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INFLUENCE OF SURFACTANT ADDITIVES ON LIQUID FLOW FIELD INTERACTION WITH THE INTERFACIAL STRUCTURE IN CO-CURRENT STRATIFIED GAS-LIQUID DOWNFLOW

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Abstract. The purpose of this work is to study the influence of small amounts of surfactant additives on the interfacial structure and on the transition from the smooth to the wavy stratified flow regime for various gas-liquid flow rates. A dilute aqueous solution of a surfactant (Tween®) is used as the liquid phase in co-current air-liquid downflow in a 2.4 cm i.d. pipe. Laser Doppler Anemometry (*LDA*) is employed to measure the axial velocity inside the thin liquid layer both with and without interfacial shear induced by the gas flow. Liquid layer thickness time-records are acquired using a parallel-wire conductance technique and their statistics are calculated. Pressure drop measurements are also made using a differential pressure transducer. The results reveal the significant effect of surfactants on the liquid flow field development and on the interfacial structure. It is believed that the above detailed experiments in conjunction with the data interpretation will help to better understand the role of the surfactant additives on the phenomena observed in stratified gas-liquid downflow.

Keywords. Stratified flow, surfactant, drag-reduction, *LDA*, pressure drop, waves.

INTRODUCTION

The drag reduction phenomenon caused by dilute solutions of surfactant additives has been extensively studied by many researchers [1,2,3]. The most common example of this phenomenon arises during turbulent pipe flow, where it is observed that the addition of small amount of long chain polymers into a single-phase liquid flow can reduce the frictional resistance at the wall up to 80% [1]. This phenomenon, known as Toms effect [1], is useful for reducing energy consumption, increasing flow rate and decreasing the size of pumps in turbulent pipe flow systems. Thus, in an effort to save energy, many additives have been applied as drag reducers, which can be generally classified in three groups: i.e. fiber, polymer and surfactant [3].

Despite the large amount of experimental data, significant gaps still exist in understanding the way in which additives affect drag reduction, as the mechanism of additive-induced drag-reduction has not been clearly described so far [4]. The liquid flow field has been extensively studied in the past decades both theoretically and experimentally, when polymers are added in single-phase flows [1,4,5]. However, studies concerning the flow structure under the wavy gas-liquid interface in inclined pipes, when surfactants are added, are not available in the literature, probably due to the difficulty in obtaining accurate velocity measurements inside such very thin layers. Lioumbas et al. [6], who studied the transition from smooth to wavy stratified downflow for various pipe inclination angles, suggested that the onset of the interfacial waves (for tap water) is strongly affected by the liquid flow structure and by the laminar to turbulent transition within the layer.

Drag reduction in **two-phase** co-current flow, among other things, causes significant alterations of the flow patterns [7,8]. Al-Sarkhi & Hanratty [9] reported that the injection of a polymer solution into an air-water flow during horizontal annular pipe flow reduce drag by 48%. Quite recently, Soleimani et al. [7] studied the influence of the addition of polymers on the transition both to slugging and to roll waves and observed a decrease of the interfacial friction coefficient as well as of the pressure drop. They interpreted their results by speculating that the additives destroy the turbulence within the liquid layer and damp the waves on the gas-liquid interface. It is believed that the accurate axial velocity measurements, within the liquid phase in co-current gas-liquid flow using the non-intrusive *LDA* measuring technique, presented in this study, in conjunction with the liquid layer characterization experiments will elucidate the mechanisms prevailing under the liquid interface when drag-reducing additives are present in the flow. Consequently, the purpose of this work is to study the surfactant effect on:

- the transition from smooth to wavy flow for various pipe inclination angles and liquid flow rates in free flowing layer,
- the liquid flow field interaction with the interfacial structure in co-current stratified gas-liquid pipe downflow.

EXPERIMENTAL METHOD

Experiments are conducted at ambient temperature and pressure in a flow rig comprising a 24 mm i.d. Plexiglas® tube with a 7 m long straight section, which can be inclined up to 15° with respect to the horizontal. The superficial velocities are in the range U_{SL}=1-20 cm/s for the liquid and U_{SG}=0-20 m/s for the air, covering the stratified flow regime as well as the transition from smooth to wavy flow. Both phases are introduced through a carefully designed entrance section in order to minimize disturbances and to promote the development of stratified flow. Lioumbas et al. [6] give a more detailed description of the experimental set-up.

Liquid layer thickness is measured using the parallel-wire conductance probe method [10], whereas pressure drop is measured by a differential pressure transducer (*Validyne*). A one-component *LDA* set-up (*DANTEC*) is employed for the measurement of local axial velocities with a spatial resolution of 100 μm within the liquid phase. A more detailed arrangement of the *LDA* system and the signal analysis method applied in this study are given elsewhere [11].

The surfactant effect on the wave patterns is studied by adding a small amount (0.15% w/w) of the hydrophilic non-ionic surfactant ***Tween 80®*** in tap water. Measurements of viscosity, μ, are carried out using a cone-and-plate viscometer (*Carri-Med CLS 100*) and indicate a Newtonian behaviour for the surfactant solution with a viscosity equal to that of water (i.e. 1.02 mPa.s) for the range of our experiments. A number of experiments are also conducted by using an aqueous *acetic acid* solution (30% w/w), which has the same surface tension as the surfactant solution. The surface tension was measured using a *KSV* surface tension meter. The physical properties of all liquids tested are listed in ***Tab. 1.***

Throughout this study, two different definitions of the Reynolds number, *Re*, are used, i.e. the ***superficial*** *Re*, $Re_{SL}=U_{SL}D/\nu_L$ and the ***actual*** *Re*, $Re_L= U_L D_L/\nu_L$ based on the superficial liquid velocity, U_{SL}, and on the mean liquid velocity, U_L, respectively. D, D_L and ν_L are the pipe diameter, the hydraulic diameter and the kinematic viscosity of the liquid phase, respectively.

