

# Buoyancy Profile Inhibition of Turbulence in Nearly Vertical Bubbly Shear Flow

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## Abstract

We report measurements of two-dimensional ( $B/D=5$ ) fully turbulent and developed duct flows (overall length/depth,  $L/D=60$ ;  $D$ -based Reynolds number  $Re>104$ ) for inclinations to 30 degrees from vertical at low voidages ( $<5\%$  sectional average) representative of disperse regime using tap water bubbles (4-6 mm) and smaller bubbles (2 mm) stabilised in ionic solution. Pitot and static probe instrumentation, primitive but validated, provided adequate (10% local value) discrimination of main aspects of the mean velocity and voidage profiles at representative streamwise station i.e  $L/D =40$ . Our results can be divided into three categories of behaviour. For vertical flow (0 degrees) the evidence is inconclusive as to whether bubbles are preferentially trapped within the wall-layer as found in some, may be most, earlier experimental work. Thus the 4 mm bubbles showed indication of voidage retention but the 2 mm bubbles did not. For nearly vertical flow (5 degrees) there was pronounced profiling of voidage especially with 4 mm bubbles but the transverse transport was not suppressed sufficiently to induce any obvious layering. In this context, we also refer to similarities with previous work on one-phase vertical and nearly vertical mixed convection flows displaying buoyancy inhibited mean shear turbulence. However, with inclined flow (10+ degrees) a distinctively layered pattern was invariably manifested in which voidage confinement increased with increasing inclination. In this paper we address flow behaviour at near vertical conditions.

## Introduction

The flow regime observed in inclined bubbly flows ( $\geq 10$  degrees from vertical), we call "segregated-disperse" [11], is characterized by two-layer flow (schematically shown in figure 1) in which bubbles are buoyantly confined to the upper layer but dispersed within it, not only due to the mean shear turbulence but also due to the turbulence associated with bubble fluctuating motions.

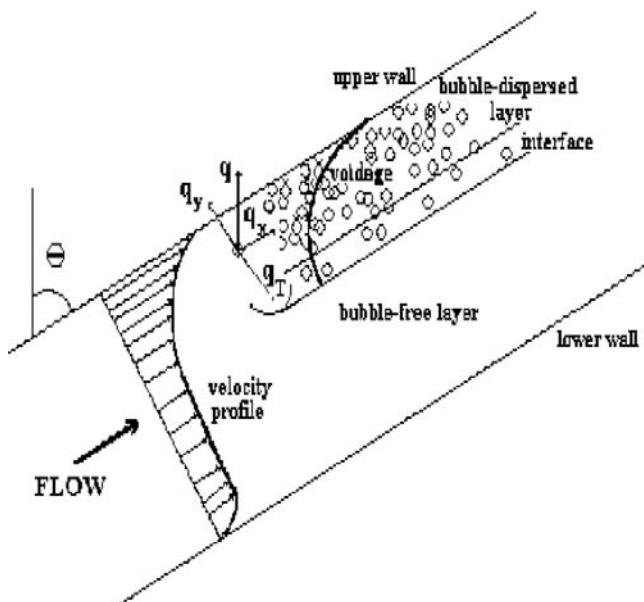


Fig. 1. A schematic view of two-layer flow, also showing buoyancy stabilised shear layer in steeply inclined bubbly flows

For two-phase air-water bubbly duct flows, inclination of just 5 degrees from vertical suffices departure from nominal similarity, however, possessing distinctively skewed voidage profiles though not considerably confined to describe regime as segregative pattern. For this 'nearly-vertical' flow the normal turbulence dispersion is manifestly reduced by buoyancy gradient but is certainly not completely vanished as occurs in the layered regimes observed at higher inclinations. Importance of 'segregative-disperse' regime was discussed with particular attention on interior shear layer in [11]. Here another potentially important connection, drawn from our study, links to mixed convection in vertical (or nearly) single-phase flows where symmetric normal velocity profiles of pumped flows are distorted by axial buoyancy forces induced by sufficient wall temperature excess or deficit. Such mixed convection regime has been studied in detail (e.g. [8]; [14]; [5], [15]) in relation to phenomenon of buoyancy-induced laminarisation and its capability to causing disastrous collapse for intensive heat exchangers. The reduced turbulence due to laminarisation, can be assessed by thickening of viscous sub-layer [6], however, was caused by impaired turbulence eddy shear stress in the vicinity of the wall. Alternatively, cooled wall provides negative buoyancy which enhances the wall shear stress and thus the heat transfer coefficient is increased in comparison with forced flow.

