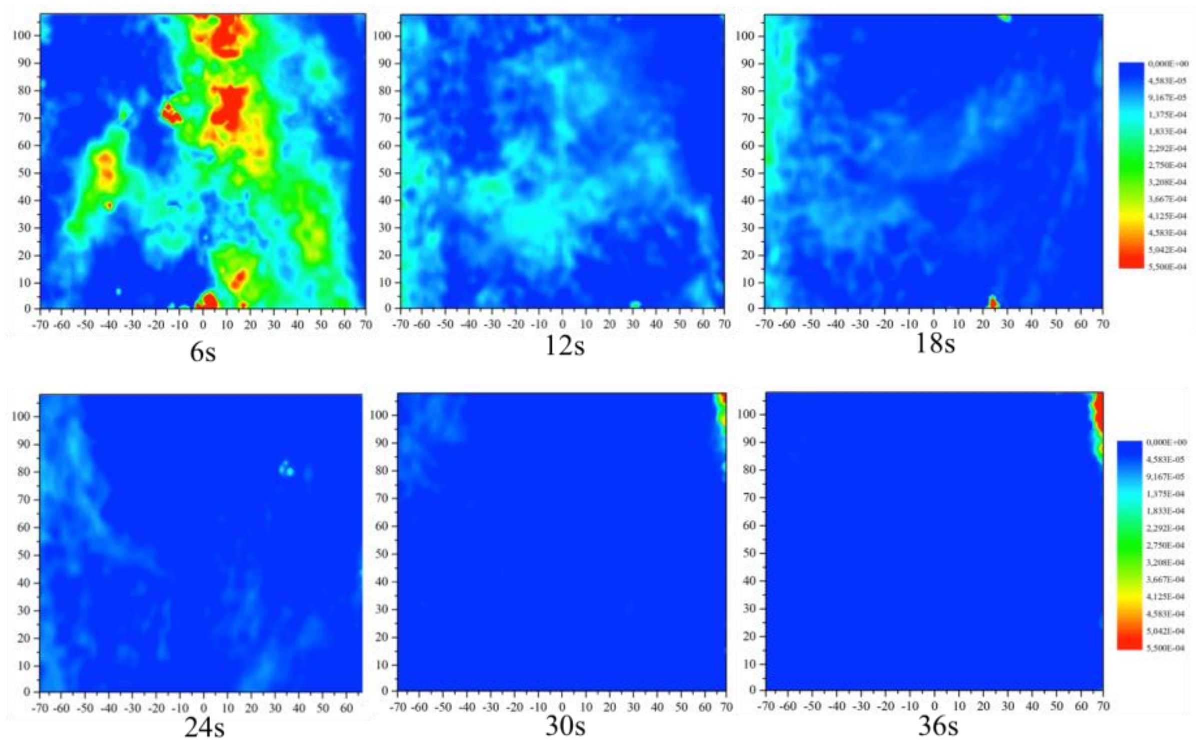


Figure 4: Fields of turbulent kinetic energy for transition regime (up to 36 s for a superficial gas velocity of 2.0 cm/s).

With regard to the dissipation of the turbulent kinetic energy in the heterogeneous regime, the concentration of bubbles is greater, and bubble breakup and coalescence play an important role in the flow dynamics. Figure 5 shows the maps of the turbulent kinetic energy for a superficial gas velocity of 3.5 cm/s.

The same tendency observed in the transition regime is found in the heterogeneous regime, that is, after 30 s the residual movement did not significantly affect the turbulent kinetic energy distribution along the column domain.