Tab. 1: Physical properties of the liquids used.

	index	*%, w/w*	***ρ,** kg/m³*	***σ,** mN/m*	***μ,** mPa.s*	***T,** °C*
water	w	-	1000	72	1.00	22
Tween 80®	*T*	0.15	1000	45	1.03	22
acetic acid	*a*	30.0	1000	43	1.01	22

EXPERIMENTAL RESULTS

Free flowing layer

Modelling and simulation of co-current stratified gas-liquid downflow require an adequate understanding of the characteristics of the ***free flowing*** liquid layer, which is considered a first step before introducing the complication of two-phase flow. In a recent paper, Lioumbas et al. [6] provided an overview of the gravity-driven liquid layer interfacial structure for water in inclined pipes, obtained both by visual observations (supported by fast video recordings) and by liquid layer thickness measurements. For the lower Re_L examined, small amplitude gravitational waves are observed on the liquid surface (*Region I*). As the liquid flow rate increases, the liquid interface becomes practically smooth and undisturbed (*Region II*). At even higher flow rates, solitary waves make their appearance, travelling along the pipe on the liquid interface (*Region III*). A critical Re_L (Re_{LC}) is related to the emergence of these solitary waves, which are relatively large amplitude coherent waves that are nearly two-dimensional and retain their original shape while travelling along the pipe. Lioumbas et al. [6] claim that these waves are generated as the result of the transition from laminar to turbulent flow within the liquid layer. As the flow rate further increases (turbulent structures become the dominant features within the liquid layer), the solitary waves become more frequent, retain their original amplitude and tend to merge forming *3D* structures (*Region IV*).

The time series of the layer thickness data are statistically analyzed to obtain the main free flowing layer characteristics, namely h_{mean} and h_{rms}. In ***Fig. 1*** the h_{rms} values are plotted versus Re_L, for water as well as for Tween® solutions for an inclination angle, β, equal to 1^o. The Regions, as reported in the previous paragraph for free flowing water, are also recognized for the Tween® solution. It is interesting that the gravitational waves observed in *Region I*, when water is used, ***disappear*** when the Tween® solution is applied, a fact that is in agreement with the remarks of Spedding & Hand [8], who reported that the addition of the surfactant suppresses the small-amplitude gravitational waves on the liquid surface. *Region II* is observed for all the liquids tested (i.e. water and Tween®). As the liquid flow rate further increases (*Region III*), Re_{LC} is shifted to higher values for the Tween® solution attaining a maximum h_{rms} value 25% larger than that of water, a fact that is also attributed to the reduced surface tension of the Tween® solution. Visual observations reveal that the Re_{LC} values fall between 2100 and 2300 when water is used, but in the case of the Tween® solution, solitary waves appear at ***higher*** Re_L (i.e. Re_L ~2500-2800) for all pipe inclination angles tested [12].

Since Lioumbas et al. [12] have suggested that the solitary wave appearance is related to the transition from laminar to turbulent flow (regardless of the liquid viscosity) it is assumed that the ***transition*** to turbulence is "delayed" when a small quantity of surfactant is added to water. This observation is in agreement with the well-known drag-reduction effect caused by additives in single-phase pipe flow. The drag-reduction effect of the Tween® solution is confirmed by pressure drop measurements during single-phase horizontal pipe flow.

In ***Fig. 2*** the friction factor, f, is plotted against Re_L for horizontal single-phase pipe flow, for both water and Tween® solution. It is apparent that for moderate Re_L (Re_L<7000) the f values for the Tween® are significantly lower than the ones for water, but as the flow rate further increases the f values for the surfactant solution are becoming similar to those of water. This implies that for higher liquid flow rates the drag reduction is insignificant. This is in agreement with the experimental results of Usui et al. [13], who studied the drag reduction effect caused by a cationic surfactant in single-phase flow.

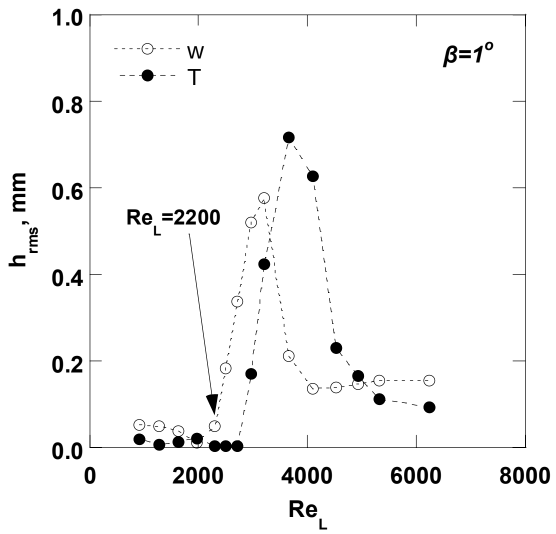

Fig. 1: h_{rms} vs. Re_L for various liquids.

