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Drops on a resonantly forced interface

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Abstract. – We present experimental results about drops moving on a liquid-vapour CO_2 interface externally and periodically excited by moving the container perpendicularly to gravity.

Introduction. – Drop creation and behaviour has been an interesting field of research for many years, due to its applicability to raindrop formation, preparation and stability of emulsions and foams, fluid-fluid extraction, nuclear fusion, spraying processes, etc. Previous works in this field concern drop and interface shapes and coalescence times [1], [2] or coalescence and bouncing in droplet collision, principally of hydrocarbon drops in gas phases [3], [4], or coalescence and bouncing of water charged/uncharged drops at an air-water interface [5], among others. Also, there are papers about stability of drops under pressure fluctuations [6].

We present some new experimental results about CO_2 drops moving on a CO_2 liquid-vapour interface mechanically excited. CO_2 liquid phase fills half of a cylindrical tube placed horizontally and moved along its main axis perpendicular to gravity with a periodic force for a wide range of excitation frequencies (10–110 Hz). This experimental set-up (fig. 1) was used to study interfacial waves excited when the tube was moved [7]-[9]. In this experimental context, it is necessary to define a *structure observation threshold* (s.o.t.), which is the minimum excitation amplitude necessary to detect the minimum observable interface deformation in the measuring region (for a detailed discussion see [8], [9]). When the s.o.t. is reached we observe quasi-linear waves at the interface. For excitation amplitudes where non-linear effects become important, drops appear at the end walls and move to the centre of the tube (as well as other types of localized structures like non-propagating solitons and defects [9]). These drops remain on the interface for relatively long times compared to the rest of characteristic times of the experiment and they annihilate either by coalescence with the interface or by drop collision or by collision with the walls. They appear at a given excitation frequency for excitation amplitudes greater than a creation threshold, afterwards they move along the tube on the interface and interact with surface waves, walls and other drops. The annihilation of these drops occurs at a different threshold showing hysteresis.

Experimental set-up. – The experiments were performed using a Natterer tube, which is a CO_2 filled tube at vapour pressure for room temperature (20°C). In these conditions, the physical characteristics of the fluids are [10] $\rho_l = 773$ kg/m^3, $\rho_g = 189$ kg/m^3, $\nu_l = 9.2 \cdot 10^{-8}$ m^2/s, $\nu_g = 7.8 \cdot 10^{-8}$ m^2/s, $\sigma = 1.16 \cdot 10^{-3}$ kg/s^2, where l and g subscripts mean

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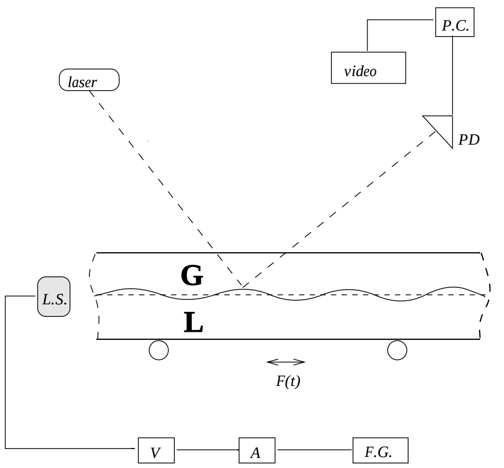


Fig. 1

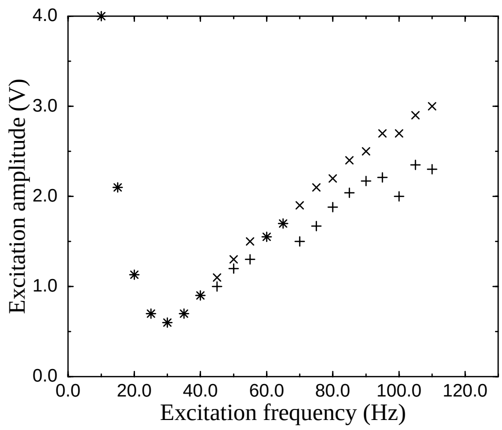


Fig. 2

Fig. 1. – Sketch of the experimental apparatus. LS, A, V, PD, G and L mean loudspeaker, amplifier, voltmetre, photo-detector, gas phase and liquid phase.

