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GRAVITY INDUCED MIXING OF MISCIBLE FLUIDS IN VERTICAL AND INCLINED TUBES

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Summary Gravity induced mixing of two miscible fluids in a long tube is studied as a function of the tube tilt angle from vertical θ and of the density contrast characterized by the Atwood number At. At high At values and/or low θvalues, the relative concentration of the two fluids follows a macroscopic diffusion law characterized by a diffusion coefficient D increasing strongly with the tube tilting (by a factor of 100 between 0 and 70^o). At higher θ values and/or for low density contrasts, a segregation of the two fluids in the tube section is induced by gravity resulting in a stable counterflow with little mixing at the interface. The value of At at the transition between the diffusive and counterflow regimes increases with the θ from $At = 10^{-4}$ for $\theta = 0^o$ to $At = 5 \times 10^{-2}$ for $\theta = 80^o$.

OBJECTIVES AND PRINCIPLE OF EXPERIMENT

Buoyant mixing of miscible fluids of different densities ρ_1 and ρ_2 in gravitationally unstable configurations in vertical or inclined channels is frequently encountered in chemical and petroleum engineering[1] as well as in fire propagation in shafts[2] : in the present work we study experimentally the influence of the tilt angle on these mixing processes.

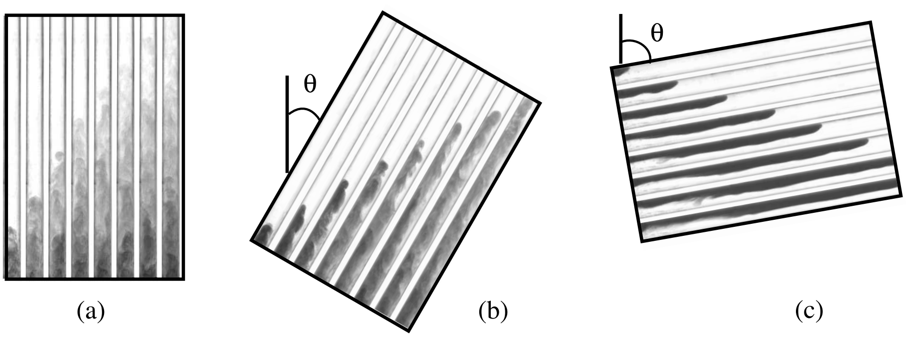

Figure 1. Sequences of pictures obtained right after beginning of experiments for three different tilt angles $\theta = 0, 30, 80^o$. Atwood number $At = 4 \times 10^{-3}$. Respective durations of sequences = 50 s, 20 s and 20 s.

Experiments are realized in a 4 m long transparent tube of diameter $d = 20\ mm$ with a slot valve in the middle[3, 4]. The tilt angle θ varies from 0 to 90^o. The lighter fluid is dyed water and the heavy fluid is a solution of water and $CaCl_2$ salt. Density contrasts are characterized by the Atwood number $At = (\rho_2 - \rho_1)/(\rho_2 + \rho_1)$ varying from 2×10^{-5} to 10^{-1}. The upper and lower halves of the tube are initially filled with the heavy and light solutions and mixing is initiated by opening the slot valve. Figure 1 displays the flow above the slot valve for three different angles θ. Increasing θ results in a transition from weakly turbulent mixing to fully stratified flow with no transverse mixing.

EXPERIMENTAL RESULTS

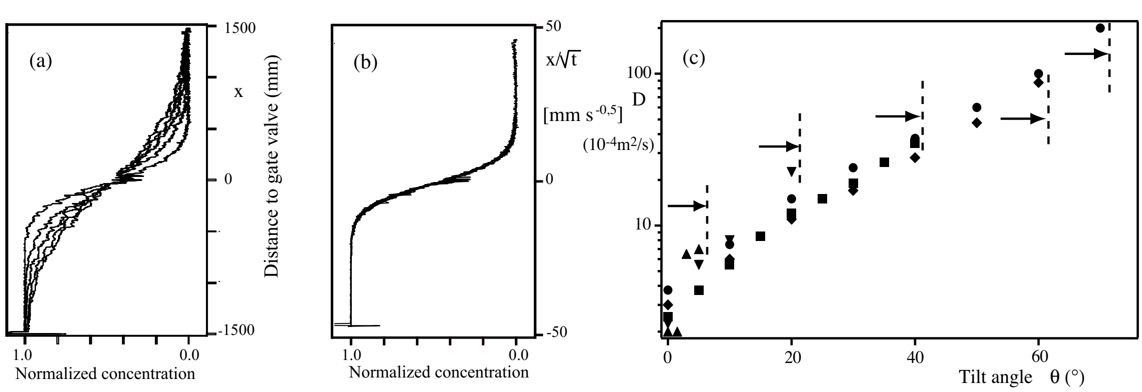

Figure 2. Normalized concentration profiles obtained at successive times $t = 100, 300, 500, 700$ and $900s$ for $\theta = 0^o$ and $At = 4 \times 10^{-3}$ - (a) profiles plotted vs distance x from slot valve. - (b) profiles plotted vs $x/\sqrt{t}$. - (c) Variation of diffusion coefficient D with the tilt angle θ for different density contrasts. ● : $At = 3.5 \times 10^{-2}$, ◆ : $At = 10^{-2}$, ■ : $At = 4 \times 10^{-3}$, ▼ : $At = 10^{-3}$, ▲ : $At = 4 \times 10^{-4}$). Arrows mark the values of θ corresponding to the upper limits of the diffusive domains for the various contrasts.