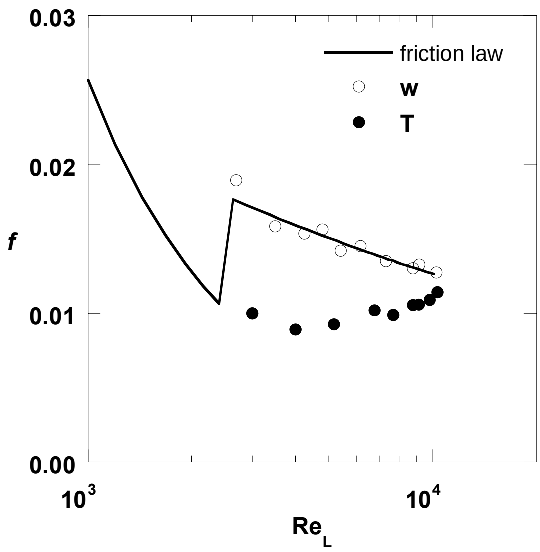

Fig. 2: Friction factor vs. Re_L for water and Tween®.

While the liquid flow field is well documented in single-phase pipe flow in the presence of additives [1], to the best of authors' knowledge there are no studies concerning the flow field within ***free flowing*** liquid layers in inclined pipes under the surfactant effect. Therefore, with the intention to elucidate the relation between the flow structure inside the liquid layer, the onset of the turbulence and the drag-reducing effect of surfactant additives, the flow field structure under the interface should be closely studied. The axial velocity component is measured for various Tween® flow rates and is compared with those obtained for water [6].

A typical distribution of the normalized velocities, u^+, obtained for various liquid flow rates (for Tween® and water, β=1°) is presented in ***Fig. 3***. The comparison with the von Karman universal velocity distribution for single-phase water flow reveals that the free flowing flow is laminar for Re_L=2000, turbulent for Re_L=5500, while for Re_L=2300 it appears to be in the transitional region. It is interesting that for surfactant solution the flow continues to be in the laminar region even for Re_L=2300, a fact that it is expected, since the addition of the surfactant in the water apparently causes drag reduction.

Furthermore, in ***Fig. 4*** time dependent local axial velocity measurements are presented for water and for the Tween® solution for U_{SL}=0.04 m/s (Re_L=3000) and at a distance y=1.6 mm from the bottom pipe. It is well known that eddies generated by the bursting motions in the near wall region are lifted up toward the free surface and they become the surface-renewal eddies, as it is explained in details by Mosyak & Hetsroni [5] and by Gurka et al. [14]. Lioumbas et al. [6] suggested that the minima in U (observed in ***Fig. 4***) could be considered the result of the burst creation near the pipe wall during the transition from laminar to turbulent flow into the liquid layer. This burst generation seems to be suppressed for the surfactant solution (***Fig. 4b***), since the corresponding root mean square of the axial velocity fluctuations, u', is lower compared with those of the water, a fact that is in agreement with the observation of Gurka et al. [14] in single-phase flow in flumes.

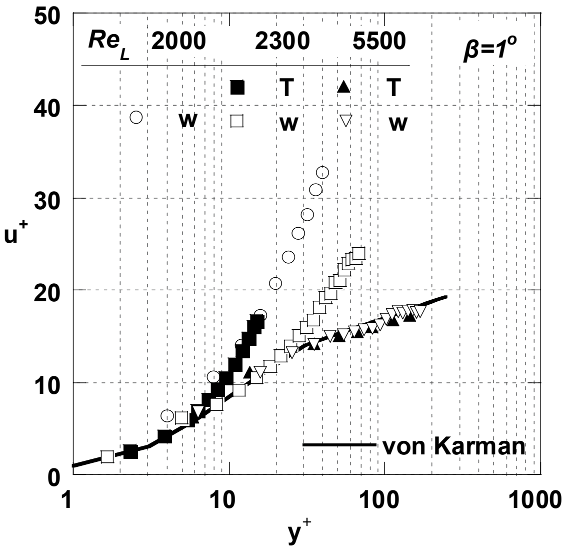

Fig. 3: Comparison of experimental data with von Karman velocity distribution ($\beta=1^o$).

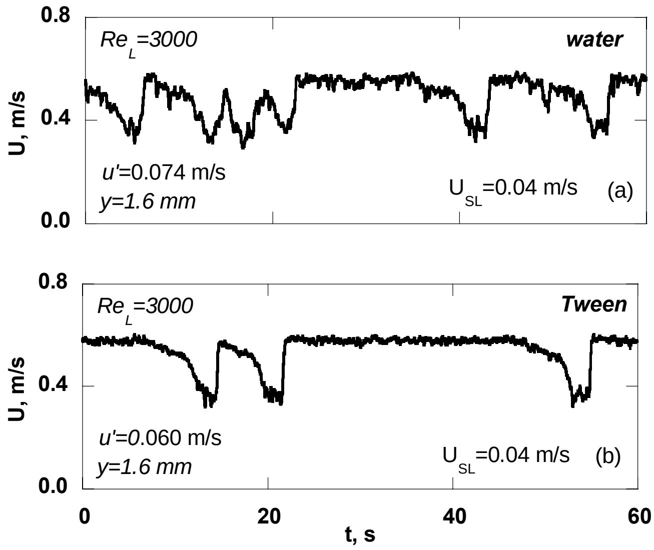

Fig. 4: Time dependent U trace for a) water and b) Tween®.

Fig. 5 presents the distribution of u' as a function of y both for the water and the surfactant solution (at Re_L=5500 where the flow is considered to be fully turbulent). The maximum u' values observed close to the interface (for water) are attributed to the influence of the interfacial *3D* high-frequency small-amplitude waves on the velocity fluctuations ("wave-induced turbulence" [15]). However, when a small amount of surfactant is added to the water, the velocity fluctuations are significantly damped (up to 30% compared to water) in a region near the interface, while in a region closer to wall (e.g. y<4 mm) u' attains similar values for both liquids tested. Consequently, since the "wave-induced turbulence" at a region close to the gas-liquid interface is "damped" by the surfactant action, it would be interesting to examine how the co-current gas-liquid flow interacts with the interface under the influence of the surfactant.

