

**LIQUID LAYER CHARACTERISTICS IN STRATIFIED GAS-LIQUID
DOWNFLOW: A STUDY OF TRANSITION TO WAVY FLOW**

JS Lioumbas, AA Mouza, SV Paras*, AJ Karabelas

Laboratory of Chemical Process and Plant Design
Department of Chemical Engineering
Aristotle University of Thessaloniki
Univ. Box 455, GR 54124 Thessaloniki, GREECE

*Author for correspondence: paras@cheng.auth.gr

ABSTRACT

Realistic modelling and simulation of long distance two-phase pipe flow necessitate, among other things, an adequate understanding of the liquid layer characteristics in stratified gas-liquid downflow. The purpose of this work is to study the transition from the smooth to the wavy stratified flow regime for various pipe inclination angles and liquid physical properties. Accurate characterisation of both the structure of the gas-liquid interface and of the flow field inside the liquid layer will improve our physical understanding of the mechanisms involved in the evolution of waves in stratified gas-liquid flow. To study the influence of liquid properties on the mechanisms promoting wave formation, several liquids have been used (i.e. water, Tween[®] and aqueous-glycerin solutions). The experiments are conducted in a 24mm i.d. pipe for various inclination angles (1 to 9deg) with respect to the horizontal position.

Liquid layer thickness time records are acquired using a parallel-wire conductance technique from which mean layer thickness, *rms* and power spectra of the fluctuations, as well as wave celerities are calculated. Measurements of the axial velocity component in the liquid layer using Laser Doppler Anemometry are also reported. Statistical analysis of such local liquid velocity data in conjunction with the liquid layer characteristics reveals a strong interplay between wave evolution at the interface with the flow field development inside the liquid layer. Finally, results of numerical calculations using a CFD code are obtained to facilitate data interpretation.

INTRODUCTION

The co-current stratified downflow of gas-liquid mixtures is a flow regime frequently encountered in long distance hydrocarbon pipelines, as well as in transfer lines in process plants. Moreover, mass and heat transport across gas-liquid interfaces is very important in chemical process equipment, since interfacial waves enhance both heat and mass transfer. To understand the mechanisms involved in the evolution of waves at the transition from smooth to wavy stratified flow regime, the accurate characterization of both the structure of the interface and of the flow field inside the liquid layer is required.

Extensive research work, both experimental and theoretical, carried out over the last three decades suggests that the rate of momentum, heat and mass transfer is strongly influenced by the liquid layer characteristics and especially by the waviness of the gas-liquid interfaces. Barnea et al.^[1] and Brauner & Maron^[2] studied the flow patterns for gas-liquid flow in inclined pipes and, after comparing their results with the theoretical model by Taitel & Dukler^[3], they found that this model is not capable of predicting the transition from smooth to wavy stratified flow, as it does not take into account the waves generated by gravity in downward flow. Ng et al.^[4] point out the lack of work on free surface pipe flow and use CFD to evaluate the integral and local flow gravity-driven laminar flow in a partially filled pipe. Despite the plethora of studies regarding liquid layer flow in inclined pipes, it appears that detailed studies on the interrelation of the liquid layer characteristics with the interface waves are not available in the literature for low to moderate Reynolds numbers. Recently Lioumbas et al.^[5], obtained complete sets of detailed data on water layer flow inside slightly inclined pipes of various diameters, and suggested that the transition from laminar to turbulent flow in the liquid layer may be related to the transition from a smooth to a wavy interface where solitary waves make their appearance.

The flow characteristics, such as liquid hold-up and pressure drop, have been extensively studied in horizontal stratified two-phase flows^[6, 7, 8]. However, to the best of authors' knowledge, studies concerning the flow structure under the wavy interface in thin liquid layers in *inclined* pipes are not available in the literature, most probably due to the difficulty in obtaining accurate velocity measurements inside such thin liquid layers. Several investigators^[3, 9, 10, 11] have reported on the effect of liquid properties on the flow patterns in co-current pipe flow, but no experimental data concerning gas-viscous liquid and gas-low surface tension liquid flows in *inclined* pipes are available.

