TITLE: Magnetically-Induced Rotating Rayleigh-Taylor Instability

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KEYWORDS:
interfacial instability, rotation, Rayleigh-Taylor instability, stratification, strong magnet field, paramagnetism, diamagnetism

SHORT ABSTRACT:

We present a protocol for preparing a two-layer density-stratified liquid that can be spun-up into solid body rotation and subsequently induced into Rayleigh-Taylor instability by applying a gradient magnetic field.

LONG ABSTRACT:

Classical techniques for investigating the Rayleigh-Taylor instability include using compressed gasses[1], rocketry[2] or linear electric motors[3] to reverse the effective direction of gravity, and accelerate the lighter fluid toward the denser fluid. Other authors[*e.g.* 4–6] have separated a gravitationally unstable stratification with a barrier that is removed to initiate the flow. However, the parabolic initial interface in the case of a rotating stratification imposes significant technical difficulties experimentally. We wish to be able to spin-up the stratification into solid-body rotation and only then initiate the flow in order to investigate the effects of

rotation upon the Rayleigh-Taylor instability. The approach we have adopted here is to use the magnetic field of a superconducting magnet to manipulate the effective weight of the two liquids to initiate the flow. We create a gravitationally-stable two-layer stratification using standard flotation techniques. The upper layer is less dense than the lower layer and so the system is Rayleigh-Taylor stable. This stratification is then spun-up until both layers are in solid-body rotation and a parabolic interface is observed. These experiments use fluids with low magnetic susceptibility, $|\chi| \sim 10^{-6} — 10^{-5}$, compared to a ferrofluid. The dominant effect of the magnetic field is to apply a body force to each fluid layer changing the liquid's effective weight. The upper layer is weakly paramagnetic and the lower layer is weakly diamagnetic so that as the magnetic field is applied, the lower layer is repelled from the magnet while the upper layer is attracted toward the magnet. The upper layer behaves as if it is heavier than it really is, and the lower layer behaves as if it is lighter than it really is. If the applied gradient magnetic field is large enough, the upper layer may become "heavier" than the lower layer and so the system becomes Rayleigh-Taylor unstable. and we see the onset of the Rayleigh-Taylor instability. We further observe that increasing the dynamic viscosity of fluid in each layer increases the observed lengthscale of the instability.

INTRODUCTION:

A density stratified fluid system consisting of two layers can be arranged in a gravitational field in either a stable or an unstable configuration. If the dense heavy layer underlies the less dense, light layer then the system is stable: perturbations to the interface are stable, restored by gravity, and waves may be supported on the interface. If the heavy layer overlays the light layer then the system is unstable and perturbations to the interface grow. This fundamental fluid instability is the Rayleigh-Taylor instability[7,8]. Exactly the same instability may be observed in non-rotating systems that are accelerated towards the heavier layer. Due to the fundamental nature of the instability it is observed in very many flows that also vary greatly in scale: from small-scale thin film phenomena[9] to astrophysical scale features observed in, for example, the crab nebula[10], where finger-like structures are observed, created by pulsar winds being accelerated through denser supernova remnants. It is an open question as to how the Rayleigh-Taylor instability can be controlled or influenced once the initial unstable density difference has been established at an interface. One possibility is to consider bulk rotation of the system. The purpose of the experiments is to investigate the effect of rotation on the system, and whether this may be a route to stabilization.

We consider a fluid system that consists of a two-layer gravitationally unstable stratification that is subject to steady rotation about an axis parallel to the direction of gravity. A perturbation to an unstable two-layer density stratification leads to baroclinic generation of vorticity, *i.e.*, overturning, at the interface, tending to break-up any vertical structures. However, a rotating fluid is known to organize itself into coherent vertical structures aligned with the axis of rotation, so-called 'Taylor columns'[11]. Hence the system under investigation undergoes competition between the stabilizing effect of the rotation, that is organizing the flow into vertical structures and preventing the two layers overturning, and the destabilizing effect of the denser fluid overlying the lighter fluid that generates an overturning motion at the interface. With increased rotation rate the ability of the fluid layers to move radially, with opposite sense to each other, in order to rearrange themselves into a more stable configuration, is increasingly inhibited by the Taylor-Proudman theorem[12,13]: the radial movement is reduced and the observed structures that materialize as the instability develops are smaller in scale. Fig. 1 shows qualitatively the effect of the rotation on the eddies that form as the instability develops. In the left hand image there is no rotation and the flow is an approximation to classical non-rotating Rayleigh-Taylor instability. In the right hand image all experimental parameters are identical to the left hand image except that the system is being rotated about a vertical axis aligned with the center of the tank. It can be seen that the effect of the rotation is to reduce the size of the eddies that are formed. This, in turn, results in an instability that develops more slowly than the non-rotating counterpart.