It is reasonable to explore application of above findings to the nearly vertical two-phase bubbly flows and

seek whether the underlying physical issues can be understood in terms of buoyancy associated with the voidage profiles and whether they are sufficiently confined close to the wall as to reduce the mean shear and hence restrict turbulence production. Another facet for nearly vertical bubbly flows is to assess whether the turbulence associated with bubbles is sufficient to compensate for the reduced mean shear. Both aspects ask for additional scaling of bubble size characterized by ratio of rms shear dispersion as a measure of voidage confinement and the rms fluctuations arising from the bubbles. Indeed these matters are important to boiling water heat exchangers as an diagnostic for dry out due to collapse of shear turbulence caused by bubbles, preferentially accommodate at the upper wall.

We describe some studies of nominally two-dimensional fully turbulent and developed duct flows ( $B/D=5$ ;  $Re > 10^4$ ;  $L/D > 40$ ) for inclination departures from vertical up to  $30^\circ$  at low voidages representative of disperse regime ( $\alpha < 5\%$  or so) using both typical tap-water bubbles (4-6 mm) and smaller bubbles (2 mm) stabilised in ionic solution.

### Equipment and instrumentation

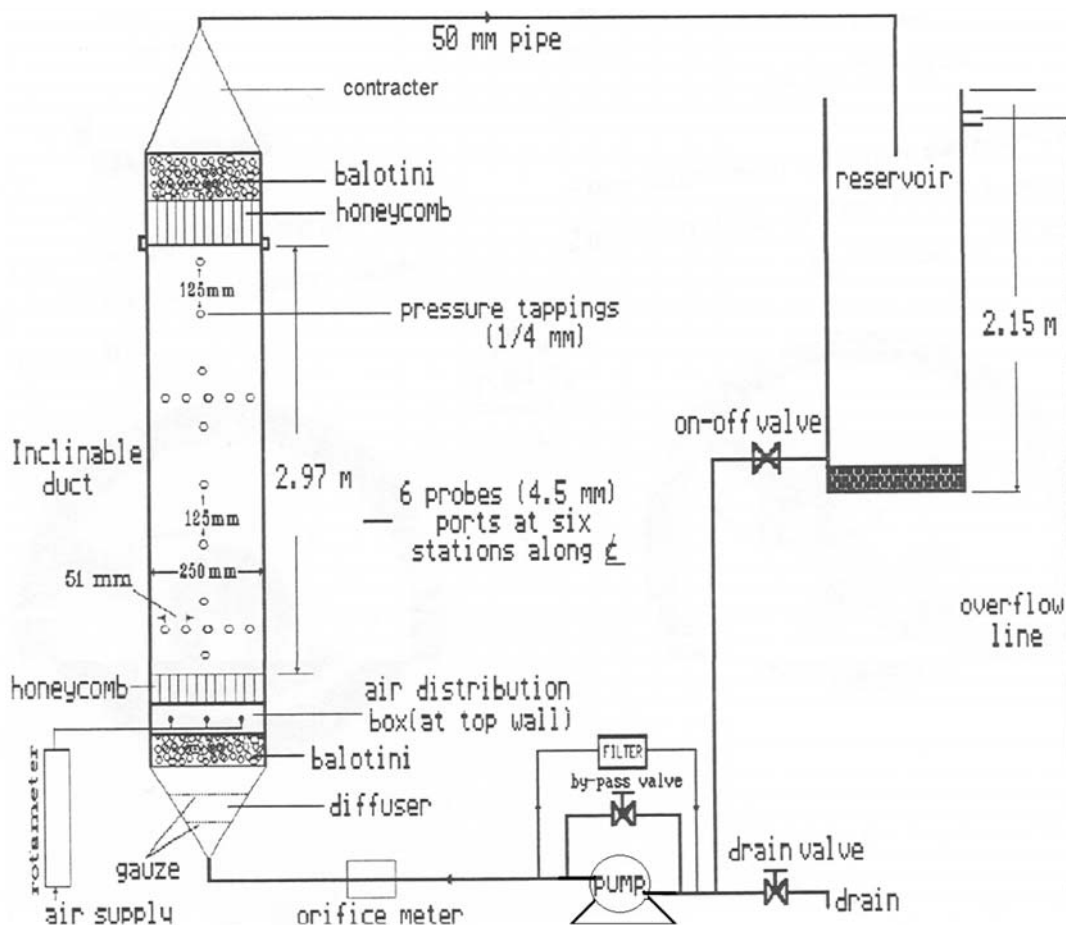
Main elements of the experimental set-up (schematically shown in figure 2) and findings were reported in [11]. Here we briefly describe how gas is injected into pumped duct