Two-phase co-current gas-liquid downflow

In this section an overview of the liquid layer interfacial structure is presented in ***co-current gas-liquid downflow***, obtained both by visual observations and liquid layer thickness measurements. An aqueous acetic acid solution with surface tension similar to that of the Tween® solution (σ=45 mN/m) is also employed as testing fluid in order to study the co-current gas flow effect on the liquid layer characteristics of a low surface tension solution which displays no drag reducing effect. Henceforth, the superficial liquid Reynolds number (Re_{SL}) and the superficial gas Reynolds number (Re_{SG}) will be used as a measure of the liquid and the gas flow rate, respectively.

Starting from a smooth interface, the gas flow rate was gradually increased until the ***first*** solitary wave makes its appearance. Measurements and visual observations reveal that the transition from smooth to wavy stratified two-phase flow (for water and acetic acid) occurs in a narrow Re_L range (~ 2100-2300). However, when a small amount of surfactant is added to the water, the first solitary wave appears at a Re_L (~1600-2000) ***lower*** than that corresponding to water and acetic acid.

The liquid layer thickness, h_{mean}, normalized with respect to the layer thickness in the absence of air, h_0, is plotted against the gas flow rate for all liquids tested (***Fig. 6***). It is clear that the thickness reduction with gas flow rate is much smaller for the Tween® solution and it should lead to smaller mean liquid velocity (compared to that for water). As a result, the Re_L corresponding to water is higher than the one associated with the surfactant solution. Soleimani et al. [7] and Spedding & Hand [8] have also observed that the addition of very small quantities of polymers in water results to a significant increase of the liquid hold-up (up to 30%) and to a reduction of the wave amplitude (i.e. h_{rms}) compared with that of water. Several researchers [7,8] attribute this fact either to an increased surface viscosity or to the turbulence damping at the liquid interface.

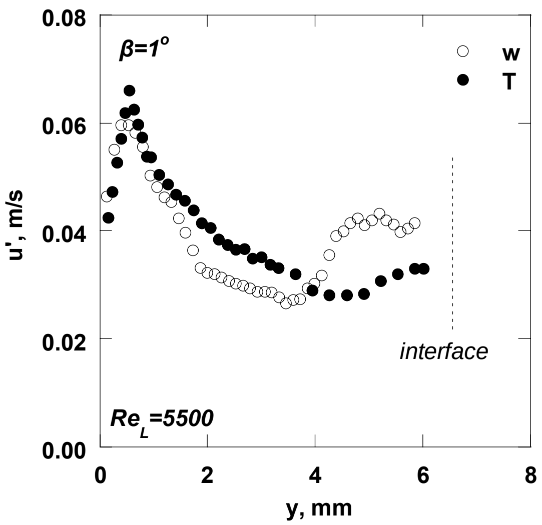

Fig. 5: Comparison of u' for water and Tween® ($\beta=1^o$).

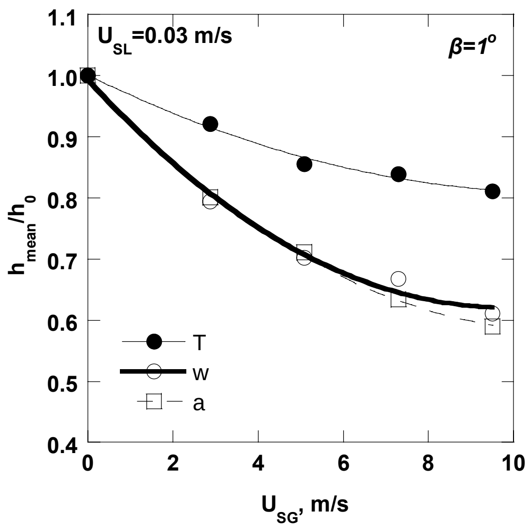

Fig. 6: Normalized h_{mean} with respect to the corresponding h_0 vs. U_{SG}; for water, Tween® and acetic acid ($\beta=1^o$).

In order to clarify how the interfacial waves and the liquid flow field interact with the ***co-current*** air flow, it is useful to determine the axial liquid velocity profile (both for the case of water and the surfactant solution) for various gas flow rates and a typical liquid flow rate (e.g. U_{SL}=0.07 m/s). In ***Fig.*** *7* the axial velocity, U, and its fluctuations, u', away from the pipe wall (for both water and Tween®) are plotted for various gas flow rates and are combined with the h_{mean} distribution vs. the gas flow rate; the thick solid line stands for the water h_{mean} measurements, while the dashed for the surfactant solution. It becomes apparent that for water, U decreases as the gas flow rate increases (***Fig. 7a***), whereas it seems to be unaffected by the increased gas flow rate for the Tween® solution. The above result is in agreement with ***Fig. 7b***, where it is obvious that in the Tween® case u' is not significantly influenced by the increased gas flow rate. In conclusion, it seems that, despite the gas-induced turbulence, the surfactant addition creates a "protective layer" near the gas liquid interface that prevents the gas induced shear to enter the liquid phase.