Fig. 2. – Drop creation and annihilation thresholds. Cross signs mean the drop creation threshold and plus signs the annihilation one. Star signs mean that both thresholds are the same.

liquid and gas phase and ρ, ν, σ are density, kinematic viscosity and surface tension. The used tube is cylindrical (diametre = 1 cm, length = 28 cm) and is mounted in a metallic holder (fig. 1). The CO_2 liquid phase fills just one half of the whole volume of the tube; therefore, in its horizontal position the depth of the liquid phase is 0.5 cm.

A sinusoidal mechanic force was applied by a loudspeaker in the direction of the long axis of the tube. We verified that the mechanical displacements of the tube were proportional to the loudspeaker applied voltages. The driving frequencies lie between 10 and 110 Hz (resolution = 10 mHz). A system of digitazion acquiring images directly by a CCD camera was used in order to study drops and their evolution when the control parameters (frequencies and amplitudes) were changed. In all the cases we synchronized the signal to avoid the stroboscopic effect. It has been observed that drops appear for the frequency range used and for excitation amplitudes greater than a threshold. This experimental set-up does not allow to control the drop creation process at the end walls. However, we give a qualitative explanation later.

Results. – We measured the drop creation threshold when at a given excitation frequency we slowly increased the excitation amplitude from 0 until any drop appeared. Also, to measure the drop annihilation threshold at a given excitation frequency and at a given excitation amplitude greater than the drop creation threshold, we slowly diminished the excitation amplitude until a regime without drops was reached. Both thresholds are shown in fig. 2. It can be seen that the creation threshold has the same behaviour as the s.o.t. cited above [8], [9]. As the s.o.t. is taken at constant interface deformation amplitude [9], it follows that the drop creation threshold depends much more on the interface deformation amplitude than on the excitation amplitude. Both thresholds shown in fig. 2 decrease for increasing excitation frequencies till a minimum and then increase. These thresholds present hysteresis at excitation frequencies greater than 65 Hz (clearly corresponding to capillary waves region). In the hysteresis region the annihilation threshold is significantly less than the creation threshold. We also took digitized images of a drop annihilation when the sustaining force is reduced below the annihilation threshold (fig. 3).

It was observed that the drops were created at the end walls of the tube except in fully developed turbulence regimes. Also, the number of drops increased monotonously when the

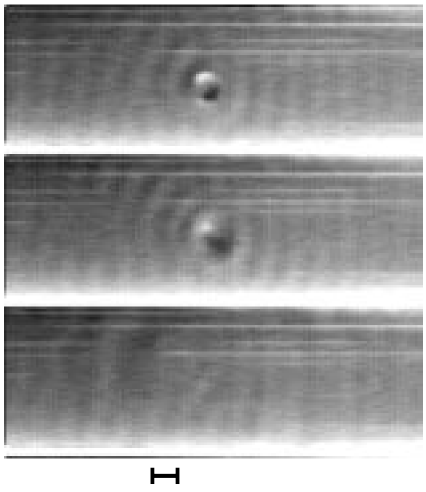


Fig. 3. – Consecutive images of a drop annihilation. The time interval between them is about 1/10 s.