flow. The bubbles were injected via a manifold through  $20 \times 1$  mm holes located on the upper face at the entry section and turbulently dispersed transversely into the main body of flow. However, for smaller bubbles orifices with hole diameter 0.2 mm for the air injector manifold were adopted in line with the findings of [10] for rigid sparger holes delivering bubble sizes of about 2 mm. Twenty holes of 9 mm were made through the front section of duct. Rubber bungs, each with three capillary tubes (2.5 mm apart) with i.d of about 0.2 mm piercing them were inserted into 9 mm holes so that the surface of the bung was flush with the inside surface of the front wall.

Pitot and static probe instrumentation, primitive but validated, used for this study were described in paper [11]. The pressure signals from these tubes were recorded using the differential pressure pressure transmitter (Honeywell model type 4101) generated a signal over the scale range 4-20mA which was fed to the analogue digital converter (DCP microdevelopments, Interbeeb). The ADC output ranges from zero to 255 bits (0.48 to 2.4 volts) and the ADC output was processed using a BBC (model B) computer.

### Results & discussion

Experiments were conducted at  $40d$  downstream of entry; here  $d=50$  mm. The mean liquid velocity profiles were obtained for inclination angles ranging from zero (vertical) to  $30$  degrees from the vertical. The voidage and velocity



**Fig. 2.** A schematic facility for two-phase air-water inclined flow (up to  $30$  degrees from vertical)

profiles were also obtained for both ionic (Sodium Sulphate, NaSO<sub>4</sub> solution, 5 g/L; [4],[9],[10]). and non-ionic two-phase solutions. The liquid flow rates varied from 1.25 L/s to 5 L/s corresponding to a Reynolds numbers (based on flow depth, d=50 mm) range of 10<sup>4</sup> - 2×10<sup>4</sup>. The liquid superficial velocities range from 0.2 to 0.4 m/s and the air flow rates were varied from 10 L/min. to 40 L/min., corresponding to superficial velocities of 0.013 to 0.07 m/s. The mean void fraction was estimated as ranging from 0.015 to 0.05 approximately.

**Vertical flow**

The present study recovered only velocity profiles for vertical flow (figure 3). The results with 4-6 mm bubbles were certainly consistent with voidage excess retained in the wall zone insofar as the velocities were higher than expectation for neutral buoyancy. On the other hand, in our set-up the bubbles were introduced at the wall so this finding might equally be explained in terms of insufficient test-section length to properly accommodate evolution to fully developed conditions. Establishment of equilibrium voidage profiles is known to take considerably longer than for mean velocity and shear stress in uni-phase turbulent flows because of the weak lateral forces associated with bubble transverse fluxes. Indeed, although the mean velocity profiles obtained with 2 mm bubbles showed no obvious indication of wall-layer confinement we equally cannot take this contrary result as satisfactory evidence that attraction is absent from the asymptotic approach to far downstream fully developed flow. More studies are required to resolve these uncertainties, including systematic attention to bubble size as independent parameter determining the bubble induced turbulence (burbulence) scale and intensity for prescribed voidage independent of mean shear turbulence (shurbulence) scale and intensity.