Typical U and u' profiles for water and Tween® are presented in ***Fig. 8***. Due to the risk of obtaining erroneous results by trying to measure close to a gas-liquid interface, axial velocity measurements near the interface are not provided, since Laser light coming from reflections at the interface acts as a spurious "reference beam" reaching the photomultiplier. However, in the surfactant solution case, the waves are suppressed and it becomes easier to approach the gas-liquid interface. A significant reduction of the axial velocity close to the gas-liquid interface is evident for the water but **not** for the Tween® solution. Paras & Karabelas [11] have pointed out that this reduction could be attributed to the existence of strong normal velocity components and to the kinetic energy transfer from the faster moving gas to the liquid.

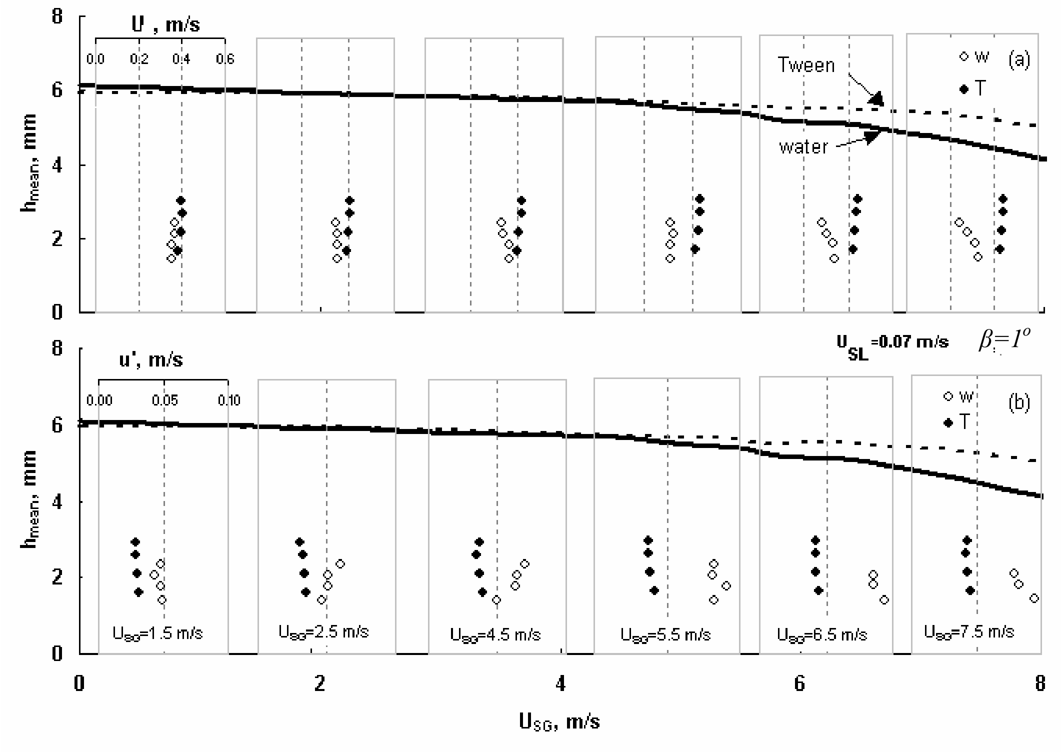

Fig. 7: Distribution of h_{mean}, U and u' for water and Tween®, for various gas flow rates, $\beta=1^o$.

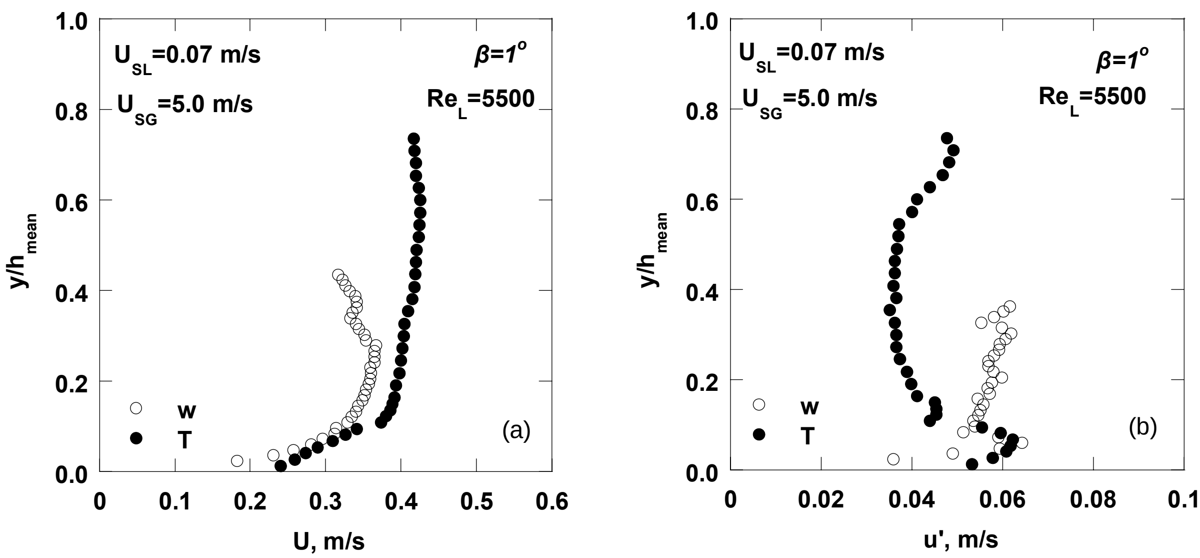

Fig. 8: Comparison of: a) U and b) u' for water and Tween®, for the same flow rates, $\beta=1^o$.

