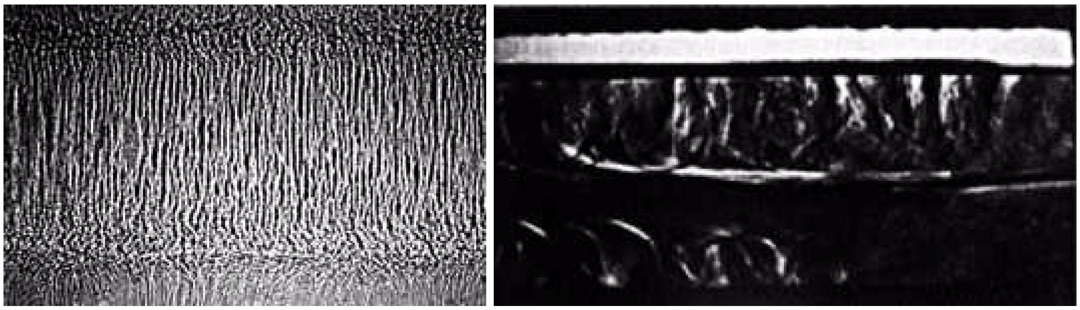
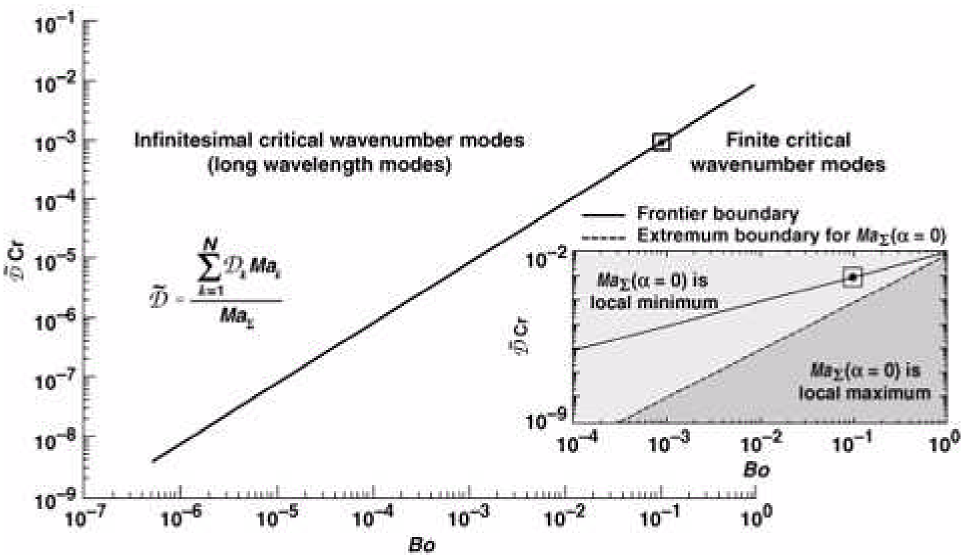
Onset of Convection Due to Surface Tension Variations in Multicomponent and Binary Fluid Layers



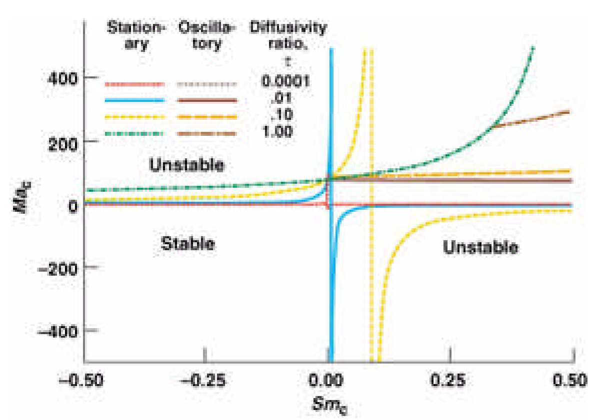
Left: Salt fingering formation. Right: Onset of double-diffusive instability (ref. 1). (Copyright Professor C.F. Chen, Univ. of Arizona; used with permission.)