The purpose of this work is to study the transition from smooth to wavy stratified flow for various pipe inclination angles and types of liquids. Liquid layer thickness time records are acquired using a parallel-wire conductance technique from which mean layer thickness, root mean square (*rms*) and power

spectra of the fluctuations, as well as wave celerities are calculated. Measurements of the axial velocity component in the liquid layer using *LDA* are also reported to clarify the type of flow prevailing inside the liquid layer. Finally, to facilitate data interpretation, numerical calculations using a *CFD* code are also carried out.

EXPERIMENTAL METHOD

Experiments are conducted at ambient temperature and pressure conditions in a flow rig consisting of a 24mm i.d. Plexiglas® tube with a 7m long straight section, which can be inclined up to 15° with respect to the horizontal. Properly conditioned air (filtered, dried) is supplied to the rig while the liquid is recirculated by means of a centrifugal pump. The gas and liquid flow rates are measured using a bank of calibrated rotameters with accuracy better than ±1%. The liquid layer thickness is measured using the parallel wire conductance probe method, described in detail elsewhere [6]. The specially designed test section, which is constructed to accommodate parallel wire conductance probes, is positioned approximately 6m away from the mixing section of the two phases, where the flow can be considered developed. The liquid conductivity is measured both prior to and after each set of experiments and a correction factor is incorporated in the layer thickness calculations to compensate for temperature effects. The accuracy of the measurements is estimated to be around ±10% taking into account uncertainties in the calibration procedure. The statistical quantities and other parameters of the layer thickness time records are calculated from 10,000-point samples, obtained over a period of 100s with a 100Hz sampling frequency. An *LDA* set-up, which operates in the fringe mode, is employed to conduct measurements of local axial velocities within the liquid phase. The non-intrusive *LDA* technique is suitable for detailed local velocity measurements in very thin films, since it permits measurements very close to the wall (~100µm) with very good spatial resolution (~70µm). A more detailed arrangement of the *LDA* system and the signal analysis method applied in this study is given elsewhere [12].

Table 1. Physical properties of the liquids used.

	<i>index</i>	% w/w	ρ kg/m ³	σ mN/m	μ mPa.s	<i>T</i> °C
water	w	-	1000	72	1.00	22
glycerin 1	<i>g1</i>	30.0	1090	70	2.50	22
glycerin 2	<i>g2</i>	20.0	1050	70	2.00	22
Tween 80®	<i>T</i>	0.15	1000	45	1.03	22

To examine the liquid viscosity effects on the flow patterns, two aqueous-glycerin solutions (i.e. 20 and 30% w/w) were employed, whereas the effects of the reduced surface tension on the wave patterns was studied by adding a small amount of *Tween 80*®, a hydrophilic non-ionic surfactant (**Table 1**). Throughout this study two different definitions of the Reynolds number, *Re*, are used, i.e. the **superficial** $Re_{SL} = U_{SL}D/\nu_L$ and the **actual** $Re_L = U_L D_L/\nu_L$ based on the superficial liquid velocity, U_{SL} , and on the mean liquid velocity, U_L , respectively.

EXPERIMENTAL RESULTS

Liquid layer characteristics

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 previous paper Lioumbas et al. [5] provided an overview of the gravity-driven liquid layer interfacial structure, obtained both by visual observations (supported by fast video recordings) and liquid layer thickness measurements for **water** in inclined pipes. 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 appears to be practically smooth and undisturbed (*Region II*). At still 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. As the flow rate further increases, the solitary waves become more frequent, retain their original amplitude and tend to merge forming 3D structures (*Region IV*).

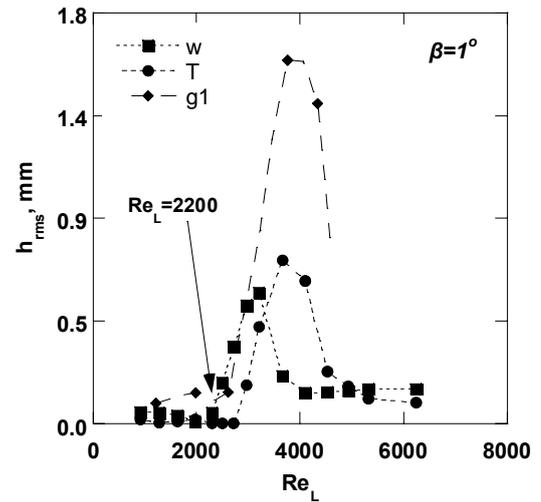


Figure 1: h_{rms} vs. Re_L for various liquids. Onset of the waves.