The magnetic effects that modify the stress tensor in the fluid may be regarded as acting in the same way as a modified gravitational field. We are therefore able to create a gravitationally stable stratification and spin it up into solid body rotation. The magnetic body forces generated by imposing the gradient magnetic field then mimic the effect of modifying the gravitational field. This renders the interface unstable such that the fluid system behaves, to a good approximation, as a classical Rayleigh-Taylor instability under rotation. This approach has been previously attempted in two dimensions without rotation[14,15]. For an applied gradient magnetic field with induced magnetic field $\boldsymbol{B}$, the body force applied to a fluid of constant magnetic volume susceptibility χ is given by $\boldsymbol{f} = \mathrm{grad}(\chi B^2/\mu_0)$, where $B = |\boldsymbol{B}|$ and $\mu_0 = 4\pi \times 10^{-7}$ N A^{-2} is the magnetic permeability of free-space. We may therefore consider the magnet to manipulate the effective weight of each fluid layer, where the effective weight per unit volume of a fluid of density ρ in a gravitational field of strength g is given by $\rho g - \chi\,(\partial B^2/\partial z)/(2\,\mu_0)$.

PROTOCOL:

NOTE: The experimental apparatus is shown schematically in Fig. 2. The main part of the apparatus consists of a rotating platform (300 mm × 300 mm) mounted on a copper cylinder (55 mm diameter) that descends under its own weight into the strong magnetic field of a superconducting magnet (18 T) with a room temperature vertical bore. The platform is made to rotate via an off-axis motor that turns a slip-bearing with a keyhole orifice. The copper cylinder is attached to a key-shaped drive shaft that simultaneously rotates, and descends once the holding-pin is removed.

1) Preparation of non-standard equipment

1.1) Flotation boat

1.1.1) Make the size of the boat such that it fits comfortably within the experimental tank without touching the sides.

NOTE: The flotation boat (see Fig. 3) consists of polystyrene walls and a sponge base.

1.1.2) Protect the sponge with a layer of strong tissue paper.

NOTE: The purpose of the tissue paper is to dissipate as much vertical momentum from the fluid poured into the boat as possible.

2) Preparation of Experiment

2.1) Preparation of liquid layers

2.1.1) Allow distilled water to come up to laboratory temperature (22 +/- 2 C). Approximately 650 ml is required for each experimental realization.

NOTE: Allowing the mixture to equilibrate prevents formation of bubbles in the experiment due to exsolving air.

2.1.2) Separate the distilled water into equal volumes in two separate containers, *A* and *B*, which will be used to prepare liquid for the dense lower layer and light upper layer respectively.

2.1.3) *Ex-situ* preparation of dense lower layer. To the contents of container *A*:

2.1.3.1) Add NaCl to achieve a concentration of 0.43 mol NaCl per liter of water (approximately 25 g of NaCl per liter of water will be required);

2.1.3.2) Add 0.33 g red and blue water-tracing dyes to the lower layer container (*e.g.*, Cole-Parmer 00295-16 & -18);

2.1.3.3) Add 0.1 g l^{-1} fluorescein sodium.

NOTE: The lower layer will be now be opaque in appearance and have a density of approximately 1012.9 +/- 1.2 kg m^{-3}.

2.1.4) *Ex-situ* preparation of light upper layer. To the contents of container *B*:

2.1.4.1) Add $MnCl_2$ salt to achieve a concentration of 0.06 mol $MnCl_2$ per liter of water (approximately 12 g of $MnCl_2$ per liter of water);

NOTE: The upper layer will be transparent in appearance and have a density of approximately 998.2 +/- 0.5 kg m^{-3}.

2.1.5) To vary the viscosity of the fluid layers, add glycerol $C_3H_8O_3$ in equal amounts to each layer until the desired viscosity is attained. Typical viscosities lie in the range 1.00×10^{-3} — 21.00×10^{-3} Pa s. The viscosity of each layer is the same.

NOTE: The mixtures may be safely stored in their separate containers until required.

2.1.6) *Ex-situ* preparation of density stratification.

2.1.6.1) Add 300 ml of the contents of container *A* to the cylindrical inner tank (see Fig. 2).

2.1.6.2) Immerse the flotation boat's sponge in fluid from container *B*.

NOTE: After (2.1.6.2) the procedure is time sensitive, so do not carry out any further steps until all the magnet and the lighting, recording and mechanical mechanisms are ready.

