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Effect of bubble on the pressure spectra of oscillating grid turbulent flow at low Taylor-Reynolds number

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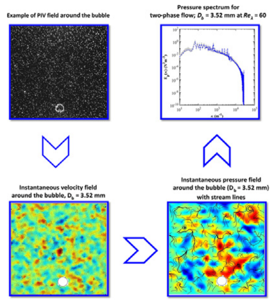
HIGHLIGHTS

- Pressure field estimated from N-S equation using PIV velocity data.
- Pressure spectrum determined with and without bubble for Re_λ = 12 to 60.
- With bubble, pressure spectra exhibited a slope less steep than −7/3.
- With bubble, length scale ratios L_p/L and λ_p/λ deviated from single phase DNS data.
- ε (m^2/s^3) from pressure spectrum deviated by ∼32% max compared to velocity spectrum.

GRAPHICAL ABSTRACT



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ABSTRACT

For many engineering applications, measurements of velocity and pressure distributions in the system are of fundamental importance to provide insights into the flow characteristics. In the present study, the experiments were carried out in an oscillating grid system in absence and presence of two different bubble diameters (D_b = 2.70 and 3.52 mm) rise using the non-intrusive two-dimensional (2D) particle image velocimetry (PIV) at the low Taylor-Reynolds number (Re_λ) ranging from 12 to 60. Using the measured PIV velocity data, the instantaneous pressure fluctuations were estimated by integrating the full viscous form of the Navier-Stokes (N-S) equation. The obtained pressure field was compared with three dimensional (3D) computational fluid dynamics (CFD) simulation which was found to be in good agreement. The pressure spectra of single and two phase flow cases were evaluated by taking Fast Fourier transformation (FFT) of the computed pressure fluctuations. A spectral slope of −7/3 was found in the inertial subrange of the single-phase pressure spectrum. In contrast, the two-phase pressure spectrum exhibited a slope less steep than −7/3 in the inertial subrange because of the extra production of turbulence in the presence of bubble. For single-phase flow, the ratio of pressure integral length scale to the velocity integral length scale (L_p/L) was found to be ∼0.67, and the pressure Taylor microscale (λ_p) was approximately 0.79 ± 0.03 of the velocity Taylor microscale (λ) within the Taylor-Reynolds number range studied. The scaling ratios based on the single-phase experimental results were compared with existing theory and DNS results and found to accord well; however, these ratios deviate from the theoretical values for two-phase flow. Also, the energy dissipation rate was evaluated based on the pressure spectrum and found to be over-predicted (∼32%) compared those calculated from the velocity spectrum.

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Nomenclature

C	Kolmogorov's constant (–)
$C_P(r)$	spatial autocorrelation function for pressure fluctuation (–)
D_b	diameter of bubble (mm)
$E_p(\kappa)$	pressure energy spectrum (N^2/m^3)
$E_v(\kappa)$	velocity spectrum (m^3/s^2)
f_g	oscillating grid frequency (Hz)
L	velocity integral length scale (m)
L_p	pressure integral length scale (m)
M	grid mesh size (mm)
p	pressure components (Pa)
P_{mean}	mean pressure (Pa)
r	difference in the two locations for calculation of structure function (m)
Re_M	grid Reynolds number (–)
Re_λ	Taylor Reynolds number (–)
S_L	Stroke length (mm)
t	time (s)
U	mean velocity (m/s)
u	instantaneous velocity components in x-direction (m/s)
V_g	grid velocity (m/s)
v	instantaneous velocity components in y-direction (m/s)
u_{rms}	root mean square velocity in x-direction (m/s)

Greek symbols

μ	dynamic viscosity (kg/m·s)
μ_1	marker function (–)
ε	energy dissipation rate (m^2/s^3)
κ	resultant wavenumber (m^{-1})
ν	kinematic viscosity (m^2/s)
λ	Taylor microscale (m)
λ_p	pressure Taylor microscale (m)
ρ	fluid density (kg/m^3)