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 glycerin and Tween® solutions. The Regions reported for free flowing water in the previous paragraph are also recognized for the Tween® and the glycerin solution (*g1*). The gravitational waves observed in *Region I* when tap water is used, disappear when a small quantity of the surfactant Tween® is added to the water. The above observation is in agreement with the remarks of Spedding & Hand [10] who report that the small amplitude gravitational waves on the liquid surface are suppressed due to the addition of the surfactant. *Region II* is observed for all the liquids employed. *Region III*, which is related to the appearance of the large amplitude waves, begins at the same Re_{LC} for both the water and the increased viscosity glycerin solutions. However, Re_{LC} is shifted to higher

values for the Tween[®] solution and the maximum h_{rms} value is 25% larger than that of water, a fact attributed to the reduced surface tension of the Tween[®] solution. *Region IV* cannot be attained in the case of glycerin solutions, due to limitation of the experimental setup. Visual observations reveal that the Re_{LC} values fall between 2100 and 2300, except for the Tween[®] solution, which displays transition at **larger** Re_L (i.e. $Re_L \sim 2500-2800$) for all inclination angles tested (**Fig. 2**). These observations are in agreement with Barnea et al. [1] and Lioumbas et al. [5] who report that the appearance of large amplitude waves depends on the liquid flow rate and must be associated with the type of flow inside the liquid layer (i.e. laminar or turbulent).

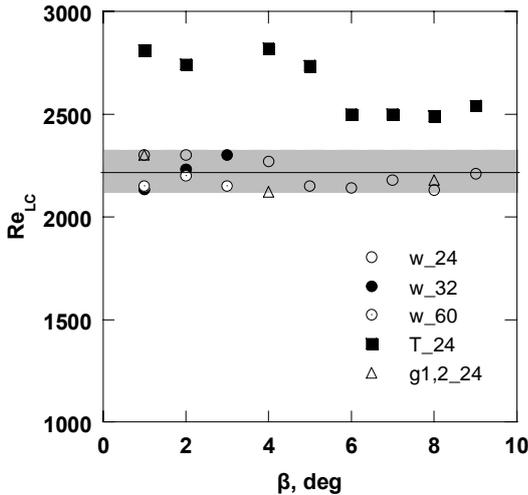


Figure 2: Effect of pipe inclination and liquid properties on Re_{LC} , for various pipe i.d.

Furthermore for all the liquids tested, the calculated h_{mean} , decreases as the pipe inclination increases (**Fig. 3**). The experimental results (h_{mean}) are in good agreement with the model proposed by Lioumbas et al. [5], based on simplified force balance which takes into account the type of flow prevailing inside the layer.

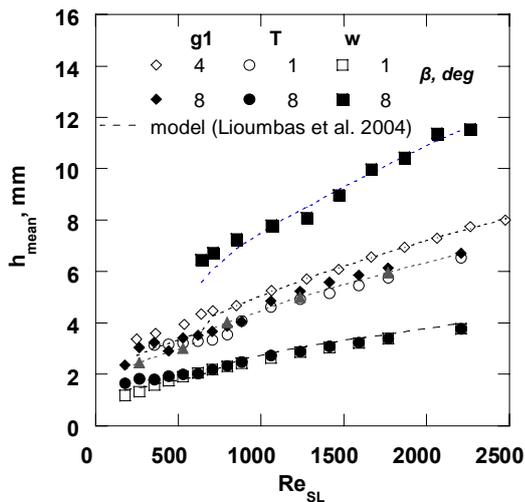


Figure 3: h_{mean} vs. Re_{SL} for all liquids tested and for various pipe inclinations.