Furthermore, it is obvious that when surfactants are added to the flow, u' values at a region close to interface seem to be unaffected by the gas-induced shear (***Fig. 8b***); it is possible that significant alteration of the energy exchange process under the interface finally leads to reduced turbulence [7]. Consequently, in the case of the Tween® addition, the liquid layer behaves drastically different than that of water. It is likely that such surfactants act in the following ways:

- they weaken the turbulent ejection and sweep events within the liquid layer, which is manifested as drag reduction [3]
- they damp the waves at the interface and destroy the gas-induced turbulence structures in the liquid phase.

Pressure drop measurements in the liquid phase

The dimensionless ratio, λ, (which represents the normalized pressure gradient, dP/dx, with respect to the pressure gradient for water) is plotted in ***Fig. 9*** vs. the gas flow rate for both the Tween® and the acetic acid solution, for two liquid flows (i.e. U_{SL}=0.03 and 0.07 m/s) and for various gas flow rates. For the lower gas and liquid flow rates tested (i.e. U_{SG}<5.0 m/s) λ values are similar for all the liquids used (***Fig. 9a***). However, as the gas flow rate increases (U_{SG}>5.0 m/s) λ values for the surfactant solution are **lower** (~30%) than those of water, whereas for the acetic acid solution λ values are considerably **higher** (~40%) than those of water (***Fig. 9***).

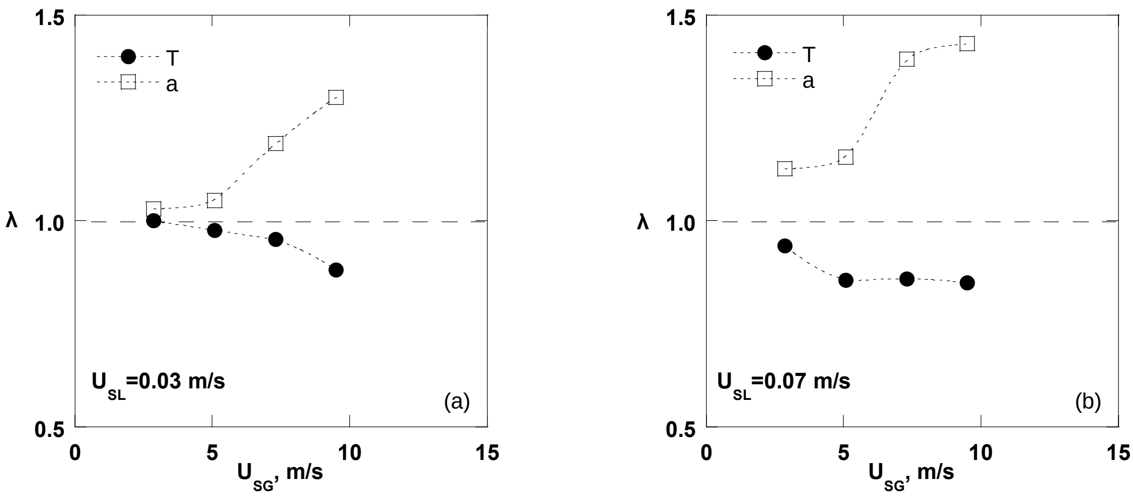

Fig. 9: Normalized pressure drop measurements for a) U_{SL}=0.03 m/s and b) U_{SL}=0.07 m/s.

With the intention to examine how the dP/dx values are influenced by the liquid layer characteristics, traces of the liquid layer thickness, h, are presented for the same liquid (U_{SL}=0.07 m/s) and gas flow rate (U_{SG}=5.0 m/s) for the water, the acetic acid and the surfactant solution (***Fig. 10***). It is apparent that interface of the acetic acid is rougher (h_{rms}=0.93 mm) than that of water (h_{rms}=0.57 mm) while, the layer thickness of the surfactant solution is higher (h_{mean}=4.9 mm) than that of water (h_{mean}=3.8 mm) and of acetic acid solution (h_{mean}=4.0 mm), exhibiting smaller amplitude waves (h_{rms}=0.33 mm) on the interface. Therefore, the hold-up increase (in the Tween® case) causes higher gas velocity values, which result in an increase of both the wall shear stress (in the gas phase), τ_{WG}, and the interfacial shear stress, τ_i. On the other hand, since in general a smoother interface leads to a decrease of τ_i, a reduction of *dP/dx* values could also be expected. Thus, since the experimental results (***Fig. 9***) indicate that *dP/dx* values are lower for the Tween® solution (compared to the corresponding values of water and acetic acid), it is likely that the smoother interface (observed after the surfactant addition) is **mainly** responsible for the drag reduction. Therefore, with the intention to further examine:

- whether the friction factor in the gas-liquid interface, f_i, or the wall shear stress in the liquid phase, τ_{WL}, is responsible for the drag reduction and
- the influence of the increased gas flow rate on f_i and τ_{WL} values

f_i and τ_{WL} values are calculated using the: h_{mean}, *dP/dx* measurements, the force balance on the gas and the liquid phase (*Eqs. 1 & 2*) and the definitions of τ_{WG}, τ_i and τ_{WL} (*Eq. 3*):

$$-A_G \frac{dP}{dx} - \tau_{WG} S_G - \tau_i S_i + \rho_G A_G g \sin\beta = 0 \qquad (1)$$

$$-A_L \frac{dP}{dx} - \tau_{WL} S_L + \tau_i S_i + \rho_L A_L g \sin\beta = 0 \qquad (2)$$

$$\tau_{WG} = f_G \frac{\rho_G U_G^2}{2}, \tau_i = f_i \frac{\rho_G (U_G + U_L)^2}{2}, \tau_{WL} = f_L \frac{\rho_L U_L^2}{2} \qquad (3)$$

where g is the gravitational acceleration, S_i is the gas-liquid interface length on the pipe cross-section, S_G and S_L are the parts of the circumference in contact with gas and liquid, A_G and A_L are the cross-section area, U_G and U_L are the mean velocity, f_G and f_L are the friction factor, ρ_G and ρ_L are the density, for the gas and the liquid phase respectively.