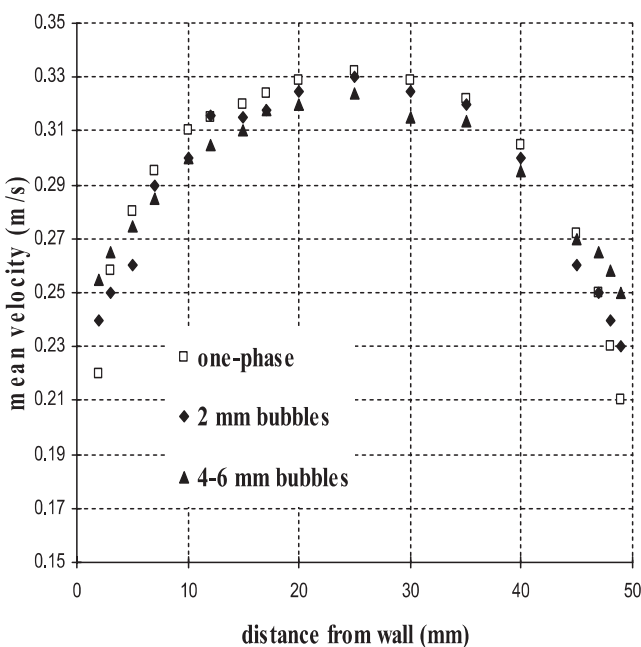


Fig. 3. Velocity profiles for vertical bubbly duct flows obtained at Re=14000 and gasrate 15 L/min

**Nearly vertical flow**

Inclination of just 5 degrees from vertical is sufficient to encourage flow evolution to a nominally fully developed state possessing distinctively skewed profiles of voidage (figure 4), though not sufficiently confined to warrant description as a segregative pattern. Figures 4-6 show the local void fraction profiles for ionic and non-ionic solutions at angles of inclination of 5 & 10 degrees. As expected for the smaller bubbles the bubbly layer deepens somewhat and for near vertical conditions (i.e 5 degrees) the bubbly layer for 2 mm bubbles deepens more as compared to results for 4-6 mm bubbles. These findings are further consolidated when we examine the effect of gasrate on voidage profiles (figure 5). As expected, with increased gasrate, the bubbly layer (figure 6) spreads further into the flow at both 5 and 10 inclinations, until it covers the whole width at gasrates over 10 L/min at 5 degrees. For 5 degrees we see here the bubbly layer covers more than 90% of the flow width for ionic flow, whereas this was about 80% of the flow width for non-ionic flow. The apparent reason for this is increased voidage due to the smaller slip speed associated with smaller bubbles, although of course, the increased voidage also represents an increase in the buoyancy flux, and hence also more turbulent energy consumed working against gravity.

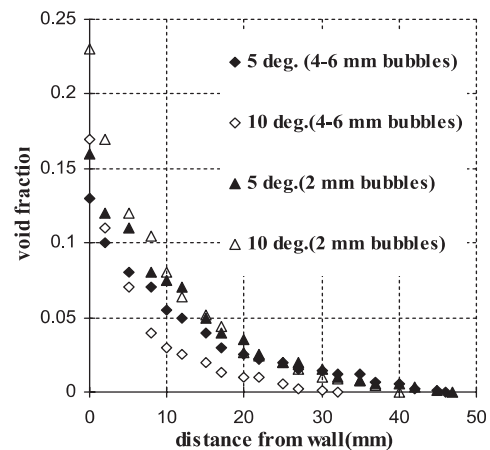


Fig. 4. Void fraction profiles for 5 and 10 degrees inclination obtained for Re=14000 & 15 L/min