The tube is illuminated from the back and digital images are recorded at regular intervals. They are translated into normalized concentration maps and averaged over the width of the tube to obtain mean concentration profiles $\overline{C}(x,t)$. Figure 2a displays such profiles measured at regular time intervals in a weakly turbulent regime in a vertical tube. All profiles overlay perfectly when plotted as a function of $x/\sqrt{t}$ (Figure 2b) and are well fitted by an error function (continuous line). The mixing process is therefore diffusive and the fit provides the value of the corresponding macroscopic diffusion coefficient D. These diffusive characteristics are only observed up to a limiting tilt angle which gets larger as At increases.

The variation of D with the tilt angle θ is plotted in Figure 2c for different density contrasts. A key feature is the very strong increase of D with θ (by a factor of 100 between $\theta = 0^o$ and 70^o). On the contrary, for a given tilt angle, D increases only weakly with At. For tilt angles higher than the limit of the diffusive domain, the instabilities of the interface beween the two fluids do not develop : this reduces transverse mixing across the tube section. At very large tilt angles, one reaches a final state in which the two fluids are segregated in a *stable* configuration.

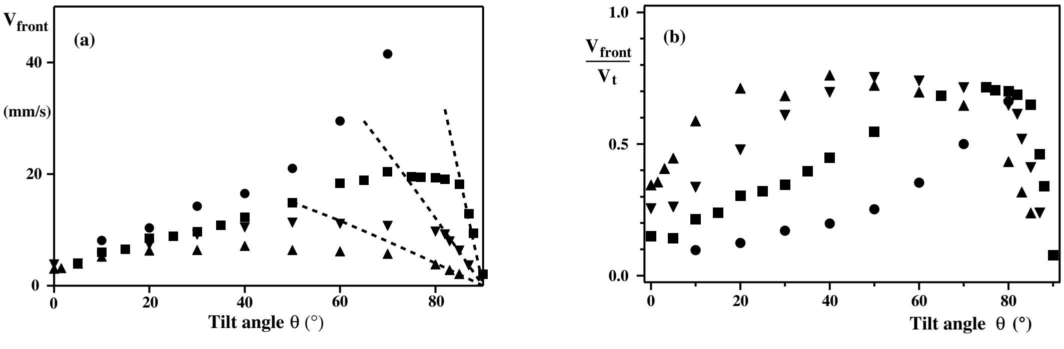

Figure 3. (a) Mixing front velocity variation as a function of tilt angle θ - (b) Normalized velocity V_{front}/V_t as a function of θ. ● : $At = 3.5 \times 10^{-2}$, ■ : $At = 4 \times 10^{-3}$, ▼ : $At = 10^{-3}$▲ : $At = 4 \times 10^{-4}$.

Another important parameter is the velocity V_{front} of the upper and lower fronts marking the limit of the penetration of each fluid into the other. Figure 3a displays the variation of V_{front} with the tilt angle θ for several values of the Atwood number At. A clear-cut feature is the strong initial increase of V_{front} with θ. On the contrary, for very large tilt angles close to $90\,^o$, V_{front} decreases sharply : it is likely that, in this latter domain, the potential energy gained from buoyancy forces just compensates for viscous dissipation in the counterflow of the two fluids (dotted lines in Figure 3a are the corresponding theoretical velocity variations). At the low θ values, flow is determined by a balance between inertia and buoyancy forces : the characteristic velocity of this mechanism is $V_t = \sqrt{Atgd}$. Figure 3b shows that the ratio V_{front}/V_t is at first lower than 1, indicating a lower effective density contrast at the front due to local mixing and becomes of the order of 1 when the two fluids are segregated. The increase of V_{front}/V_t is much slower at the largest density contrasts - also due to a stronger mixing.

CONCLUSION

These experiments illustrate that tilting the tube slows down transverse mixing across the flow section and influences strongly the interpenetration of the fluids. For moderate tilt angles θ and high enough Atwood numbers At, mixing is diffusive : the diffusion coefficient D increases very fast with θ but is almost independent of At. At larger angles, a stable counterflow of the fluids with almost no transverse mixing takes place. The transition between these regimes occurs at larger angles whenAt increases. Both the variation of D and that of the mixing front velocity depend strongly on the *local* density contrasts in the flow and not only on At. These local contrasts are very much influenced by the efficiency of mixing and then by the tilt angle. A full understanding of these processes requires therefore a small scale analysis of the spatial and temporal characteristics of the velocity and concentration fluctuations in the flow.

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