2.1.6.3) Lift the flotation boat out of the container *B* and, when it has stopped dripping, carefully place the flotation boat on top of the layer of dense fluid in the inner cylindrical tank.

2.1.6.4) Begin to add light-layer fluid from container *B* to the flotation boat at a flow rate of 3 ml/min. Gradually increase this flow rate as the flotation boat lifts away from the interface between the two layers. Maintain a slow enough flow rate that the interface is not disturbed by the increased momentum of the fluid flow, but fast enough that this process takes no more than 20 min. Keep filling until the upper layer contains 320 ml of fluid.
NOTE: The lower layer will be at a depth of approximately 33 mm, and the upper layer will be at a depth of approximately 39 mm.

2.1.6.5) Carefully lower the lucite lid into the upper layer such that the layer depths of each layer are equal. Allow fluid and air to flow through the bleed holes, ensuring that no air is trapped beneath. Observe a layer (approx 6 mm) of clear light layer liquid on top of the lucite lid.
NOTE: If the process has been successful there will be two layers of liquid of equal depth with a sharp interface between them. The thickness of the diffusion layer at the interface will be less than 2 mm at this stage.

2.1.7) Fill the outer tank with clear distilled water to a height 6 mm above the lucite lid of the inner tank. Upon observing square-on there will be no curvature-induced parallax resulting from the inner cylindrical tank.
NOTE: Since the liquids in each layer are continuously diffusing across the interface at this point, proceed immediately to the following steps.

2.2) Spin-up of the stratification

2.2.1) Place the experimental tank on the platform.

2.2.2) Position the arrangement with the copper cylinder in the bore of the magnet, the drive shaft through the keyhole orifice in the track and the holding pin in position. Ensure that the tank is far away (60 cm) from the magnet such that the magnetic forces on the liquids are negligible at this position.
NOTE: Carrying the experimental tank containing the stratification presents few difficulties; long, low amplitude, sloshing waves set up by walking with the tank will decay away, having negligible effect on the quality of the interface achieved when floating the upper layer on.

2.2.3) Turn on the motor, increasing the rate of rotation at 0.002 rad s^{-2}, spinning-up the fluid to the desired rotation rate. For the rotation rates in [16] the spin-up time was of the order 20 min — 60 min. The fastest rotation rate used was 13.2 rad s^{-1}.

3) Execution of experiment

3.1.1) Ensure that the magnet is indicating a field strength of 1.2 T, and that at the height at which the instability is initiated the field gradient is $(\text{grad } B^2)/2 = -14.3\ \text{T}^2\ \text{m}^{-1}$, where *B* is the magnetic induction.

3.1.2) Ensure that the video camera is arranged such that when the drive shaft is in its lowest position either the side view of the experiment is in focus, or a plan view is in focus through a mirror placed above the experiment.

3.1.3) Ensure the ambient lighting is at the correct levels, such that none of the image captured by the camera is saturated, but that the full response is used (grayscale intensities in the range 0—255).

3.1.4) Begin video recording (240 fps). Use a remote control to prevent moving the camera while operating the record function.

3.1.5) Remove the holding pin, allowing the tank to descend, while rotating, into the magnetic field.

4) Reset experiment

4.1) Reset experimental rig

4.1.1) Use the remote control to stop the video recording.

4.1.2) Save the movie file to disk.

4.1.3) By hand, lower the voltage to the motor so that it slows to a standstill. Perform this gradually so as to prevent spillages.

4.1.4) Remove experimental arrangement from magnet.

4.1.5) Dispose of the mixed liquid layers appropriately (see Manganese Chloride Tetrahydrate MSDS).

4.1.6) Rinse the tank with water (it does not need to be distilled), until all traces of salts have been washed away. Avoid direct skin contact with liquids.

4.1.7) Dry the tank carefully with tissue paper to ensure that no residue is left that may contaminate subsequent experiments.

5) Image Processing

5.1) Extract the individual images from each movie frame and save in lossless .png format. Mask out any unwanted areas of each frame, for example the platform or copper cylinder.

5.2) Calculate the two-dimensional auto-correlation function[16] of each image frame for 2 s after initiation of the instability using a discrete Fast Fourier Transform. Record the minimum, mean, and maximum value of the observed wavelength for the rotation rate of the experiment and the viscosity of the fluid layers.