Under certain conditions, such as in thin liquid films or microgravity, surface tension variations along a free surface can induce convection. Convection onset due to surface tension variation is important to many terrestrial technological processes in addition to microgravity materials processing applications. Examples include coating, drying crystallization, solidification, liquid surface contamination, and containerless processing. In double-diffusive and multicomponent systems, the spatial variations of surface tension are associated with two or more stratifying agencies, respectively. For example, both temperature and species (concentration) gradients are associated with convection in the solidification of binary alloys or salt ponds. The direction of the two (or more) gradients has a profound effect on the nature of the flow at or slightly beyond the onset of convection, as illustrated in the preceding photos. In the photo on the left, salt fingers have formed at the interface between a 10-percent sugar-water solution over a 12-percent salt-water solution. In the photo on the right, a salt-water solution, the temperature has increased from bottom to top while the salt concentration increased from top to bottom. In this case, oscillatory instability occurred via a "Hopf bifurcation," resulting in the diffusive convection pattern observed. (We are indebted to Prof. C>F> Chen for providing these photographs.) The fluid properties and operating conditions that lead to a specific convection onset behavior can be predicted from neutral stability curves and maps, like those of the remaining figures.



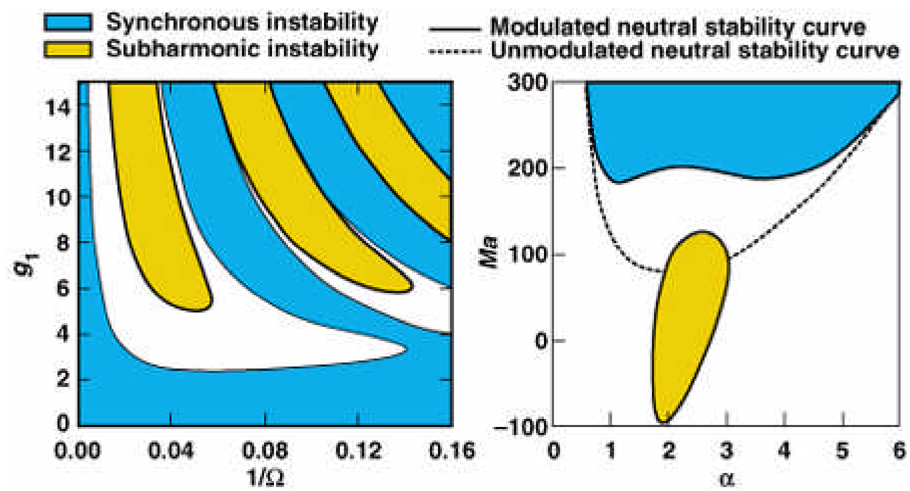
Frontier point boundaries in (Bo, Cr) space. The dashed line in the insert is the extremum boundary for Ma_S(a = 0). Above the dashed line, Ma_S(a = 0) is a local minimum; below this line, it is a local maximum.

Our recent work at the NASA Lewis Research Center focused on characterizing surface-tension-induced onset of convection, often referred to as Marangoni-Benard convection. Exact solutions for the stationary neutral stability of multicomponent fluid layers with interfacial deformation were derived. These solutions also permit the computation of a boundary curve that separates the long and finite wavelength instabilities, which is shown in the graph on the right. Computing points along this boundary using the exact solution (when possible) is more efficient than the typical numerical approaches, such as finite difference or spectral methods. Above the curve, a long wavelength instability was predicted, suggesting that convection would occur principally through one large flow cell in the layer, whereas below the curve, finite wavelength instabilities occur which suggest multiple finite-sized circulation cells. For many common liquids with layer depths greater than 100 µm, finite wave instability is predicted under terrestrial conditions; however, with little exception, long wavelength instability is predicted in microgravity for the identical fluid systems.