excitation amplitude was increased. They had a well-defined diametre of the order of 1 mm, the diametre of the drops being very similar to the wavelength of the subjacent wave structure. It was observed that the drops moved on the interface at greater velocities than the velocity of the subjacent wave structure. When there were a few drops, they moved in a straight line at a constant speed in both directions along the tube. A sketch of the drops is shown in fig. 4. There the wave structure scale has been exaggerated for visualization. Figure 5 shows a spatio-temporal digitized image, composed of a line of pixels corresponding to the centre of the tube taken in increasing times, with drops moving in both directions along the tube at a constant speed in the measuring region. Also it can be seen that the trajectories are straight lines and that the speed of drops is much greater than the speed of the subjacent wave structure. The velocity difference between drops travelling in opposite directions was measured and it turns to be equal to the subjacent wave structure velocity (of the order of 1 mm/s for the capillary wave region). Therefore it can be said that drops move in a frame of reference which is the subjacent wave structure. In fig. 6 the absolute values of drop velocities at different excitation frequencies are shown for excitation amplitudes near the drop creation threshold. Error bars mean the range of allowed drop velocities at a given excitation frequency. It can be observed that the drop velocities have a maximum near 65Hz and they are of the order of $3 \cdot 10^1$ mm/s. When two drops collide they can: bounce and reach quickly the velocities before the collision (fig. 7), simply collide inelastically producing a single drop with a diametre greater than the usual one and therefore becoming unstable, and collide inelastically forming a new bound stable state of two drops moving together as shown in fig. 8. Similarly it is possible to observe bound states of more than two drops. In fig. 7 it can also be seen that the deformation

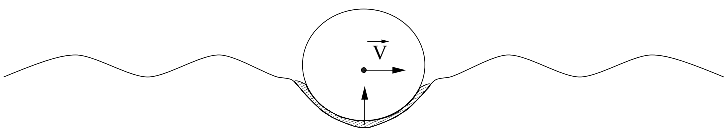
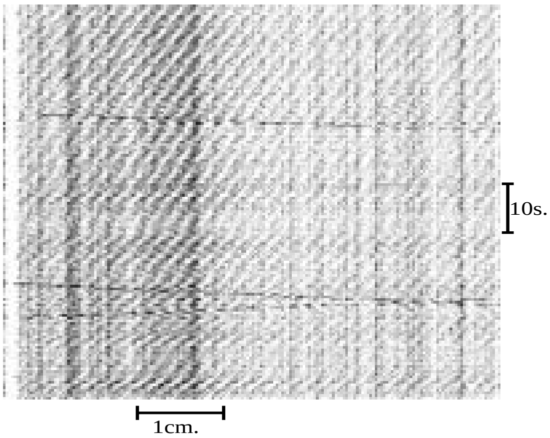


Fig. 4. – Sketch of a drop suspended on the interface moving in it. The vertical arrow shows the lifting force due to film overpressure and the horizontal arrow shows the direction of the movement related to the wave structure.



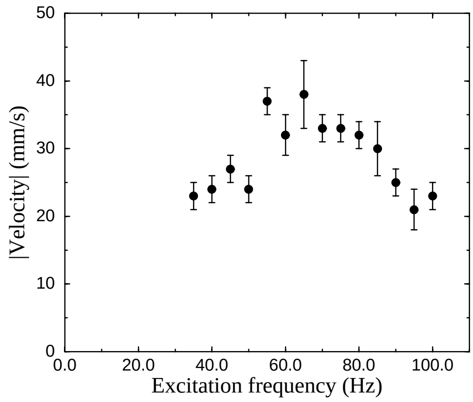


Fig. 5

Fig. 6

Fig. 5. – Spatio-temporal image of drop propagation (excitation frequency: 95 Hz).

Fig. 6. – Absolute value of drop velocities in the creation threshold for different excitation frequencies in laminar regimes (this excludes drops for excitation frequencies less than 35 Hz).

of drops in a collision is negligible. However, for drops much bigger (corresponding to lower excitation frequencies) this deformation can be visualized. The wave structure is only slighty deformed when a drop passes through.

