# An experimental study of liquid films flowing down a vertical plate for low Reynolds numbers: effect of surface tension

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## 1. INTRODUCTION

Understanding flow of thin liquid films falling under the influence of gravity is of fundamental interest in designing a variety of industrial equipment, including wetted-wall absorbers, falling-film chemical reactors, condensers and other processes involving interfacial heat and mass transfer. The experimental work reported herein is part of an effort to elucidate the characteristics of such falling films and in particular of surface waves, at relatively small liquid Reynolds numbers ($Re_L$). Previous studies in this Laboratory [1,2,3] of counter-current gas-liquid flow inside narrow vertical channels, suggest that the (gravity-induced) structure and evolution of free falling films play a decisive role in flooding phenomena. Additionally, the liquid properties, and in particular surface tension, appear to significantly affect flow development.

## 2. EXPERIMENTAL SET-UP AND PROCEDURE

Experiments were carried out in a 70cm high and 12cm wide vertical rectangular channel made of Plexiglas with 10mm spacing between the two parallel plates. Liquid phase was introduced at the top of the channel and removed from the bottom via porous sections covering the entire active channel width. The length of the plate between porous sections was 38cm. The test section surface was treated with a silica solution in order to improve its wettability. Visual studies of the flow pattern were made using a *Redlake MotionScope PCI®* high-speed camera, either slightly above the liquid exit or below the liquid entrance section. Film thickness characteristics were also measured, using a "parallel-wire conductance" technique. Three liquids with *σ= 40, 50* and *75mN/m* were used; i.e. 2.5% and 1.5% w/w *butanol solutions* and *water*.

## 3. RESULTS

### *Visual observations*

The pictures in ***Figure 1*** are an example of liquid film development for *water* and *2.5% butanol solution* near the liquid entry for two values of $Re_L$, which is defined as $4\Gamma_L/\mu_L$, where $\Gamma_L$ is the liquid mass flow rate per unit length of plate width and $\mu_L$ the liquid viscosity. The film appears to be initially smooth and undisturbed. Downstream nearly two-dimensional waves develop first, traveling a significant distance without any noticeable change in their shape, eventually evolving into a three-dimensional, small-amplitude wave structure. This behavior is very similar to that observed in previous free falling film studies [1,3,4]. Increasing the liquid rate leads to an extended ripple-free entry region, while for relatively low flow rates, the onset of waves appears closer to liquid entry [4,5,6]. Also, one can see the effect of surface tension on the wave inception line; i.e. for water at $Re_L=128$ the waves make their appearance at a distance of approx. 10cm from liquid entry, while for the butanol solution at $Re_L=122$ waves are observed at a distance of approx. 5cm. The same trend is observed for higher $Re_L$ values; i.e. for the higher interfacial tension water there is a longer smooth-film entry region, compared to butanol solution, before the first wave is observed.

***Film thickness characteristics***

Instantaneous film thickness measurements were made at various locations along the channel, for the three liquids at relatively low $Re_L$ ($Re_L<350$), using the "parallel-wire conductance" technique. Detailed falling film characteristics (i.e. mean film thickness and *RMS* values, wave amplitude, frequency and celerity) were obtained through a statistical data treatment. In ***Figure 2*** the mean *wave height* above the substrate, $\Delta h$, is plotted versus the corresponding $Re_L$, at a typical location of 19cm from the liquid entry, where the liquid film seems to be developed. It appears that, for all liquids examined, the waves grow in amplitude by increasing $Re_L$, but $\Delta h$ seems to remain nearly constant above $Re_L$~200 (for the $Re_L$ range of the present observations). Another interesting feature is the greater values of $\Delta h$ corresponding to butanol solutions, which is attributed to the lower surface tension of these solutions, compared to water, that facilitates wave development. The same trend is observed for the *RMS* values of film thickness fluctuations.