The influence of the **gas flow** on the appearance of the waves on the gas-liquid interface as well as the liquid layer characteristics was also studied. Starting from liquid flow in the absence of gas and a smooth interface, the gas flow was increased until the *first* solitary wave appearance for all the liquids employed. From visual observations it was found that for tap water and glycerin solutions small amplitude waves exist between the large solitary waves, whereas for the reduced surface tension solution these waves are suppressed. A further increase of the gas flow leads to more frequent fluctuations, whereas for even higher gas flow rates the solitary waves tend to merge and high-frequency 3D small-amplitude waves are formed on the liquid interface.

Typical liquid layer traces at a constant liquid flow rate corresponding to free flow of water and glycerin (*g1*) (for $\beta=1^\circ$) with a smooth interface are shown in **Fig. 4a**; in both cases $Re_L=2000$. By increasing gas flow to $U_{SG}=3\text{m/s}$, the interface is disturbed with large amplitude waves (**Fig. 4b**). It is interesting that in both cases $Re_L=2300$ and this holds true for all cases tested for water and the viscous glycerin solutions. However, when the surfactant solution is used the Re_L related with the onset of the waves on the gas-liquid interface is shifted to lower values (i.e. at Re_L in the range 1800-2300).

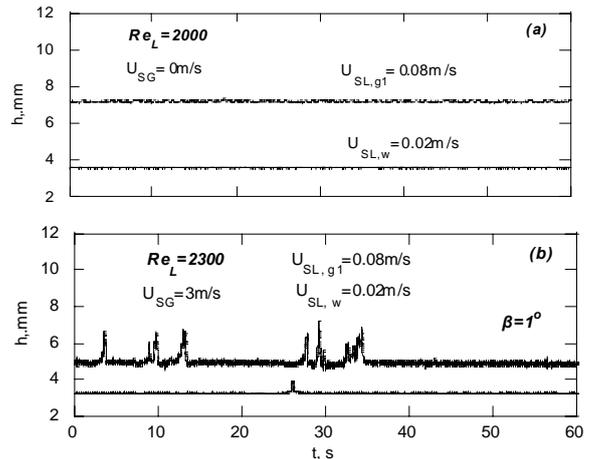


Figure 4: Typical layer thickness traces for: a) free flowing layer ($U_{SG}=3\text{m/s}$); b) co-current air-liquid flow ($U_{SG}=3\text{m/s}$) for glycerin and water, $\beta=1^\circ$.

In a flow pattern map (**Fig. 5**) where the stratified smooth and wavy regions are marked, it is shown that the boundaries for the wavy stratified region are the same for the water and the Tween[®] solution. However, the transition to wavy stratified region occurs at higher gas flow rates (than for water and Tween[®]) as the liquid viscosity is increased. The model proposed by Taitel & Dukler [3], showed in dash in **Fig. 5**, predicts that as the liquid viscosity is increased the transition to wavy stratified region occurs at higher liquid flow rates, a fact confirmed by the present experimental data. However, the drawback of this model is that it does not take into account the influence of liquid layer characteristics on transition, which is found here to be significant.

Measurements and visual observations reveal that the transition from smooth to wavy stratified two-phase flow (for

water and glycerin solutions) occurs in a narrow Re_L range (approximately 2100 and 2300) which is in agreement with the results concerning the transition from smooth to wavy interface in free flowing liquid layers^[5]. However, for the surfactant solution it is observed that as the gas flow rate increases the first solitary wave appears at a lower Re_L than the corresponding for water and glycerin solutions. An explanation of this observation is based on the fact that, although the h_{mean} values for Tween[®] decrease with gas flow, they still remain higher than these of pure water and glycerin solutions, for all the gas and liquid flow rates tested.

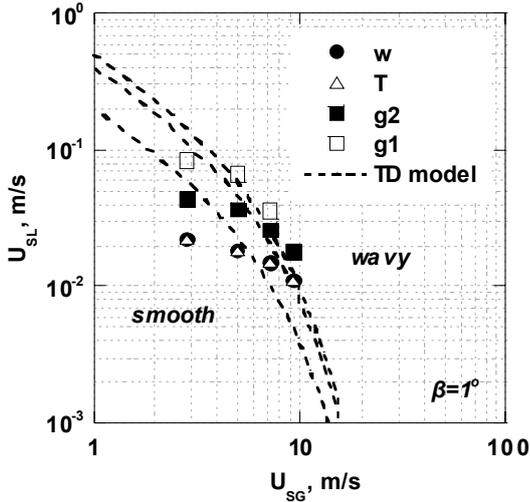


Figure 5: Effect of fluid properties on transition to wavy stratified flow, comparison with Taitel-Dukler model, $\beta=1^\circ$.