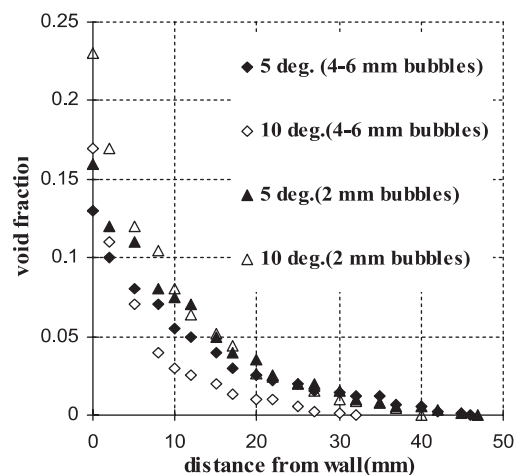
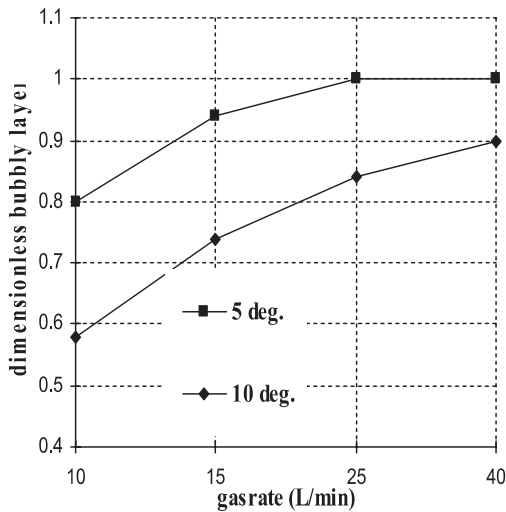


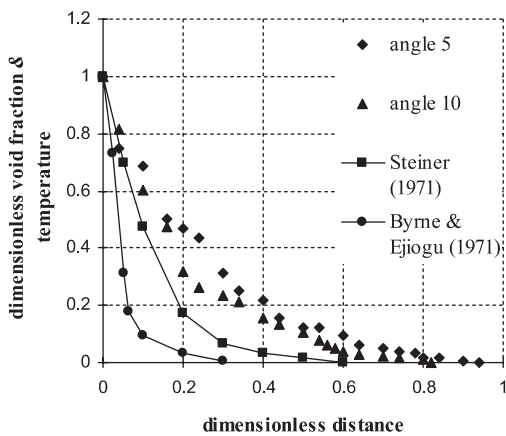
Fig. 5. Void fraction profiles for 5 and 10 degrees inclination obtained for Re=14000



**Fig. 6.** Bubbly layer thickness for 5 and 10 degrees inclination for same conditions as for figure 7

### Buoyancy inhibited turbulence

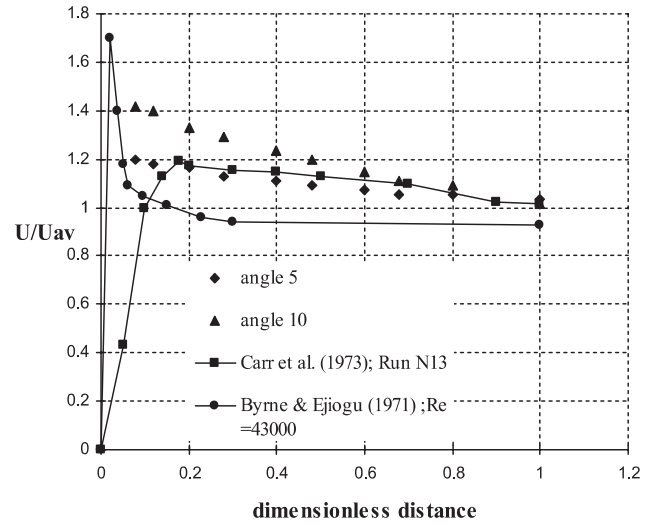
The profiles with smaller bubbles more nearly represent the influence of buoyancy alone: i.e., with bubble slip Reynolds number only 100 or so, as compared with perhaps 1000 or so for the larger bubbles ( $> 2$  mm), there is a greatly reduced bubble dispersive turbulence. Peaking near the upper wall here specially for smaller inclinations ( $10^\circ$  or lower) is similar to that found in mixed convection heat transfer of one-phase flows (e.g.[3];[13]; see figures 7 ). In effect, we are saying that buoyancy introduced by upper layer excess voidage must be effectively confined within this wall layer if laminarisation of the mean shear turbulence is to occur in bubbly flow. Our results (figure 7) suggest that the upper bubbly layer may be sufficiently confined as to introduce such inhibition; i.e., the buoyancy profiles are comparable to measurements in thermal mixed convection flows by [1] and [2] amongst others.