Abbreviations

1D	one dimensional
2D	two dimensional
3D	three dimensional
CFD	computational fluid dynamics
DNS	direct numerical simulation
FFT	fast Fourier transform
OGT	oscillating grid turbulence
PIV	particle image velocimetry

1. Introduction

In recent years, considerable interest has emerged in the study of pressure spectra related to turbulence research. Understanding the behaviour of pressure spectra and related statistics in turbulent flow can enlighten many fields of fundamental research interest such as gas-fluid or fluid-solid interactions including drag and lift forces, flow separation, eddy shedding, etc., which are affected by the variation of velocity and pressure. Also, in a turbulent flow field, pressure fluctuations lead to the production of sound and cavitation which are of significant practical interests (Pumir, 1994). Many researchers have experimentally and numerically studied the statistics of pressure (Dong et al., 2001; Donzis et al., 2012; Pearson and Antonia, 2001; Tsuji and Ishihara, 2003), however, studies on pressure spectrum in the literature are scarce due to the difficulty involved in measuring pressure in the laboratory experiments. Conventional pressure measurement relies on the use of probes which due to their significant physical presence distort the flow field and affects the reliability of the results. The practical limitation involved in the manufacturing of miniature probe comparable to the size of small length scales of the flow field often obscures relevant information.

The limitation resulting from inaccuracy of estimating the pressure in an intrusive manner is often circumvented by determining pressure from the measured particle image velocimetry (PIV) velocity information. There are now several studies considering the evaluation of the pressure field from the application of the Navier-Stokes (N-S) equations to the measured velocity field by PIV (Baur and Köngeter, 1999; Unal et al., 1997). The pressure distribution can be obtained directly from the momentum equation by performing the spatial integration over the flow domain along different paths depending on the reference particle location. However, the obtained pressure may be different if the integration is achieved along the different paths. A proper integration path is needed to minimise the errors of integration and decrease the effect of uncertainties related with velocity measurement (Fujisawa et al., 2004). The other method involves the use of Poisson equation which can be utilised to predict the pressure field (Fujisawa et al., 2004; Gurka et al., 1999; Hosokawa et al., 2003) by taking the gradient of Navier-Stokes equation where the source term yields two parts of the noticeably distinctive character. The so-called ***rapid*** part represents the direct interaction between the gradient of turbulent velocity fluctuation and the gradient of the mean velocity while the ***slow*** part represents the turbulence-turbulence interaction (Tsuji et al., 2007). It is noted that Neumann type boundary condition is needed for the pressure fluctuations, which complicates the application of this method (Jaw et al., 2009).

From the aforesaid studies (Baur and Köngeter, 1999; Fujisawa et al., 2004; Gurka et al., 1999; Hosokawa et al., 2003; Jaw et al., 2009; Tsuji et al., 2007; Unal et al., 1997), it is apparent that the pressure field is attainable from PIV velocity data from the direct solution of the Navier-Stokes equation. These studies however did not emphasise on the accurate estimation of the material derivative term which is a critical requirement for the appropriate estimations of pressure field. There are few studies (Chang et al., 1999; Jakobsen et al., 1997; Jensen and Pedersen, 2004; Jensen et al., 2001; Liu and Katz, 2006) available in the literature where the material derivative term has been shown to be estimated robustly. Chang et al. (1999) employed a single-camera system with double exposure in the first image and single exposure in the second image to calculate this acceleration term. Liu and Katz (2006) estimated the material acceleration term and derived the pressure field with high precision using a four-exposure PIV system invloving two cameras. Nonetheless, these multi-exposure PIV systems involves cumbersome calibration procedure requiring cross-correlation to precisely orient the two cameras to the same field of view (FoV). Liu and Katz (2006) reported that a bias error in velocity estimate in the order of 0.1 would lead to significant errors in the pressure field. Recently, Dabiri et al. (2014) presented an appropriate method for pressure field estimation from the PIV velocity data using median polling of several integration paths. Their technique is relatively simple yet effective in estimating the pressure gradient term with higher accuracy. Such research endeavours in recent time have opened up the possibility