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 (**Fig. 6**). It is clear that the water and glycerin solutions exhibit the same behavior, whereas for the Tween[®] solution the thickness reduction is much smaller and leads to smaller mean liquid velocity (compared to that for pure water for the same liquid volumetric flow rate). As a result, the Re_L corresponding to water and glycerin solutions is higher than the one associated with the surfactant solution. Spedding & Hand^[10] and Soleimani et al.^[11] have also observed that the addition of very small quantities of polymers in water results in significant increase of the liquid hold up (up to 30%) compared to that of pure water as well as in the reduction of the wave amplitude (i.e. h_{rms}) despite the reduced surface tension. Several researchers^[10, 11] attribute this fact either to an increased surface viscosity or to the turbulence damping at the liquid interface. In summary, the smooth-to-wavy flow transition Re_L for the surfactant solution is smaller than that for the water and glycerin solutions, also suggesting that a similar trend may hold true in the case of transition to turbulence with these fluids.

Axial velocity in liquid phase

In order to examine the flow type which prevails under the interface before and after the wave appearance, the liquid velocity profile is measured for various flow rates and for all liquids tested in the *absence of air*. In **Fig. 7** a typical axial velocity trace at $y=2.0\text{mm}$ from the pipe wall and the corre-

sponding layer thickness trace (at the same location across the pipe) are presented, for a liquid flow rate corresponding to the appearance of the first large wave on the interface ($Re_L=2800$). It is obvious that the solitary wave appearance is directly related to the local axial velocity fluctuation; this is observed in all experiments regardless of the liquid employed. Evidently, a local minimum of the U_z trace is related to the appearance of a wave.

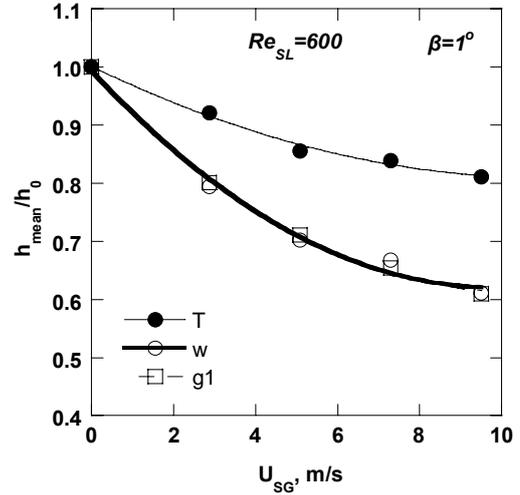


Figure 6: Normalized h_{mean} with respect to the corresponding h_0 vs. U_{SG} ; for water, Tween[®] and glycerin ($\beta=1^\circ$).

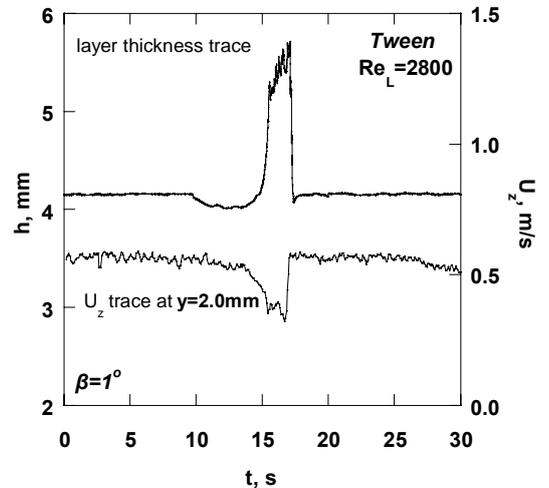


Figure 7: Simultaneous layer thickness and U_z traces for Tween[®], $\beta=1^\circ$ (at $y=2\text{mm}$ from pipe wall).

