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Original Article

FLUID INSTABILITIES AND TRANSITION

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Abstract:

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Keywords**: **Instability, Turbulence, Transition, Rayleigh-Taylor, Richtmyer-Meshkov, Kelvin-Helmholtz, Orr-Sommerfeld.

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Introduction:

Fluid instabilities show up everywhere in nature. Fluid flow will start off laminar and smooth and then quickly transition to an irregular pattern eventually transitioning to turbulence. All you have to do to see its prevalence is look up at the sky on a cloudy day when the conditions are right such that there will be large clouds rolling past one another and spirals develop. This is the Kelvin-Helmholtz instability (where there is a shear between two fluids with different relative veloc ities). Another common instability is when you add cold milk to hot tea. The larger density of the cold fluid falls and displaces the hotter less dense fluid, and it is clear that specific structures form.

Discussion:

A similar phenomenon occurs for contained flows, such as in pipes, or as in unbounded flow, such as that over a wing or out of a faucet. In all of these cases, solving too simplified equations of motion would lead to the solution that our ignorant view of the world might expect, where the fluids retain their smooth laminar structure, but this does not happen. Instead a specific size and shape of structure forms, usually in a periodic fashion from this we see that a pressure gradient across a density gradient can create vorticity (this is a buoyancy-driven instability) and a velocity gradient can create vorticity as well (shear-driven instability).

Methodology:

Both of these require a perturbation at the interface to develop. 2.1 Buoyancy-driven instabilities Buoyancy-driven fluid instabilities occur in a stratified fluid system when the light fluid is accelerated into the heavier one often by means of a pressure gradient. One way to understand this form of instability is from the baroclinic torque present at the stratified, perturbed interface. This baroclinic torque is created from the misalignment of the pressure and density gradients at the perturbed interface. Whenin the unstable configuration, for a particular harmonic component of the initial perturbation, this torque between the two fluids will create vorticity. This vorticity will impose a velocity field that will tend to increase the misalignment of the gradient vectors, which in turn will create additional vorticity, leading to more misalignment. This is observed in Eq. 4,

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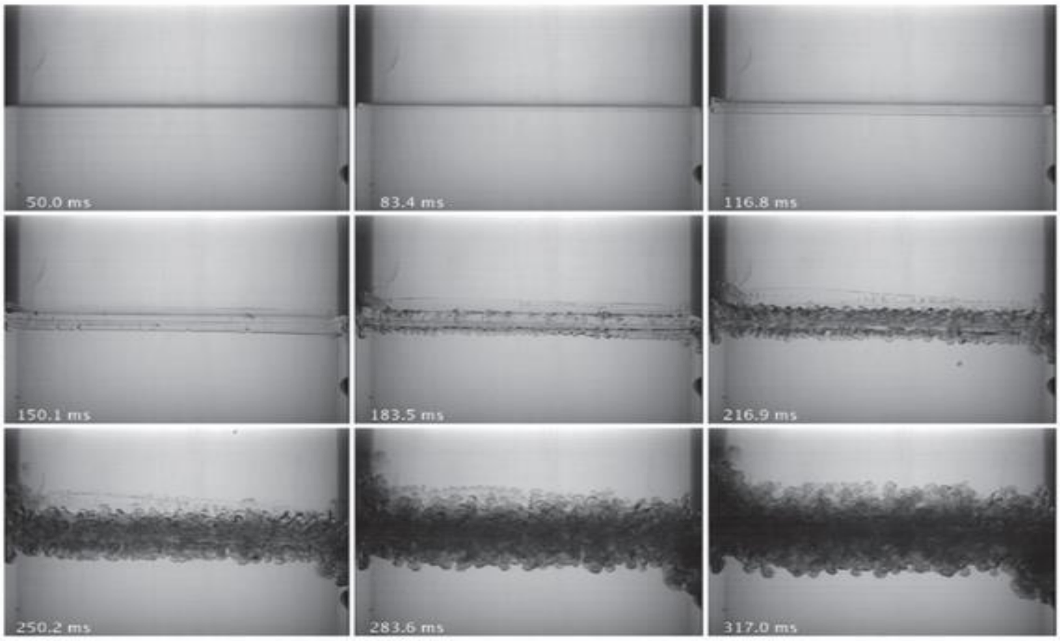

Figure 2.
Experimental images of Roberts [1] in which an unstable Rayleigh-Taylor configuration is formed where the light over heavy fluid system is made unstable. A progression of a specific wavelength is observed to develop and eventually a turbulent mixing region.