REPRESENTATIVE RESULTS:

Fig. 4 shows the development of the Rayleigh-Taylor instability at the interface between the two fluids, for four different rotation rates: Ω = 1.89 rad s^{-1} (top row), Ω = 3.32rad s^{-1}, Ω = 4.68 rad s^{-1}, and Ω = 8.74 rad s^{-1} (bottom row). The interface is shown evolving in time from t = 0 s (left hand column) with increments of 0.5 s to *t* = 3.0 s (right hand column). The right hand column therefore represents 0.90, 1.59, 2.23, and 4.17 complete revolutions respectively from top to bottom row.

At early times (*t* ~ 0.5–1.0 s) a perturbation to the interface can be seen which exhibits a dominant length scale. Structures reminiscent of snake-like convection rolls[17] can be observed. Despite the center of the tank becoming unstable first there is no clear initiation at the center of the tank; the instability, to a good approximation, is initiated across the whole extent of the tank. (At the highest rotation rate some reflection from the lighting rig can be observed, this is unavoidable with the implemented configuration and occurs due to the curvature of the free surface of the fluid above the tank lid.)

It is apparent that with an increase in rotation rate, the observed instability decreases in length scale. At the lower rotation rates the paths followed by the initial disturbance structures have significant radial deviation, meandering in towards the center of the tank and back out to the side walls again. At the lowest rotation rates the instability is more cellular than serpentine. As the rotation rate is increased the cellular initial perturbation is no longer observed and a more serpentine-like structure appears. With increasing rotation rate the width of these structures decreases. It can also be observed that the amount of radial meandering decreases too. It can be seen that, for the rotation rates shown, the instability develops radially first with the azimuthal perturbations becoming more pronounced as time evolves. By the time *t* ≈ 3.0 s it is difficult to distinguish which structures arose due to a radial or azimuthal perturbation.

The key observation from the images is that the observed length scale of the structures is smaller for greater rotation rates. We can also see the strength of the technique in that the instability does not develop from a vortex sheet created by a lock-removal.

Fig. 5 shows images from a series of experiments keeping the rotation rate fixed (Ω = 7.8 ± 0.1 rad s^{-1}), but varying the fluid viscosity. The ratio of the viscosity of each layer compared to the viscosity of water, $\mu/\mu_{W,}$ varies from 1.00 (top row) to 20.50 (bottom row) and the time of each image varies from *t* = 0 s (left column) to *t* = 1.5 s (right column). It is apparent that as the viscosity of the two layers is increased the observed length scale increases. In the most viscous case shown the observed length scale is approximately 18 mm compared to the 6 mm length scale observed in the least viscous case. It can also be seen that in the most viscous case there appears to be a strong wall effect. We observe a general trend from short to long wavelength instability as viscosity is increased.

The observed instabilities have a wavelength which changes slowly in time and which we measure experimentally via an auto-correlation of each image in the movie of the experiment. The auto-correlation is computed from a two-dimensional discrete Fast Fourier Transform of the image intensity. Light regions of the image represent peaks in the instability, and dark regions indicate troughs. A maximum in the auto-correlation is therefore a measure of the instability wavelength that is of key importance as the dispersion relation for the Rayleigh-Taylor instability shows that the growth rate of a given mode of instability depends upon its wavelength. Fig. 6 shows representative measurements of the observed wavelength of instability for varying rotation rates. We observe that as the rotation rate increases the observed wavelength of instability decreases to a lower threshold of approximately 6mm for rotation rates greater than approximately 4 rad s^{-1}.

FIGURE LEGENDS:

Figure 1: Qualitative effect of rotation on the Rayleigh-Taylor Instability. The image on the left hand side is of the Rayleigh-Taylor instability developing in a non-rotating system. The instability develops in time, forming large vortices that transport the ‘denser’ (green) fluid downwards. The image on the right hand side is of the same fluids, and therefore the same gravitational/magnetic instability, but here the system is rotating. The effect of the rotation can be seen to restrict the size of the vortices that form and inhibit the bulk vertical transport of fluid. The times shown are 1.92 s and 3.52 s after initiation on the left hand side and right hand side respectively. The tank diameter is 90 mm, and the rotation rate in the right hand image was 2.38 rad s^{-1}.

Figure 2: Experimental set-up. A cylindrical tank contains the two liquid layers. A Lucite lid forms a solid lid for the two layers. Fluid above the lid helps to remove reflections and glare from the Lucite. The cylindrical tank is immersed in distilled water in a rectangular outer tank. These tanks are placed on a platform and spun-up above the magnet where the magnetic forces are negligible. The platform is spun by an off-center motor rotating a keyhole shaped slip-bearing. To begin the experiment the pin is removed and the experiment descends under its own weight into the magnetic field, simultaneously rotating. (This figure has been modified from [16].)