In **Fig. 8** typical plots of the normalized axial velocity versus the normalized distance from the pipe wall (for Tween[®] and water, $\beta=1^\circ$) are presented. The comparison with the von Karman universal distribution reveals that for $Re_L=2000$ the water flow is laminar, for $Re_L=2300$ is in the transitional region, while for $Re_L=5500$ is turbulent. It is interesting that for the Tween[®] solution the flow continues to be in the laminar region even for $Re_L=2300$, a fact that may be expected since the small addition of surfactants in the water apparently causes drag reduction^[10, 13].

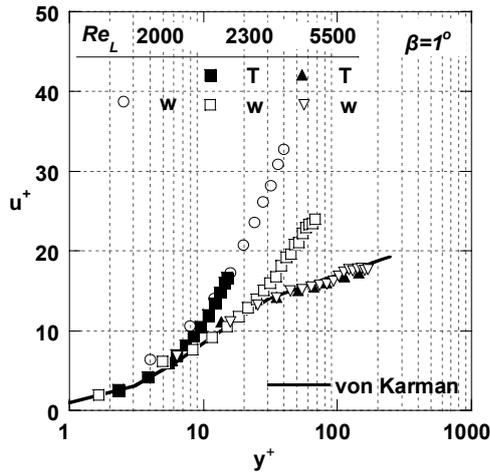


Figure 8: Comparison of experimental data for water and Tween[®] with von Karman universal velocity distribution ($\beta=1^\circ$).

An attempt was also made to explore the potential of a commercial CFD code, namely CFX[®] 5.7, for computing detailed characteristics of the *free flowing liquid layer* in both the laminar and turbulent regime. The pipe diameter, as well as the measured mean liquid thickness, h_{mean} , is used for constructing the 3D computational domain (Fig. 9). The mean velocity of the liquid phase is applied as boundary condition at the channel entrance (i.e. Dirichlet BC on the inlet velocity). No-slip condition, i.e. zero streamwise velocity, is employed on the pipe wall, while a free slip condition, i.e. zero shear stress, is used to represent the flat gas-liquid interface. A simple model appropriate for laminar flow is used for the laminar flow case, whereas a $k-\omega$ based Shear-Stress Transport (SST) model, recommended for high accuracy boundary layer simulations [14], was employed for the turbulent case. The calculated values are found to be in good agreement with the experimental ones both for the laminar and the turbulent flow regime (Fig. 9).

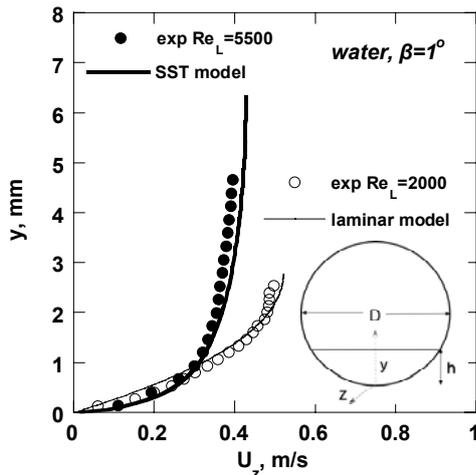


Figure 9: Comparison of experimental data for water with CFD results, $\beta=1^\circ$.

In order to clarify how the interfacial waves may interact with the *co-current airflow* it is useful to examine the velocity profile within the liquid layer for various gas and liquid flow rates. For low gas and liquid flow rates, the liquid layer velocity profile maintains typical laminar flow characteristics. For higher liquid flow rates, where the liquid surface is dominated by 3D small amplitude high-frequency waves, the liquid flow displays typical turbulent characteristics; e.g. it is shown that the turbulence intensity value, u'/u^* , has a maximum at $y^+\sim 13$ and the slope of the PSD in the high frequency range is roughly $-5/3$, as in the case of turbulent single phase flow [7]. However, the mean axial velocity, U_z , deviates from the von Karman distribution as the gas flow rate increases [5, 12].