Discussion. – Experimentally, it was verified that the drop creation occurs at the end walls of the tube. This effect may be explained considering that for a given excitation frequency when a certain interface deformation amplitude is achieved the subjacent waves impinge the end walls expelling drops. Thus, there is a threshold for the drop creation. Since the interface deformation amplitude at the end walls is related to the interface deformation amplitude and, consequently, to the s.o.t. as commented above, then it follows that the drop creation threshold has a similar qualitative behaviour. Also, it was experimentally observed that drop annihilation occurred anywhere on the interface. It is known that when a stable drop descends on the interface (assuming that one of the fluids is the same as the drop one), a film is produced, which thins in time, and the drop coalesces [1], [2], [5] at a film width of about 100 Å. We measured the film thinning time when no excitation force was applied and turned to be of the order of 1/2 s. When an excitation force is applied, there is a time and space periodic pressure field in both phases in such a way that there is a pressure difference between the two sides of the interface (Laplace law) which curves it. Besides, when a drop is on the interface, the gravity (plus buoyancy forces) acting upon the drop is balanced by this overpressure of the vapour film between the interface and the drop, allowing the drop to levitate. If the characteristic time of the periodic pressure field (or forcing) is less than the film thinning time, then this mechanism is sustained by the periodic interface deformation which replaces vapour periodically into the film. As the experimental applied frequencies give always characteristic times less than the film thinning time, we observe stable drops on the interface, providing that the pressure differences would be greater than the pressure due to gravity plus buoyancy forces. To estimate this, we just compare these two terms using the Laplace law for the one-mode approximation (that is a good approximation because of the small viscosity fluids we used) in order to achieve a closed relation with directly measurable quantities. A simple calculation gives: $4\pi^2\sigma\xi/\lambda^2 > \frac{2}{3}Rg(\rho_{\mathrm{l}} - \rho_{\mathrm{g}})$, where g is the gravity constant, λ the wavelength, ξ the interface deformation amplitude and the other parameters are defined above. In this estimation the area where pressure acts is taken to be $2\pi R^2$ as a simple

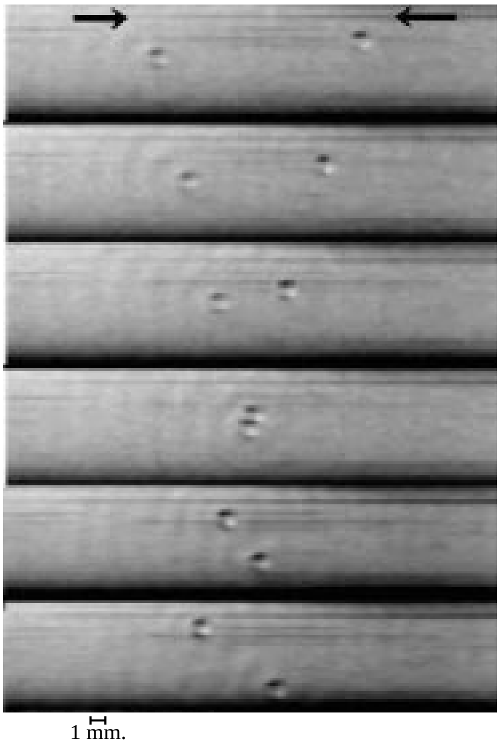


Fig. 7

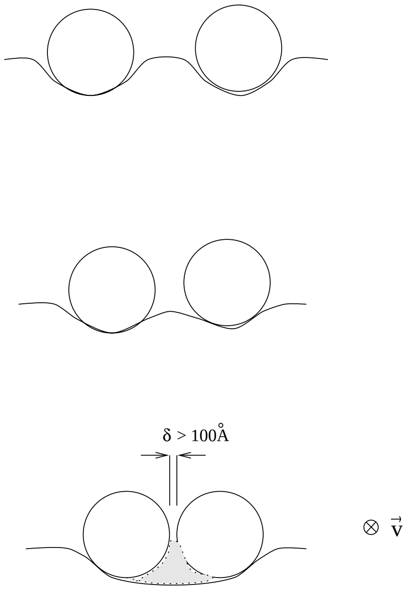


Fig. 8

Fig. 7. – Collision and bouncing of two drops moving in opposite directions and equal speed. The time interval between images is of the order of 1/10 s.