**Fig. 7.** Comparison of voidage, measured at  $Re=1.4000$  and gasrate  $15L/min$  for 2 mm bubbles, with temperature gradient profiles in one-phase mixed convection flows

Figure 8 compares velocity profiles in mixed convection flow with our results for bubbly flows. Whilst for [1] the velocity peak was very close to the wall, [2] found the velocity peak further away from the wall, corresponding to reduced confinement of buoyancy. Our

present results, although less confined than Byrne & Ejiogu's [1], certainly suffice to indicate potential impairment of heat transfer by buoyant inhibition of turbulence. We briefly assess the implication below.



**Fig. 8.** Comparison of velocity profiles at  $Re=14000$  and gasrate  $15 L/min$  for 2 mm bubbles, with those in mixed convection flows

### Heat transfer impairment

Applying Bousinesq's approximation in which the density is assumed constant except as the product with gravity (i.e. buoyancy force), the momentum equation then takes the following form for fully developed flow:

$$\frac{dp}{dx} = \frac{d\tau}{dy} + g\Delta\rho \quad (1)$$

where  $\tau = \mu \frac{dU}{dy} - \overline{\rho uv}$  is shear stress,  $\mu$  is the

dynamic viscosity and  $u$  and  $v$  are turbulent fluctuating velocities. Since wall friction ( $\tau_o$ ) and hydrostatic weight ( $g\bar{\rho}$ ) contribute to streamwise pressure gradient, replacing  $dp/dx$  by these terms and integration of equation (1) results in the following form:

$$\frac{\tau}{\tau_o} = (1 - y/a) - \frac{g\bar{\rho}_L}{\tau_o} \int_0^y (\alpha - \bar{\alpha}) dy \quad (2)$$

Where is local void fraction,  $\bar{\alpha}$  is void fraction averaged over duct's cross-section and  $\tau_o$  is wall shear stress. From the definition of thermal expansion coefficient  $\beta$ , the density difference can be approximated as:

$$(\bar{\rho} - \rho) = -\beta\bar{\rho}(\bar{T} - T) \quad (3)$$

Substituting this relation in Equation (2) and setting  $\eta = y/a$  and  $\theta = T_o - T$ , the dimensionless shear stress profile takes the following form:

$$\tau_+ = 1 - \eta - (g\beta\tau_o^{-1}) \int_0^y (1 - \theta/\bar{\theta}) dy \tag{4}$$

The above relation can be presented as

$$\tau_+ = 1 - \eta - Gr \int_0^y (1 - \theta/\bar{\theta}) dy \tag{5}$$

where Gr is a Grashof number, equal to  $= ag\beta\bar{\theta}(\tau_o/\bar{\rho})^{-1}$ . The procedure adopted to obtain shear stress distribution is described in [12]. Here we will discuss the effect of buoyancy on shear stress velocity and ultimately on heat transfer. The buoyancy parameter,  $\Gamma_\delta$  for present flows can be expressed as:

$$\Gamma_\delta = \frac{g(\alpha_\delta - \bar{\alpha})v}{u_\delta^3} \tag{6}$$

where  $v$  is kinematic viscosity,  $u_\delta$  is the friction speed based on eddy shear stress at distance  $\delta$  from wall, rather than the wall friction value. The distance  $\delta$  is based on a wall parameter ( $y^+ = yu_o/v$ ) whose value of 30