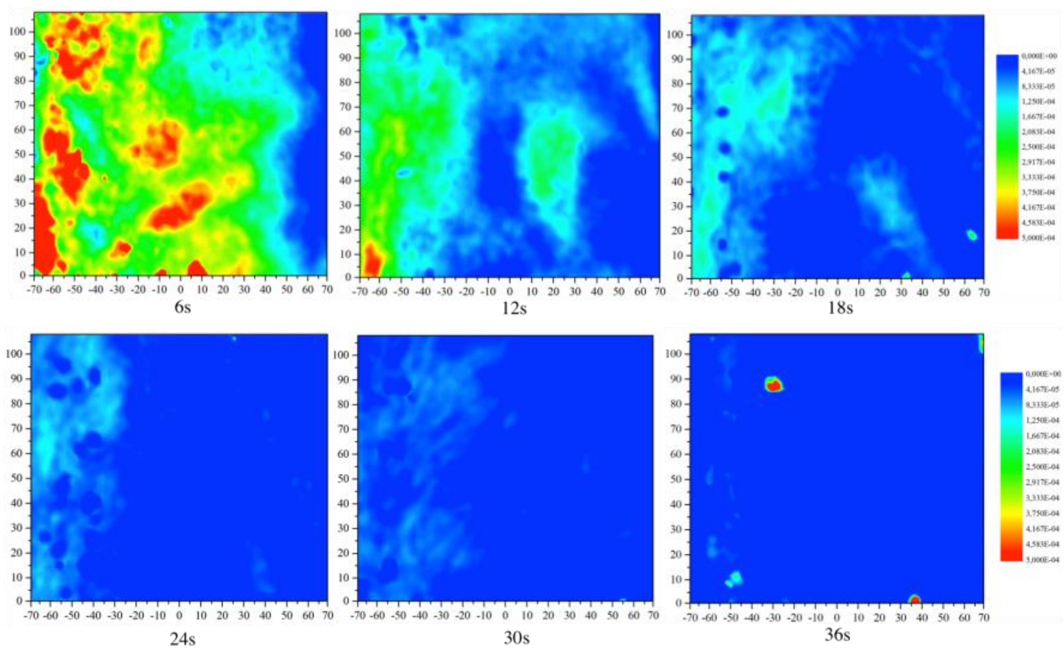
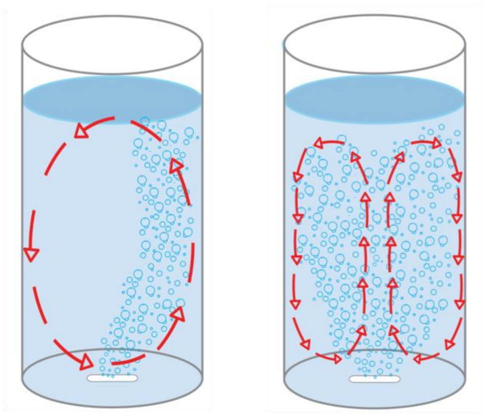


Figure 5: Fields of turbulent kinetic energy for the heterogeneous regime (up to 36 s for a superficial gas velocity of 3.5 cm/s).

According to Sathe *et al.*, 2013, large-scale structures are dependent on the non-uniform gas holdup distribution and the sparger configuration.

Therefore, at lower superficial gas velocities, the large-scale formation of “snake type” structures oscillates with the continuous fluid movement, with recirculation to one side of the column or to the other, as shown in Figure 6 (a). When the energy source, which supplies this structure, is interrupted, the turbulent kinetic energy dissipation is slower with little influence of the micro-scale on the meso-scale.

Specifically, for the lowest superficial gas velocity of 0.5cm/s, even after the energy source had ceased, the plume oscillation movement probably feeds back kinetic energy, retarding its balance with diffusion and dissipation and delaying the loss due to viscous forces.



(a) (b)

Figure 6: Plume movement: (a) homogeneous regime and (b) heterogeneous regime.

On the other hand, for the heterogeneous flow regime, the frequency of the large-scale “snake-type” formation increased, producing recirculation on both sides of the column (Figure 6 (b)). This promotes an acceleration of the energy dissipation as a result of the effect of the micro-scale on the meso-scale. The greater concentration of bubbles reduces the energy production and increases the dissipation rate (Lelouvetel et al., 2011), which could explain the faster reduction in the kinetic energy for superficial gas velocities of 2.0cm/s and 3.5cm/s.

4. Conclusions

In this study, the experimental analysis of a laboratory bubble column operating in different flow regimes was carried out to evaluate the behavior of the turbulent kinetic energy when the gas flow source is ceased, in order to provide information on how the passage of bubbles affects the liquid movement. All of the measurements were taken at 50 cm from the column bottom using a PIV system under very controlled conditions in the homogeneous, transition and heterogeneous regimes.

According to the results obtained, when transition and heterogeneous regimes are establish, the energy dissipation occurs faster than in the homogeneous regime. In the latter, the turbulent kinetic energy is concentrated at the column wall, while in the former two regimes the energy peak occurs in the center. This can be attributed to the plume oscillation movement. For the lowest superficial gas velocity, this oscillation makes the liquid flow alternately. When the gas flow is stopped, energy dissipation is slower probably due to the oscillation movement, which feeds back kinetic energy contributing to its production, and the energy balance takes longer to dissipate into viscous forces.

However, in both the transition and heterogeneous regimes, a faster dissipation is reached indicating an increasing plume oscillation frequency. At both sides of the column recirculation is observed, which accelerates the energy dissipation as a result of the influence of the micro-scale. For this flow regime the plume movement is not observed, so there is no contribution to the kinetic energy production, and only diffusion and dissipation occur.

It is well known that part of the liquid turbulence in a bubbly flow is generated by the passage of the bubbles; however, the non-uniform gas holdup distribution plays an important role in the dynamics of the turbulent kinetic energy. Depending on the plume oscillation period, the energy dissipation can be considerably increased.

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