Fig. 11a, where the calculated f_i/f_{WG} values are plotted vs. the gas flow rate, shows that the f_i/f_{WG} ratio is lower for the surfactant solution than for the water and for the acetic acid solution for a typical gas flow rate (e.g. U_{SG}=10m/s). The large values of f_i/f_{WG} ratio, observed for the acetic acid solution, are expected since the gas-liquid interface is rough due to the reduced surface tension of the acetic acid solution [8]. Despite the fact that the acetic acid and the Tween® solution have similar surface tension, the surfactant solution interface is smoother, since the surfactant addition in the water results in a damping of the interfacial waves, which in turn leads to a decrease of the interfacial friction factor and the pressure drop [7].

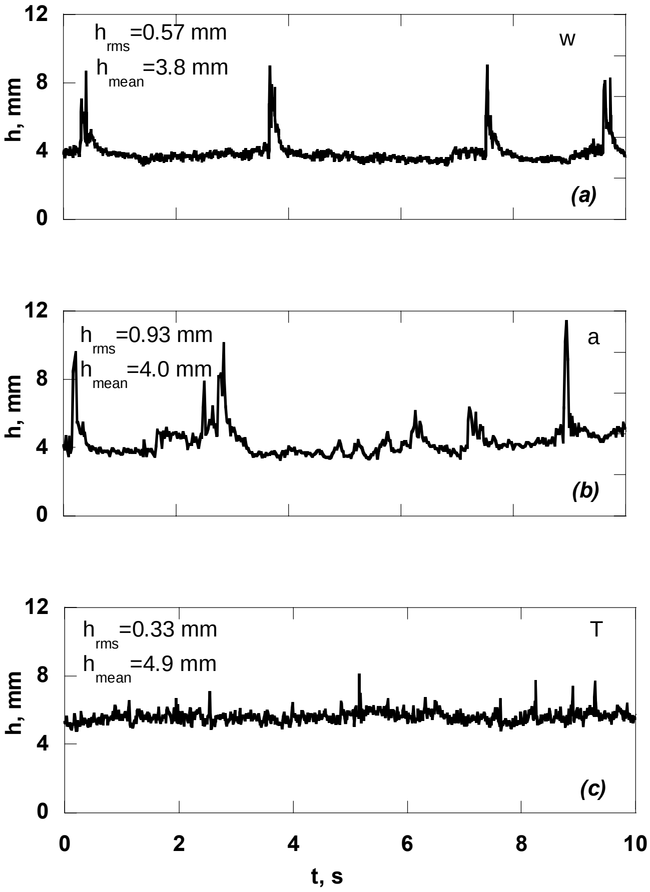

Fig. 10: Typical layer thickness traces: a) water; b) acetic acid; c) Tween®; U_{SL}=0.07 m/s; U_{SG}=5.0 m/s.

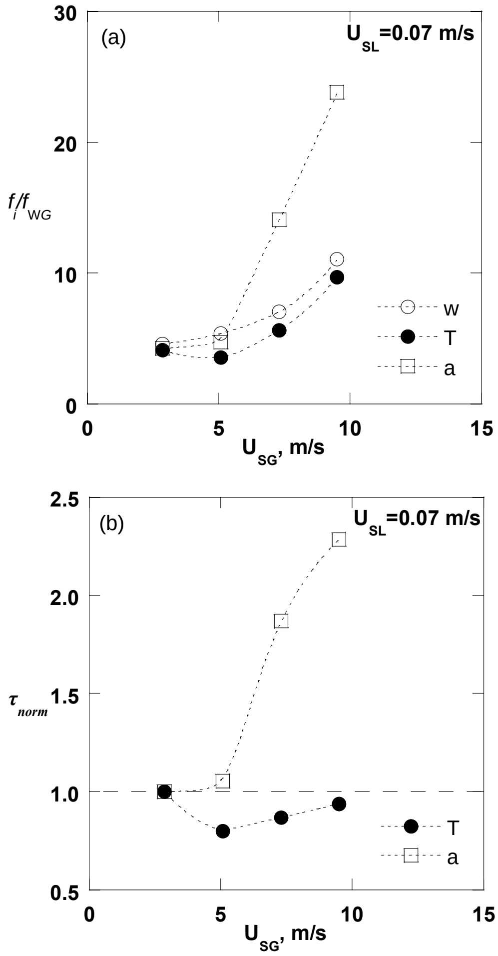

Fig. 11: Estimation of: a) f_i/f_{WG}; b) τ_{norm} for various gas flow rates.

The dimensionless ratio, τ_{norm}, (i.e. the normalized wall shear stress, τ_{WL}, with respect to the wall shear stress for water) is plotted vs. the gas flow rate for both the Tween® and the acetic acid solution, for U_{SL}=0.07 m/s and for various gas flow rates (***Fig. 11b***). It becomes apparent that the surfactant addition causes a reduction of the wall shear stress, since the τ_{norm} values are lower for the surfactant than for the water and the acetic acid solution. Nevertheless, for the higher gas flow rates applied (i.e. U_{SG}=10m/s) the τ_{WL} values are similar to those of the water and the Tween® solution (τ_{norm} ~1). Consequently, since the surfactant addition affects more the interface friction factor, f_i, (***Fig. 11a***) than the wall shear stress, τ_{WG}, (***Fig. 11b***), the pressure drop reduction observed for the higher gas flow rates applied should be mainly attributed to the wave damping.