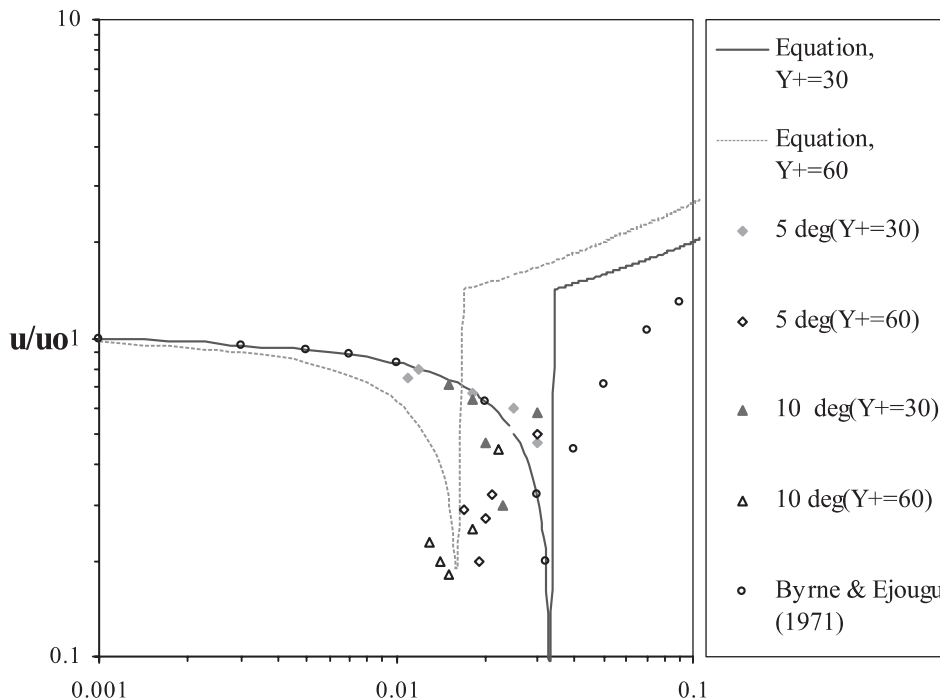
- 60 or so (e.g [7]) represents the region of maximum turbulence production in a normal fully developed channel flow. As a basis for assessing the analogy with heat transfer impairment in uni-phase buoyant wall layers, we restrict attention to small inclinations (no more than 10°) from the vertical. Figure 9 shows the effect of buoyancy on turbulence velocity scale  $u_\delta$ . The buoyancy parameter  $\Gamma_\delta$  and turbulent velocity distribution are estimated independently from experimental results by the model equations, presented above. The results are broadly encouraging since they indicate that turbulence impairment due to bubble buoyancy broadly follows the scaling relation, namely

$$\frac{u_\delta}{u_o} = \sqrt{1 - u_\delta y^+} \tag{7}$$

Also, as can be seen in this figure, the data of [1] for one-phase heat transfer studies support this picture of an impaired basis for buoyant impairment of shear turbulence, whether it is due to thermal density effect or due to bubble voidage.

**Conclusion**

A potentially important practical connection suggested by our study links to mixed convection in (nearly) vertical flows of uni-phase fluids where axial buoyancy forces due to thermally induced density reduction can attenuate the wall zone shear stress sufficiently to cause major reduction in the turbulence energy and thus also the heat flux. Comparison of our profiles with those found in mixed convection flows indicate that the buoyant layer in our



**Fig. 9.** Buoyancy inhibition of turbulence in nearly vertical bubbly flows and one-phase heated flows

flows is sufficiently confined as to sufficiently inhibit the production of wall shear stress. Whilst there is no room here to incorporate established and emerging fundamental literature on the behaviour and effects of bubbles in turbulent wall-layers, we must mention that bubble size appears to be a key factor insofar as microbubbles (100 microns) seemingly can reduce the wall shear stress whereas macrobubbles (mm sizes as used here) apparently act to increase it.

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