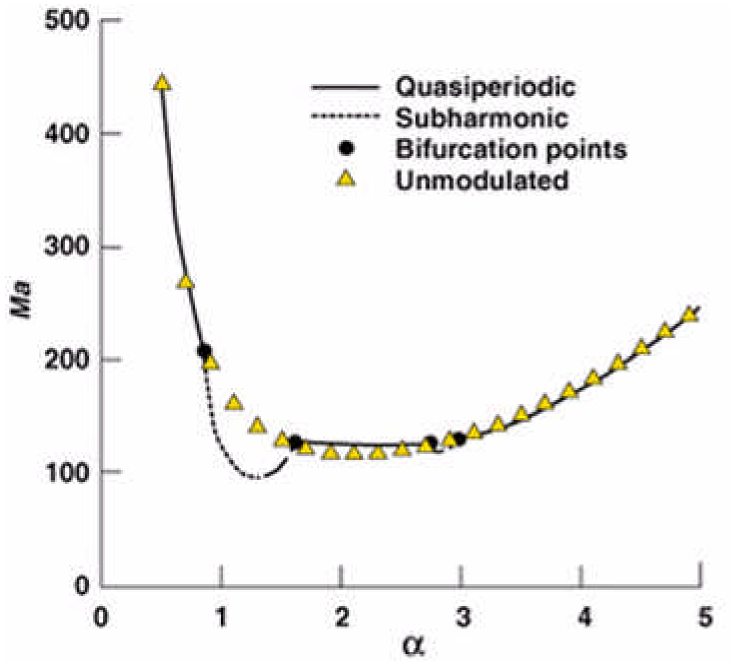
Effect of diffusivity ratio, t, on stability maps in (Sm_c, Ma_c) space, where Sm_c and Ma_c are the critical surface tension Soret number and Marangoni number, respectively. The concentration difference is induced by an applied temperature difference. Oscillatory instability occurs above the oscillatory boundaries in the upper right quadrant.

The governing equations for double-diffusive systems that include cross-diffusion, such as the Soret and Dufour effects, were rescaled for limit-zero buoyancy, and exact solutions were derived for the stationary neutral stability of these systems. An extensive investigation of stationary and oscillatory instabilities was performed. It spanned parameter values associated with binary systems, such as lead-tin alloys, to those associated with water-alcohol mixtures. Stability maps similar to the one shown in the preceding graph were developed to characterize the fluid behavior. Exact solutions for the location of the asymptotes, also shown in this graph, are suitable for validating the computational schemes that will ultimately be used to analyze the behavior of more complex systems.



Left: Stability boundaries in (1/W, g_1) space; a = 2, Ra = 1000, Ma = 118.77, Pr = 1, g_o = 0. Right: Neutral stability curve; Pr = 1, g_o = 0, g_1 = 5, Ra = 1000.

Researchers at Lewis are also examining the response of a fluid layer to time periodic accelerations or gravity modulation. For Marangoni-Benard type convection, gravity modulation can stabilize an unstable (or destabilize a stable) unmodulated system. Results such as those in the preceding stability plots can be used to assess the sensitivity of these fluid systems to residual accelerations. The response of a double-diffusive fluid system to modulation can be more complex, exhibiting regions of quasi-periodic, subharmonic, and synchronous behavior along the neutral stability curve, as shown in the following graph. For more information and definitions of symbols used in the figures, see references 2 to 4.



Neutral stability curves for gravity-modulated double diffusion; Ms = -700, Pr = 10, D_{22} *= 0.1, Ra = 1000,* $g_0 = 0$*,* $g_1 = 1$*, W = 5.*

Find out more:
http://zeta.grc.nasa.gov/6712/home6712.htm
http://zeta.grc.nasa.gov/6712/people/skarda.htm

References

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