Figure 3: Flotation “Boat”. The flotation boat is made by hot-gluing a dense sponge layer (yellow) to the underside of polystyrene walls (gray) to make a “boat”. The light upper layer fluid will slowly diffuse through the sponge, floating on top of the dense lower layer with minimal mixing between the two layers. The stratification can be further improved by placing a layer of tissue paper (blue) on top of the sponge layer to further diffuse the momentum of the incoming light fluid layer.

Figure 4: A sequence of images of the developing instability from the second series of experiments demonstrating the effect of increasing rotation rate. The rates of rotation increase from $\Omega = 1.89$ rad s^{-1} in the top row to $\Omega = 8.74$ rad s^{-1} in the bottom row. The times shown are measured from the time that the onset of instability is observed. The scale bar shows a length of 10 cm in steps of 1 cm. The diameter of the black circle represents a length

of 10.7 cm. (This figure has been modified from [16].)

Figure 5: A sequence of images showing the effect of varying fluid viscosity on the instability. The rotation rate was fixed at Ω = 7.8 ± 0.1 rad s^{-1} for each experiment, and the time shown is at intervals of 1.5. The middle row shows the instability in a system that has viscosity approximately 8.36 times that of water. In the top row the viscosity of the system is approximately 20.50 times that of water. It can be seen that the observed length of the instability scale increases with increasing fluid viscosity. The scale bar shows a length of 10 cm in steps of 1 cm. The diameter of the black circles represents a length of 10.7 cm. (This figure has been modified from [16].)

Figure 6: The dominant observed wavelength at the onset of the instability. We observe a lower threshold for the scale of the instability at approximately 6 mm for all rotation rates greater than approximately 4 rad s^{-1}. The error bars indicate maximum and minimum measured wavelength over the first 2 seconds after initiation of the instability. (This figure has been modified from [16].)

DISCUSSION:

There are two critical steps within the protocol. The first is 2.1.6.4. If the light layer is floated on the dense layer too rapidly then irreversible mixing of the two miscible fluid layers takes place. It is essential that this is avoided and that a sharp (<2 mm) interface between the two layers is achieved. The second critical step is 3.1.5. If the experiment is released toward the magnet without being fully spun-up into solid body rotation or without the visualization and image capture apparatus in position and on stand-by then repeat the procedure (2.1.6).

The composition of the liquid layers, the magnetic field strength and the motor performance can all be verified prior to beginning to make the stratification (2.1.6). Most practical difficulties can therefore be resolved before commencing any given experiment. We have found a small and undesirable variation in descent speed into the magnet field however. Typically, faster rotating experiments descend slightly more slowly into the magnetic field than slowly rotating experiments. It may be necessary to modify the slip bearing though we found greasing did not help reduce the variability in descent speed. We found that placing a small (non-magnetic) weight on the platform allowed us to achieve consistent descent speeds of 10±1 mm s^{-1} for all of the experiments.

The main limitation of the apparatus is that the magnetic field cannot be applied instantaneously; the superconducting magnet requires 1-2 hours to energize. Ideally, once the fluid layers are spun-up we would instantly apply a strong uniform magnetic field to the tank to trigger the instability. For this reason, in this experiment, the tank was lowered at uniform velocity into the magnetic field.

Despite the necessity for lowering the experiment into the magnetic field, this technique has a number of advantages over established methods. The method is both smooth, unlike rocketry methods[2], and requires no lock, as with LEM methods[3], but unlike lock-release methods. This is a significant advantage in rotating Rayleigh-Taylor flow as the initial spun-up state of the fluid layers has a paraboloidal interface. Furthermore, by not having a lock the difficulties associated with the imparted vortex sheet induced by lock-removal are avoided. We believe our experiments to be the first experimental realization of the effects of rotation on the Rayleigh-Taylor instability.

Our technique has been developed with a view to applications in classical fluid mechanics thus far. We have used weakly paramagnetic and diamagnetic liquids to manipulate the effective weight of fluid parcels. We have, to date, been able therefore to consider the magnetic field and the fluid mechanics to be de-coupled. Future directions for research using this technique include considering the behavior of ferrofluids and their interaction with the magnetic field in the rotating Rayleigh-Taylor instability set-up, where this de-coupling is no longer valid.

ACKNOWLEDGMENTS:

RJAH acknowledges support from EPSRC Fellowship EP/I004599/1, MMS acknowledges funding from EPSRC under grant number EP/K5035-4X/1.

DISCLOSURES:

The authors have nothing to disclose.

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