CONCLUSION

The purpose of this work is to examine the influence of a non-ionic surfactant additive (e.g. Tween®) on the interfacial structure and on the transition from the smooth to the wavy stratified flow regime for various gas-liquid flow rates. In *free flowing liquid*, the first solitary wave occurs in a narrow Re_L range (~ 2100-2300) for all the liquids tested [12], except for the Tween® solution where solitary waves appear at ***higher*** Re_L (i.e. Re_L ~2500-2800). The axial liquid velocity measurements show that the "delayed" wave appearance is related to turbulence damping in the liquid layer, due to the drag reduction effect of the non-ionic surfactant.

For *co-current gas-liquid downflow*, the transition to wavy stratified two-phase for the surfactant solution, occurs in a Re_L range (~1600-2000) ***lower*** than that corresponding to water and acetic solution (Re_L ~ 2100-2300). This trend is attributed to the fact that the addition of small quantities of surfactant to water results in the damping of the small-amplitude waves on the gas-liquid interface. Therefore, to satisfy the force balance and the mass conservation principle, h_{mean} is higher for the surfactant solution and the mean velocity is comparatively smaller compared to that for pure water for the same liquid and gas flow rates. Finally, local axial velocity measurements under the interface in two-phase flow (in the case of Tween®) suggest that the fluid resistance in gas-induced eddies increases and as a result, the formation and the growth of small scale eddies decreases.

The surfactant (which is concentrated at the interface) acts like a "shock absorber", which dissipates eddies originating from the gas shearing motion and it also creates a smoother interface (*wave damping*). All the above result to a significant reduction of pressure drop for the higher gas flow rates applied (e.g. U_{SG}>5.0 m/s).

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REFERENCES

[1] Warholic, M. D., Massah, H. & Hanratty, T. J., 1999 Influence of drag-reducing polymers on turbulence: effects on Reynolds number, concentration and mixing, *Exp. Fluids*, **27**, 461-472.

[2] Kawaguchi, Y., Segawa, T., Feng, Z. & Li, P., 2002 Experimental study on drag-reducing channel flow with surfactant additives-spatial structure of turbulence investigated by PIV system, *Intern. J. Heat and Fluid Flow,* **23**, 700-709.

[3] Yu, B., Li, F. & Kawaguchi, Y., 2004 Numerical and experimental investigation of turbulent characteristics in a drag reducing flow with surfactant additives, *Intern. J. Heat and Fluid Flow,* **25**, 961-974.

[4] Angelis, E., Cassiola, C.M., L'vov, V.S., Pomyalov, A., Procaccia, I. & Tiberkevich, V., 2004 Drag reduction by a linear viscosity profile, *Phys. Rev. E,* **70**, 055301(R).

[5] Mosyak, A. & Hestroni, G., 2004 Visual study of bursting using infrared technique, *Exp. Fluids* **37**, 40-46.

[6] Lioumbas, J.S., Paras, S.V. & Karabelas, A.J., 2005 Cocurrent stratified gas-liquid downflow – Influence of the liquid flow field on interfacial structure, *Int. J. Multiphase Flow* (*in press*).

[7] Soleimani, A., Al-Sarkhi, A. & Hanratty, T.J., 2002 Effect of drag-reducing polymers on pseudo-slugs–interfacial drag and transition to slug flow, *Int. J. Multiphase Flow,* **28**, 4, 1911–1927.

[8] Spedding, P.L. & Hand, N.P., 1997 A revised analysis of the effect of surfactants on two-phase phenomena in horizontal air-water pipe flow, *Dev. Chem. Eng. Mineral Process*, 5(3/4), 267-279.

[9] Al-Sarkhi, A. & Hanratty, T.J., 2001 Effect of drag-reducing polymers on annular gas-liquid flow in a horizontal pipe, *Int. J. Multiphase Flow,* **27**, 1151-1162.

[10] Paras, S.V. & Karabelas, A.J., 1991 Properties of the liquid layer in horizontal annular flow, *Int. J. Multiphase Flow,* **17**, 4, 439-454.

[11] Paras, S.V. & Karabelas, A.J., 1992 Measurements of local velocities inside thin liquid films in horizontal two-phase flow, *Exp. Fluids*, **13**, 190-198.

[12] Lioumbas, J.S., Mouza, A.A., Paras, S.V. & Karabelas, A.J., 2005 Liquid layer characteristics in stratified gas-liquid downflow: a study of transition to wavy flow, *4th International Conference on Heat Transfer, Fluid Mechanics & Thermodynamics*, Cairo, Egypt.

[13] Usui, H., Kamada, T. & Suzuki, H., 2004 Surfactant drag reduction caused by a cationic surfactant with excess addition of counter-ions, *J. Chem. Eng. Japan,* **37**, (10), 1232-1237.

[14] Gurka, R., Liberzon, A. & Hetsroni, G., 2004 Characterization of turbulent flow in a flume with surfactant, *J. Fluids Eng.*, **126**, 1054-1057.

[15] Karimi, G. & Kawaji, M., 1999 Flow characteristics and circulatory motion in wavy falling films with and without counter-current gas flow, *Int. J. Multiphase Flow,* **25**, 1305-1319.