As shown in Fig. 10, where U_z measurements are presented for water and Tween[®], a significant alteration (i.e. reduction) of the axial velocity close to the gas-liquid interface is evident for water but not for the Tween[®] solution. An explanation for this alteration in the case of water may be based on the existence of strong normal velocity components and the kinetic energy transfer from the faster moving gas to the liquid, as Paras & Karabelas [12] have pointed out. In the case of the surfactant (Tween[®]) addition, the liquid layer displays a behavior drastically different than that of pure water. It is likely that such surfactants act in the following ways:

- weaken the turbulent ejection and sweep events within the liquid layer, which is manifested as drag reduction [13]
- damp the waves at the interface and destroy the turbulence structures in the liquid phase [11]; it is possible that significant alteration of the energy exchange process at the interface due to elasticity changes, finally leads to reduced turbulence.

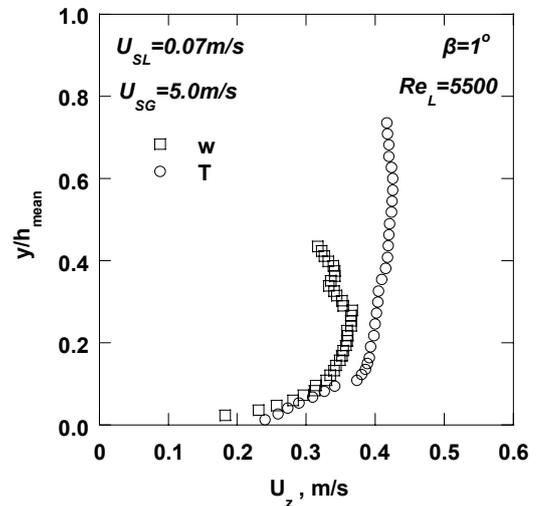


Figure 10: Axial velocity profiles for water and Tween[®], for the same flow rates, $\beta=1^\circ$.

CONCLUSION

New experimental data are reported concerning liquid layer thickness and axial velocity distribution for liquid down-flow in inclined pipes with and without co-current gas flow. Several liquids are employed to study the effect of physical properties.

In free flowing liquid, it is observed that large-amplitude waves first appear in a narrow range of $Re_L \sim 2100$ to 2300 ; these waves are related to changes within the liquid flow field and specifically to the transition from laminar to turbulent flow (regardless of inclination angle). This holds true for the water and the glycerin solutions, whereas for the Tween[®] solution it is found that the transition to wavy flow occurs at higher Re_L ($Re_L \sim 2800$). The axial liquid velocity measurements show that this “delayed” wave appearance with Tween[®] solution is related to turbulence damping in the liquid layer, possibly due to the drag reduction effect of the surfactant.

For co-current gas-liquid downflow, the transition to wavy stratified flow occurs in a narrow Re_L range near that for the appearance of solitary waves in the free flowing layer. However, for the Tween[®] solution the first large amplitude wave appears at lower Re_L as the gas flow rate increases. 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 mass conservation, h_{mean} appears to be 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. Consequently, the transition to wavy stratified flow occurs at lower Re_L . Finally local axial velocity measurements under the Tween[®] interface in two-phase flow suggest that the interface waves induced by both the air and the liquid flow rate generate turbulent structures that may be “absorbed” due to the drag reducing effect of the surfactant.

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NOMENCLATURE

D	pipe diameter, m
D_L	hydraulic diameter, m
f_m	modal wave frequency, s^{-1}
h	height of liquid layer, m
h_{mean}	mean height of liquid layer, m
h_{rms}	root mean square (<i>rms</i>) of the fluctuations of h , m
Re_L	actual Reynolds number based on D_L , dimensionless
Re_{SL}	superficial Reynolds number, dimensionless
Re_{LC}	actual Reynolds number (where the first solitary waves appear), dimensionless
Q	volumetric flow rate, m^3/s
u'	<i>rms</i> of axial velocity, m/s
u^*	friction velocity, m/s
U_L	mean liquid velocity, m/s
U_{SL}	superficial liquid velocity, m/s
U_z	time-averaged axial velocity, m/s
y^+	distance from wall, dimensionless

Greek letters

β	angle of inclination with respect to horizontal, deg
μ	molecular viscosity, kg/ms
ν	kinematic viscosity, m^2/s

ρ density, kg/m^3

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