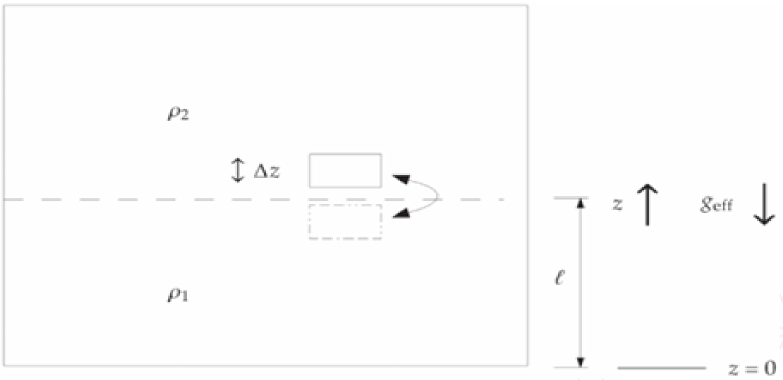

Figure 3.
A fluid particle in the upper fluid is interchanged with one from the lower fluid in a stratified system with downward acting acceleration [1]. Once displaced to the bottom fluid, the force balance on the particle might yield a configuration where it will continue to move from equilibrium. If $\rho_2 > \rho_1$, the fluid particle is accelerated further downward and the system is unstable. If $\rho_2 < \rho_1$, the fluid particle is pushed back across the interface and the system is stable.

with one from the lower fluid where the density is ρ_1, from Newton's second law, for the initial particle, we obtain (noting that the pressure forces have changed since we are in the lower fluid),

$$\begin{aligned}\left\{\left[P_0 - \rho_1 g_{\text{eff}} z\right]A - \left[P_0 - \rho_1 g_{\text{eff}}(z + \Delta z)\right]A\right\} - \rho_2 g_{\text{eff}} \Delta z A \\ = \rho_1 g_{\text{eff}} \Delta z A - \rho_2 g_{\text{eff}} \Delta z A = (\rho_2 \mathcal{V} + \rho_1 \beta)\frac{d^2 z}{dt^2}.\end{aligned} \tag{6}$$

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Conclusion:

Where if we neglect the velocity gradient in the base flow as we have not considered that here, an increase in vorticity will be realized if 1 ρ ! 2 ∇ρ ∇P !,which means that for instability ∇P ! ∇ρ !ρ1, the fluid particle is accelerated further downward and the system is unstable. If ρ2 ρ2, the fluid particle is pushed back to where it came from (the system is stable). However, if ρ2 >ρ1, the fluid particle is pushed further away from where it originated and the system is unstable. This concept of a fluid particle moving across the interface resulting in instability can be extended to the deflection of an interface in the Rayleigh-Taylor instability and illustrates the necessity of an initial perturbation on the interface since there is no mechanism to interchange a fluid particle across the interface. An example of a simple interface is shown in Figure 4, where the coordinate system is the same as in Figure 3. The interface has been deformed, simulating perturbations on the interface. For sim plicity the geometry of the interface deformation has been chosen to be rectangular (the derivation here can be generalized to an individual Fourier mode so that any interface deformation would follow the same behavior). The fluid particle relocation is caused by deformation of the interface. The pressure force on the fluid particle's lower surface is P0 ρ1geffℓA and is P0 ρ1geffℓ ρ2geffΔzAfor the upper surface. The force due to the weight of the fluid particle (which has density ρ1)is ρ1 Vgeff ¼ ρ1ΔzAgeff. Note that once again we have chosen the interface deformation shape to simplify the calculations. We can then form the equation for the force balance as, ρ2geffΔzA ρ1geffΔzA ¼ ρ1 V þρ2β ð Þ d2z dt2 : (7) In this arrangement, if ρ1 >ρ2, the fluid particle is pushed back to its original position (and thus the interface is brought back to equilibrium, so the system is 5 Engineering Fluid Mechanics Figure 4. Here an interface is shown [1] downward acting acceleration of a fluid particle displaced from the lower to upper fluid by means of interface deformation. If ρ2 >ρ1, the system is unstable (the fluid particle moves up farther from the center further deforming the interface). If ρ2 ρ1, the fluid particle is pushed further away from where it originated (deforming the interface further) and thus the system is unstable. From this derivation, it is seen how the instability progresses, but does not say much about the initial stages (for that we need to use linear stability theory, Section 2.1.4) or late time. For the late time development, from Eq. (7), we can make some back of the envelope assumptions and arrive at a well-known expression for the late time turbulent Rayleigh-Taylor instability. If we assume β in the added mass is the same as the Volume and rearrange and integrate twice, we can arrive at the well-known expression: h ¼αAgt2, (8) where α is the growth constant and A is the Atwood number (derived from the ratio of density difference to sum). This equation has been consistently found to fit the Rayleigh-Taylor instability in late time after it has become turbulent [2]. 2.1.2 Richtmyer-Meshkov instability We can extend our understanding of the Rayleigh-Taylor instability to that of the Richtmyer-Meshkov instability (RMI). From the vorticity argument for the instability it is obvious that all that is needed is ∇P ∇ρ

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