Fig. 8. – Sketch of the generation of a two drops bound state.

approximation. To check the orders of magnitude we consider an excitation frequency of 50Hz, which experimentally gives a wavelength of 1.6 mm. Then, it is necessary to have an interface deformation amplitude greater than 0.2 mm in order to have stable drops, which matches with the expected interface deformation. Also, the drop annihilation threshold behaviour is reproduced as follows: if the excitation frequency is increased, then the wavelength of the subjacent wave structure decreases, and then by the equation given above the necessary subjacent wave structure amplitude decreases. This makes the appearance of hysteresis for high frequencies possible because the drop creation threshold behaves like the s.o.t. and then it is higher than the drop annihilation threshold. Also, this permits the existence of stable drops for high frequencies at subjacent wave structure amplitudes less than those corresponding to the s.o.t. In addition, if the excitation frequency is decreased then the necessary subjacent wave structure amplitude increases making the appearance of drops at laminar regimes for low excitation frequencies (gravity waves region) difficult. To estimate the drop diameters, it is necessary to take into account various phenomena. Besides the fact that the equation given above gives an upper bound to R, there is the principle of minimizing surface energy, which for a given volume tries to maximize the drop radius. Also, there is a loss of stability for drops with a diametre greater than the characteristic length of the pressure field (equal to the wavelength of the subjacent wave structure) [6]. The order of magnitude of the drop radius may be obtained considering the drop creation mechanism at the end walls referred to above. The displaced volume which produces the drop is of the order of magnitude of $\Delta x_0 \xi d/6$, where d is the tube width (10 mm), Δx_0 the tube displacement amplitude (about

1 mm) and ξ the wave amplitude at the end walls (about 3 mm). The $\frac{1}{6}$ factor is for taking approximately the cylindrical shape of the tube into account. Then, it is obtained that the drop radius is of the order of 1 mm according to experiments. It is possible to understand the drop velocities results taking into account the periodic horizontal gradient of the pressure field. On a drop with a large enough initial velocity acts a periodical force (due to the pressure field). Thus, drops may travel at an averaged constant speed on the interface, if the wave structure amplitudes are large enough. It happens that the drop rides the troughs of the subjacent wave structure, so the drop averaged constant speed is the interfacial wave phase speed. This is of about 80 mm/s, which is of the same order of magnitude as the measured drop speed. In addition it is possible to construct a drop movement equation from an irrotational model for the subjacent wave structure [9] consisting on calculating the pressure differences between the head and the back of the drop. Although it is beyond the scope of this letter, a nonlinear damped parametrically forced pendulum equation can be obtained, which gives the same results as those phenomenologically explained above. Also, according to the previous arguments, if the initial drop velocity is not large enough the drop oscillates in a wave trough, as was observed in experiments. When two drops collide, they bounce depending on the Weber number (which compares kinetic energy with surface energy) and on the impact parameter. For bouncing it is necessary that the Weber number be in a range, which exists depending on the ratio μ/σ [3], [4]. As Jiang *et al.* [3] reported, if this ratio increases the bouncing is favoured. In our case, the ratio is larger than the limiting case, then the drop bouncing is possible. Moreover, the interface also favoured the bouncing of drops as can be understood by means of fig. 8, which also explains the formation of a bound state as explained below. When two drops approach on the interface a high-pressure region is formed (marked in fig. 8) between both drops which can make the drops bounce even at high-velocity collisions. The drop collisions (fig. 7) seem to be elastic, in conflict with [5] where a great loss of kinetic energy in the collisions has been measured. In order to explain this discrepancy, we can consider that the loss of kinetic energy in the collision is quickly restored (and, consequently, also the drop velocity is) by the subjacent wave structure. This result reinforces previous arguments about drop constant-speed experimental results. If the drop collision is made at less velocities, it can occur that the high pressure commented above was not high enough to gain upon the attraction force due to the flattening of the region at the interface between the colliding drops (fig. 8), but high enough to balance it and avoid that the film would thin to the coalescence distance of 100 Å. In such a way it is possible to understand the appearance of stable bound states.

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