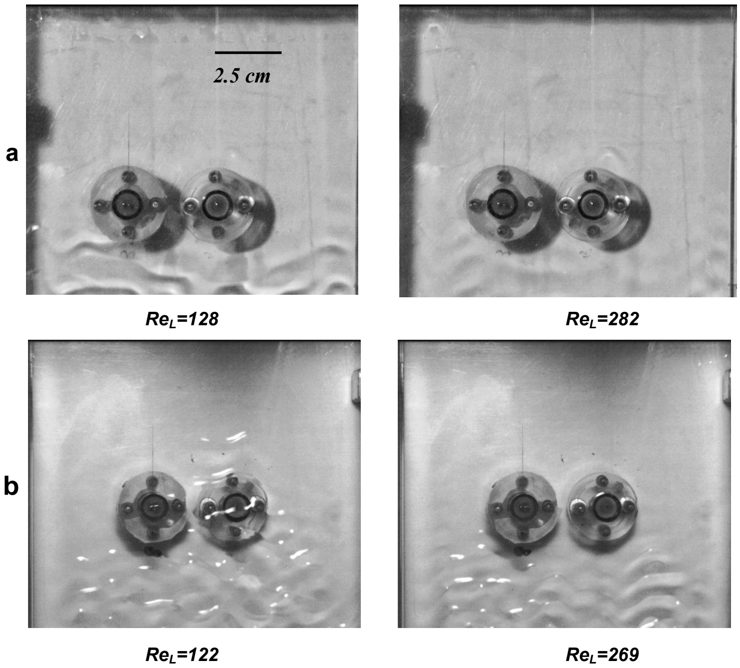


**Figure 1.** Liquid film flow on a vertical wall for two typical $Re_L$: a) water and b) 2.5% butanol solution

The power spectral density (PSD) distributions of the film thickness fluctuations, display a very pronounced maximum *wave frequency* between 17 and 20Hz (for all liquids). This dominant frequency is weakly dependent on $Re_L$, which is in good agreement with earlier findings [5, 7]. This modal frequency appears to be lower for the lower surface tension butanol solutions compared to water. As expected, the peak of the *modal frequency*, which is associated with the energy conveyed by the waves, is significantly increased both with $Re_L$ and surface tension. This is attributed to the fact that the lower surface tension butanol solution results in larger amplitude waves compared to water.

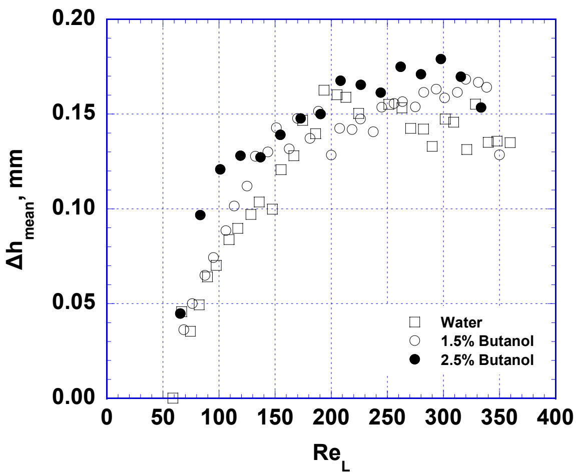


**Figure 2**. Free falling film mean wave height vs $Re_L$

*Celerities* of the surface waves were calculated by cross-correlating two film thickness traces recorded simultaneously at two neighboring points. The average wave celerity increases for all liquids with increasing $Re_L$, attaining larger values for water. This increase is especially pronounced in the low $Re_L$ region ($Re_L$<200).

## 4. CONCLUDING REMARKS

Free falling films for all liquids examined, display waves on the interface, even at low $Re_L$, which are nearly two-dimensional. For the higher $Re_L$ the wave-free region is longer but the two-dimensionality is maintained only near the entry region; downstream, waves evolve into a 3-D structure. Increased surface tension tends to extend the length of the wave-free entry region. Mean wave height and *RMS* values of film thickness fluctuations increase with increasing $Re_L$, but tend to attain a nearly constant value above $Re_L$ ~*200*. This increase is more pronounced for the butanol solutions. For the liquids examined, the dominant wave frequency appears to increase slightly with $Re_L$, with the greatest values for water. Both the energy conveyed by the waves, and the wave celerity depend on the liquid flow rate and surface tension. Information provided by these new data is considered helpful in efforts to clarify the mechanism by which flooding occurs in compact process equipment.

## 5. REFERENCES


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